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16. Abstract

Data produced from this study are analyzed statistically for trends showing significant influences on the bond performance in bonded concrete overlays (BCO). The study examines the effects of three bonding agents and their application rates, moisture, three substrate surface textures, two intervals between the application of the bonding agents and the overlay, and three substrate temperatures. Recommendations are given to increase the likelihood of well-bonded BCO when placement must occur in adverse conditions.

Bond strengths are compared, using three field and two laboratory methods. The advantages and disadvantages of each method are discussed.

A computerized remote telemetric data acquisition system for collecting field data in heavily congested highway construction projects was developed and implemented into a concurrent BCO construction project.

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AN INVESTIGATION OF VARIOUS FACTORS AFFECTING BOND IN BONDED CONCRETE OVERLAYS

by

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Research Report Number 920-5

Research Project 3-12D-84-920

Evaluation of the Performance of the Bonded Concrete Overlay on Interstate Highway 610 North, Houston, Texas

conducted for

Texas Department of Transportation

by the

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

June 1992

NOT INTENDED FOR CONSTRUCTION,
PERMIT, OR BIDDING PURPOSES

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PREFACE

Bonded concrete overlays (BCO) are rapidly becoming a preferred strategy for Texas highway rehabilitation projects. These overlays have worked well in most areas, but have had occasional problems with debonding and subsequent cracking. This report describes a large-scale laboratory study of many of the factors that are suspected of influencing the bond between overlays and their substrates. Additionally, several bond strength test methods are compared. The study was made in an effort to provide timely information to the Texas Department of Transportation for assistance in specifications and concurrent construction.

LIST OF REPORTS

Research Report 920-1, "Design Analysis for Rehabilitation of the CRCP on the Southeast Quadrant of Houston Loop 610," by the Center for Transportation Research staff and faculty, presents existing pavement and support materials characteristics and the development of the most economical design, based on expected traffic over the life of the pavement. October 1986.

Research Report 920-2, "Evaluation of Thin Bonded Concrete Overlay in Houston," by Koestomo Koesno and B. Frank McCullough, presents the findings of a pavement monitoring program on the IH-610 North Houston project. October 1987.

Research Report 920-3, "Monitoring and Testing of the Bonded Concrete Overlay on Interstate Highway 610 North in Houston, Texas," by Kok Jin Teo, D. W. Fowler, and B. Frank McCullough, presents the results of the monitoring and testing program on the two inside lanes on the IH-610 North Houston project. November 1988.

Research Report 920-4, "An Evaluation of Repair Techniques Used for Uncontrolled Longitudinal Cracking and Failed Longitudinal Joints," by Brock E. Hoskins, David W. Fowler, and B. Frank McCullough, reviews long-term results of experimental techniques for repairing major longitudinal pavement distresses. January 1991.

Research Report 920-5F, "An Investigation of Various Factors Affecting Bond in Bonded Concrete Overlays," by David P. Whitney, Polykarpos Isis, B. Frank McCullough, and David W. Fowler, presents results of a laboratory evaluation of over 150 experimental BCO slabs from eight experimental sections of BCO on IH-610 South in Houston. June 1992.

ABSTRACT

Data produced from this study are analyzed statistically for trends showing significant influences on the bond performance in bonded concrete overlays (BCO). The study examines the effects of three bonding agents and their application rates, moisture, three substrate surface textures, two intervals between the application of the bonding agents and the overlay, and three substrate temperatures. Recommendations are given to increase the likelihood of well-bonded BCO when placement must occur in adverse conditions.

Bond strengths are compared, using three field and two laboratory methods. The advantages and disadvantages of each method are discussed.

A computerized remote telemetric data acquisition system for collecting field data in heavily congested highway construction projects was developed and implemented into a concurrent BCO construction project.

SUMMARY

This report concludes the laboratory evaluation portion of a larger BCO study and includes four experiments with over 150 slabs, each measuring 3 feet x 3 feet x 5 inches before being overlaid. Experiments were designed to evaluate materials, application and testing methods, and the environmental effects on BCO bond strengths. Additionally, eight experimental sections were constructed on the South Loop of IH-610 in Houston, Texas. Both short-term construction and long-term performance monitoring methods and equipment were developed and implemented during the course of the study. Conclusions and recommendations consider the test methods and variables that demonstrated significant effects on the bond strengths of BCO.

IMPLEMENTATION STATEMENT

Immediate rehabilitation needs in Houston resulted in frequent cooperative interaction between those conducting the study and the Texas Department of Transportation (TxDOT). Most of the information contained in this report was reported to TxDOT project contact personnel as it was collected in order to assist them in writing specifications and in constructing the South Loop IH-610 BCO. The conclusions and recommendations that result from this study are suggested as a guide for improving the overall performance of future bonded concrete overlay projects.

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CHAPTER 1. INTRODUCTION

This report summarizes the findings of laboratory and field studies conducted under Research Project 920, "Evaluation of the Performance of the Bonded Concrete Overlay on Interstate Highway 610 North, Houston, Texas." In this chapter, a brief background, objectives, and scope of the study are presented.

BACKGROUND

Bonded concrete overlays (BCO) have considerable potential as a cost-effective, long-term CRCP rehabilitation option, particularly on congested, high-volume urban arteries. The Texas Department of Transportation (TxDOT) has a strong interest in optimizing the use of BCO in Texas.

When the laboratory study began, the Houston District of TxDOT had completed two BCO and was in the process of constructing a third one on IH-610. The first BCO on the South Loop, an experimental section, was successful and primarily responsible for proving the feasibility of BCO in Houston. Shortly after the North Loop BCO was finished, delaminations of the overlay were observed. An extensive survey showed that in some areas the debonding was extensive, while in other areas it was not observed. The delaminations, approximately one percent of the total area, have not increased since the first surveys were performed.

A database containing available data for materials and construction variables was established and maintained in Austin by The University of Texas Center for Transportation Research (CTR). An exhaustive study was made to find those variables which adversely affected the bond of the overlay. It was important to investigate all possible causes of the debonding in order to make recommendations for specifications that could prevent the likelihood of extensive debonding of the next overlay, which was scheduled to begin in 1988.

OBJECTIVES

The overall objective of the project was to utilize all available resources so as to determine the requirements for achieving successful bonded concrete overlays on CRCP in the Houston area. Whenever problems developed, CTR provided timely information, made recommendations for investigation into the causes, and suggested corrective or preventative actions. During early meetings between TxDOT planners and CTR personnel, several specific tasks were identified as being important in attaining the overall objectives. The tasks that were the responsibility of CTR are briefly described below.

(1) Specifications Development

  a. Provide Houston District personnel with information and recommendations needed to develop plans, specifications, and estimates.
  b. Assist District personnel with information regarding special provisions and specifications prior to bid lettings.
  c. Assist District personnel with information regarding special provisions and specifications prior to actual construction.

(2) Testing Program

A testing program was conducted to identify those factors that affected bond strengths of BCO and to evaluate the level of influence on bond.

  a. *Laboratory Study*. Experiments were performed in which many small slabs were overlaid and observed under controlled conditions in order to identify those factors that significantly affect bond strength. These experiments were also intended to develop and to evaluate testing equipment and procedures that are necessary to determine bond strengths.

b. *Field Study.* Test sections on IH-610 permitted the implementation and the evaluation of laboratory study findings under actual construction and weather conditions. They also provided conditions for developing and evaluating bond strength test equipment and an automatic data collecting system for monitoring weather conditions that affected the evaporation rate of the concrete overlay as it cured.

(3) Monitoring

a. *During Construction*. Information was provided to Houston District personnel for job control purposes. BCO construction was assessed and recommendations were provided for any field changes as problems occurred. Pertinent construction and weather information was collected and developed into a database.

b. *Performance*. Both short-term and long-term performance has been under evaluation and will continue to be monitored over the life of the pavement.

(4) Documentation

Information specifically pertaining to the implementation of testing results, monitoring procedures, and pavement performance results has been reported through previous Research Project 920 reports and other CTR project reports, as well as through many interim Project 920 technical memoranda.(1-13)

SCOPE OF REPORT

Chapter 2 discusses the selection of materials, the recommended surface preparations, and the application methods for the BCO involved in the study. Since the purpose of the study was to evaluate feasible BCO paving methods under real or simulated environmental conditions, the methodologies required utilization of readily available materials and equipment. These considerations determined the scope of the testing program.

Chapter 3 describes the details of the laboratory study of influences on bond strength for BCO placed on 3-ft-square slabs. The experimental designs for the study are presented, as are the procedures for preparing the specimens and for evaluating their bond strengths.

Chapter 4 details the field trial portion of the study. Specifics pertaining to variables embodied in each full-scale experimental section, as well as their locations, are reported.

Chapter 5 discusses the development of field-monitoring equipment designed to aid in quality assurance for bonded overlay paving. Automated datalogging equipment for monitoring and recording weather conditions during paving is discussed, as are dataloggers for recording pavement shrinkage and temperatures. Field methods for determining bond strengths are also evaluated in this chapter.

Chapter 6 summarizes the development and maintenance of the BCO database, as well as the analysis procedures for all of the test and field data.

Chapter 7 discusses the results, including the effects of the variables studied and the effectiveness and feasibility of the evaluation methodologies.

Chapter 8 gives conclusions and recommendations for future overlays. Further studies suggested by the findings of this study are also presented.

CHAPTER 2. MATERIALS AND APPLICATION CONSIDERATIONS

A bonding agent is often used to increase the bond between the overlay and the substrate. Some of these bonding agents have been in use for years as structural adhesives, while some are being developed as less expensive materials to be used specifically for BCO. The necessity of using specific bonding agents has been debated since before the use of BCO.(14-16) Other groups have reported on the apparent merits of applying one bonding agent or another, or none.

In 1959, the Army Corps of Engineers reported results from an extensive testing program to determine whether grout applications prior to placement of fresh concrete onto hardened concrete gave higher bond strengths.(17) The results indicated that bond was better without grout. The Corps reported results from another similar testing program in 1963, and the conclusions—based upon bond testing (shear, tension and flexure)—were that there were "no significant differences in effectiveness of any joint treatments investigated in this program," and that "therefore, within the limits of the data presented, the most economical joint treatment is as effective as any that are more costly."(18)

In the search for the most economical way to achieve adequate bond strengths, the consideration of materials, construction techniques, and test methods is of primary importance. A brief discussion of these controlled variables follows.

BONDING AGENTS

Whenever debonding of a bonded concrete overlay occurs, the first consideration is how to rebond it with injections of epoxy or bonding grouts. Because of their reported bonding successes, these were natural candidates for priming or pretreating the substrate in the study of enhancing the bond of BCO.

In this study, the performance of BCO that employed three types of bonding agents was compared against those that used no bonding agent. All specimen substrates in the study used the same basic pavement mix design, and the overlays were made using the mix design specified for the South Loop BCO contract. Performances were compared for each of the three surface treatments and temperatures described in Chapter 4.

Portland Cement Slurry

The first bonding agent selected was a portland cement slurry, which was the material specified by TxDOT for all the Houston overlays. The slurry consisted of 11 gallons of water per sack (94 lbs) of Type I cement. No sand was used, even though the slurry was referred to by TxDOT as "grout." For brevity, and to avoid confusion with other grouts used by TxDOT for other purposes, this portland cement bonding slurry will be referred to as PBS throughout the remainder of this report.

Latex

The second bonding agent to be evaluated was a latex-modified bonding slurry. It will be referred to as LBS (latex bonding slurry). LBS consisted of 77.4 lbs of water, 28.2 lbs of Dow Chemical Company's "Modifier A" (a 50 percent water-based latex emulsion), and 94 lbs of Type I portland cement. This formula was based upon TxDOT specifications for PBS and the manufacturer's recommendations for 15 percent latex solids (50 percent of the emulsion weight) based upon the weight of the cement. The reason for including this experimental bonding agent was to determine if the latex modification would improve long-term performance. It has been well documented that latex-modified portland cement concrete (LMC) overlays have been very successful in maintaining their bond to old concrete bridge decks.(19) The incorporated latex is known to improve the adhesion of fresh concrete to old concrete.

The use of the LBS is similar to what is typically done to prepare a bridge deck for LMC overlays. Some of the fresh LMC is dumped from the truck onto the deck surface and some of the mortar is broomed thinly, but thoroughly, over the deck as a precoating. The unembedded coarse aggregate is shoveled off and the deck is then overlaid with the rest of the LMC before the precoating reaches initial set. This precoating of the deck surface is recommended by all latex suppliers as an essential procedure for proper bonding of LMC overlays. For this reason, after many conversations with concrete experts at the Portland Cement Association, Purdue University, and with technical representatives from the three major U.S. latex emulsion manufacturers, as well as with laboratory engineers and technicians at the California Department of Transportation, it was decided that, although no one contacted had ever used a latex-modified bonding slurry, the idea seemed to be an improvement over PBS.

Epoxy

The third material to be evaluated was an epoxy bonding agent specifically sold for structural bonding of fresh concrete to hardened concrete. This type of system is specified by the State of California for their bonded concrete overlays and is a more expensive method of ensuring better bond properties. TxDOT specifies this epoxy as a Type VI concrete adhesive.

Water

Water was investigated as an aid to adequate bonding. A water spray is commonly specified to ensure that there is no significant water loss from the fresh concrete to the dry substrate interface due to absorption. Additionally, the base surface temperature is lowered by the water, which should prevent flash-setting of the fresh concrete at the interface.

TEXTURE

Because bond strength is affected by surface texture, bond characteristics were investigated for three surface preparation methods considered for BCO applications.

Cold-Milling

The first method, cold-milling, is the procedure by which approximately 98 percent of the South Loop substrate has been and is currently specified to be treated. This method employs a large revolving drum fitted with tungsten carbide teeth to chip away the top surface of the pavement. It has been the most widely used method for large areas of concrete surface preparation where deep surface scarification is specified. Advantages of this method include its ability to expose any marginally stable areas near the top surface of the substrate that might otherwise not be readily apparent during the surface preparation by other methods, and the widespread availability of the cold-mill machine itself. The method's major drawbacks are (1) the high volume of dust or contamination left which must be removed by sandblasting or shotblasting, and (2) the potential for creating delamination of the concrete caused by substrate microcracking that results from the heavy impact of the scarification process.

Shotblasting

The next surface preparation method evaluated was shotblasting. This method is newer to the transportation pavement applications but has been used extensively in plant environments where polymer concrete or chemically resistant mortars are used for overlaying deteriorating concrete floors. Because these materials bond better to clean concrete substrates than the fresh portland overlays, scarification systems that leave only cleaned and dry concrete are essential. For industrial floor overlays, deep surface scarification for added mechanical advantage in bonding is unnecessary and much more costly than sandblasting or shotblasting. In the BCO application, it was hoped that the bonding agents would help the overlay bond sufficiently without the deep scarification produced by the cold-milling process. Although this method is relatively new for transportation pavement applications, its recent use has been extensive for pavement BCO in other states. In particular, the Iowa DOT, which is generally acknowledged as the leader in BCO, employs this method as the standard BCO surface preparation. It was also the method specified for the earlier BCO on the North Loop in Houston.

The shotblasting process involves a spinning drum that throws steel shot against the surface of the concrete. A vacuum and a magnetic pickup are employed simultaneously to remove the debris and shot from the concrete surface and to separate the shot from the debris for continuous reuse. The debris and dust are collected in a bag, a process which leaves the surface clean and minimizes air pollution. The effect of shotblasting on the substrate is the same as that produced by sandblasting except that a more uniform treatment results. There is also no cleanup of debris or sand when the blasting is finished. Typically, a smooth surface remains, and the mortar and coarse aggregates are cleanly exposed.

The terms "light shotblasting" and "heavy shotblasting" are used throughout this report. Light shotblasting indicates the same degree of surface preparation that was specified for the North Loop BCO Project and for BCO placed in other states. Specifically, "over these areas the entire existing concrete pavement surface shall be cleaned with a shotblasting machine capable of removing all dirt, oil, paint and other foreign material, as well as any laitance or loose concrete from the surface edges against which new concrete is to be placed." The CTR-recommended amendment to the specification added, "A Type I shot blast treatment shall produce a surface uniform in appearance and having a surface texture of 0.025 inch or less when measured by Test Method Tex 436A. A Type II shot blast treatment shall produce a surface which is uniform in appearance and having a surface texture of 0.080 inch or more when tested by Test Method Tex 436A. The number and location of the texture tests shall be as directed by the engineer."

Heavy Shotblasting

A third surface treatment that resulted from previous experimentation uses heavy shotblasting. A coarsely textured substrate surface resulted from having the shotblaster engaged for a longer period of time over the treated surface and/or from using larger shot. This procedure enabled the shot to blast away more of the mortar from around the coarse aggregate, allowing the coarse aggregate profiles to protrude about 3/8 in. above the surface of the surrounding mortar. This texture was actually coarser than the cold-milled surface, and it was less expensive to achieve. Of course, smoother, harder aggregates such as uncrushed river gravel might provide better bond surfaces after the cold-milling process fractures the exposed faces than after heavy shotblasting only etches the round surfaces.

TEMPERATURE

Temperature is one of the variables expected to affect bond strengths. It also is one of the most difficult variables to predict or to control.

High Substrate Temperatures

Under the summer sun in Texas, concrete substrate surface temperatures may reach 140°F or higher. It was hypothesized that these high temperatures might cause premature setting or flashing of the PBS, LBS, and possibly even the overlay concrete at the interface. Another temperature-based hypothesis predicted thermal-induced shear failures from extreme temperature shifts at the overlay. Some daily temperature shifts were expected to be severe enough to cause flash set, which results in reduced shear bond strength when the hot substrate is significantly higher than the ambient temperature.

Low Substrate Temperatures

A north wind in the winter may drop the ambient temperature by 40°F in a few hours. Low temperatures were considered because of the concern that when paving is performed at marginally low and falling temperatures, bond strengths may not develop quickly enough at the cold interface to resist stresses caused by contraction or shrinkage.

EVAPORATION RATE

Evaporation rate has long been considered an important factor that influences the quality of concrete. This influence may be especially true on an overlay where the surface-to-volume ratio is high. Shrinkage cracking is the typical result of concrete in which the water evaporates faster than the excess mix water can bleed through the matrix capillaries to the surface. Since every crack has the potential of propagating through the overlay, and of thus creating a new boundary condition from which delamination could be initiated, evaporation rate seemed to be an important environmental variable that could significantly affect the bonding of BCO.

CHAPTER 3. LABORATORY STUDIES

EXPERIMENTAL DESIGN

Considering the relatively large number of control variables to be incorporated into the study, it was important to develop an experimental design that would minimize the number of slabs required to provide statistically valid conclusions. The planning resulted in one large experiment that investigated the various bonding agents and construction variables, and led to three smaller satellite experiments that examined isolated problems.

The Main Experiment

This large study was intended to examine a wide variety of factors at two and three levels. Consequently, a statistically derived fraction of the full factorial was designed to reduce the number of specimens to accommodate the time and money constraints of the project without sacrificing accuracy. The experimental factors and their levels are shown in Table 3.1.

The full factorial of the experiment would have required 162 treatment combinations (two levels for one factor, and three levels for four factors, or $2^1 \times 3^4 = 162$). By designing a one-half fractional factorial, 81 treatment combinations can be evaluated, and all of the main effects, as well as all of the 2-factor interactions, can be measured. However, all higher factor interactions must be considered insignificant for this fractional factorial, though they may, in fact, be proved significant. The specific treatment combinations that were evaluated are listed in Table 3.2.

Additionally, there seemed to be little need to evaluate the treatment combination of low substrate surface temperatures with bonding agent application times of less than two minutes, since these short intervals seem to have no significant effect on bond strengths. Thus, by subtracting 9 specimens (the 3 specimens at the low temperatures that were multiplied by the 3 materials at application times less than 2 minutes), the main experiment can be run with 72 specimens instead of the original 162. Trial analyses were run using

Table 3.1 Main experiment factors and levels

Factors	Number of Levels	Description
Bonding agents	3	PBS, LBS, and epoxy
Textures	3	Cold-milled, normally shotblasted, and severely shotblasted
Application rates of bonding agents	2	High and low
Time of application of bonding agents	2	< 2 minutes, and 5-30 minutes
Surface (substrate) temperature	3	50-60°F, 90-100°F, and 125-140°F

fictitious data to prove the viability of this fractional factorial.

THE "NO-GROUT" STUDY

Different factors and levels from the main experiment necessitated a smaller experiment which was designed to investigate implications of the earlier findings of the Army Corps of Engineers. Their two studies had indicated that concrete placed on a clean, dry substrate bonded better than concrete placed on a portland cement substrate that had been immediately preceded by a fresh treatment of portland cement grout.(17,18) Their grout was different from the bonding slurry used by TxDOT, but this satellite study would determine specifically whether any bonding slurry was necessary for the Houston District overlay. Table 3.3 lists the factors and corresponding levels involved in the "no-grout" study.

The "no-grout" experiment evaluated the full factorial of 18 treatment combinations.

The Evaporation Rate Study

This satellite study explored the effects of those variables that affect evaporation rate as it relates to bond strength. The factors and their levels are shown in Table 3.4.

Table 3.3 Factors and levels considered in the "no grout" study

Factors	Number of Levels	Description
Textures	3	Cold-milled, normally shotblasted, and severely shotblasted
Surface conditions	2	Dry, and wet
Surface (substrate) temperature	3	50-60°F, 90-100°F, and 125-140°F

The "no grout" experiment evaluated the full factorial of 18 treatment combinations.

The Flash Set Study

There were major concerns about higher temperatures producing a premature or "flash" set of the grout before it was overlaid. Therefore, the decision was made to pay special attention to any indications of this phenomenon actually occurring at higher temperatures. Although initial discussions implicated the high ambient temperatures found in Texas, it was decided that the much higher temperatures of the substrate would, in fact, more seriously affect the set of the slurry. Since all the pertinent factors and levels are found

Table 3.2 Main experiment treatment combinations

Texture	Bond Agent	Application Rate	Low Substrate Temperature < 2 min	Low Substrate Temperature > 5 min	Medium Substrate Temperature < 2 min	Medium Substrate Temperature > 5 min	High Substrate Temperature < 2 min	High Substrate Temperature > 5 min
Light shotblast	Latex	Low	•			•		•
		High		•	•		•	
	Epoxy	Low		•		•	•	
		High	•		•			•
	PCC grout	Low		•	•			•
		High	•			•	•	
Cold mill	Latex	Low		•		•	•	
		High	•		•			•
	Epoxy	Low		•	•			•
		High	•			•	•	
	PCC grout	Low	•			•		•
		High		•	•		•	
Severe shotblast	Latex	Low		•	•			•
		High	•			•	•	
	Epoxy	Low	•			•		•
		High		•	•		•	
	PCC grout	Low		•		•	•	
		High	•		•			•

in the first, large experiment, the necessary data for this study were generated in the main experiment.

Table 3.4 Factors and levels considered in the evaporation rate study

Factors	Number of Levels	Description
Concrete temperature (fresh)	2	High and low
Ambient temperature	2	High and low
Humidity	2	High and low
Wind velocity	2	High and low

The full factorial of 16 treatment combinations was examined.

SPECIMEN PREPARATION

Substrate Preparation

Specimens for the preconstruction phase of the project consisted of 5,000-psi concrete slabs that were cast, cured, and textured in a large gang mold and placed on a large polyethylene film-covered concrete slab (Figure 3.1). The individual 3-ft-square slabs were then carefully separated and overlaid one at a time, according to the particular variables that the specimen was to represent.

Substrate Slab Design

In order to make a mix design that would fit into typical TxDOT paving specifications, a special attempt was made to keep strengths high enough so that bond tests would not fail in the substrate with values below generally accepted standards. The 3-ft × 3-ft × 5-in. test slabs were made using Class C portland cement concrete.(20) Quality control tests on transit mixed concrete insured conformity to specifications. QC tests included slump, air content, and compressive strength. After curing for more than 28 days under polyethylene film, the slabs remained in their forms but were ready for surfacing.

Texturing of the Substrate Slabs

Texturing was an important variable so care was taken to ensure that the depth of texturing was in the specified range for cold-milling, shotblasting, and severe shotblasting. To ensure similar textures for similar methods of scarification, the slabs of each group were treated while still adjacent to each other in their forms (Figure 3.2).

Figure 3.1 Slab specimens for laboratory study are made in large gang forms

Cold-milling. A paving contractor was hired to mill the slabs in situ. The milling was performed with the forms still in place to keep the mill from excessively chipping and spalling edges of the slabs. Also, the forms kept the top surfaces of all the slabs in the same plane while simultaneously restraining the slabs laterally, which prevented them from being thrown by the force of the rotating mill drum. Texture depths corresponded to a sand-patch depth of 0.090 in.(23)

Shotblasting. An attempt was made to hire the company that built and operated the large shotblaster on the South Loop. The 8-ft-wide unit that would have been used on the lab slabs should have given virtually the identical results as the equipment used on the actual Loop 610 overlay contract. Unfortunately, the 8-ft unit was sold immediately prior to the date needed for the test slabs, so the only other available shotblasting contractor was hired. His blasting unit was much smaller than the original unit and was in disrepair. To overcome the unexpected poor-quality results from this unit, sandblasting was employed to touch up any slab areas that did not meet specifications for depth of texturing. Uniform sandblasting produces the same surface texture on concrete as does uniform shotblasting when sand and shot are of similar size and applied with similar force. Final touched-up texture depths corresponded to a sand-patch test depth of 0.056 in.

Severe Shotblasting. Since the only available shotblasting contractor proved inconsistent, severe sandblasting was needed to get the specified texture. Final touched-up texture depths for the severely shotblasted (and sandblasted) slabs corresponded to a sand-patch depth of 0.070 in. Once the slabs were properly textured, they were removed from their forms, labeled, and stacked for storage until their scheduled overlay date.

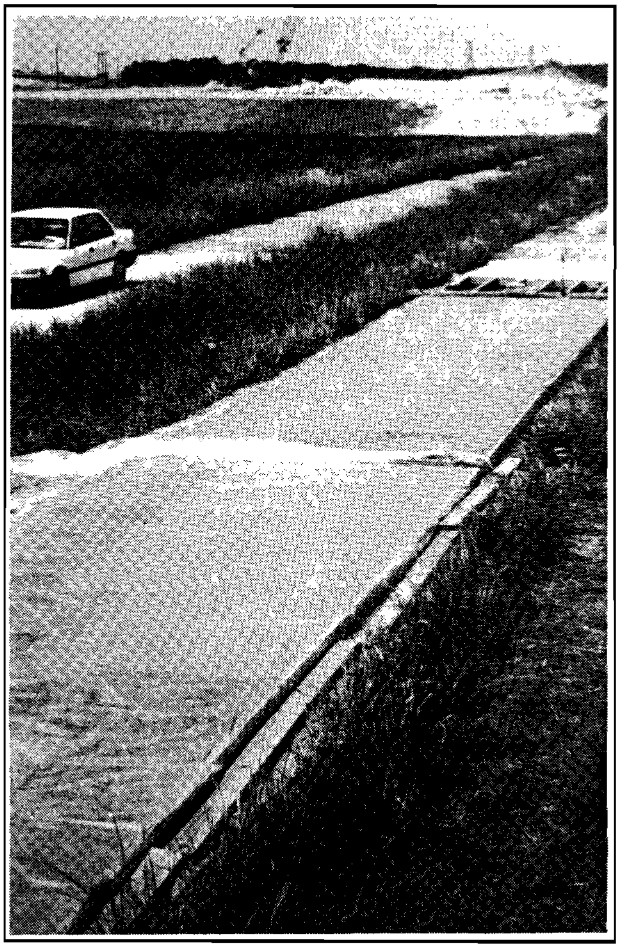


Figure 3.2 Cured specimens in gang forms ready to be milled while still in the forms

Bonding Agents

After selection of the desired bonding agents, acceptable ranges for the application rates and open times were determined. While optimal levels would have been useful, the major concern for TxDOT inspectors was to determine if the levels being applied by the contractor were in accordance with specifications. Therefore, maximum and minimum levels were determined based upon manufacturer's recommendations, relative cost, workability, and bond strengths. Bonding agents were applied to test slabs using spray equipment that was similar to what was expected to be used in the field and was based upon the equipment used by the contractor on the North Loop overlay. (Later, however, in the actual field tests the contractor opted to apply the epoxy bonding agent manually by brooming it onto the pavement surface.) The minimum application rate limit was based upon the least amount that could be sprayed to appear to completely wet out the substrate with the bonding agent. The maximum application rate limit was based upon the most that could be sprayed without ponding.

PBS

This material and its application rate were specified by TxDOT based upon usage for the previous IH-610 overlays. The minimum application rate was 37 sq ft/gal, and the maximum was 75 sq ft/gal. The mix design is described in Chapter 2.

LBS

This bonding agent was a polymer-modified version of the PBS. Its design was identical to PBS except that 50 percent latex emulsion was added based upon manufacturers' recommendations of 15 parts latex solids to 100 parts of cement (although manufacturers indicated that they would not warrant the use of their material in a field experiment). The plain water addition was reduced by the same amount of water found in the emulsion to keep the water/cement ratio constant. The latex emulsion was provided directly by the manufacturer, Dow Chemical Company, as "Modifier A." The following mix design was used:

- 1 sack of Type II portland cement (94 lbs),
- 9.5 gallons of water,
- 3.5 gallons of Dow Modifier A, and
- 5 ounces of defoamer.

Because LBS is so similar in composition to PBS the minimum and maximum application rates for this material were the same as for the PBS, which were 37 and 75 sq ft/gal, respectively.

Epoxy

This bonding agent conformed to ASTM C 881 specifications for Type II (bonding freshly mixed concrete to hardened concrete), Grade 1 (low viscosity), Class C (to be used above 60°F) epoxy-resin bonding systems.(21) The TxDOT Specification D-9-6100 for epoxies classifies this as a Type VI concrete adhesive.(20) The epoxy was called Rescon 649® and was supplied by Epoxy Design Systems of Houston. The system was mixed according to the manufacturer's recommendations and applied directly to the clean and dry textured substrate in compliance with ACI 503.2-79.(22)

Slabs were treated at an epoxy application rate of either 126 sq ft/gal or 47 sq ft/gal, although the manufacturer recommended a rate of 75 sq ft/gal.

OVERLAYS

Overlays for the test slabs were batched according to the mix design in the Special Specification Item 3433 for the Houston Construction Project IR 610-7(290) 775, except that Type III was substituted for Type I cement and crushed limestone was used in place of gravel. Type III was used to speed up the return of critical test data before the contractor began placing the overlays in the field, and the limestone represented the coarse aggregate to be used in the new South Loop BCO. The specific mix design is shown in Table 3.5.

Quality control tests including slump, air content, and compressive strength were performed to be sure the overlay concrete was within specifications.

EVALUATION PROCEDURES

Equally as important as specimen preparation are the methods by which the critical properties of the test specimens are evaluated. In addition to gathering the physical properties data, researchers were required to determine which test methods produced the most consistent results as well as which methods were the most practical for TxDOT use.

Texture Evaluations

Since substrate texture was one of the control variables to be studied in the experiments, a reliable method for qualifying and quantifying the surface texture of the substrate was needed. Three methods were utilized, and their results were evaluated for consistency and ease of use in the field.

Table 3.5 Batch design for laboratory overlays

Type III cement	7 sacks/yd^3
Coarse aggregate factor	0.60
Coarse aggregate	Crushed limestone as follows:

Sieve Size	Percent Retained
1-1/2 in.	0
1 in.	0-5
1/2 in.	40-75
No. 4	90-100
No. 8	95-100

Water factor	4.5 gal (max) per sack cement
Entrained air	4-6 percent
High range water reducer	570 cc Master Builders Pozzolith 400N as per Item 427 of the TxDOT 1982 Standard Specifications

The Sand-Patch Method. Texas Test Method, Tex-436-A, "Measurement of Texture Depth by the Sand-Patch Method," (23) is based upon ASTM E 965, "Measuring Surface Macrotexture Depth Using a Sand Volumetric Technique," (24) and is the most commonly used method in the state of Texas. It proved to be the simplest, least expensive, and most reproducible of all the tests evaluated. A disadvantage is that the method does not indicate angularity or roughness of the surface texture. Consequently, it was used to monitor all the substrate surfaces in each overlaid section of the South Loop and every slab in the laboratory study. This surface texture data was then stored in the database for later examination (Figure 3.3).

Texas Texture Meter Method. This method was developed by researchers in 1970 in an attempt to get better information regarding texture of pavement surfaces.(25) It was hoped that by recording the actual surface profile on paper, a better understanding of the true texture could be made from a simple averaged surface depression reading (Figure 3.4). Unfortunately, this method is inconsistent and is operator-dependent. It was abandoned early in the program in favor of the more reliable sand-patch method.

RTV Silicone Casting Method. This method uses room temperature vulcanizing, RTV silicone to record impressions of the substrate texture. The liquid components are mixed and poured onto the surface where the silicone is allowed to set (Figure 3.5). The solid rubbery surface casting is then removed, labeled, and stored until it can be taken to the lab for evaluation. The data received

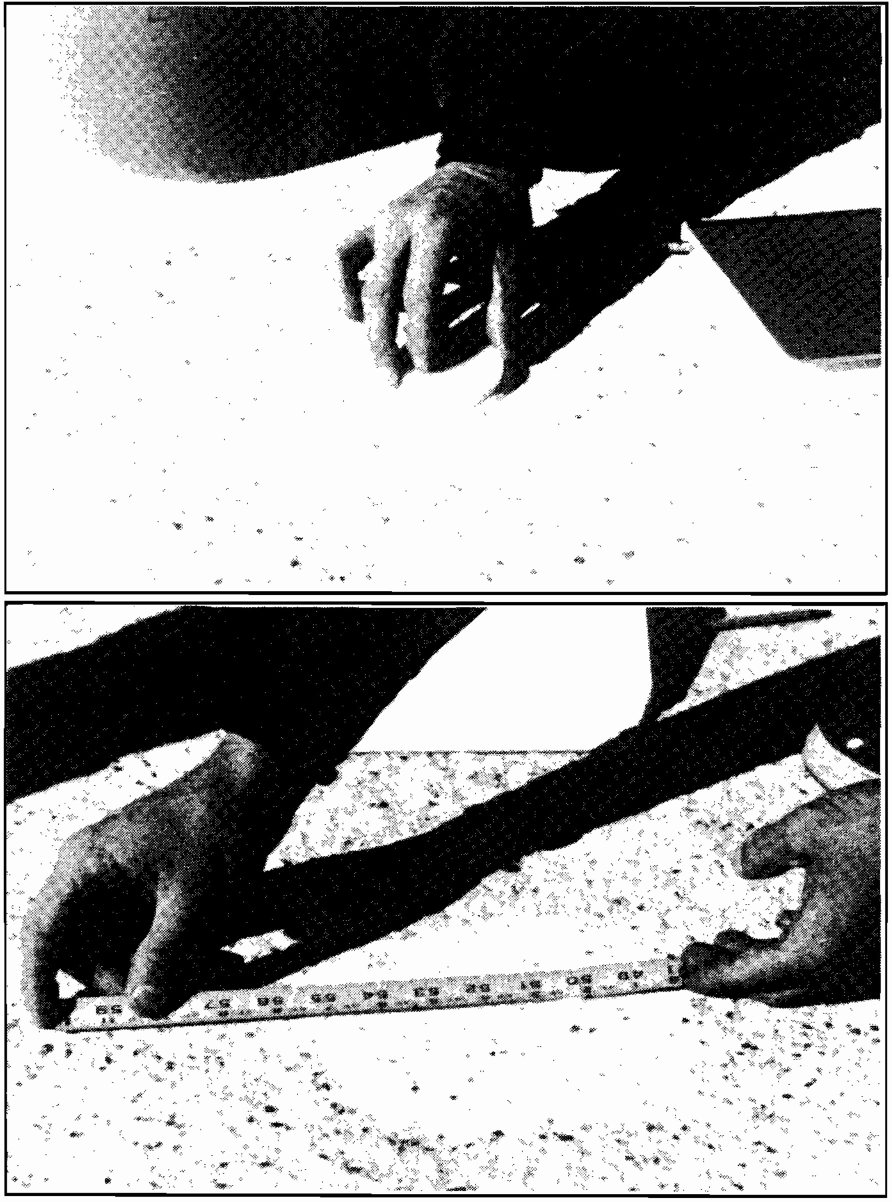


Figure 3.3 Conducting texture evaluations of the substrate using the sand-patch method

from the scan are recorded and evaluated by a surface analysis program similar to that used for studying fracture mechanics and for studying the surface formations of Earth's crust. The objective of this method was to get a true three-dimensional surface classification. Although this method may be able to provide a more detailed report of surface texture, it is still too early in the developmental stages to be of much use to the inspection personnel. It is also much more expensive to use than the sand-patch test.

Bond Strength Testing Procedures

Bond strengths were the sole basis for evaluating the performance effects of the different variables in this study. For this reason, several methods for determining bond strengths were examined. It was hoped that once the best laboratory method was found, modifications of this method would produce a reliable, simple-to-run field test.

Laboratory Method

Slant Shear Method. This method is based upon ASTM C 882 (26) and ASTM C 1042 (27) and is the most commonly specified method for determining bond strengths of epoxies and latex-modified concretes for concrete applications. It uses a precast half-cylinder blank that has been cast in a position that is skewed 30° from the horizontal. A bonding agent is hand applied to the sandblasted, skewed

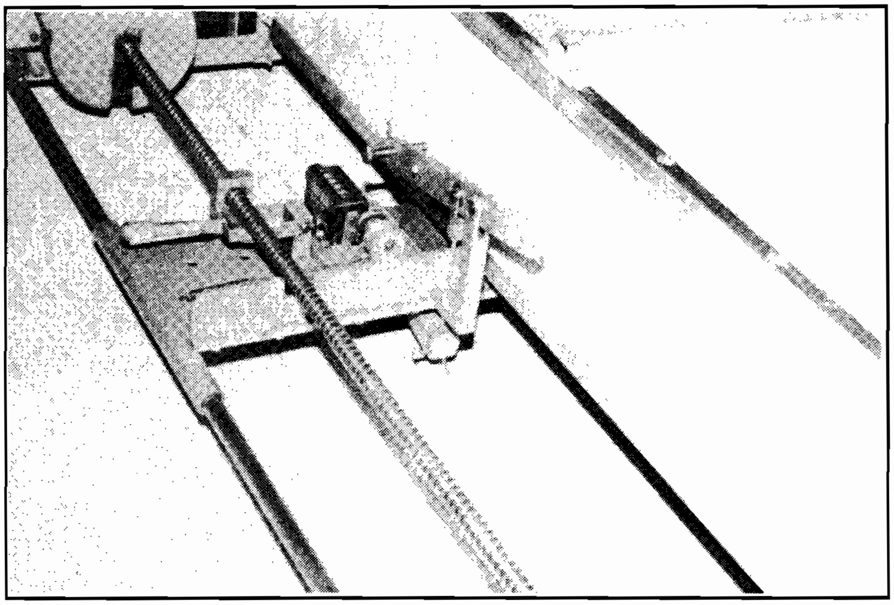


Figure 3.4 Conducting texture evaluations of the substrate with the Texas Texture Meter

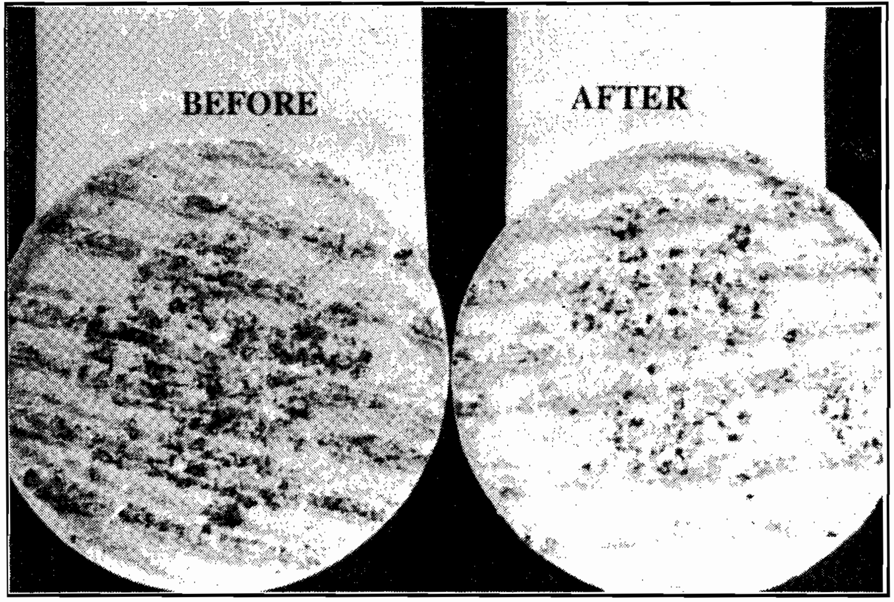


Figure 3.5 RTV silicone castings showing three-dimensional negatives of the substrate surface

face of the cured blank. The blank is then placed into the empty cylinder mold, and the cylinder is filled with the overlay matrix (Figure 3.6). When the overlay cures, the specimen is removed from the cylinder mold and tested in compression.

The test breaks the specimens at the bond line but is not very realistic for BCO applications. The axial compression force on the cylinder produces a shear component parallel to the skewed interface and a normal component perpendicular to the interface. The normal component provides more friction than is likely in shear-induced (and/or tension-induced) failures of BCO.

Guillotine Direct Shear Method. This procedure is based upon the test method used and specified by the Iowa Department of Transportation.(28) In this procedure, the cored specimen is loaded perpendicular to the axis of the specimen and parallel to the bondline, and the opposing load-and-reaction shear plane is aligned precisely at the interface between the overlay and the substrate by means of a jig (Figure 3.7).

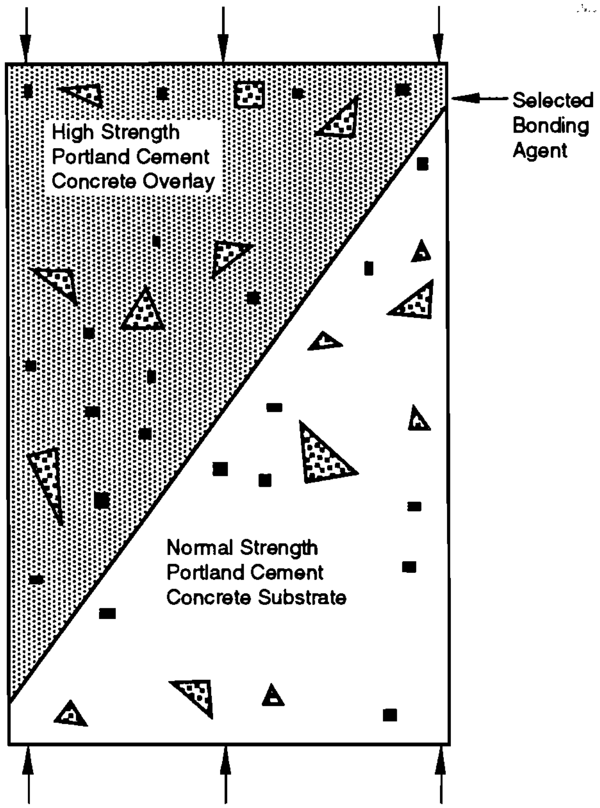


Figure 3.6 Schematic of slant shear method for determining bond strengths between overlays and substrates. Once overlays are cast on the precast slanted substrates they form 6-inch x 12-inch cylinders and are tested as such

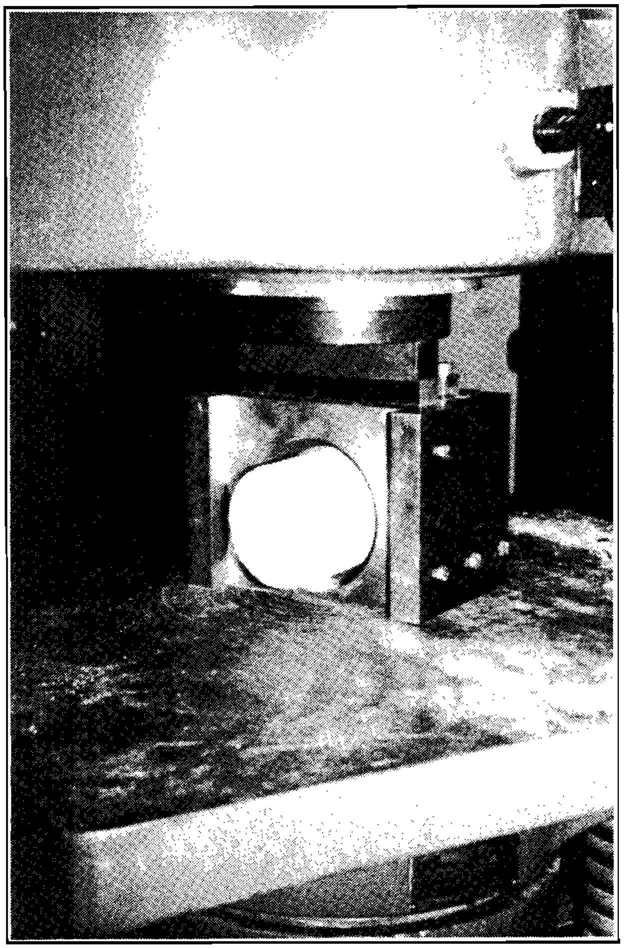


Figure 3.7 Guillotine direct shear method of determining bond strengths between overlays and their substrates

This test attempts to eliminate the normal force component of the slant shear method, which results in a nearly pure shear force at the interface of the substrate and the overlay. However, it is very difficult to eliminate all bending since the test apparatus is not completely rigid and the cored specimens are not perfectly uniform. Additionally, heavy texturing in the cold-milled and severely-shotblasted surfaces does not provide clean shear planes with which to align the shear loading edges. Although the tests were run in the laboratory, the method could be easily adapted to the field with a portable load machine.

<u>Direct Tension Method.</u> The direct tension test is adapted from tests for evaluating bond strengths of adhesives and coatings and is included for evaluation of the bond strength between the overlay and its substrate in pure tension. This method uses a positioning jig to provide precise axial alignment of the steel end plates (Figure 3.8) when bonding them to the cores with epoxy. When the epoxy cures, the specimen is attached to the tensile grips via the end plates and non-moment-transferring rings (Figure 3.9). The load machine then pulls the specimen apart.

Considerable effort was spent on perfecting this test method, even though it was more labor intensive and required that core specimens be brought back to a laboratory that had a large universal testing machine.

<u>Field Methods</u>. One of the major goals was to find or develop a dependable and easy-to-use field method with which inspectors could perform on-the-job quality assurance tests. The two methods examined were developed from non-destructive test methods for adhesives and mortars.

<u>ACI 503R Direct Tension Method</u>. This tensile bond test was adapted from the ACI method for determining the adhesion of epoxies to concrete substrates.(22) This method consists of a mechanical or hydraulic racking device that pulls a steel plate that has been epoxied to a cored area of the overlay (Figure 3.10). Although the overlay is cored, it is left with its original bond to the substrate. The diameter of the core was increased

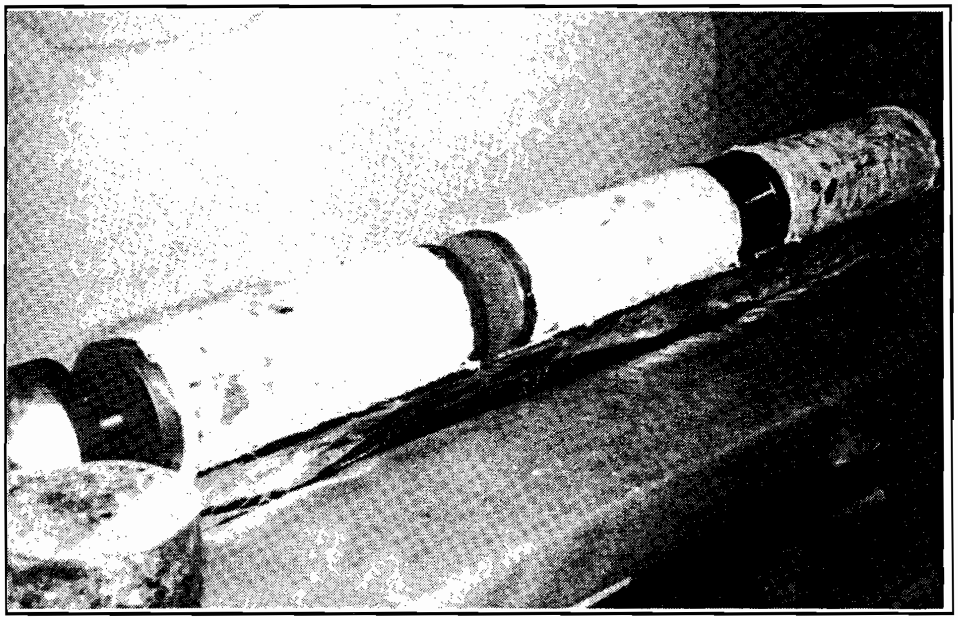


Figure 3.8 *The direct tension method employs a positioning jig for proper alignment of the specimens while epoxying the end plates to them*

from the original 2 in. to 4 in. (i.e., the nominal thickness of the overlay). Since the bond between the overlay and the substrate is normally weaker than the bond between the epoxy and the steel plate or the epoxy and the overlay, the pulling device records the tensile strength required to pull the overlay core from the substrate (Figure 3.11).

Torsion Method. This method was developed from another experimental non-destructive method for determining sufficient early-age strength in mortars. The purpose of the adapted method was to determine at an early age (i.e., less than 8 hours) whether the early bond strength was sufficient to remain bonded to the substrate for service conditions.

The torsion test method consisted of placing a hollow double-sleeved cylindrical assembly (Figure 3.12) into the fresh overlay in solid contact with the substrate (Figure 3.13). After the overlay matured sufficiently to develop bond strength, the inner sleeve assembly was turned with a recording torque wrench (Figure 3.14) at a time specified for each surface treatment (texture and bonding agent) and temperature. If the strength in less than 8 hours was more than 100 ft-lbs, the bond was considered adequate.

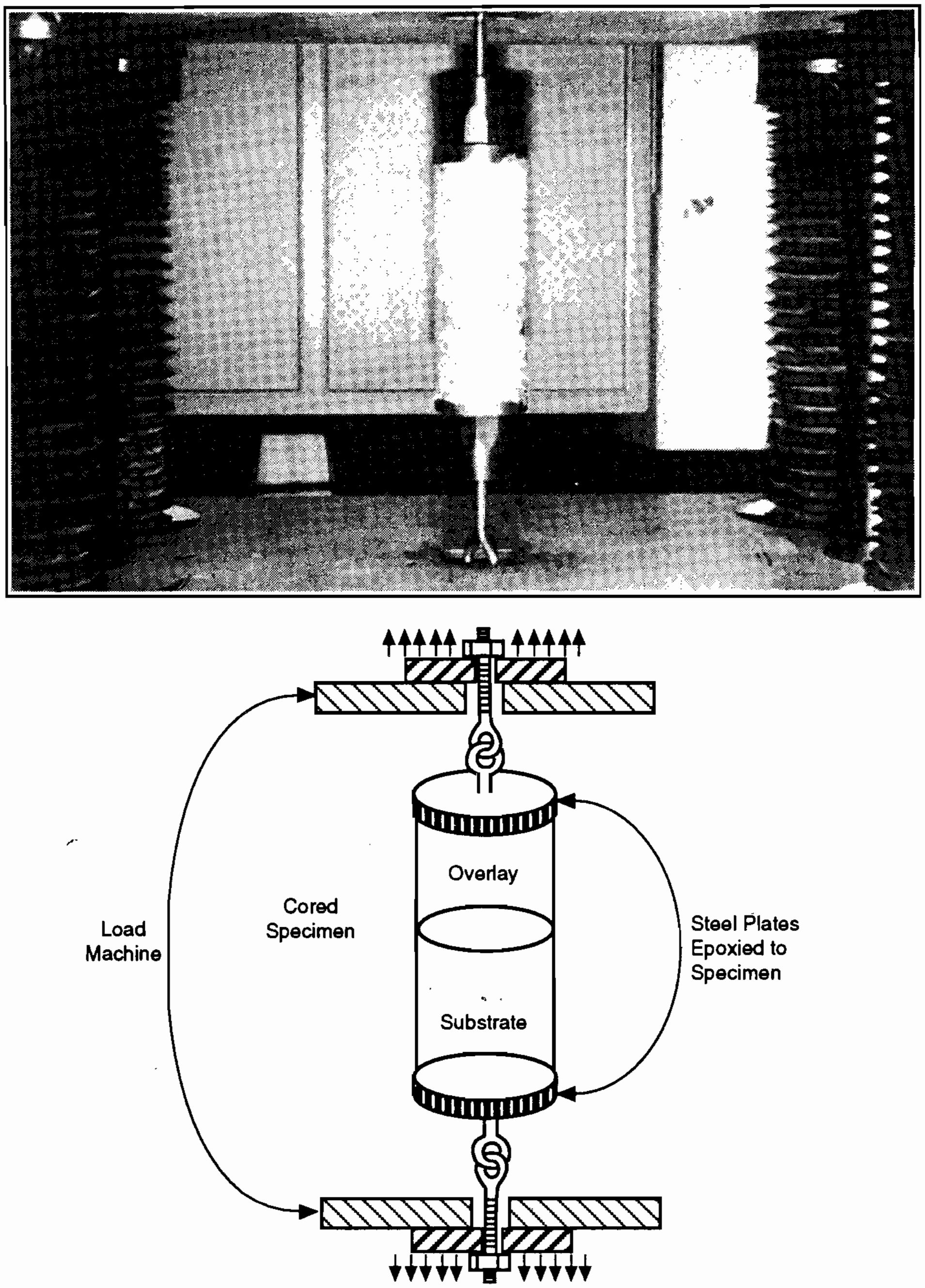


Figure 3.9 Specimens ready for direct tension bond testing

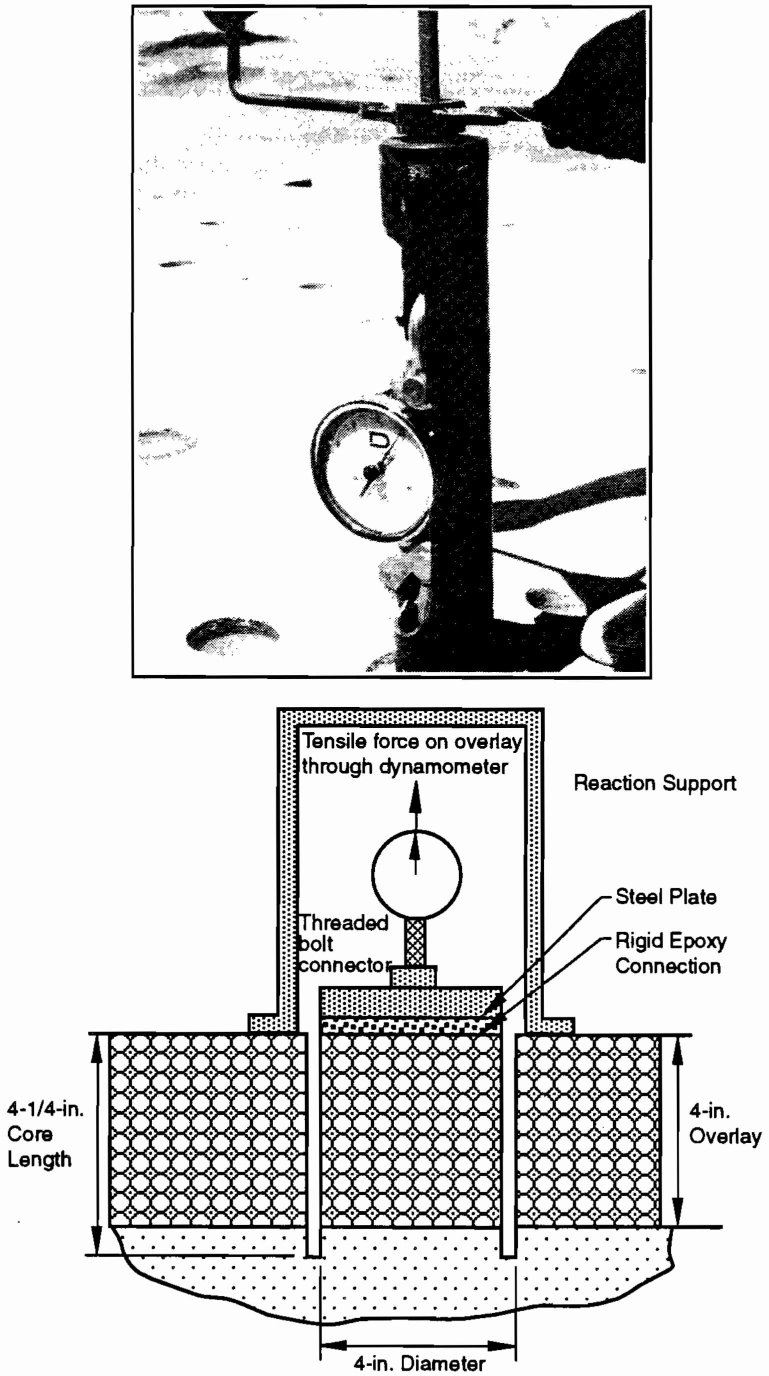


Figure 3.10 Modified ACI 503 tension bond test apparatus

Figure 3.11 Failed specimens shown in foreground after undergoing modified ACI 503 tension bond tests

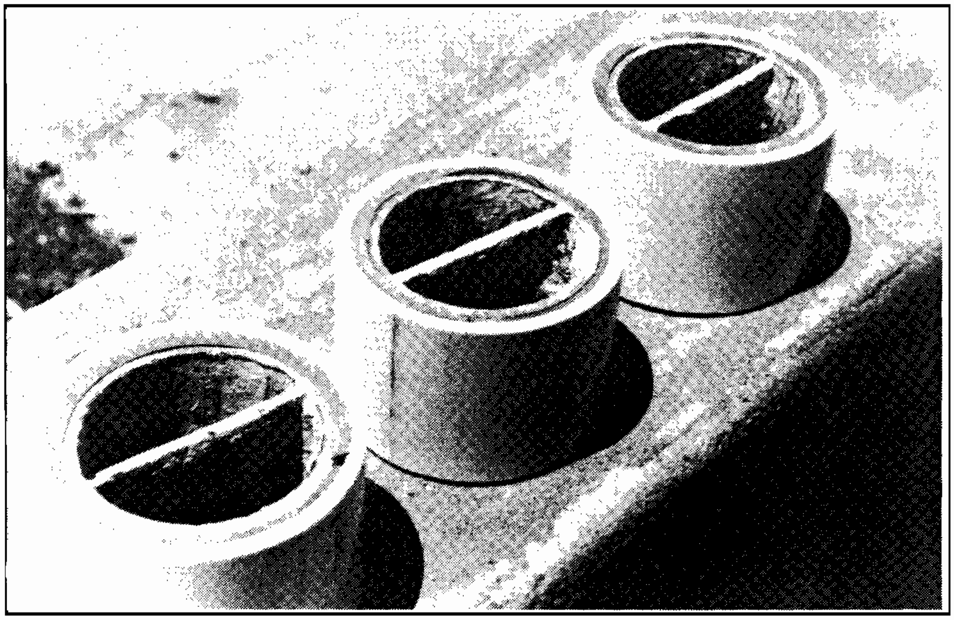


Figure 3.12 Cylinder assembly for the torsion bond tests

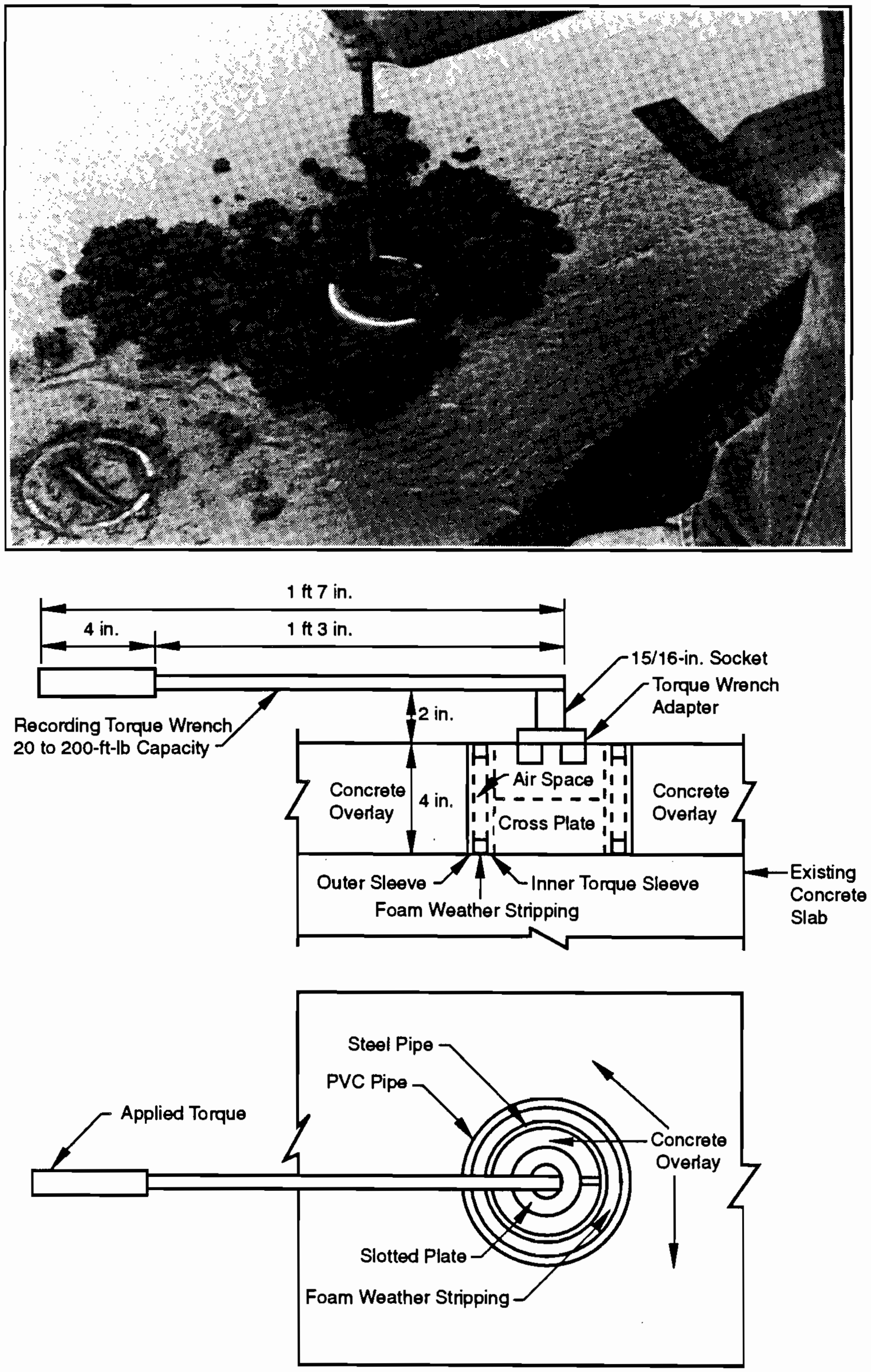


Figure 3.13 Torsion test cylinder assembly must solidly contact the substrate after the overlay is placed

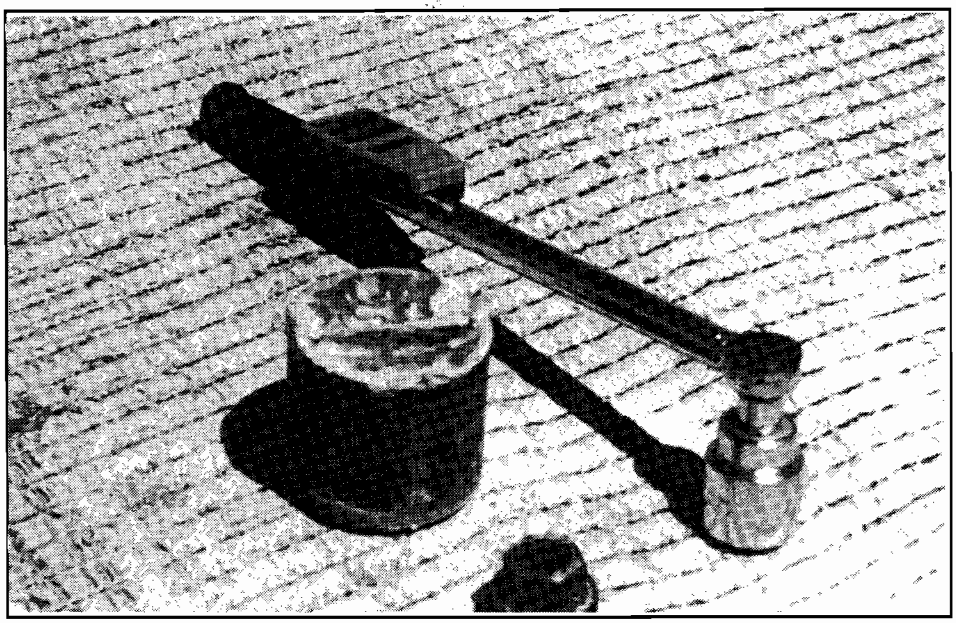


Figure 3.14 Recording torque wrench used to turn the cylinder assembly during the torsion tests

CHAPTER 4. FIELD TRIAL: EXPERIMENTAL SECTIONS

The laboratory slabs that were made, treated, overlaid, and tested under relatively controlled circumstances were only one element in evaluating the many factors that might significantly influence bond strength. That portion of the study attempted to identify factors that caused the overlay to debond from the substrate, and such knowledge would permit recommendations for future overlay procedures on the South Loop.

The second part of the study, however, allowed researchers to select any beneficial variables that seemed most immediately implementable in the field, and to include them in large experimental sections of overlay on the South Loop. Each section was 400 ft long and in each of the four adjacent eastbound lanes across the South Loop (Figure 4.1). This field trial method proved invaluable in finding performance flaws in the materials and methods that showed good results under more controlled laboratory conditions.

REPAIRING THE BASE SLAB

The only attempt to repair the base slab in the experimental sections involved the use of a high molecular weight methacrylate monomer (HMWM) treatment over the cracked substrate in Experimental Section 3. Section 3 was typical of all the other experimental sections in that there were many transverse cracks and few longitudinal ones. No punchouts or joint separations were found in Section 3.

One large longitudinal crack was routed to widen it to about 3/4 in. and to deepen it to about 3/4 in. The slab was then swept clean with a power sweeper, and the initiated monomer (hardener added) was applied as a flood coating, which permitted the monomer to fill the cracks by brooming it back and forth across the cracks for about 10 min. The routed longitudinal crack and any large spalled areas in the cracks were filled with a mortar made from the initiated HMWM mixed with dry blast sand. After allowing the monomer to cure for several days, the slab was cold-milled, as were the sections which were not treated with HMWM. The intent was to repair the cracks enough to improve stiffness before the overlay was placed.

OVERLAY PROCEDURE

All overlay procedures for the experimental sections followed the methods outlined in the South Loop contract specifications. Each of the experimental sections is described in detail below and shown in Table 4.1.

Experimental Section Descriptions

a. Section A was a control section that was prepared and overlaid according to the general paving specifications. The section was placed on the same day as Sections 1, 2, and 3 in order to more closely compare the paving conditions found for these four sections. Sections 4, 5, 6, 7, and 8 were paved on a different date, and a separate control section was used for that group.
b. Section 1 was overlaid in the same way as the control, except that no grout or bonding agent was used. The substrate was textured by cold-milling, and the overlay was reinforced with welded-wire fabric (WWF).
c. Section 2 was overlaid in the same way as the control, except that the overlay was reinforced with steel fibers instead of the reinforcing mesh used on the majority of BCO. PBS was the bonding agent.
d. Section 3 was the monomer pretreatment section, where a HMWM was painted over the cracked substrate's clean and dry surface before scarifying it. The monomer was allowed to cure before the surface was cold-milled to prepare for the overlay. The objective of this method was to allow the low-viscosity monomer to sufficiently fill any cracks in the substrate and, hopefully, seal the rebar and the interface from any subsurface moisture. Also, it was hoped that by filling the cracks, some of the original substrate stiffness might be

regained. PBS was the bonding agent, and the overlay was placed in the same manner as the control, including WWF reinforcement.

e. Section 4 was lightly shotblasted to remove road film from the substrate. Just prior to the placement of the WWF-reinforced overlay, an epoxy bonding agent was broom-applied to the substrate at an application rate of 91 sq ft/gal. The epoxy was broom-applied at the request of the contractor. For such a relatively small quantity, the cost of the extra time, manpower, and epoxy used in the hand-broom application method was still less expensive than the intended option of hiring a spray applicator or purchasing the spray equipment that could apply the epoxy at a rate of 126 sq ft/gal. A small area at the end of the epoxy section was accidently contaminated with grout just before the epoxy application. Some paste and standing water remained when the epoxy was applied, but they were removed before placing the concrete.

f. Section 5 was similar to Section 4, except that LBS was used as the bonding agent instead of epoxy. The actual mix used by the contractor was 1 sack Type I cement: 3-1/2 gal 50 percent latex emulsion: 5-1/4 gal water. The LBS was spray-applied at an approximate rate of 70 sq ft/gal. Because of irregular arrivals of transit trucks, and paving equipment breakdowns, and because the grout sprayer operator continually sprayed too far ahead of the paving train, delays in the overlay allowed much of the LBS to dry. Before the actual overlay was applied the contractor resprayed fresh grout over the dried grout. This procedure is not recommended, as the dried LBS will only form an unbonded barrier between the fresh LBS and the substrate. The recommended procedure was to mill, sandblast, or shotblast the dried LBS off so that clean substrate was again exposed to the fresh LBS.

   Because of observations of substantial debonding during the first week, both LBS Sections 5 and 6 were ordered to be cleaned off down to the substrate. They were then regrouted with PBS and overlaid as for the control sections A and B.

g. Section 6 was textured with heavy shot-blasting. LBS was the bonding agent employed before placement of the overlay, and WWF was used for reinforcement.

h. Section 7 used heavy shotblasting to texture the substrate, but had PBS as a bonding agent and WWF for reinforcing.

i. Section 8 was textured with heavy shot-blasting and used no bonding agent at all. Reinforcing was the typical WWF.

j. Section B was a control section that was prepared and overlaid according to the general paving specifications. The section was placed on the same day as Sections 4, 5, 6, 7, and 8 in order to more closely compare the paving conditions found for these six sections.

Location of Experimental Sections

The four sections, A, 1, 2, and 3, began on the eastbound lanes immediately east of the Calais Street Bridge. They were paved on January 2, 1990. The other group of experimental sections just east of the Broad Street Bridge had been paved earlier on July 10 and 11, 1989, because the contractor's paving schedule made this order more advantageous for his crews. Station location references of the sections are listed in Table 4.1, and a schematic layout is shown in Figure 4.1.

MONITORING PAVING VERSUS PERFORMANCE

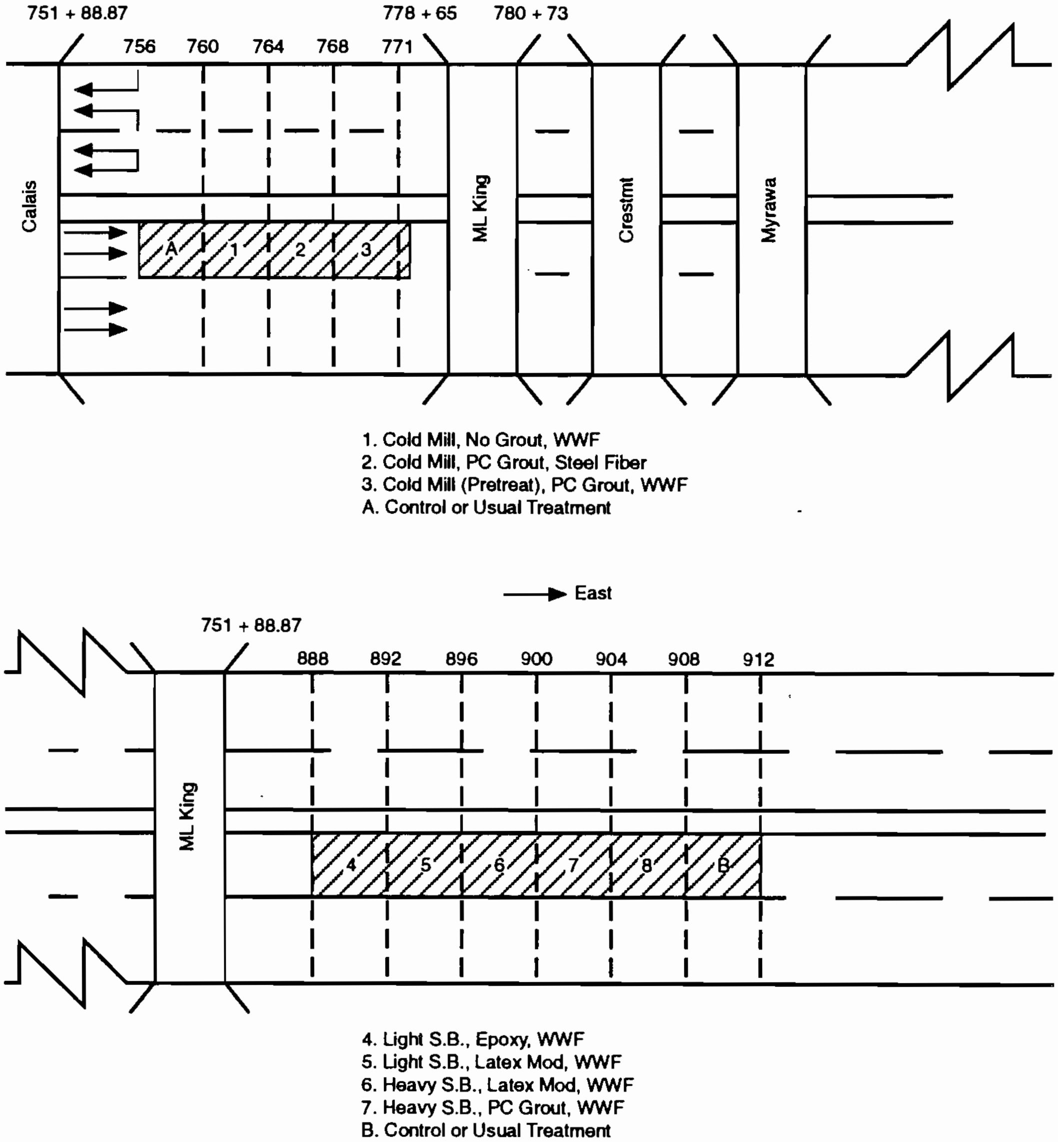
In order to be sure that laboratory findings could be expected in the field under real construction conditions, the experimental sections were paved by the same construction crew under the same supervision as for all other sections. During paving operations, CTR personnel closely monitored both the construction process and the environmental conditions. Since the TxDOT inspectors were present, the supervision and enforcement of the contract specifications were the responsibility of TxDOT and the contractor. CTR staff only observed and recorded pertinent paving data for the database. When any serious problem became obvious to CTR staff, TxDOT was advised of the problem. Actual reported problems included ready-mix deliveries that were in excess of fresh concrete temperature specifications, occurrences of conditions exceeding or about to exceed limits for evaporation rates and daily temperature swings, and grout applications that appeared too dry at the time of BCO placement.

It is expected that as the BCO ages and performance differences in experimental sections become apparent, the differences may be related to recorded paving variations in construction or weather conditions. For this reason, monitoring of the condition and the performance of the pavement will continue at regular intervals throughout the life of the BCO.

Table 4.1 Details for the South Loop experimental sections

Test Section Number	Limits (Stations)	Date of Paving	Type of Surface Texturing	Type of Bonding Agent	Type of Reinforcement
A	753 + 60 to 756	1/2/90	Cold-milling	PBS	WWF
1	756 to 760	1/2/90	Cold-milling	None	WWF
2	760 to 764	1/2/90	Cold-milling	PBS	Steel fiber
3	764 to 768	1/2/90	Cold-milling after HMWM	PBS	WWF
4	888 to 892	7/10/89	Light shotblast	Epoxy	WWF
5	892 to 896	7/10-11/89	Light shotblast	LBS*	WWF
6	896 to 900	7/11/89	Heavy shotblast	LBS*	WWF
7	900 to 904	7/11/89	Heavy shotblast	PCC	WWF
8	904 to 908	7/11/89	Heavy shotblast	None	WWF
B	908 to 912	7/11/89	Cold-milling	PBS	WWF

*Substantial early LBS debonding led to the removal of the overlay and remilling on these sections. They were then rerouted with PBS and overlaid as for the control sections A and B.



1. Cold Mill, No Grout, WWF
2. Cold Mill, PC Grout, Steel Fiber
3. Cold Mill (Pretreat), PC Grout, WWF
A. Control or Usual Treatment

4. Light S.B., Epoxy, WWF
5. Light S.B., Latex Mod, WWF
6. Heavy S.B., Latex Mod, WWF
7. Heavy S.B., PC Grout, WWF
B. Control or Usual Treatment

Figure 4.1 Schematic of IH 610 (S) test sections

CHAPTER 5. FIELD MONITORING

One of the most important tasks specified by TxDOT was monitoring. Both construction and long-term monitoring were to be included in the project.

To accomplish the construction monitoring, a technician was required at the construction site whenever paving occurred. The primary functions of the technician were to observe, record, and advise TxDOT of weather conditions and related problems. Other functions were to take measurements, record field information, calculate certain construction parameter limits, and keep records. The technician was responsible for running computer programs in the field, and keeping TxDOT and CTR personnel appraised of any critical problems. The responsibilities did not include construction decisions or supervision of any kind.

PROCEDURES FOR CONSTRUCTION MONITORING

The daily responsibilities on paving days involved close communications and cooperation with the contractor and TxDOT residency personnel. Particular procedures are described in the following paragraphs.

Ambient Temperature Differential

The CTR field technician began the morning of every paving day by obtaining the official National Oceanic and Atmospheric Administration (NOAA) daily low temperature forecast for the next 24 hours. This forecast was originally supplied by telephone from the National Weather Services at Houston Intercontinental Airport, and subsequently from Hobby Airport because of its close proximity and more accurate daily information. Later, the contractor agreed to receive this information from Hobby for TxDOT, and finally, the District decided it would obtain the forecast and supply it to the CTR technician.

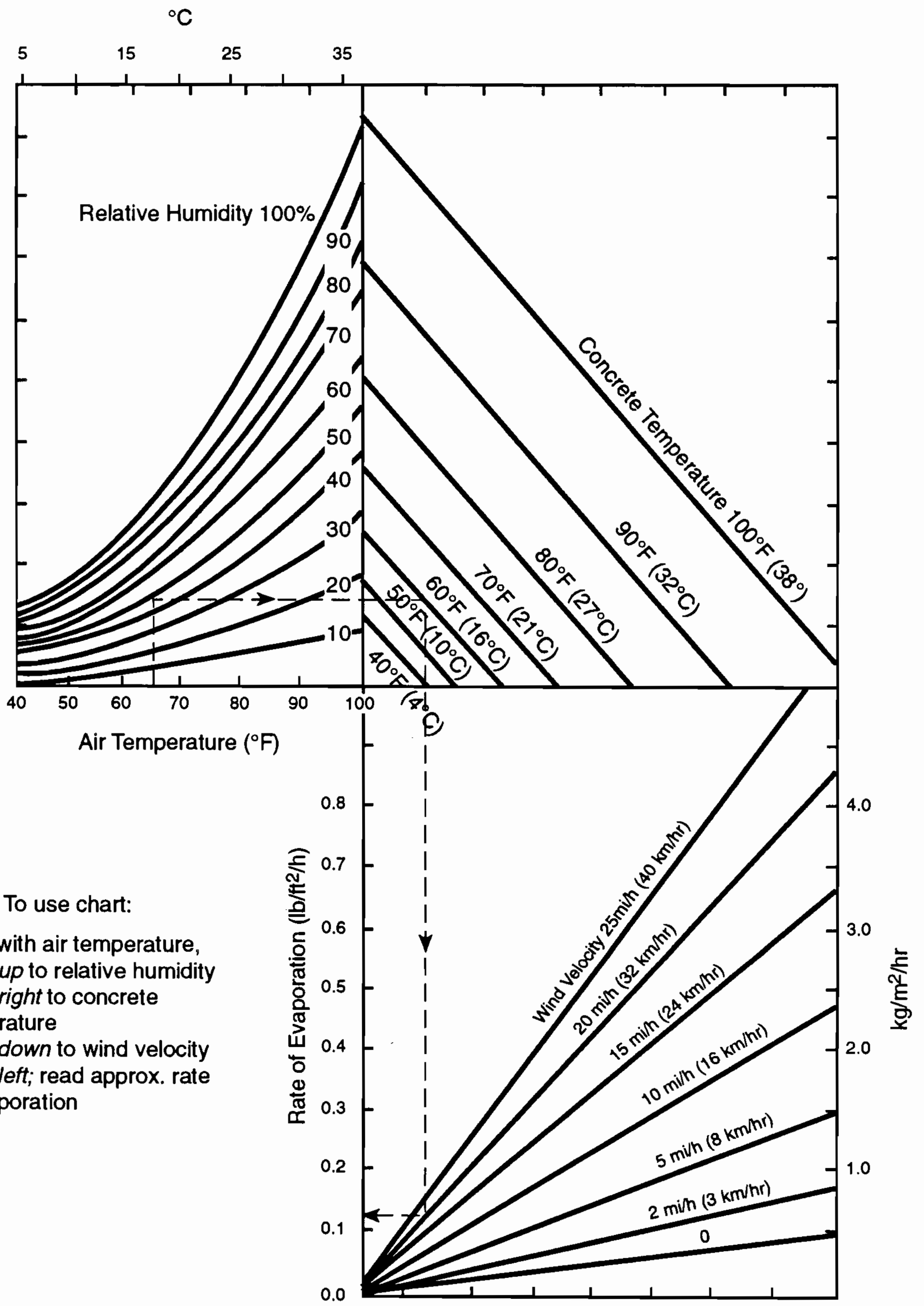
The predicted low was compared against ambient temperatures during paving. Whenever ambient temperatures approached 25°F higher than the expected low for the next 24 hours, the TxDOT superintendent was advised. The technician recorded the occurrence into a logbook and into the computer database. Although this was specified in the job contract as a construction control item (Section 4 "Construction Methods" of Special Specification 3538.000), all decisions were at the complete discretion of the supervising TxDOT Engineer. The CTR technician was in no way involved in any policy enforcement responsibilities.

Evaporation Rate Monitoring

Because of the complexity of the evaporation rate equation,(29) a nomograph (Figure 5.1) from the 1968 edition of the Portland Cement Association's *Engineering Bulletin* (30) was initially used. The nomograph allowed the technician to follow intersecting paths of graph skew lines for ambient temperature, relative humidity, fresh concrete temperature, and windspeed in order to obtain the evaporation rate in pounds of water per square foot per hour.

The complicated evaporation rate equation was programmed into a microcomputer so that the actual field data could be either hand-entered or electronically loaded via wireless telemetric transmissions from a programmed, portable, multichannel weather station (data logger) that could automatically and continuously collect the data.

The evaporation rate was a construction control item in the paving contract specifications. The rate was not to exceed 0.2 lb/sq ft/hr. The rate was continuously monitored and when the 0.2 limit was approached or exceeded, the technician reported the event to the TxDOT superintendent. The technician was not responsible for supervision or enforcement of the construction controls. Early efforts by the state and the contractor to cover the fresh pavement with polyethylene film caused large sheets of plastic to blow all over the highway and into traffic. After that experience, whenever conditions exceeded the evaluation rate limit early in the day, the contractor was advised that he might have to quit paving for the rest of



To use chart:

1. Enter with air temperature, move *up* to relative humidity
2. Move *right* to concrete temperature
3. Move *down* to wind velocity
4. Move *left*; read approx. rate of evaporation

Figure 5.1 Nomograph for calculating the evaporation rate of water from freshly-placed concrete the day. If the "too dry" conditions occurred late in the day, the contractor normally completed the job for the day. In neither case was anything done to protect the freshly placed BCO.

Other Data Collected

Other construction data were collected by the field technician during the monitoring portion of the project. Air content values, slumps, and flexural beam strengths that were determined by the TxDOT inspectors and laboratory technicians were recorded and entered into the database by the CTR field technician as important job record information. Sand-patch method textures and substrate surface temperatures were determined by the technician and recorded just prior to the BCO placement. Shrinkage and BCO internal gradient temperatures were monitored electronically via data loggers. Finally, torsional bond strength tests were conducted at several locations to determine early bond strengths between the overlay and the substrate.

LONG-TERM MONITORING

In order to determine the long-term performance of the BCO, periodic evaluations of the inside two lanes of the experimental sections (and the control sections) of the South Loop were made before and after the BCO was placed. These evaluations will continue to be conducted periodically after the overlay is placed. Evaluation procedures include pavement deflection measurements, condition surveys, and ride-quality evaluations.

The condition survey consists of determining transverse crack spacing; locating, measuring, and mapping of longitudinal crack spacing, spalls, punchouts, and pumping; and manual sounding of the overlay for delaminations. Sounding for delamination is planned at intervals of six months and one year after placement of the BCO. Also, before the placement of the BCO, TxDOT's Automated Road Analyzer (ARAN) unit was employed to record on videotape the pre-overlay condition of all the pavement that was scheduled to be overlaid.

SPECIAL MONITORING EQUIPMENT

The IBM-compatible computer system (Figure 5.2) used for storing data, computing the evaporation rates during paving, and generating daily reports to the TxDOT Superintendent was purchased specifically for this project. Field-related tasking and associated software required one megabyte of random access memory and 20 megabytes of data storage on an internal hard disk. The computer was equipped with a monitor, a dot-matrix printer for required daily hard-copy records, and a telemetry hardware and software communications package. This computer system allowed access to remote, battery-powered data loggers and their data could thus be downloaded into the computer files from distances approximately 1/4 mile away from South Loop traffic (Figure 5.3).

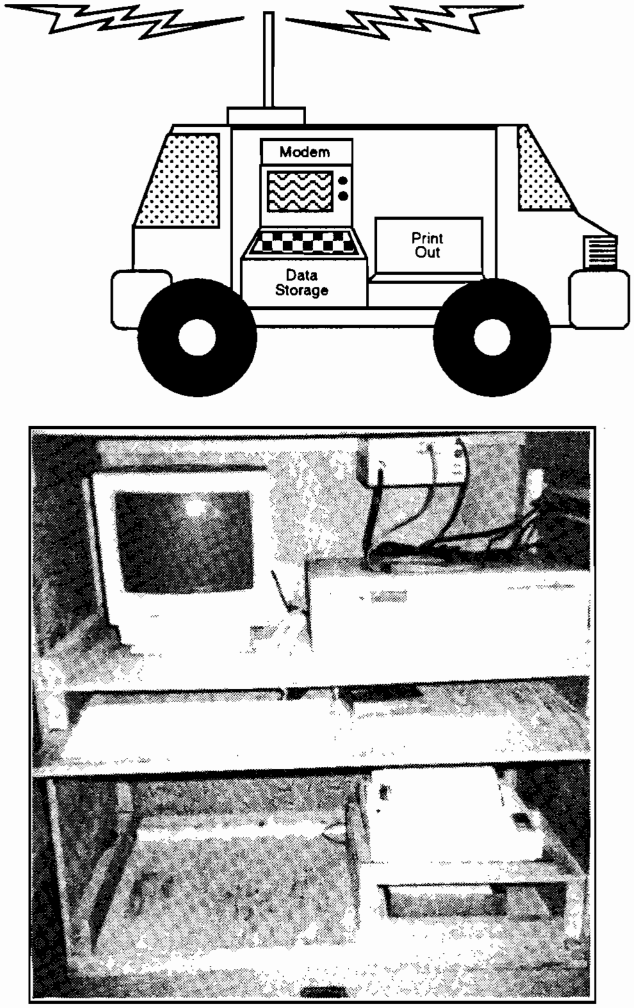


Figure 5.2 Schematic of the computer system used to collect and report data during placement of the overlay

Figure 5.3 Data logger used to collect and report data to the computer system

Four battery-powered data loggers were purchased to automatically collect data pertaining to environmental, paving, and curing conditions. One unit was equipped with sensors that recorded windspeed, ambient temperature, and relative humidity in real time. The other three loggers recorded external and internal pavement temperatures as well as strains caused by temperature changes and curing shrinkage at several locations. Temperature data was collected via standard Type J thermocouple wires connected to the back of the data loggers. Strains were determined and monitored via embedded electro-mechanical comparators made specially for the project by CTR technicians. They, too, were hard-wired to the loggers for recording and sending data to the computer.

Torsion testing equipment was developed and tested in the laboratory for field evaluation of bond strengths in BCO less than eight hours after placement. This equipment was used at several locations during the placement of the South Loop BCO. The equipment and procedures are described in Chapter 3 under the field testing section.

CHAPTER 6. STATISTICAL ANALYSIS OF THE EXPERIMENTAL AND FIELD-GENERATED INFORMATION IN THE DATABASE

EXPERIMENTAL DESIGN

This investigation is an integrated effort to compare results from several experiments and from several bond test methods used within each experiment. Each experiment was intended to generate data to answer particular concerns relating to the bond of BCO. Detailed descriptions of the experiments are found in Chapter 3.

A large main experiment investigated the two-way interactions and individual influences of several predetermined construction and environmental variables and their effects on bond. This experiment was based upon a fractional factorial matrix design in order to generate more correlated results with only a fraction of the required specimens. Smaller, less complicated, full factorial experiments were designed to look at wet versus dry substrates, grout versus no grout, evaporation rate effects, and flash set of the grout.

The large fractional factorial was designed to minimize the large number of test slabs necessary to identify the individual factors that significantly contributed, either positively or negatively, to bond. Evaluation of more complicated multiple interactions involving these same factors is not addressed in this study. However, the data generated in this study will remain compatible with and viable for any future study that might examine some of the more obvious multiple interactions.

The method of isolating factors and evaluating them under different test methods enables investigators to search for consistent trends in all collected data. When trends are not clear, more investigation is needed. However, since research projects are limited with respect to time and budget, further investigations of complicated phenomena may not be possible within the constraints of a single project. The consequence may be that researchers draw conclusions from inconclusive data. To avoid this problem, conclusions from this study are based both on the analysis of data generated in the study and on hypotheses that remain consistent with these data, as well as any other knowledge available to the authors at the time of this publication.

When intensive efforts to discover the causes of the debonded overlay on the North Loop produced considerably more data than answers, it became obvious that any attempted analysis procedure would require a sophisticated database to manage the tremendous amount of information. The precise type of database and the analysis system used in the handling of project data were just as important to the study as were the experimental designs.

THE DATABASE

All relevant test data and field information were stored in a Microsoft Excel® database named "Database 1." This database system was chosen for its accessibility and user-friendly interface inasmuch as many students and staff will need to access it.

THE ANALYSIS SYSTEM

The analysis of data was conducted on an IBM AT microcomputer through the assistance of a highly sophisticated proprietary mainframe statistical program, Statistical Analysis System (SAS)(31), adapted for use by the more powerful IBM microcomputers.

STATISTICAL ANALYSIS METHODOLOGY

Once all the data were collected and stored in the database, the statistical analysis began to sort through the large volume of information to produce some meaningful results from which conclusions could be drawn.

Based upon each experimental design, statistical models were developed for each experiment. A statistical procedure called analysis of variance (ANOVA) was then conducted in order to find and plot the main effects and interactions that resulted from each experiment. Multiple comparison tests (Newman-Keuls test) were performed to determine the significance of the ANOVA results.

Chapter 7 presents only those statistically significant results that have emerged after undergoing the above multi-step analysis procedure.

CHAPTER 7. DISCUSSION OF RESULTS

BOND-STRENGTH EVALUATION RESULTS

Because the comparison of bond strengths was the sole criterion for evaluating the effects of various external factors on the bonding of concrete overlays to concrete substrates, five methods were employed, and their respective results were compared. For the comparison, each method was performed on each slab.

A complete listing of all the data generated in the laboratory slabs is shown in the Appendix, but the nature of the fractional factorial experimental design makes it difficult to understand the results without the benefit of a statistical analysis program. With the powerful SAS computer program, this analysis was completed for all the listed variables and their two-way interactions. This chapter presents the results of the statistical analysis of the data collected during the laboratory study.

All results from the bond strength enhancement evaluation program were analyzed using ANOVA, and the limiting assumptions were made in the experimental design. In the main experiment, these assumptions included ignoring all combinations of variables that were more complicated than two-way interactions. A good example of a two-way interaction would be a particular substrate texture combined with a specified substrate temperature.

As can be seen in Table A.1, bond strength data from different test methods (slant shear and direct shear) that were used in the same experiment frequently gave different results in their relative performances under the same conditions. Although the differences made the analysis more complicated, they should have been expected. Such differences are attributable to the different failure modes induced by the various test methods and to the relative sensitivity of each bonding agent and test method to texture or to the orientation of the texture (i.e., the striations from the cold-milling). Each test method used to examine the BCO bond strengths in this study specifically attempted to isolate one major direction of stress at the interface between the overlay and the substrate.

It may be inferred, however, that the performance of the BCO in the field is caused by the ability of the bond at the interface to sustain complex combinations of both short-term and long-term combinations of shear, tensile, and/or compressive forces exerted by the curing process, traffic, temperature, and other environmental changes.

The slant shear test is commonly employed for evaluating the acceptability of epoxy bonding systems for concrete-to-concrete joints as well as for evaluating the adhesion of LMC overlays to concrete substrates. Because the results of this laboratory method are usually more consistent, it was hoped that the slant shear test results might be the standard against which the other methods could be compared. The results of slant shear tests in this study, however, proved to be nondiscriminating for the laboratory comparison. Since the test is impractical for field quality control, slant shear testing was abandoned.

Large Experiment

Because of the complexity of the large experiment, the bond strength results are explained by separately addressing every two-way interaction for a given variable.

Direct Shear (Guillotine) Test Method. The direct shear test, often referred to as the guillotine method, has been used by others for quality control and quality assurance on many previous BCO(32-35), including those placed earlier in Houston. Table A.2 indicates the best performing combinations based solely upon the direct shear bond strengths for this large experiment. Table A.3 shows actual shear strength data for this experiment.

Bonding Agent Effects

1. Varying surface texture treatments alone indicated that:
   a. when PBS was used, highest shear strengths occurred on severely shotblasted surfaces; and
   b. highest strengths occurred for epoxy or LBS on cold-milled or on lightly shotblasted surfaces.
2. For the materials evaluated, the application rates of bonding agents did not seem to affect shear bond performance.
3. The difference in the time interval (less than 2 minutes and slightly more than 5 minutes) between bond agent application and the overlay did not seem to significantly affect the shear bond performance for any of the bonding agents.
4. Varying the temperature of the substrate showed that:
   a. at low temperatures, epoxy works best;
   b. at medium temperatures, PBS or LBS produced their highest strengths; and
   c. at high temperatures, epoxy or PBS gave the best results.

Substrate Surface Texture Effects

1. Higher shear bond strengths resulted when heavier application rates of bonding agents were applied to substrates that had been only lightly shotblasted. The application rate had little effect on other textures.
2. Variations in the time interval between bond agent application and overlay resulted in the following shear bond performances.
   a. Cold-milled surfaces provided better bond with 5-minute intervals than with 2-minute intervals.
   b. Lightly shotblasted surfaces gave better bond when application times were less than 2 minutes.
   c. Time intervals tested had little effect on severely shotblasted surfaces.
3. Bond performance on all of the substrate textures was not affected by substrate temperature alone, but temperature may have influenced bond when its effects were combined with varying textures and bond agents. Because of project limitations, the experiment was not designed to evaluate three-factor interactions.

Substrate Temperature Effects

1. Varying the application rate of the bonding agents indicates that:
   a. for low temperatures, higher rates gave better results; and
   b. for medium and high temperatures, the different rates worked equally well.
2. Differences in the interval between the application of the bonding agent and the overlay did not affect the bond performance for any temperature tested.

Direct Tension (4-in. Cores in Universal Load Machine) Method. Direct tension bond tests are commonly used in the field for comparing bond strengths of very thin polymer concrete overlays.(36) This study used 4-in.-diameter cores, taken through the overlay into the substrate, for testing in direct tension in the laboratory using a universal load machine. Table A.4 gives main experiment performance results based on direct tension tests alone. Table A.5 shows tension data for this experiment.

Bond Agents

1. Results from surface texture variations showed that:
   a. epoxy worked best on all surfaces;
   b. severely shotblasted surface texture was best for non-epoxy bond agents; and
   c. highest bond strengths occurred with epoxy on a lightly shotblasted surface.
2. Low application rates gave the highest strengths for the epoxy and LBS, while high application rates gave the best results for PBS.
3. The time intervals evaluated in this study did not seem to significantly affect the tension bond performance for epoxy or PBS, but LBS seemed to give better strengths when intervals were more than 5 minutes.
4. Results from varying the temperature of the substrate indicate that epoxy produced the best tension bonds of the three bonding agents at any temperature, and that all bonding agents performed better at lower temperatures.

Substrate Surface Texture

1. For all three surfaces, high application rates gave better tensile bond strengths.

2. On all three surface textures, intervals greater than 5 minutes gave the best tension results.
3. Severe shotblasting gave highest tensile bond strengths for medium temperatures, but at high or low substrate temperatures either severely shotblasted or cold-milled surfaces gave better tensile bond strengths than did lightly shotblasted ones.

Temperature of the Substrate

1. At high temperatures, high application rates worked best.
2. For low or medium temperatures, intervals of more than 5 minutes gave the highest results.

ACI 503 Direct Tension Method (2-in. Cores Tested in the Field). Although this method was designed by the ACI 503 Adhesives Committee for determining adequacy of the substrate preparation, the method resulted in more consistent data than most other tests. Table A.6 presents the performance data as determined by this modified ACI 503 method. Test data is shown in Table A.7.

Bond Agents

1. Surface
   a. Epoxy worked best on any surface.
   b. Severely shotblasted surface texture was best for non-epoxy bond agents.
   c. Highest bond strengths occurred with epoxy on a lightly shotblasted surface.
2. Application Rate
   a. Rates had no significant effect on bond strengths for any of the three bonding agents.
   b. PBS gave better tension bond results when application intervals were less than 2 minutes, but epoxy gave better strengths when intervals were more than 5 minutes.
3. Temperature of the Substrate
   a. Low temperature gave the highest strengths for all three bond agents.

Substrate Surface Texture

1. For cold-milled surfaces, low application rates worked best.
2. Low temperatures gave the highest strengths on all surfaces.

Temperature of the Substrate

1. For all application rates, low temperatures worked best.
2. For all intervals, low temperatures gave the best tensile bond results.

Torsion Method. This torsional shear method of testing for interface bond strengths was developed by researchers for this project in an attempt to find a reliable means of determining and comparing early-age bond strengths. Because this method relied on the physical strength of the operator, it proved to be very difficult to find appropriate test times for all the different paving conditions. Proper testing times in which bond strengths were high enough to provide consistent data and low enough for the operator to be able to manually turn the torque wrench at a uniform rate varied significantly with the many combinations of substrate and environmental conditions. For this reason, most torsion strength data points were missing. Therefore, results from the torsion method are not included in Tables A.1 and A.4. Since this test is primarily an indicator of whether the BCO bond strength is adequate, these data are insufficient to indicate precise bond performance differences based upon torsion test results alone.

Wet-Dry Experiment

Direct Shear (Guillotine) Test Method. Direct shear performance results and data from the wet versus dry experiment are presented in Tables A.8 and A.9.

1. For dry surfaces, severe shotblasting gave the best shear bond strengths. All other moisture-texture combinations gave low strengths.
2. a. At either high or low temperatures, light or severe shotblasting gave best shear bond results.
   b. At medium temperatures, severe shotblasting or cold-milling resulted in higher shear bonds.
   c. Severely shotblasted surfaces gave consistently higher strengths and did not seem to be affected by temperature variations.
3. At low temperatures, dry surfaces gave the best results.

Direct Tension Test (4-in. Cores in Universal Load Machine). Direct tension performance results and data from the wet versus dry experiment are presented in Tables A.10 and A.11.

Substrate Surface Texture

1. Moisture on the Substrate Surface
   a. For lightly and severely shotblasted surfaces, moistening gave the best tensile bond strengths.

   - b. The highest overall strengths were obtained on wet, lightly shotblasted surfaces.
2. Temperature of the Substrate
   - a. At medium temperatures, light shotblasting produced higher tensile bond strengths.
   - b. Low temperatures gave the highest strengths for all textures.
   - c. High temperatures gave the lowest strengths for all textures.
3. At medium or high temperatures, the presence of moisture on the substrate gave the highest bond strengths.

ACI 503 Tension Test (2-in. Cores Tested in the Field). ACI 503 bond test performance results and data from the wet versus dry experiment are presented in Tables A.12 and A.13.

1. Moisture on the Substrate Surface
   - a. For lightly shotblasted and cold-milled surfaces, moistening gave the best strengths.
   - b. Severely shotblasted surfaces were dry for the highest strengths.
   - c. Both lightly shotblasted and severely shotblasted surfaces, when wet, gave higher strengths than did wet cold-milled surfaces.
2. Temperature of the Substrate
   - a. Medium temperatures gave higher strengths than high temperatures for all surfaces.
   - b. At low temperatures, light or severe shotblasting produced higher strengths.
   - c. At high temperatures, severe shotblasting produced the highest strengths.
3. Moisture in the Substrate
   - a. On both wet and dry surfaces, low temperatures gave the highest strengths, and high temperatures gave the lowest strengths.
   - b. At high temperatures, wet surfaces gave the highest strengths.

Grout versus No-Grout Study

Direct Shear Test (Guillotine). The guillotine (direct shear) bond test performance results and data from the grout versus no-grout experiment are presented in Tables A.14 and A.15.

1. Surface Textures
   - a. The use of PBS did not affect the guillotine bond strengths on any texture.
   - b. Medium temperatures gave the best direct shear results on both cold-milled and lightly shotblasted substrates.
2. Presence or Absence of Grout
   - a. Severely shotblasted substrate gave the highest shear strengths regardless of whether BCO was placed on PBS or clean and dry substrate.
   - b. Substrates without bonding agent gave better shear bond strengths if BCO was applied when the surface was at medium temperatures.
   - c. PBS-treated substrates gave higher strengths when their temperatures were high or medium before placement of the BCO.
3. Substrate Temperatures
   - a. Substrates at all three temperature ranges gave the highest strengths when the substrate was severely shotblasted. Cold-milled substrates at medium temperature ranges also performed well.
   - b. The medium-temperature substrate showed better strengths with the use of PBS than without. Low and high temperatures showed no preference for grout or no grout.

Direct Tension Test (4-in. Cores Tested in the Laboratory). Direct tension bond test performance results and data from the grout versus no-grout experiment are presented in Tables A.16 and A.17.

1. Surface Textures
   - a. Cold-milled surfaces gave higher strengths at low temperatures than at medium or high temperatures.
   - b. Light shotblasted surfaces gave lower strengths at high temperatures rather than at medium or low.
   - c. Severely shotblasted surfaces showed higher strengths with grout than without, and on low temperature substrates rather than on medium or high-temperature ones.
2. Bonding Agents
   - a. Both grouted and ungrouted samples gave higher strengths on low-temperature substrates.
   - b. Grouted specimens gave higher strengths with severe shotblasting.
3. Substrate temperature comparisons showed that both low and high temperatures gave higher strengths on severely shotblasted surfaces than on the other textures, and that all

three temperatures gave higher strengths with grout than without.

ACI 503 Tension Test (2-in. Cores Tested in the Field). ACI 503 bond test performance results and data from the grout versus no-grout experiment are presented in Tables A.18 and A.19.

1. Surface Textures
    a. Both cold-milled and light shotblasted surfaces performed their worst in high temperatures.
    b. Severe shotblasting performed better on low-temperature substrates.
2. Bonding Agent
    a. Grouted specimens performed better on severely shotblasted substrates and at low temperatures.
    b. Non-grouted specimens performed better at low temperatures, and they showed higher strengths when the texture was severely shotblasted.
3. Substrate Temperatures
    a. Low and high temperature substrates performed better when the surfaces were severely shotblasted.
    b. The low and high temperature substrates also gave better bond performances when grout was applied than when there was no grout.
    c. Medium temperature substrates, however, gave better strengths when the grout was omitted than when it was used.

FIELD STUDY RESULTS

An important part of this study was to corroborate laboratory data with the actual field data, which is presented below.

Bond Test Results from Experimental Sections

In addition to the bond tests performed on cores from the laboratory slabs, several cores were extracted and tested from the experimental sections on the South Loop 610 BCO project. Table A.20 shows a comparison of the test section strengths for each of the bond tests.

Within a week of placement, the BCO in Sections 5 and 6 showed such extensive cracking and debonding over the entire two-lane (24 ft x 800 ft) test area that the sections were condemned by TxDOT officials. Shortly thereafter, Sections 5 and 6 were removed, remilled, treated with PBS as bonding agent, and overlaid with the standard reinforcement and control mix.

No tests were conducted to determine the degree of dryness in the LBS, nor were any observations recorded as to the percentage of dry area in the entire presprayed area of pavement. Throughout the project, CTR personnel frequently observed and informed TxDOT inspectors that the grout was being sprayed too far ahead of the paving machine, and that when delays were encountered from frequent breakdowns in the paving machine and the associated hold-ups in transit mix deliveries, the grout surface would dry out. Because these delays occurred so frequently, the TxDOT inspector and the contractor were not concerned when CTR personnel reported that the LBS surface appeared dry or "crusty" immediately in front of the paving machine, a condition which occurred when the delays seriously exceeded the longest laboratory tested-delay intervals of five to ten minutes. Observations regarding the dry bonding agent, LBS, were brought to the attention of the inspector, who simply asked the contractor to respray the LBS and to resume paving when the paving machine and transit delivery were ready. That simple respray procedure was normally used for any long delays in paving the PBS sections.

As mentioned previously, the recommended practice for dealing with "dried" LBS was to completely remove the dried LBS from the substrate, retexture it, and reapply fresh LBS. Because laboratory experiments had not included delays of more than ten minutes, CTR and TxDOT personnel had no way of determining what was "dry" other than by visual appearances, and there was little interest from the contractor or the inspector in delaying overlayment of the experimental sections any further, especially when the decision was to be based solely on a little crusting of the grout surface.

Also, reported laboratory test data had not revealed any type of major bonding problems particular to the LBS. It should be noted that some of the slant-shear test data indicated poor performance for LBS (and also for PBS). However, the slant-shear test had been discontinued early in the laboratory program because it was determined that the texture of the slant-shear specimens at the interface was not representative of the texture of the actual substrate on Loop 610.

Early examinations of the debonded overlay and exposed substrate revealed that debonding occurred immediately above the LBS.

Other Results from the Field

Results were also determined from field tests that were conducted in addition to the bond strength tests. These other tests included substrate sand-patch texture tests, evaporation rates, daily temperature swings, and falling weight deflection readings.

Evaluations of Test Methods

Since one of the specified tasks in this project was to find or develop a reliable and easy-to-use field method for determining bond strengths as part of a comprehensive quality assurance program, the individual test methods were compared against each other on the same slabs and field sections. Data consistency and ease of use are discussed and shown in Tables 7.1 and 7.2, respectively. Other details on each test method are discussed in Chapter 3.

Data Consistency. As can be seen in Table 7.1, the laboratory test data were highly variable; however, trends in consistency can be discussed with confidence. The laboratory direct tension test data was the most consistent, followed by the modified ACI 503 tension test. The torsion test was the least consistent. The high degree of variability may be attributed to only two specimens per slab for any pair of factors examined.

Ease of Use. Ease of use, as a parameter for comparing the different bond test methods, is a relative term since none of the methods is particularly easy to use when compared with some other QC or QA methods, such as slump or air content, beam breaks, or sand-patch texture tests. Since the area of interest in the study was the interface between the overlay and the substrate, only destructive test methods could be utilized to evaluate specimens from the actual overlays. The torsion test required embedment of several 4-1/2-in. removable fixtures through the overlay to the interface. The direct shear and both tension methods required coring before specimens could be tested. The non-standard tests and modifications to standard tests meant that all but the abandoned slant shear required the manufacture of special testing equipment for the field or for use with a universal load machine in the laboratory. The results are listed in Table 7.2, in which the tests judged easiest to use are shown first.

Table 7.1 Comparisons of data consistency for different test methods

		Coefficients of Variation for Each Test Method			
Surface Preparation	**Slab Number**	**Slant Shear (%)**	**Direct Shear (%)**	**Direct Tension (%)**	**ACI 503 (%)**
Cold-milled	35		32.68	10.81	
Cold-milled	24		13.93	0.56	38.86
Cold-milled	22		5.33	18.74	
Cold-milled	23				
Cold-milled	27	5.48			31.29
Cold-milled	32	11.46	3.09	3.09	9.51
Cold-milled	33	8.37	4.00	4.00	40.27
Cold-milled	36		8.93	8.93	43.28
Cold-milled	39		20.34	20.34	14.23
Cold-milled	44		4.39	1.20	12.92
Cold-milled	51		24.86		32.59
Cold-milled	43		18.31	21.34	28.28
Cold-milled	37		42.48	14.14	44.77
Cold-milled	26	17.27	30.65	3.97	25.65
Cold-milled	25	23.38	2.50	22.16	41.71
Cold-milled	50		16.43	17.07	4.58
Cold-milled	48		12.76	22.43	3.03
Cold-milled		**Average**	**16.04**	**12.05**	**26.50**
Lightly shotblasted	16		4.79	18.73	46.40
Lightly shotblasted	18		15.57	32.76	38.89
Lightly shotblasted	30		11.21	10.33	28.43
Lightly shotblasted	19			31.56	69.97
Lightly shotblasted	17		47.14	69.99	
Lightly shotblasted	15		58.53	1.99	
Lightly shotblasted	5	28.55			
Lightly shotblasted	4	6.47			
Lightly shotblasted	13		44.12	3.03	12.46
Lightly shotblasted	14		20.08	6.46	57.23
Lightly shotblasted	22	23.96	6.55	10.52	
Lightly shotblasted	10		47.31		25.11
Lightly shotblasted	28	5.79		10.02	35.63
Lightly shotblasted	11		6.07	15.79	
Lightly shotblasted	6	3.42	4.58	3.90	12.36
Lightly shotblasted	20	6.50	0.00		0.00
Lightly shotblasted	21	45.03	3.64	13.54	10.93
Lightly shotblasted		**Average**	**20.74**	**17.59**	**30.67**
Severely shotblasted	37		3.87	7.38	
Severely shotblasted	8	11.95			
Severely shotblasted	16	2.62	1.87	2.53	12.93
Severely shotblasted	17	2.99	0.88	8.26	7.91
Severely shotblasted	32		10.76	11.49	34.11
Severely shotblasted	34		12.58	35.08	104.33
Severely shotblasted	19	4.70			
Severely shotblasted	31		19.56	8.12	19.96
Severely shotblasted	28				47.14
Severely shotblasted	30		15.55	7.20	9.51
Severely shotblasted	10	9.21	4.44	18.45	6.18
Severely shotblasted	9	18.69	13.42	5.07	5.92
Severely shotblasted	35		18.99	37.28	11.64
Severely shotblasted		**Average**	**10.19**	**14.09**	**25.96**

Table 7.2 Comparison of bond strength tests according to their ease of use

Test Method	Type/Test Location	Equipment or Materials	Ease of Use	Variability
Slant-shear	Shear/lab	Comp. load machine; shear blanks (manufactured in house)	Easy	Low
Guillotine	Shear/lab	Comp. load machine; guillotine device; (manufactured in house); coring machine	Medium	High
Direct tension	Tensile/lab	Tens. load machine; tension accessories and alignment jig for epoxying (manufactured in house); coring machine; epoxy	Difficult*	Medium-Low
Modified ACI 503	Tensile/field	503 tension device (manufactured in house); coring machine; epoxy	Medium	Medium
Modified torsion	Torsion/field	Recording torque wrench; torsion inserts (manufactured in house)	Difficult**	Medium

* Difficulty lies in keeping the core's substrate/overlay interface perpendicular to the tensile force.

** Difficulty lies in catching the accelerating bond (shear) strength between 50 and 200 psi.

CHAPTER 8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

More than 150 concrete base slabs, 3 ft x 3 ft x 5 in., were constructed, prepared, and overlaid in order to examine the effects of temperature, different types of bonding agents, application rates, times of application, and surface texture on the bond between portland cement concrete overlays and their concrete substrates.

Eight pavement sections, each 400 ft x 48 ft, on South Loop 610 were prepared, overlaid, and compared with adjacent sections of BCO placed at the same time under a large rehabilitation paving contract in order to corroborate findings from the slab study. The two pavement sections treated with LBS grout debonded extensively in less than one week. It is believed that the LBS may have been too dry before the BCO was placed.

Five test methods were used to compare the bond strengths for each of the overlaid slabs and highway sections. In addition to being used for bond strength comparisons, the test methods themselves were compared for consistency of data and ease of use in an effort to find a practical method that could readily be adapted for use in the field.

Conclusions from all field and laboratory evaluations and those from finite-element analyses are presented below. Following the conclusions are recommendations for construction and for further studies based on the findings of this project.

CONCLUSIONS

1. One of the most important findings, based on the finite-element analysis, is that most debonding is induced at relatively low stresses (under 50 psi) while the overlay is still in its early curing stage. Strain-gauge placements and temperature monitoring during this study provided critical information for the finite-element model. This information was needed to verify the predictions of the model. Indications are that the sum of all the likely stresses, even under the most extreme conditions, is normally low enough that the bond with any substrate texture (with or without bonding agent) is completely adequate once the BCO is cured. The bond is also adequate under most conditions while the overlay is curing. Early debonding problems (except in the LBS sections) seemed to occur only when environmental conditions caused a significant combination of stresses at the interface very early, before the overlay has achieved any appreciable strength.

   The LBS debonding problem probably occurred as a result of premature setting of the latex in the LBS. The solid latex at the interface results from inadvertent local moisture loss in the slurry. The solid latex would make a semi-permeable membrane which could act as a bond breaker.
2. Once the overlay has attained enough cohesive strength to be cored and tested, either it has probably already debonded or it has attained more than sufficient bond strength to later survive most environmentally induced stresses. For this reason, all of the bond evaluation methods compared in this study (except for the torsion test) did little more than provide proof that test specimens had survived the controlled curing and the controlled, environmentally induced strains particular to each specimen, up to the time of testing.
3. Paving conditions that seem to have had a significant adverse effect on the bond between the overlay and the substrate include:
   a. high surface temperatures (over 125°F) on the substrate immediately prior to the placement of the overlay,
   b. ambient temperature variations including drops of more than 25°F during the 24-hour period immediately following the placement of the overlay, and
   c. evaporation rates that exceed 0.2 lb water/sq ft/hr when calculated according to the ACI nomograph.(30)

4. Although results for various test methods are given in Chapter 7, there is some risk in drawing any general conclusions from individual tests. Rather, conclusions may be drawn by combining the best bond performance factors from all test methods and examining those that are common to all methods (Tables A.21-A.23). The consensus is that for BCOs placed under adverse environmental conditions in which the engineer suspects the likelihood of poor bond performance to a clean, sound substrate, the best way to ensure a good bond at the interface is to specify:
   a. using epoxy bonding agents for any texture (especially effective on the less expensive light shotblasting), or
   b. texturing the substrate with severe shotblasting for other bonding agents (and for no bonding agent).
5. The LBS system used as a bonding agent failed under field conditions.
6. The best test method for monitoring bond strengths in the field is the modified ACI 503 pullout test as described in Chapter 3, although these tensile strength values do not necessarily indicate relative tendencies toward debonding.
7. The torsion test that was developed during this project does indicate early bond strengths in the field. However, in its present primitive state, this method is too time-sensitive to be considered practical.

RECOMMENDATIONS

The findings of this study emphasize the importance of good surface preparation and application techniques, carefully supervised and monitored by experienced personnel who can anticipate immediate weather, construction, and curing variables that are likely to cause early interface stresses.

Monitoring of evaporation rates has proved to be easily accomplished either automatically by computer or manually with the use of the ACI nomograph. Because cracks, especially early shrinkage cracks, have been shown to represent boundary condition opportunities for debonding of overlays, evaporation rate monitoring should be regularly performed during those times when excessive evaporation may be a problem.

The use of latex in the grout or bonding slurry should be avoided. Paving should be avoided—or conditions should be artificially improved—whenever the following environmental conditions exist:

a. high surface temperatures (over 125°F) on the substrate immediately prior to the placement of the overlay,
b. ambient temperature variations of more than 25°F during the 24-hour period immediately following the placement of the overlay, and
c. evaporation rates which exceed 0.2 lb water/sq ft/hr when calculated according to the ACI nomograph.(30)

For BCO placed under adverse environmental conditions in which the engineer suspects the likelihood of poor bond performance to a clean, sound substrate, specifications should require:

a. using epoxy bonding agents for any texture (especially effective on the less expensive light shotblasting), or
b. texturing the substrate with severe shotblasting for other bonding agents (and for no bonding agent).

Bond strengths may be easily monitored in the field with the modified ACI 503 pullout test as described in Chapter 3, although these tensile strength values do not necessarily indicate relative tendencies toward debonding.

A method that can easily and reliably determine critical early bond strengths is still needed. Consequently, it is recommended that efforts continue in the development of a torsion test method that could enable an inspector or technician to get a reading at any convenient time in a period from early set to 14 hours after the placement of the BCO, regardless of the specifics of substrate texture and normal ambient paving conditions.

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APPENDIX

Table A.1 Laboratory data from large experiment

Surface Prep.	ID No.	Surface Temp., °F	Grout Type	Applic. Rate	Time Lapse, min.		Comp. Test, psi	Slant Shear, psi	Direct Shear, psi	Direct Tension, psi	Tension Bond,** psi
CM	35	H	G	L	5		7445		517	183	40
CM	35	H	G	L	5		7551		828	157	
CM	35	H	G	L	5	*AVG.*	***7498***	-	***673***	***170***	***40***
CM	24	H	G	H	2		6755		368	251	95
CM	24	H	G	H	2		6578		302	253	167
CM	24	H	G	H	2	*AVG.*	***6667***	-	***335***	***252***	***131***
CM	22	H	L	L	2		7021		481	173	
CM	22	H	L	L	2		6667		446	226	
CM	22	H	L	L	2	*AVG.*	***6844***	-	***464***	***200***	-
CM	23	H	L	H	5		5517				
CM	23	H	L	H	5		5853				
CM	23	H	L	H	5	*AVG.*	***5685***	-	-	-	-
CM	27	L	G	L	2		8223	536			223
CM	27	L	G	L	2		8250	496			350
CM	27	L	G	L	2	*AVG.*	***8237***	***516***	-	-	***287***
CM	32	M	E	L	2		7144	198	201	201	111
CM	32	M	E	L	2		6844	233	210	210	127
CM	32	M	E	L	2	*AVG.*	***6994***	***216***	***206***	***206***	***119***
CM	33	M	E	H	5		7852	548	275	275	286
CM	33	M	E	H	5		6720	617	291	291	159
CM	33	M	E	H	5	*AVG.*	***7286***	***583***	***283***	***283***	***223***
CM	36	M	G	L	5		7073	336	202	202	127
CM	36	M	G	L	5		7197		178	178	239
CM	36	M	G	L	5	*AVG.*	***7135***	***336***	***190***	***190***	***183***

* *Symbols in table are defined on page 46*

** *ACI 503R Test*

Table A.1 Laboratory data from large experiment (continued)

Surface Prep.	ID No.	Surface Temp., °F	Grout Type	Applic. Rate	Time Lapse, min.		Comp. Test, psi	Slant Shear, psi	Direct Shear, psi	Direct Tension, psi	Tension Bond,** psi
CM	39	M	G	H	2		6596		131	131	143
CM	39	M	G	H	2		7286		175	175	175
CM	39	M	G	H	2	*AVG.*	***6941***	-	***153***	***153***	***159***
CM	44	M	L	L	5		7940	441	914	298	199
CM	44	M	L	L	5				859	293	239
CM	44	M	L	L	5	*AVG.*	***7940***	***441***	***886.5***	***295.5***	***219***
CM	51	M	H	H	2		7940		729	203	167
CM	51	M	H	H	2		8205		511		267
CM	51	M	H	H	2	*AVG.*	***8073***	-	***620***	***203***	***217***
LS	16	H	L	L	2		6844		684	167	127
LS	16	H	L	L	2		6667		732	218	64
LS	16	H	L	L	2	*AVG.*	***6756***	-	***708***	***192.5***	***96***
LS	18	H	H	H	5		6508		485	335	127
LS	18	H	H	H	5				605	209	72
LS	18	H	H	H	5	*AVG.*	***6508***	-	***545***	***272***	***100***
LS	30	H	H	H	2		7303		796	235	239
LS	30	H	H	H	2		6950		933	203	159
LS	30	H	H	H	2	*AVG.*	***7127***	-	***864.5***	***219***	***199***
LS	19	H	L	L	5		6631		485	148	48
LS	19	H	L	L	5		6455			94	143
LS	19	H	L	L	5	*AVG.*	***6543***	-	***485***	***121***	***96***

Table A.1 Laboratory data from large experiment (continued)

Surface Prep.	ID No.	Surface Temp., °F	Grout Type	Applic. Rate	Time Lapse, min.		Comp. Test, psi	Slant Shear, psi	Direct Shear, psi	Direct Tension, psi	Tension Bond,** psi
LS	17	H	L	L	5		5889		366	146	64
LS	17	H	L	L	5		6437		183	49	
LS	17	H	L	L	5	*AVG.*	***6163***	-	***274.5***	***98***	***64***
LS	15	H	H	H	2		5836		485	144	80
LS	15	H	H	H	2		6278		1170	140	
LS	15	H	H	H	2	*AVG.*	***6057***	-	***827.5***	***142***	***80***
LS	5	L	L	L	5		7516	427	199		
LS	5	L	L	L	5			643			
LS	5	L	L	L	5	*AVG.*	***7516***	***535***	***199***	-	-
LS	4	L	G	H	2		8117	514	167	170	
LS	4	L	G	H	2		7905	469			
LS	4	L	G	H	2	*AVG.*	***8011***	***491.5***	***167***	***170***	-
LS	13	M	E	L	5		6791		492	334	207
LS	13	M	E	L	5		6738		258	320	247
LS	13	M	E	L	5	*AVG.*	***6765***	-	***375***	***327***	***227***
LS	14	M	E	H	2		7569		724	334	64
LS	14	M	E	H	2		7392		544	366	151
LS	14	M	E	H	2	*AVG.*	***7481***	-	***634***	***350***	***107.5***
LS	22	M	G	H	5		8232	635	271	231	159
LS	22	M	G	H	5		7958	451	247	199	
LS	22	M	G	H	5	*AVG.*	***8095***	***543***	***259***	***215***	***159***
LS	10	M	G	L	2		6366	514	376	119	183
LS	10	M	G	L	2		7940		754		262
LS	10	M	G	L	2	*AVG.*	***7153***	***514***	***565***	***119***	***222.5***

Table A.1 Laboratory data from large experiment (continued)

Surface Prep.	ID No.	Surface Temp., °F	Grout Type	Applic. Rate	Time Lapse, min.		Comp. Test, psi	Slant Shear, psi	Direct Shear, psi	Direct Tension, psi	Tension Bond,** psi
LS	28	M	L	H	2		5146	356		136	159
LS	28	M	L	H	2		5092	328		118	95
LS	28	M	L	H	2	*AVG.*	***5119***	***342***	-	***127***	***127***
LS	11	M	L	L	5		7250	465	703	191	207
LS	11	M	L	L	5		7816		766	239	
LS	11	M	L	L	5	*AVG.*	***7533***	***465***	***734.5***	***215***	***207***
SS	37	H	G	L	2		6260		883	209	167
SS	37	H	G	L	2		6295		836	232	
SS	37	H	G	L	2	*AVG.*	***6278***	-	***859.5***	***220.5***	***167***
SS	8	L	G	L	5		7445	569	183		
SS	8	L	G	L	5		8028	674			
SS	8	L	G	L	5	*AVG.*	***7737***	***621.5***	***183***	-	-
SS	16	M	E	H	2		7383	605	306	275	191
SS	16	M	E	H	2		7427	583	298	285	159
SS	16	M	E	H	2	*AVG.*	***7405***	***594***	***302***	***280***	***175***
SS	17	M	E	L	5		7604	370	318	266	151
SS	17	M	E	L	5		7622	386	322	299	135
SS	17	M	E	L	5	*AVG.*	***7613***	***378***	***320***	***282.5***	***143***
SS	32	M	G	L	5		6844		1068	346	151
SS	32	M	G	L	5		6649		917	294	247
SS	32	M	G	L	5	*AVG.*	***6747***	-	***992.5***	***320***	***199***
SS	34	M	G	H	2		7781		732	317	48
SS	34	M	G	H	2		8241		875	191	318
SS	34	M	G	H	2	*AVG.*	***8011***	-	***804***	***254***	***183***

Table A.1 Laboratory data from large experiment (continued)

Surface Prep.	ID No.	Surface Temp., °F	Grout Type	Applic. Rate	Time Lapse, min.		Comp. Test, psi	Slant Shear, psi	Direct Shear, psi	Direct Tension, psi	Tension Bond,** psi
SS	19	M	L	H	5		8453	524	402	263	167
SS	19	M	L	H	5		7781	560			
SS	19	M	L	H	5	*AVG.*	***8117***	***542***	***402***	***263***	***167***
SS	31	M	L	L	2		7321	380	517	267	143
SS	31	M	L	L	2		7250		683	238	190
SS	31	M	L	L	2	*AVG.*	***7286***	***380***	***600***	***252.5***	***166.5***

Surface Prep:	*"CM" is the acronym for cold-milling,* *"LS" for light shotblasting, and* *"SS" is for severe shotblasting.*
Surface Temp:	*"H" indicates high substrate temperatures (125-140°F)* *"M" indicates medium substrate temperatures (90-100°F), and* *"L" indicates low substrate temperatures (50-60°F).*
Grout Type:	*"G" indicates the District's standard portland cement slurry "grout,"* *"E" indicates epoxy bonding agent, and* *"L" indicates latex modified portland cement slurry.*
Application Rate:	*"L" indicates a low application rate (just enough to wet out the entire substrate surface), and* *"H" indicates a high application rate (as much as could be sprayed without ponding or puddling of the bonding agent on the substrate surface).*
Time Lapse:	*Refers to the time interval between the application of the bonding agent and the placement of the overlay.* *"2" means 2 minutes or less, and* *"5" means 5 minutes or more.*

Table A.2 *Large experiment: optimum two-way treatment combinations for producing highest direct shear bond strengths*

Bonding Agent	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Surfacing Method
Epoxy	Low	<2 or >5	High or Low	Cold Mill, Light Shot, or Severe Shot
Latex	Low or Medium	<2 or >5	High or Low	Cold Mill, Light Shot, or Severe Shot
PC Grout	Medium or High	<2 or >5	High or Low	Severe Shot

Surfacing Method	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Bonding Agent
Cold Mill	Low	>5	High or Low	Epoxy or Latex
Light Shot	Low or High	<2	High	Epoxy or Latex
Severe Shot	Low or High	<2 or >5	High or Low	PC Grout

Substrate Temperature	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Application Rate
High	Cold Mill, Light Shot, or Severe Shot	Epoxy or Grout	<2 or >5	High or Low
Medium	Cold Mill, Light Shot, or Severe Shot	Latex or PC Grout	<2 or >5	High or Low
Low	Cold Mill, Light Shot, or Severe Shot	Epoxy	<2 or >5	High

Application Rate	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Substrate Temperature
High	Cold Mill, Light Shot, or Severe Shot	PC Grout, Latex or Epoxy	<2	Low
Low	Severe Shot or Cold Mill	PC Grout, Latex or Epoxy	<2 or >5	High, Medium, or Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.3 Large experiment: direct shear

		Surface Temp.	Low 50-60		Medium 70-100		High 125-140	
		Application Time	<2 min.	>5 min.	<2 min.	>5 min.	<2 min.	>5 min.
Texture	Bonding Agent	Application Rate						
Light Shotblast	Latex	Low	A = 559 1 = 637 2 = 481			A = 735 1 = 703 2 = 766		A = 275 1 = 366 2 = 183
		High		A = 792 1 = 812 2 = 772			A = 828 1 = 485 2 = 1170	
	Epoxy	Low		A = 645 1 = 648 2 = 643		A = 375 1 = 492 2 = 258	A = 605 1 = 660 2 = 549	
		High	A = 1134 1 = 1409 2 = 859		A = 634 1 = 724 2 = 544			A = 573 1 = 589 2 = 557
	PCC Grout	Low		A = 199 1 = 199	A = 565 1 = 376 2 = 754			A = 485 1 = 485
		High	A = 167 1 = 167			A = 259 1 = 271 2 = 259	A = 865 1 = 796 2 = 933	
Cold Mill	Latex	Low		A = 692 1 = 891 2 = 493		A = 887 1 = 914 2 = 859	A = 464 1 = 481 2 = 446	
		High	A = 893 1 = 893		A = 620 1 = 729 2 = 511			A = 576 1 = 576
	Epoxy	Low		A = 1051 1 = 1163 2 = 939	A = 348 1 = 294 2 = 402			A = 720 1 = 522 2 = 918
		High	A = 790 1 = 828 2 = 751			A = 328 1 = 310 2 = 346	A = 689 1 = 727 2 = 651	
	PCC Grout	Low	A = 189 1 = 155 2 = 223			A = 528 1 = 528		A = 673 1 = 517 2 = 828
		High		A = 680 1 = 412 2 = 947	A = 778 1 = 829 2 = 726		A = 335 1 = 368 2 = 302	
Super Shotblast	Latex	Low		A = 589 1 = 700 2 = 477	A = 600 1 = 517 2 = 683			A = 613 1 = 653 2 = 573
		High	A = 720 1 = 780 2 = 660			A = 402 1 = 402	A = 609 1 = 645 2 = 573	
	Epoxy	Low	A = 844 1 = 907 2 = 780			A = 320 1 = 318 2 = 322		A = 641 1 = 637 2 = 645
		High		A = 912 1 = 1003 2 = 820	A = 302 1 = 306 2 = 298		A = 633 1 = 740 2 = 525	
	PCC Grout	Low		A = 183 1 = 183		A = 993 1 = 1068 2 = 917	A = 860 1 = 883 2 = 836	
		High	A = 637 1 = 637 2 = 637		A = 804 1 = 732 2 = 875			A = 740 1 = 740

▨	Two data points per slab
☐	One data point per slab

1	Data point #1
2	Data point #2
A	Average of data points #1 and #2

Table A.4 Large experiment: optimum two-way treatment combinations for producing highest direct tension bond strengths

Bonding Agent	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Surfacing Method
Epoxy	Low	<2 or >5	High or Low	Light Shot or Cold Mill
Latex	Low	>5	High or Low	Severe Shot
PC Grout	Low	<2 or >5	High	Severe Shot

Surfacing Method	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Bonding Agent
Cold Mill	Low	>5	Low	Epoxy
Light Shot	Low	>5	High	Epoxy
Severe Shot	Low	>5	High	PC Grout, Latex, or Epoxy

Substrate Temperature	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Application Rate
High	Severe Shot Cold Mill	Epoxy	<2 or >5	High
Medium	Cold Mill, Light Shot, or Severe Shot	Epoxy	>5	High or Low
Low	Severe Shot or Cold Mill	Epoxy	>5	High or Low

Application Rate	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Substrate Temperature
High	Severe Shot	PC Grout, Latex, or Epoxy	<2 or >5	Low
Low	Cold Mill, Light Shot, or Severe Shot	Epoxy or Latex	<2 or >5	Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.5 Large experiment: direct tension

Texture	Bonding Agent	Application Rate	Surface Temp.: Low 50-60		Medium 70-100		High 125-140	
		Application Time	<2 min.	>5 min.	<2 min.	>5 min.	<2 min.	>5 min.
Light Shotblast	Latex	Low	A = 159 1 = 165 2 = 153			A = 215 1 = 191 2 = 239		A = 98 1 = 146 2 = 49
		High		A = 285 1 = 271 2 = 298	A = 127 1 = 136 2 = 118		A = 142 1 = 144 2 = 140	
	Epoxy	Low		A = 348 1 = 332 2 = 364		A = 327 1 = 334 2 = 320	A = 319 1 = 357 2 = 281	
		High	A = 343 1 = 346 2 = 340		A = 350 1 = 334 2 = 366			A = 335 1 = 355 2 = 315
	PCC Grout	Low			A = 119 1 = 119			A = 121 1 = 148 2 = 94
		High	A = 170 1 = 170			A = 215 1 = 231 2 = 199	A = 219 1 = 235 2 = 203	
Cold Mill	Latex	Low		A = 220 1 = 182 2 = 258		A = 296 1 = 298 2 = 293	A = 200 1 = 173 2 = 226	
		High	A = 257 1 = 257		A = 203 1 = 203			A = 257 1 = 263 2 = 251
	Epoxy	Low		A = 368 1 = 361 2 = 374	A = 206 1 = 201 2 = 210			A = 365 1 = 361 2 = 369
		High	A = 336 1 = 336			A = 283 1 = 275 2 = 291	A = 336 1 = 326 2 = 346	
	PCC Grout	Low				A = 190 1 = 202 2 = 178		A = 170 1 = 183 2 = 157
		High		A = 283 1 = 293 2 = 273	A = 153 1 = 131 2 = 175		A = 252 1 = 251 2 = 253	
Super Shotblast	Latex	Low		A = 292 1 = 318 2 = 265	A = 253 1 = 267 2 = 238			A = 613 1 = 653 2 = 573
		High	A = 269 1 = 269			A = 263 1 = 263	A = 297 1 = 322 2 = 271	
	Epoxy	Low	A = 315 1 = 345 2 = 284			A = 283 1 = 266 2 = 299		A = 255 1 = 236 2 = 273
		High		A = 324 1 = 346 2 = 302	A = 280 1 = 275 2 = 285		A = 279 1 = 275 2 = 283	
	PCC Grout	Low				A = 320 1 = 346 2 = 294	A = 221 1 = 209 2 = 232	
		High	A = 327 1 = 333 2 = 320		A = 254 1 = 317 2 = 191			A = 297 1 = 283 2 = 310

▨ Two data points per slab
□ One data point per slab

1 Data point #1
2 Data point #2
A Average of data points #1 and #2

Table A.6 Large experiment: optimum two-way treatment combinations for producing highest ACI 503 direct tension

Bonding Agent	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Surfacing Method
Epoxy	Low	>5	High or Low	Light Shot
Latex	Low	<2	High or Low	Severe Shot
PC Grout	Low	<2 or >5	High or Low	Severe Shot

Surfacing Method	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Bonding Agent
Cold Mill	Low	<2 or >5	Low	Epoxy or Latex
Light Shot	Low	<2 or >5	High	Epoxy
Severe Shot	Low	<2 or >5	High	PC Grout, Latex, or Epoxy

Substrate Temperature	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Application Rate
High	Severe Shot	Epoxy	<2 or >5	High or Low
Medium	Cold Mill, Light Shot, or Severe Shot	PC Grout, Latex, or Epoxy	>5	High or Low
Low	Light or Severe Shot	PC Grout, Latex, or Epoxy	<2	<2

Application Rate	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Substrate Temperature
High	Severe Shot	PC Grout, Latex, or Epoxy	<2 or >5	Low
Low	Cold Mill, Light Shot, or Severe Shot	Epoxy or Latex	<2 or >5	Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.7 Test data from large experiment: modified ACI 503 tension bond method (test data values are in psi)

Surface Temp.			Low 50-60		Medium 70-100		High 125-140	
Application Time			<2 min.	>5 min.	<2 min.	>5 min.	<2 min.	>5 min.
Texture	**Bonding Agent**	**Application Rate**						
Light Shotblast	Latex	Low	A = 323 1 = 374 2 = 271			A = 207 1 = 207		A = 64 1 = 64
		High		A = 231 1 = 223 2 = 239	A = 127 1 = 159 2 = 95		A = 80 1 = 80	
	Epoxy	Low		A = 295 1 = 310 2 = 279		A = 227 1 = 207 2 = 247	A = 159 1 = 159 2 = 159	
		High	A = 295 1 = 350 2 = 239		A = 108 1 = 64 2 = 151			A = 259 1 = 263 2 = 255
	PCC Grout	Low			A = 223 1 = 183 2 = 262			A = 96 1 = 48 2 = 143
		High				A = 159 1 = 159	A = 199 1 = 239 2 = 159	
Cold Mill	Latex	Low		A = 195 1 = 286 2 = 103		A = 219 1 = 199 2 = 239	A = 179 1 = 167 2 = 191	
		High	A = 287 1 = 255 2 = 318		A = 217 1 = 167 2 = 267			A = 119 1 = 135 2 = 103
	Epoxy	Low		A = 311 1 = 271 2 = 350	A = 119 1 = 111 2 = 127			A = 279 1 = 279
		High	A = 95 1 = 95			A = 223 1 = 286 2 = 59	A = 143 1 = 159 2 = 127	
	PCC Grout	Low	A = 287 1 = 223 2 = 350			A = 183 1 = 127 2 = 239		A = 40 1 = 40
		High		A = 159 1 = 159	A = 159 1 = 143 2 = 175		A = 131 1 = 95 2 = 167	
Super Shotblast	Latex	Low		A = 259 1 = 294 2 = 223	A = 167 1 = 143 2 = 190			A = 263 1 = 279 2 = 247
		High	A = 283 1 = 326 2 = 239			A = 167 1 = 167	A = 167 1 = 199 2 = 135	
	Epoxy	Low	A = 267 1 = 294 2 = 239			A = 143 1 = 151 2 = 135		A = 203 1 = 207 2 = 199
		High		A = 231 1 = 326 2 = 135	A = 175 1 = 191 2 = 159		A = 175 1 = 199 2 = 151	
	PCC Grout	Low				A = 199 1 = 151 2 = 247	A = 167 1 = 167	
		High	A = 338 1 = 358 2 = 318		A = 183 1 = 48 2 = 318			A = 187 1 = 191 2 = 183

▨	Two data points per slab	1	Data point #1
☐	One data point per slab	2	Data point #2
		A	Average of data points #1 and #2

Table A.8 ***Wet versus dry experiment: optimum two-way treatment combinations for producing highest shear bond strengths***

Surface	Moisture	Temperature
Cold Mill	Wet or Dry	Medium
Light Shot	Wet or Dry	Medium or Low
Severe Shot	Dry	Medium

Temperature	Surface	Moisture
Low	Severe Shot	Dry
Medium	Cold Mill/Severe Shot	Wet or Dry
High	Light/Severe Shot	Wet or Dry

Moisture	Surface	Temperature
Wet	Cold Mill, Light Shot, or Severe Shot	Medium or Low
Dry	Severe Shot	High, Medium, or Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.9 Test data from wet versus dry experiment: guillotine direct tension method (data values are in psi)

Surface Prep. / Grout. / Surface Temperature, °F	Light Shotblast		Heavy Shotblast		Cold Mill	
	Dry	Wet	Dry	Wet	Dry	Wet
HIGH 130-140	A = 596 1 = 659 2 = 532	A = 450 1 = 450	A = 836 1 = 836	A = 378 1 = 419 2 = 336	A = 448 1 = 390 2 = 506	A = 435 1 = 304 2 = 565
MEDIUM 70-100	A = 231 1 = 231 2 = 231	A = 233 1 = 227 2 = 239	A = 682 1 = 590 2 = 773	A = 676 1 = 565 2 = 786	A = 728 1 = 643 2 = 812	A = 654 1 = 713 2 = 595
LOW 50-60	A = 637 1 = 637 2 = 637	A = 617 1 = 597 2 = 637	A = 637 1 = 617 2 = 657	A = 527 1 = 477 2 = 577	A = 203 1 = 247 2 = 159	A = 340 1 = 346 2 = 334

▨	Two data points per slab
☐	One data point per slab
1	Data point #1
2	Data point #2
A	Average of data points #1 and #2

Table A.10 Wet versus dry experiment: optimum two-way treatment combinations for producing highest direct tension bond strengths

Surface	Moisture	Temperature
Cold Mill	Wet	Medium or Low
Light Shot	Wet	Medium or Low
Severe Shot	Wet	Low

Temperature	Surface	Moisture
Low	Any	Any
Medium	Light Shot	Wet
High	Any	Wet

Moisture	Surface	Temperature
Wet	Light Shot	Medium or Low
Dry	Any	Medium or Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.11 Test data from wet versus dry experiment: direct tension method (data values are in psi)

Surface Prep. / Grout / Surface Temperature, °F	Light Shotblast		Heavy Shotblast		Cold Mill	
	Dry	Wet	Dry	Wet	Dry	Wet
HIGH 130-140	A = 143 1 = 137 2 = 148	A = 218 1 = 180 2 = 255	A = 196 1 = 196	A = 187 1 = 177 2 = 196	A = 143 1 = 121 2 = 164	A = 200 1 = 180 2 = 220
MEDIUM 70-100	A = 232 1 = 232	A = 319 1 = 349 2 = 288	A = 120 1 = 151 2 = 88	A = 273 1 = 247 2 = 298	A = 232 1 = 204 2 = 260	A = 227 1 = 191 2 = 263
LOW 50-60	A = 239 1 = 201 2 = 276	A = 254 1 = 261 2 = 247	A = 253 1 = 220 2 = 286	A = 287 1 = 228 2 = 245	A = 214 1 = 220 2 = 208	A = 217 1 = 251 2 = 183

▨	Two data points per slab
☐	One data point per slab
1	Data point #1
2	Data point #2
A	Average of data points #1 and #2

Table A.12 Wet versus dry experiment: optimum two-way treatment combinations for producing highest ACI 503 direct tension bond strengths

Surface	Moisture	Temperature
Cold Mill	Wet	Medium
Light Shot	Wet	Medium or Low
Severe Shot	Dry	Medium

Temperature	Surface	Moisture
Low	Light/Severe Shot	Wet or Dry
Medium	Cold Mill, Light Shot, or Severe Shot	Wet or Dry
High	Severe Shot	Wet

Moisture	Surface	Temperature
Wet	Light or Severe Shot	Medium or Low
Dry	Severe Shot	Medium or Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.13 Test data from wet versus dry experiment: ACI 503 tension method (data values are in psi)

Surface Prep. Grout. Surface Temperature, °F	Light Shotblast		Heavy Shotblast		Cold Mill	
	Dry	Wet	Dry	Wet	Dry	Wet
HIGH 130-140	▨ A = 68 1 = 72 2 = 64	☐ A = 191 1 = 191	▨ A = 215 1 = 286 2 = 143	▨ A = 119 1 = 111 2 = 127	▨ A = 40 1 = 32 2 = 48	▨ A = 139 1 = 183 2 = 95
MEDIUM 70-100	☐ A = 191 1 = 191	▨ A = 207 1 = 223 2 = 191	▨ A = 243 1 = 223 2 = 263	▨ A = 235 1 = 191 2 = 279	▨ A = 247 1 = 255 2 = 239	▨ A = 187 1 = 183 2 = 191
LOW 50-60	▨ A = 191 1 = 199 2 = 183	▨ A = 183 1 = 199 2 = 167	▨ A = 183 1 = 191 2 = 175	▨ A = 191 1 = 199 2 = 183	▨ A = 108 1 = 127 2 = 88	▨ A = 148 1 = 191 2 = 104

▨	Two data points per slab
☐	One data point per slab
1	Data point #1
2	Data point #2
A	Average of data points #1 and #2

Table A.14 Grout versus no-grout experiment: optimum two-way treatment combinations for producing highest direct shear bond strengths

Surface	Bonding Agent	Temperature
Cold Mill	G or NG	Medium
Light Shot	G or NG	Medium
Severe Shot	G or NG	High

Bonding Agent	Surface	Temperature
Grout	Severe Shot	High or Medium
No Grout	Severe Shot	Medium

Temperature	Surface	Bonding Agent
Low	Severe Shot	G or NG
Medium	Severe Shot/ Cold Mill	Grout
High	Severe Shot	G or NG

"G" indicates use of portland cement bonding slurry, "grout".
"NG" indicates no bonding agent was used.

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.15 Test data from grout versus no-grout experiment: direct shear method (data values are in psi)

Surface Prep. / Grout / Surface Temperature, °F	Light Shotblast		Heavy Shotblast		Cold Mill	
	No Grout	Grout	No Grout	Grout	No Grout	Grout
HIGH 130-140	▨ A = 596 1 = 659 2 = 532	A = 450 1 = 450	A = 836 1 = 836	▨ A = 378 1 = 419 2 = 336	▨ A = 448 1 = 390 2 = 506	▨ A = 435 1 = 304 2 = 565
MEDIUM 70-100	▨ A = 231 1 = 231 2 = 231	▨ A = 233 1 = 227 2 = 239	▨ A = 682 1 = 590 2 = 773	▨ A = 676 1 = 565 2 = 786	▨ A = 728 1 = 643 2 = 812	▨ A = 654 1 = 713 2 = 595
LOW 50-60	▨ A = 637 1 = 637 2 = 637	▨ A = 617 1 = 597 2 = 637	▨ A = 637 1 = 617 2 = 657	▨ A = 527 1 = 477 2 = 577	▨ A = 203 1 = 247 2 = 159	▨ A = 340 1 = 346 2 = 334

▨	Two data points per slab
☐	One data point per slab
1	Data point #1
2	Data point #2
A	Average of data points #1 and #2

Table A.16 Grout versus no-grout experiment: optimum two-way treatment combinations for producing highest direct tension bond strengths

Surface	Bonding Agent	Temperature
Cold Mill	G, NG	Low
Light Shot	G, NG	Medium or Low
Severe Shot	G	Low

Bonding Agent	Surface	Temperature
Grout	Severe Shot	Low
No Grout	Cold Mill, Light Shot, or Severe Shot	Low

Temperature	Surface	Bonding Agent
Low	Severe Shot	Grout
Medium	Cold Mill, Light Shot, or Severe Shot	Grout
High	Severe Shot	Grout

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.17 Test data from grout versus no-grout experiment: direct tension method (data values are in psi)

Surface Prep. / Grout / Surface Temperature, °F	Light Shotblast		Heavy Shotblast		Cold Mill	
	No Grout	Grout	No Grout	Grout	No Grout	Grout
HIGH 130-140	A = 143 1 = 137 2 = 148	A = 218 1 = 180 2 = 255	A = 196 1 = 196	A = 187 1 = 177 2 = 196	A = 143 1 = 121 2 = 164	A = 200 1 = 180 2 = 220
MEDIUM 70-100	A = 232 1 = 232	A = 319 1 = 349 2 = 288	A = 120 1 = 151 2 = 88	A = 273 1 = 247 2 = 298	A = 232 1 = 204 2 = 260	A = 227 1 = 191 2 = 263
LOW 50-60	A = 239 1 = 201 2 = 276	A = 254 1 = 261 2 = 247	A = 253 1 = 220 2 = 286	A = 237 1 = 228 2 = 245	A = 214 1 = 220 2 = 208	A = 217 1 = 251 2 = 183

▨ Two data points per slab

☐ One data point per slab

1 Data point #1
2 Data point #2
A Average of data points #1 and #2

Table A.18 Grout versus no-grout experiment: optimum two-way treatment combinations for producing highest ACI 503 direct tension bond strengths

Surface	Bonding Agent	Temperature
Cold Mill	PC Grout, Latex, or Epoxy	Medium or Low
Light Shot	PC Grout, Latex, or Epoxy	Medium or Low
Severe Shot	PC Grout, Latex, or Epoxy	Low

Bonding Agent	Surface	Temperature
Grout	Severe Shot	Low
No Grout	Severe Shot	Medium

Temperature	Surface	Bonding Agent
Low	Light or Severe Shot	Grout
Medium	Cold Mill, Light Shot, or Severe Shot	No Grout
High	Severe Shot	Grout

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.19 Test data from grout versus no-grout experiment: ACI 503 tension method (data values are in psi)

Surface Prep.	Light Shotblast		Heavy Shotblast		Cold Mill	
Grout Surface Temperature, °F	No Grout	Grout	No Grout	Grout	No Grout	Grout
HIGH 130-140	A = 68 1 = 72 2 = 64	A = 191 1 = 191	A = 215 1 = 286 2 = 143	A = 119 1 = 111 2 = 127	A = 40 1 = 32 2 = 48	A = 139 1 = 183 2 = 95
MEDIUM 70-100	A = 191 1 = 191	A = 207 1 = 223 2 = 191	A = 243 1 = 223 2 = 263	A = 235 1 = 191 2 = 279	A = 247 1 = 255 2 = 239	A = 187 1 = 183 2 = 191
LOW 50-60	A = 191 1 = 199 2 = 183	A = 183 1 = 199 2 = 167	A = 183 1 = 191 2 = 175	A = 191 1 = 199 2 = 183	A = 108 1 = 127 2 = 88	A = 148 1 = 191 2 = 104

▨	Two data points per slab
☐	One data point per slab
1	Data point #1
2	Data point #2
A	Average of data points #1 and #2

Table A.20 Comparison of bond strength values for each experimental section on South Loop IH-610

SECTION NUMBER	BONDING AGENT	SUBSTRATE TEXTURE	DIRECT SHEAR BOND, psi/coef. of var./count	ACI 503 TENSILE BOND, psi/coef. of var./count	DIRECT TENSILE BOND, psi/coef. of var./count
1	NONE	CM	739/33%/2	159/18%/3 (or 119/70%/4)*	141/1 spec.
2	PBS	CM	847/14%/2	138/15%/4	137/14%/2
3	PBS	CM	917/4%/2	155/5%/4	191/0.2%/2
4	EPOXY	LS	510/34%/3	261/29%/4	NA
5	LATEX	LS	171/1 spec.	275/1 spec. (or 93/173%/3)*	NA
6	LATEX	HS	529/1 spec.	225/10%/3 (or 135/92%/5)*	NA
7	PBS	SS	535/27%/3	222/12%/6	NA
8	NONE	HS	576/37%/6	290/10%/6	NA
B	PBS	CM	433/1 spec.	245/22%/6	NA

* *Originally zero values were dropped before averaging because premature debonding had not occurred in the laboratory study, and it was assumed that the coring process caused the breaks. Later problems indicated true debonding had already occurred, so zero values are added in for the second average.*

NA: Not available because the later numbered sections were actually placed first while the laboratory tensile tests were being perfected.

Table A.21 ***Wet versus dry experiment: optimum two-way treatment combinations for producing best combined overall bond strengths***

Surface	Moisture	Temperature
Cold Mill	Wet	Medium
Light Shot	Wet	Medium or Low
Severe Shot	-	Not High

Temperature	Surface	Moisture
Low	Severe Shot	Dry
Medium	-	Wet
High	Severe Shot	Wet

Moisture	Surface	Temperature
Wet	Light Shot	Medium or Low
Dry	Severe Shot	Medium or Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.22 ***Grout versus no-grout experiment: optimum two-way treatment combinations for producing best combined overall bond strengths***

Surface	Bonding Agent	Temperature
Cold Mill	Grout or No Grout	Medium
Light Shot	Grout or No Grout	
Severe Shot	Grout	-

Bonding Agent	Surface	Temperature
Grout	Severe Shot	-
No Grout	Severe Shot	-

Temperature	Surface	Bonding Agent
Low	Severe Shot	Grout
Medium	Severe Shot/ Cold Mill	-
High	Severe Shot	Grout

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.

Table A.23 Large experiment: optimum two-way treatment combinations for producing best combined overall bond strengths

Bonding Agent	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Surfacing Method
Epoxy	Low	>5	High or Low	Light Shot
Latex	Low	-	High or Low	Severe Shot
PC Grout	-	<2 or >5	High	Severe Shot

Surfacing Method	Substrate Temperature	Time, min. (grout to O.L.)	Application Rate	Bonding Agent
Cold Mill	Low	>5	-	Epoxy
Light Shot	Low	-	High	Epoxy
Severe Shot	Low	>5	High	PC Grout

Substrate Temperature	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Application Rate
Cold Mill	Severe Shot	Epoxy	<2 or >5	High
Light Shot	Severe Shot	-	>5	High or Low
Severe Shot	Severe Shot	Epoxy	-	High

Application Rate	Surfacing Method	Bonding Agent	Time, min. (grout to O.L.)	Substrate Temperature
High	Severe Shot	Epoxy	-	Low
Low	Severe Shot	Epoxy	>5	Low

This table shows recommended levels for each column-heading condition when paired with the respective row-heading conditions. These levels produced the highest bond strengths for the specified pairings of conditions.