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16. Abstract

Expedited bonded concrete overlays offer an economical alternative to rehabilitating concrete pavements. The construction of a bonded concrete overlay in El Paso has provided the opportunity to research pavement design, mix design, construction methods, and specification development for use in future overlay construction.

This report documents the valuable information collected during the construction of the bonded concrete overlay on IH-10 in El Paso. Although this project did not proceed as an expedited overlay, it was planned and researched as such. Unfortunately, a combination of factors led to delamination in some areas of the overlay. This report identifies the causes of these delaminations that occurred during this construction and makes recommendations for future overlay construction.

Project selection, design, construction, and quality control are addressed in an included guide for expedited bonded concrete overlays. Also addressed is the scheduling of the construction in such a way as to avoid marginal or severe environmental conditions. The methods presented in this report may be used to construct bonded concrete overlays that can be opened to traffic 12 to 24 hours after concrete placement.

17. Key Words

Bonded concrete overlays, early-age behavior of concrete, IH-10, El Paso, CRCP, long-term performance

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PARTIAL CONSTRUCTION REPORT OF A BONDED CONCRETE OVERLAY ON IH-10, EL PASO, AND GUIDE FOR EXPEDITED BONDED CONCRETE OVERLAY DESIGN AND CONSTRUCTION

by

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Research Report 2911-5F

Research Project 7-2911
Full-Scale Bonded Concrete Overlay on IH-10 in El Paso

conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

by the

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

December 1996

IMPLEMENTATION RECOMMENDATIONS

The following recommendations for expedited bonded concrete overlay (BCO) construction can be applied immediately. The recommendations apply to planning, designing pavement rehabilitation, and to developing specifications for bonded concrete overlays.

1. The decision to construct a BCO should be based on pavement condition, engineering economic analysis, and on such practical considerations as overhead clearances.
2. The BCO should be designed using BCOCAD (a thickness design program developed for this project), the steel design documented in CTR Report 920-6F, and a mixture designed according to the standard specifications (including the modifications in Appendix A of this report).
3. Construction should proceed only under acceptable environmental conditions described by the evaporation rate (<1.0 kg/m^2/hr), ambient temperature (predicted low temperature during the 24 hours following paving should not exceed 14°C below the ambient temperature at time of placement), and concrete temperature (<29°C at placement).
4. Base pavement and shoulders should be repaired or upgraded to provide adequate support as required by the design.
5. All asphalt layers should be removed by cold milling, since asphalt will act as a bond breaker.
6. The base concrete should be shotblasted or hydrocleaned to an average texture depth of 2.0 mm according to TxDOT's Sand Patch Method. Adequate soundness and cleanliness of substrate surface after preparation should be determined according to ACI 503R Appendix A.1, Field Test for Surface Soundness and Adhesion.
7. The base pavement should be air blasted within an hour before placement and be at saturated surface dry condition at the time of placement of the overlay.
8. Shear connectors are recommended where adverse weather conditions as described by Recommendation 3 are expected.
9. Curing measures as described in Table 4.1 are recommended. Evaporation retardant may be sprayed on freshly placed concrete.
10. The BCO may be opened to traffic when it is at least 12 hours old and has attained a splitting tensile strength of at least 3,450 kPa or the corresponding maturity value.
11. If extensive areas of delamination exist as identified by cracking, coring, seismic methods, and FWD testing, the bond to the substrate must be repaired in order for the pavement to reach the intended design life. The low viscosity epoxy resin repair system is an effective bond repair method.

Prepared in cooperation with the Texas Department of Transportation.

PREFACE

This is the fifth and final report for Project 2911, "Full-Scale Bonded Concrete Overlay on IH-10, El Paso." The research project was conducted by the Center for Transportation Research (CTR) of The University of Texas at Austin as part of the Cooperative Research Program administered by the Texas Department of Transportation. Specifically, this report provides a guide to expedited bonded concrete overlay construction based on the research conducted during the period leading up to construction; it also includes the data collected during construction of the project in El Paso.

The authors thank the Texas Department of Transportation (TxDOT) for the sponsorship of this project, and express special appreciation to the project director, Mr. David Head, of TxDOT's El Paso District.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

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Research Supervisor

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SUMMARY

Expedited bonded concrete overlays offer an economical alternative for rehabilitating concrete pavements while minimizing user costs. The construction of a bonded concrete overlay in El Paso has provided the opportunity to research pavement design, mix design, construction methods, and specification development for future overlay construction.

The report documents the valuable information collected during the initial construction of the bonded concrete overlay on IH-10 in El Paso. Although this project did not proceed as an expedited overlay, it was planned and researched as such. Unfortunately, a combination of factors lead to delamination in some areas of the overlay. The causes of these delaminations that occurred during construction are identified and recommendations for future overlay construction are made.

The report includes a guide for expedited bonded concrete overlay construction and includes project selection, design, construction, and quality control. Scheduling construction to avoid marginal or severe environmental conditions is also addressed. The methods presented in this report may be used to construct bonded concrete overlays that can be opened to traffic 12 to 24 hours after concrete placement.

CHAPTER 1. INTRODUCTION

The rehabilitation of concrete pavements may be necessary as a result of either structural inadequacy (inability to carry further loading) or functional inadequacy (poor ride quality). Rehabilitation strategies include removing and replacing the pavement structure, or placing on the original structure an asphalt or concrete overlay. Concrete overlays may be unbonded, bonded, or partially bonded (Ref 1). This research project focused on bonded concrete overlays, specifically that implemented on Interstate 10 in El Paso, Texas.

A bonded concrete overlay (BCO) is used to increase the thickness of the *original* pavement, thereby increasing stiffness and reducing pavement deflections and stresses. For a BCO, the bond of the overlay to the original pavement is critically important. If bond is not achieved, the overlaid sections will not behave as a single composite element, and deflections and stresses will be higher than desired. As a consequence, the BCO may not achieve its design life.

1.1 BACKGROUND

The IH-10 segment running through downtown El Paso, Texas, was constructed in 1965 as a 200-mm continuously reinforced pavement. In 1993 a section of this pavement between mile markers 18.5 and 20.0 was selected for rehabilitation using a bonded concrete overlay (Ref 7). The feasibility study performed under Project 1957 included preliminary testing of the existing pavement and design of the overlay. Project 2911 was initiated to complete a detailed design for the particular construction on IH-10 and to prepare final recommendations on materials and construction procedures for bonded concrete overlays in the El Paso District.

On February 6, 1996, two contractors — Dan Williams Company and Abrams Company — bid on the project, with the Dan Williams Company identified as the low bidder. The project included both new 330-mm CRCP sections and 165-mm BCO sections (total concrete thickness of 365 mm). Because these two construction items are similar with respect to the type of project and quantity of construction, they therefore present an excellent opportunity for comparing the cost of a BCO with that of a new pavement (satisfying the same design requirements). Table 1.1 summarizes all the costs considered for a given pavement type and are presented on a square meter basis for comparison purposes. In reviewing the costs it should be noted that the BCO can be constructed for half the cost of a new pavement for the same service life, but that the comparison does not include user delay costs. It is anticipated that new pavement construction will result in longer delays and, hence, greater overall costs.

1.2 RESEARCH AND REPORT OBJECTIVES

Given the high traffic volumes found on many highways, the user costs associated with highway closures can be inordinately high. To offset these costs, engineers have developed various techniques for expediting or accelerating concrete paving operations (Ref 2). The objective of this research is to expand these techniques to include bonded concrete overlays.

This report contains data collected during and shortly after construction, examines the occurrence and repair of delaminations in the overlay, and recommends specifications and procedures for future bonded concrete overlay construction. An additional objective of this report is to provide guidelines for expedited bonded concrete overlay design and construction. These recommendations are based on the results of previous laboratory and field studies (Refs 3, 4, and 5), as well as on the data collected during construction of the overlay on IH-10, El Paso. Although these guidelines are specifically tailored for construction in the El Paso District, it is anticipated that they may be applied elsewhere where conditions are similar or less severe.

Table 1.1 Comparison of bidders prices

Pavement Type	Activity	Quantity	Dan Williams		Abrams	
			Price per quantity	Price per total surface	Price per quantity	Price per total surface
Overlay	16.5 cm BCO	22,574 m^2	\$37.20	\$37.20	\$52.80	\$52.80
	Repair existing	417 m^2	\$72.00	\$1.33	\$216.00	\$3.99
				\$38.53		\$56.79
Recon-struction	33 cm CRCP	31,520 m^2	\$59.64	\$59.64	\$66.00	\$66.00
	Terminal anchors	375 m^3	\$173.03	\$2.06	\$232.93	\$2.77
	Hot mix base	11,691 ton	\$42.90	\$15.91	\$41.80	\$15.50
	Remove existing	31,520 m^2	\$6.00	\$6.00	\$10.80	\$10.80
				\$83.61		\$95.07

1.3 FORMAT

This document is divided into five chapters. Chapter 2 reports the data collected during the construction of the bonded concrete overlay on IH-10, El Paso, in June and July of 1996. Chapter 3 analyzes the collected data in order to make recommendations for implementation in the repair of the existing debonded overlay and to prevent debonding problems in any future BCO construction. The analysis focuses on the cause and effect of delaminations that had occurred shortly after construction. Chapter 3 also summarizes the epoxy bonding of the debonded overlay sections. Chapter 4, a construction guide for expedited bonded concrete overlay construction, includes the following sections:

1. Evaluation and repair of the existing pavement
2. Methods of selecting pavement thickness and reinforcement
3. Methods and requirements for surface preparation
4. Selection of materials
5. Climatic controls and curing
6. Procedures for determining when the BCO may be opened to traffic

Chapter 5 summarizes the recommendations of this report. Finally, Appendix A presents recommended BCO special provisions, while Appendix B identifies acronyms used in this study.

CHAPTER 2. INVESTIGATION OF INSIDE LANE OVERLAY DELAMINATIONS

This chapter describes the first-phase construction of the bonded concrete overlay on IH-10 in El Paso. This first phase included only the inside lanes in both eastbound and westbound directions.

2.1 BACKGROUND

The rehabilitation of a continuously reinforced concrete pavement on IH-10 in downtown El Paso involved the placement of a bonded concrete overlay. A 0.8-km section overlay, 165-mm thick and 3.7 to 5.5 m wide, was placed on the inside lanes in both directions, over the original 200-mm thick continuously reinforced concrete pavement. The eastbound section was placed between June 25 and 30, while the westbound section was placed between July 17 and 22. Soon after construction, delaminations identified by coring confirmed that excessive transverse cracking was due to an unbonded overlay. Continued coring and seismic testing identified the extent of the problem. Most of the delaminated sections were in the eastbound lanes, though one westbound section exhibited some delamination. Figure 2.1 shows a plan view of the project section, illustrating bonded and unbonded segments in both directions.

The objective of Chapters 2 and 3 is to document the analysis performed by the Center for Transportation Research (CTR) on the debonding of the overlay, including the latest findings on the causes of the delamination; these chapters will also evaluate the effect of the delamination on the pavement life. Finally, we present guidelines that can be used in efforts to prevent similar problems in subsequent overlay placements.

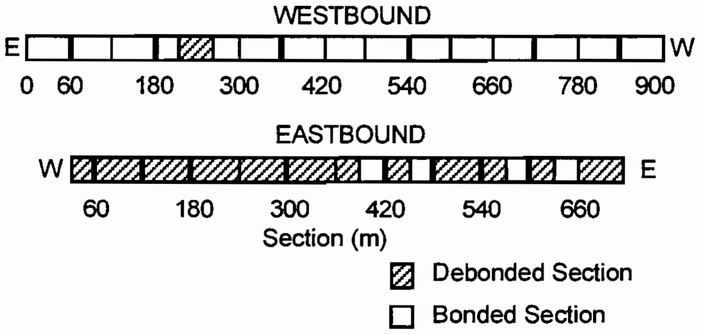


Figure 2.1 A plan view of the BCO showing the overlay bonding condition

2.2 MIXTURE DESIGN

During the period leading up to final detailed design recommendations, we constructed a test slab using various mixture designs. The mix design shown in Table 2.1 for the test slab was recommended for expedited construction (Ref 5). In designing the mix for the BCO project, equivalent attributes could not be achieved and the design was changed to the mix as shown for "Inside Lanes." The cause of the problems with the test slab mix is thought to be a change in chemical content of the cement. A chemical analysis of the cement revealed that the C_3S content had decreased during the period since the test slab mix was designed, reducing early-age strength gain and possibly ultimate bond strength. Delaminations occurred on the inside lanes. As a result of the delaminations and because expedited construction was no longer required, the mix was finally changed to that shown for "Outside Lanes" in Table 2.1. The remainder of the project is being constructed using the "Outside Lanes" mixture.

Table 2.1 Mixture design

Attribute	Test Slab	Inside Lanes	Outside Lanes
Compressive strength		48.3 MPa	24.8 MPa
Coarse aggregate size		19 mm	38 mm
Slump		60 mm	100 mm
Air content		4.5 %	4.5 %
Water-cement ratio	0.29	0.33	0.47
Cement	520 kg/m^3	417 kg/m^3	334 kg/m^3
Water	151 kg/m^3	138 kg/m^3	156 kg/m^3
Fine aggregate	652 kg/m^3	793 kg/m^3	681 kg/m^3
Coarse aggregate	1061 kg/m^3	1065 kg/m^3	1184 kg/m^3
HRWR	396 ml/m^3	541 ml/m^3	541 ml/m^3
Fiber		2 kg/m^3	

2.3 REVIEW OF ENVIRONMENT AND CONCRETE PROPERTIES

In looking for possible causes of the delamination, we analyzed the weather conditions occurring during the placement of the inside lanes, as well as the moisture content characteristics of the mix. Ambient temperatures and water evaporation rates were studied for those periods during which the concrete was placed. Information is provided by correlating the time of placement and the section placed. In Figures 2.2 to 2.9 the total length of the eastbound and westbound sections is delineated by vertical lines. The lines separate dates of placement as shown.

Figures 2.2 and 2.3 present the average temperatures occurring during the construction period for the eastbound and westbound lanes, respectively. The most critical temperatures occurred while the westbound lanes were overlaid, especially the 240- to 400-meter section, which includes the only unbonded section in that direction, where the average temperature was 33°C. In the eastbound direction, the temperatures were not as high, but the two sections showing the highest temperature recordings (600- to 700-m section) have unbonded segments.

Figures 2.4 and 2.5 show the average evaporation rates occurring during overlay placement for the eastbound and westbound lanes, respectively. The water evaporation rate from freshly placed concrete is a function of the wind speed, air and concrete temperatures, and relative humidity. Evaporation rates of 1 kg/m^2/hr or greater are considered critical during overlay placement. In this case, none of the average values surpassed that critical value, but there were higher evaporation rates associated with the delaminated areas. The highest evaporation rate (0.88 kg/m^2/hr) occurred on the 600- to 660-meter westbound section, which includes the unbonded part of the overlay.

Evaporation rates, in combination with the time elapsed between the overlay placement and the application of the curing compound, *might* have been a contributing factor to the delamination (no data were extensively collected). Information about time elapsed between overlay placement and the application of the curing compound was obtained from the District. The dry mix used to satisfy the unnecessary higher strength requirement (not constructed as an expedited project) was probably too dry to promote adequate adhesion. Figures 2.6 and 2.7 present the curing times after overlay construction for the eastbound and westbound lanes, respectively. Limiting water evaporation loss, both from the top and the bottom of the slab, is an important construction aspect that should be carefully followed up to prevent future delaminations. Moisture loss through the bottom of the slab is another critical contributor to the slab delamination. This occurred because the existing pavement was not wetted prior to the overlay placement.

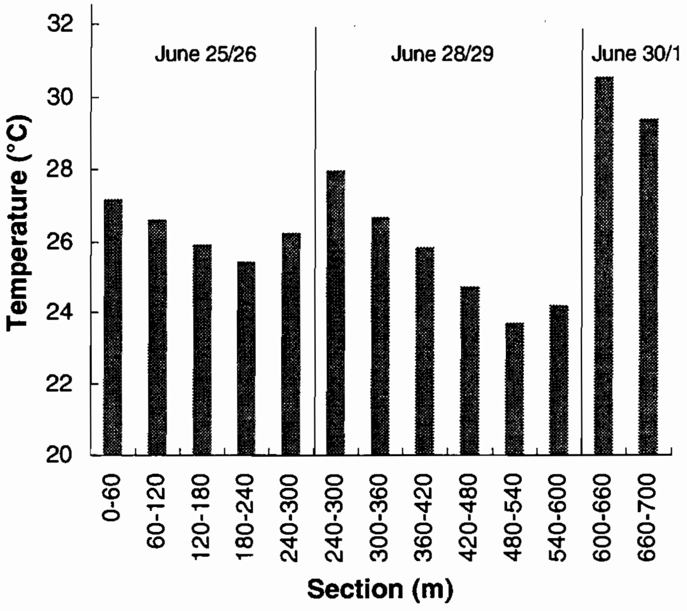


Figure 2.2 Average ambient temperatures during eastbound lane construction

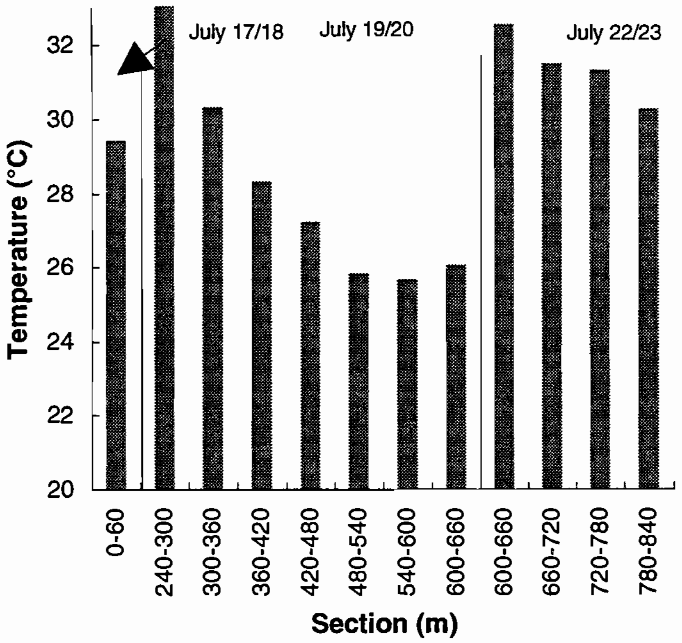


Figure 2.3 Average ambient temperatures during westbound lane construction

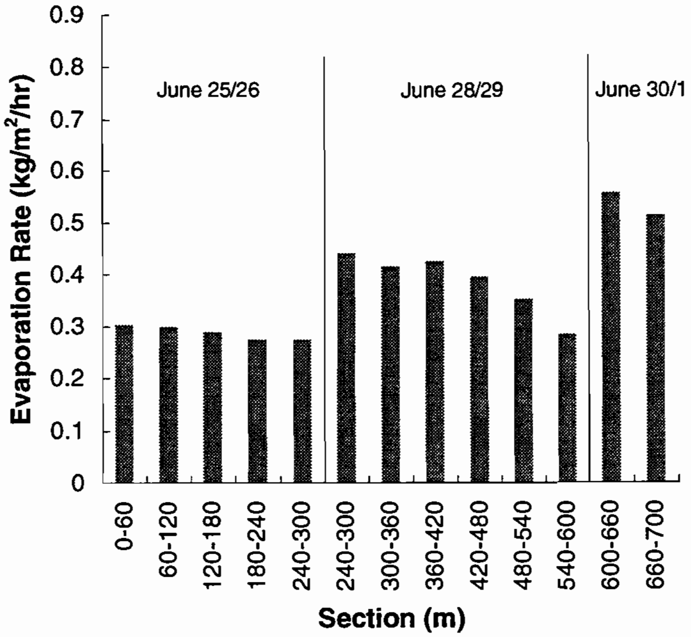


Figure 2.4 Average evaporation rates during eastbound lane construction

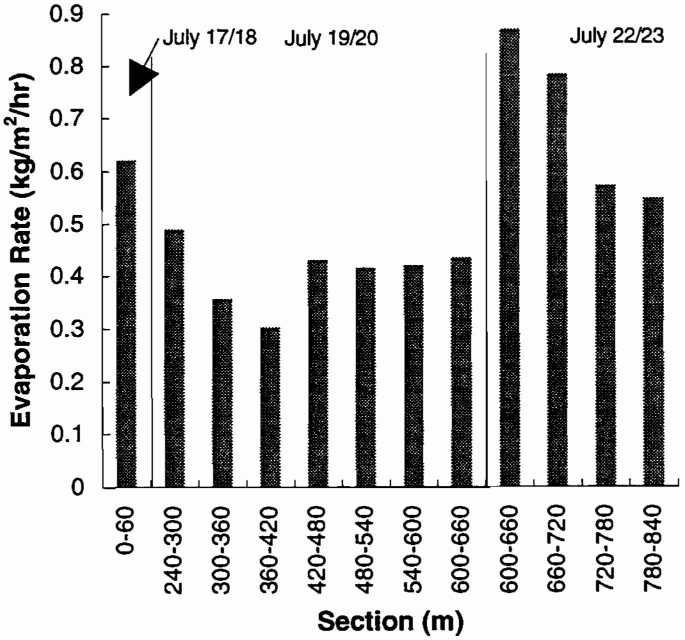


Figure 2.5 Average evaporation rates during westbound lane construction

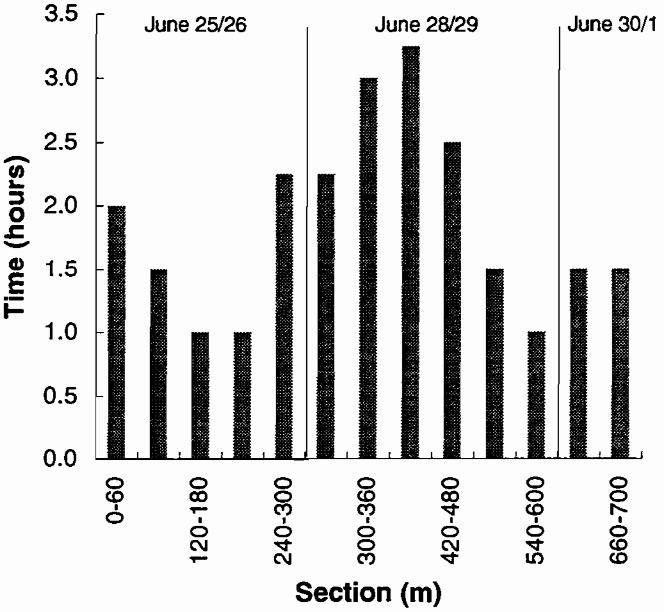


Figure 2.6 Time between concrete placement and application of the curing compound on the eastbound lane

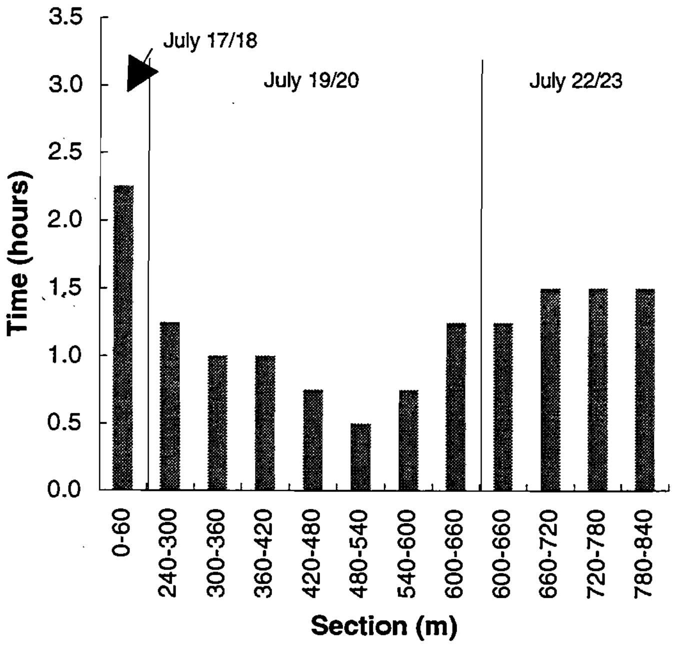


Figure 2.7 Time between concrete placement and application of the curing compound on the westbound lane

Water losses that occurred after the overlay was placed and before the curing compound was sprayed on are illustrated in Figures 2.8 and 2.9. The mix design called for a water content of 138 kg/m^3. The water content indicated in the figures as target is the water content for the mix after corrections for aggregate moisture content were made. An additional adjustment to the design water content was made by withholding water at the batch plant. The withheld water content varied from 13 kg/m^3 on the eastbound lane to 2 kg/m^3 on the westbound lane. The line in the figures indicated by the legend "before curing" was calculated by subtracting the water withheld and the water that evaporated from the pavement before curing compound was applied from the target value. The difference between the "target" and "before curing" water contents in the figures, therefore, indicate the amount of water absent from the mix at the time of curing, as was specified by the mix design. This water deficiency resulted in a stiff mix that was not workable and had low adhesion qualities, due to its inability to allow enough wet paste to both fill the substrate surface macro texture and hydrate completely.

2.4 PERFORMANCE INDICATORS

Crack spacing, crack width, and deflection measurements on the overlay were used as performance indicators. Figures 2.10 and 2.11 show crack spacing four and six weeks after placement for the eastbound and westbound lanes, respectively. The average crack spacing on both eastbound and westbound sections was 3.66 m, with a standard deviation of 1.83 m. It was found that cracks in the unbonded areas did not correspond to cracks in the underlying CRCP.

This is to be expected when no bond exists between the layers (thus allowing cracking to occur independently in each layer). Comparisons between crack spacing distributions for the original pavement and the overlay were made using the Kolgomorov-Smirnov statistical test. The results showed that the westbound lane crack spacing distribution corresponds more closely to the underlying CRCP crack spacing distribution than does the crack spacing distribution for the eastbound section.

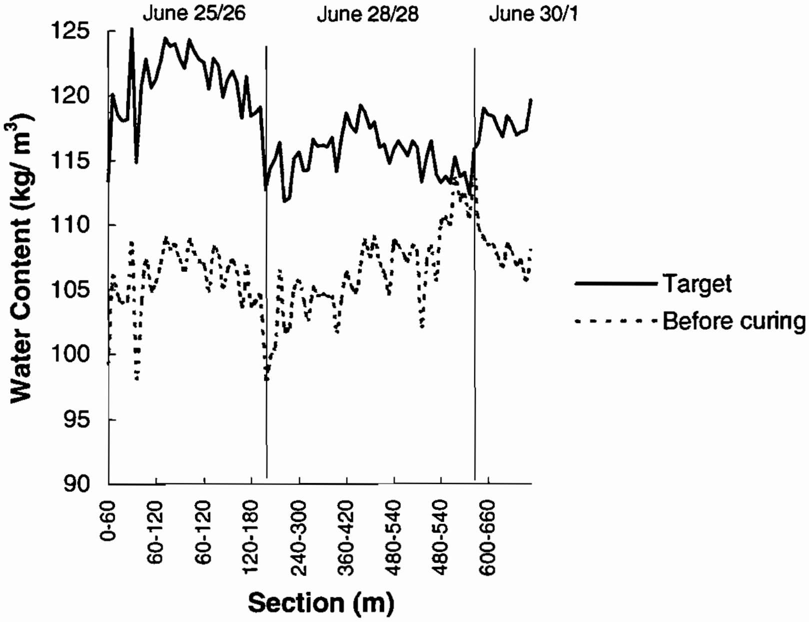


Figure 2.8 Design water content, corrected for aggregate moisture content (Target) and actual water content at the time of curing compound placement (before curing) for the eastbound lane

Crack widths for the eastbound and westbound lanes are illustrated in Figures 2.12 and 2.13, respectively. Minimum and maximum crack widths occurred at high and low ambient temperatures as the pavement expanded and contracted as a result of thermal gradients over time. Crack widths were measured using feeler gauges, ignoring the wider crack width at the surface. The eastbound section seems to exhibit larger crack widths and larger crack width ranges than the westbound section. The difference may be attributed to the difference in bond that exists between the overlay and the CRCP.

Deflections on the pavement were measured with a falling weight deflectometer (FWD) and included sections of 330 mm thick CRCP that are adjacent to the BCO. Deflections on the eastbound lane are significantly higher on the unbonded, overlaid sections than on the adjacent, new, full-depth CRCP sections (Figures 2.14 and 2.15).

The unexpected wide-scale delaminations and the associated design-versus-performance implications led us to investigate the problem further. The analysis and remedy are discussed in the following chapter.

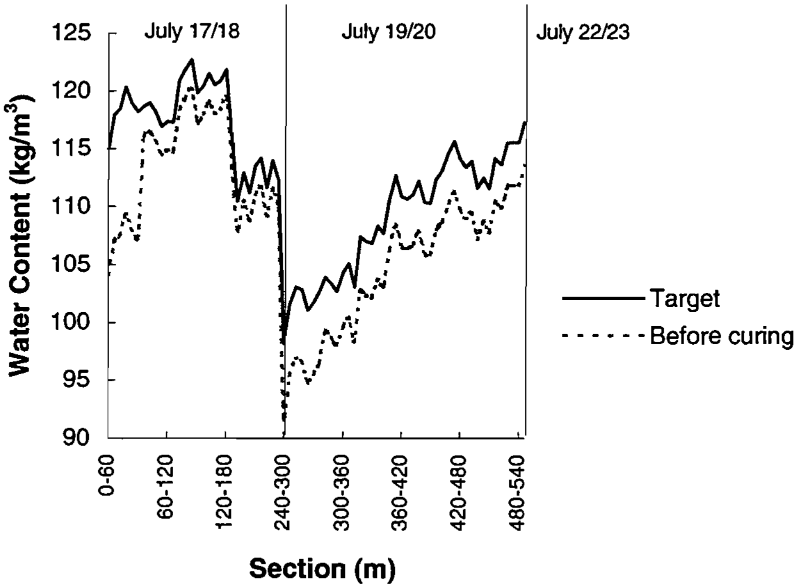


Figure 2.9 Design water content, corrected for aggregate moisture content (Target) and actual water content at the time of curing compound placement (Before curing) for the westbound lane

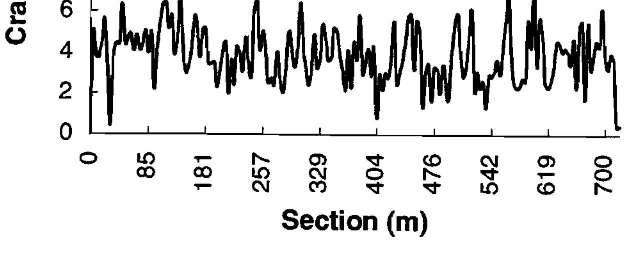


Figure 2.10 Crack spacing for the eastbound lane BCO six weeks after placement

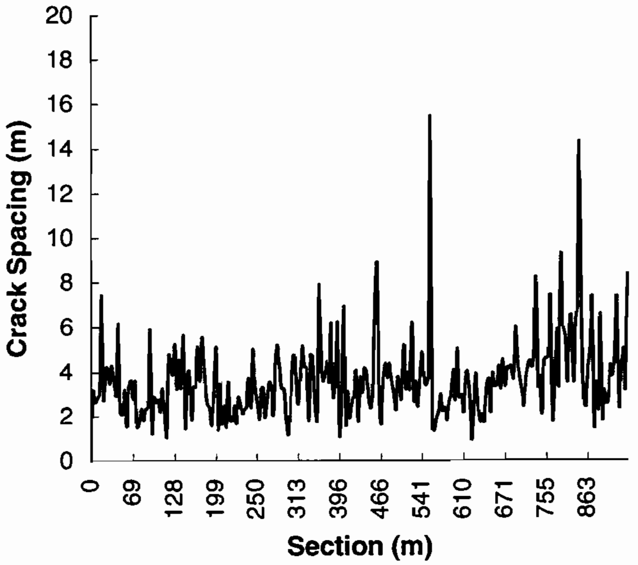


Figure 2.11 Crack spacing for the westbound lane BCO four weeks after placement

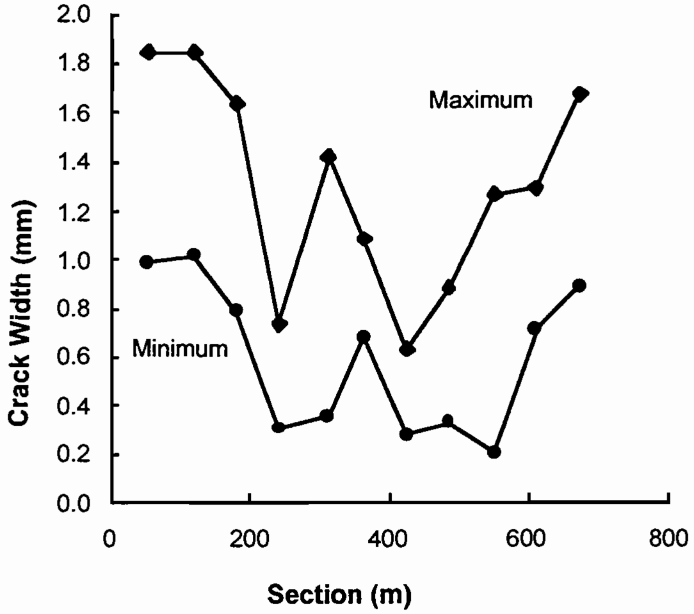


Figure 2.12 Crack width variation for the eastbound lane

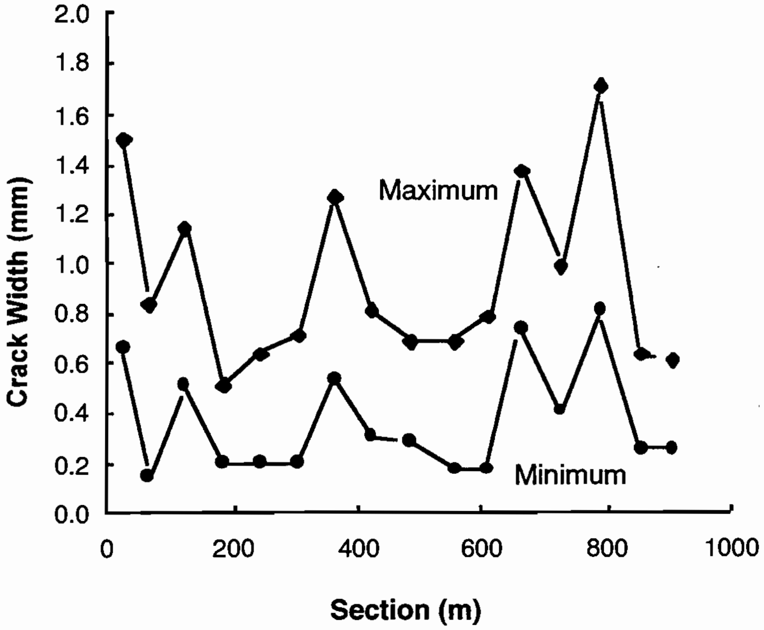


Figure 2.13 Crack width variation for the westbound lane

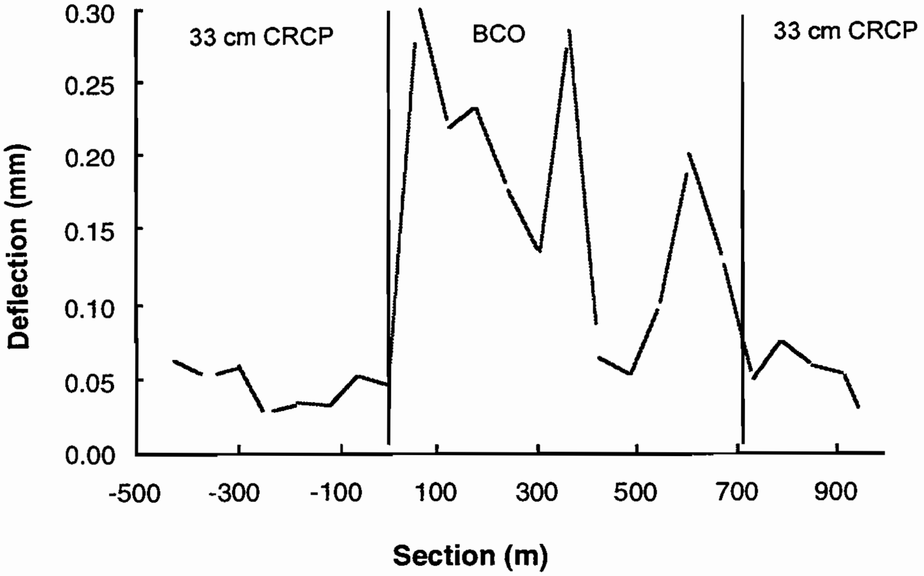


Figure 2.14 FWD deflections (normalized 40 kN load) for the eastbound BCO and 330 mm CRCP

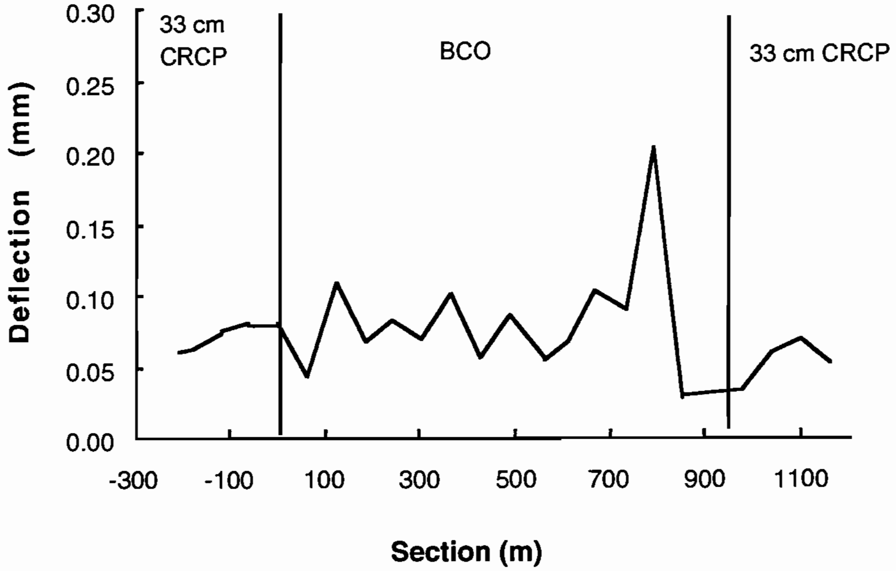


Figure 2.15 FWD deflections (normalized 40 kN load) for the westbound BCO and 330 mm CRCP

CHAPTER 3. CAUSE, EFFECT, AND EPOXY BONDING OF DELAMINATIONS

We next analyzed the data reported in Chapter 2 in order to identify the cause of the delamination of the overlay. In addition, we investigated the effect of an unbonded overlay on pavement performance; based on the findings of that investigation, we prepared recommendations concerning repair and future construction.

3.1 ANALYSIS OF DEBONDED SECTIONS

Predicted deflections, stresses, and crack widths were analyzed to determine the impact of the debonded overlay on the pavement life. Predicted deflections and stresses were calculated with BISAR, a multi-layer elastic analysis program that allows the use of a friction factor to simulate the interface between layers. This factor was utilized to model the behavior of the unbonded overlay, which, although unbonded, probably has a friction interface similar to that of a PCC slab on a cement-treated base. Deflections and stresses were calculated for both the bonded and unbonded cases using a standard 40-kN wheel load. The effect of thermal curling was investigated using Westergaard's equations for an infinitely long strip. The calculated deflections are shown in Table 3.1, and a comparison of those deflections with the deflections found with the falling weight deflectometer (FWD) is presented in Figures 3.1 and 3.2 for the eastbound and westbound lanes, respectively. In Figure 3.1, the predicted deflection generated by the FWD and curling are superpositioned. Although this may not be a theoretically sound principle, it does give an indication of the possible cause of the high deflections found on the eastbound section.

FWD deflections exceeding those calculated for the non-bonded case are therefore possibly due to the curling of the overlay. It is thought that the FWD deflections include the effect of a gap between the BCO and CRCP (caused by curling) and therefore are not an accurate depiction of the condition of the pavement. A comparison with FWD readings taken on the CRCP before the overlay was constructed revealed that the deflections are higher with the overlay. This would not be possible if the layers were in contact; thus, the curling effect is thought to be the cause of the high deflections.

Figure 3.2 indicates the accuracy of the BISAR modeling for the bonded case on the westbound section. The single high deflection on the westbound section may be at the interface between the new full depth CRCP and the BCO.

Stresses for a 40-kN wheel load are predicted at the bottom of the CRCP and at the bottom of the BCO; these are shown in Tables 3.2 and 3.3, respectively. It is seen that the maximum stress for the bonded case occurs at the bottom of the CRCP layer. This was expected, since the BCO and CRCP act as a single slab in bending. The top of the BCO is in compression, while the bottom of the CRCP is in tension. The results indicate that the neutral axis occurs somewhere in the BCO close to the CRCP interface. For the unbonded case, higher tensile stresses result in both the CRCP and BCO layers. This is the result of a loss in load carrying capacity of the unbonded layers. The maximum tensile stress occurs at the bottom of the BCO layer in the unbonded case, while both layers are in flexion. The increase in maximum tensile stress, under vehicular loading and resulting from the delamination, is an indication of the loss of potential life of the pavement. A full-stress analysis considering environmental and vehicular loading is required to predict the actual loss in life. However, it is clear that the increase in tensile stress from 345 to 759 kPa resulting from the delamination of the BCO indicates a significant loss in load carrying capabilities of the pavement.

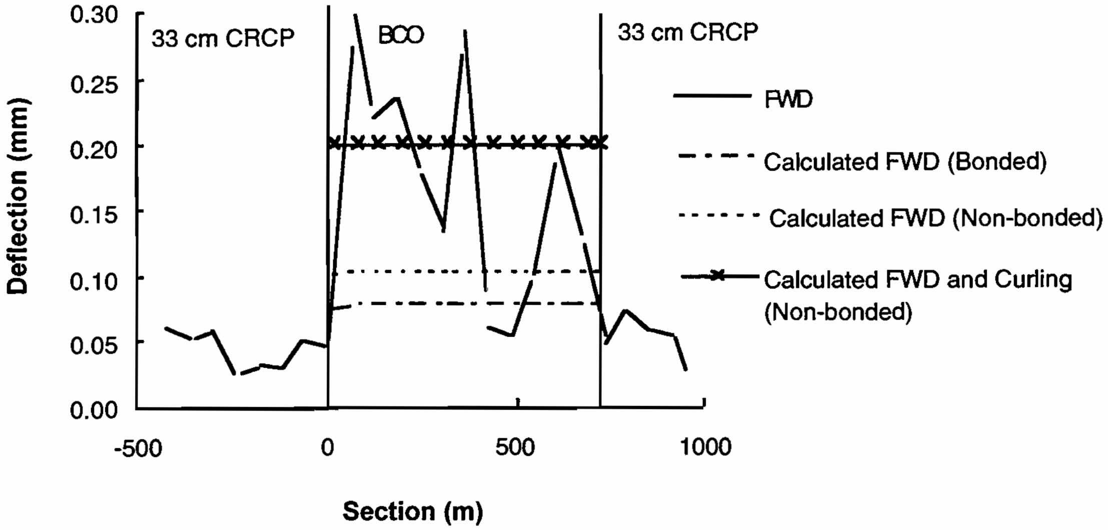


Figure 3.1 FWD and calculated deflections for the eastbound lane

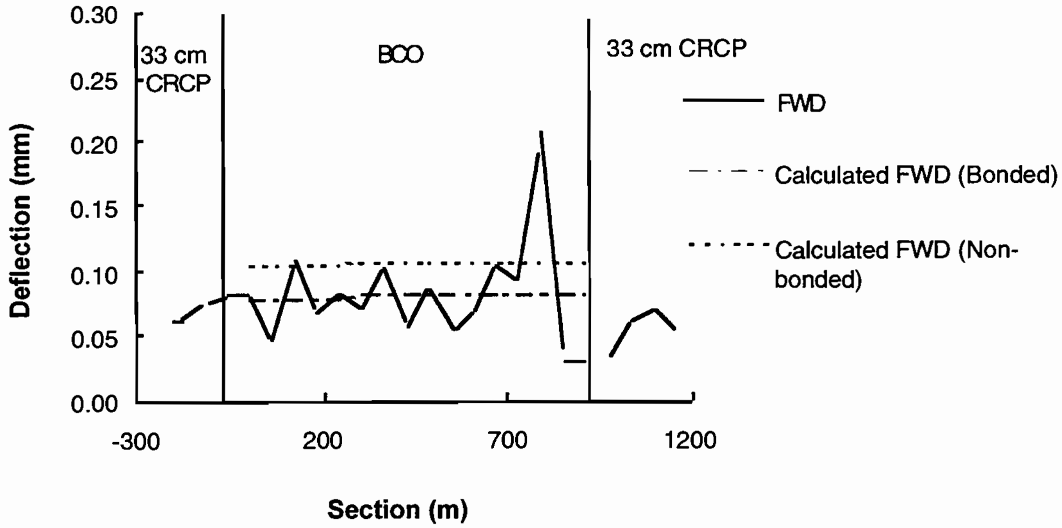


Figure 3.2 FWD and calculated deflections for the westbound lane

Table 3.1 Predicted deflections

Direction	Station	40 kN (mm) Bonded	 Non-Bonded	Curling (mm) Non-Bonded
Eastbound	348 to 350	0.076	0.102	0.100
	350 to 371	0.079	0.104	0.120
Westbound	362 to 372	0.079	0.104	
	342 to 342	0.081	0.107	

Table 3.2 Stresses at the bottom of CRCP for a 40-kN wheel load

Direction	Station	Stresses (kPa) Bonded	 Non-Bonded
Eastbound	348 to 350	352	531
	350 to 371	338	490
Westbound	362 to 372	338	490
	342 to 342	311	435

Table 3.3 Stresses at the bottom of the BCO for a 40-kN wheel load

Direction	Station	Stresses (kPa) Bonded	 Non-Bonded
Eastbound	348 to 350	55	725
	350 to 371	90	759
Westbound	362 to 372	90	759
	342 to 342	131	800

Crack widths were predicted using the CRCP8 computer program, assuming a crack spacing for the BCO of 3.60 m and of 1.80 m for the full-depth pavement. Crack widths were calculated for the eastbound bonded and unbonded cases, for the westbound (bonded), and for the 330 mm CRCP; these were then compared with actual measurements at specific points in time. Figure 3.3 shows the predicted crack widths for a range of ambient temperatures (solid lines). Actual measurements on the BCO and adjacent full-depth CRCP are included in Figure 3.3 as data points. Actual crack widths are consistently larger than predicted, though the change in crack width owing to temperature changes (slope of the line) seems to be consistent with the data. The difference in predicted versus measured crack widths may be due to inconsistencies between theory and practical measurement. In practice, the width of the crack at the surface would be larger than at mid-depth owing to increased drying shrinkage at the surface. Because predicted widths are calculated assuming equal shrinkage throughout the depth of the pavement, they would therefore differ from measurements taken at the surface. Although feeler gauges were used to measure crack widths, the method still seems to be biased by wider cracks at the pavement surface. In the case of the BCO the disparity may be amplified as a result of the position of the reinforcement. Since the reinforcement for the BCO was placed at the CRCP interface, the steel cannot keep cracks from opening up as well as if it were placed at mid-depth of the layer.

The large crack widths and sensitivity to temperature change are indicators of possible future performance problems for an unbonded overlay. Large crack widths allow water infiltration and reduce load transfer across cracks. Cracks in the unbonded BCO have been repaired by the epoxy repair of the BCO interface. Stress relieving contraction joints have been sawn at 4.50-m intervals.

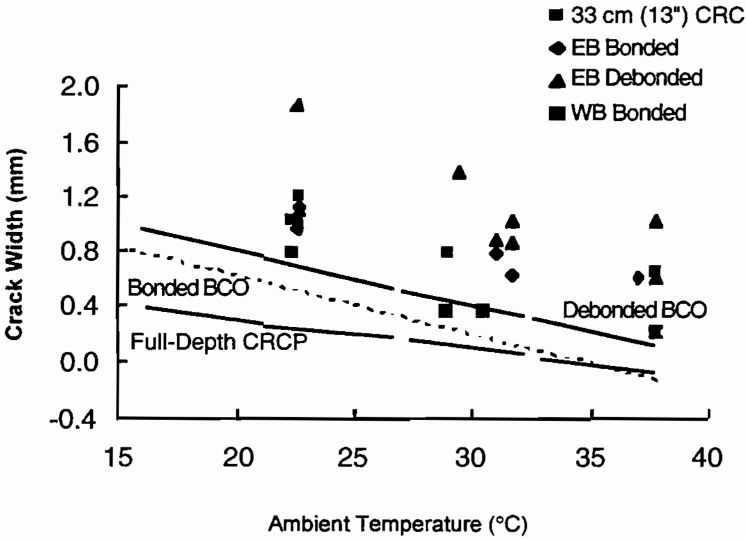


Figure 3.3 Actual and predicted crack widths

3.2 DISCRIMINANT ANALYSIS

The extent of the data collected allowed a discriminant statistical analysis to be performed. The object of the analysis was to quantitatively identify the cause of the delaminations for this specific case. Each section, identified as bonded or unbonded, included the following variables that described construction conditions or conditions of the pavement:

- Ambient temperature
- Temperature differential within 24 hours of placement
- Evaporation rate
- Time between placement and curing compound application
- Water withheld
- Substrate surface roughness (no data available)
- Crack width
- Crack spacing
- FWD deflections

The data may be divided into “cause” and “effect” variables. Data known at the time of placement and that might be considered as “cause” variables include ambient temperature, temperature differential, evaporation rate, time between placement and curing, water withheld, and surface roughness. A linear discriminant function constructed from the data may be used to predict delamination from cause variables. Unfortunately surface roughness could not be used, as the data were not available at the time of writing. Temperature differential was eliminated since the concrete was placed at night, resulting in a small differential; ambient temperature data gave better results. Equation 3.1 is the result of the analysis and may be used as follows: If the predictive value of the discriminant function is smaller than zero the section is likely to be unbonded, while if the value is larger or equal to zero the section is likely to be bonded.

$$Y = 8.152*EVAP - 0.8923*TIME - 0.3824*WATER - 0.2894*TEMP + 8.231 \qquad (3.1)$$

where:

Y = Linear discriminant function,

EVAP = Evaporation rate during curing ($kg/m^2/hr$),

TIME = Time between placement and curing compound application (hours),

WATER = Water withheld from the mixture (kg/m^3), and

TEMP = Temperature during placement (°C).

The discriminant equation is by no means robust and is specific to the project investigated. Caution must be used when applying the prediction to other projects. However, the equation does show that temperature and water content can be critical variables for achieving a bonded overlay.

3.3 CONCLUSIONS ABOUT DELAMINATIONS

The data presented imply that the delamination of the overlay is due mainly to inadequate paste adhesion. The loss in adhesion was caused by the low initial water content of the concrete mix, compounded by the loss of available water to substrate absorption, evaporation, and to the action of withholding water from the mix at batching. The water loss from the bottom of the slab was a result of inappropriate surface preparation of the existing pavement slab. To prevent these losses, the substrate surface should have been prepared by spreading water on it before placing the overlay, so as to achieve a saturated surface dry condition.

Since the placed overlay mix contained a water content at the critical level required for hydration and adhesion, any loss of water increased the likelihood of low bond strength and the occurrence of delamination. The effect of surface preparation was, therefore, critical, since dust and debris on the surface or a very dry surface will have soaked up water from the mix, decreasing adhesion strength.

It was found that delamination has a very significant impact on pavement life. That is, debonding impairs the ability of the pavement to carry traffic loads, thus shortening the life of the rehabilitated pavement. In addition, the pavement will not react to environmental loading as it was designed. An indicator of this change in behavior is the crack width and positions of crack occurrence. These factors may reduce pavement life significantly. For these reasons, the overlay condition should clearly be restored to a bonded condition.

To ensure appropriate water content of the concrete mix for future expedited placements, the water-cement ratio should be increased from what was used on the inside lanes, even if the change implies giving up some concrete strength. Placing the curing compound as soon as possible will prevent water losses owing to evaporation. Withholding water at the time of batching is strongly discouraged when concrete mixes having low-water-to-cement ratios are used. High pressure water cleaning of the substrate immediately before placement of the overlay and saturated surface dry substrate conditions are recommended for low-water-to-cement-ratio overlay mixes.

3.4 EPOXY BONDING DEBONDED OVERLAY TO SUBSTRATE

In addition to strength testing of the beam and cylinder specimens, recommended evaluation methods for quality control in the placement of bonded concrete overlays include examining the BCO surface for cracking, sounding those areas, and performing pull-off tests wherever debonding is suspected. In the El Paso case, once wide-scale debonding was evident, surface wave analysis and falling weight deflection testing were conducted on both eastbound and westbound sections. Through these methods all unbonded sections were identified and marked. Discussions between TxDOT and CTR determined that the most expedient remedy to the problem was epoxy adhesion of overlay to substrate by injection. An experienced epoxy repair contractor was hired.

Wherever the debonded areas were marked, a series of ports were drilled through the overlay in a regular grid pattern (0.67 m by 0.67 m) over the surface of the unbonded area and at 13 cm on center along any cracks running through unbonded areas (Figure 3.4). Ports were drilled to one centimeter above the overlay-substrate interface with a 1.6-cm concrete drill; the accumulated concrete dust was then vacuumed off the pavement. The additional two centimeters through the interface into the substrate was finished with a 1.6-cm vacuum drill. Vacuum drilling at the interface is important to keep concrete dust from sealing the interface around the drill hole. While this procedure took a little extra effort, it allowed faster drilling and extended the life of the much more expensive vacuum drill bits by obviating the need to drill through reinforcing bars.

Plastic sealable injection ports were epoxied into the drilled ports, and all cracks and edge interface seams were sealed with an epoxy putty. After allowing the epoxy putty to cure, a low viscosity epoxy resin system was pumped into the voids at the interface through the ports at nominal pressures of up to 280 kPa. As the voids filled, resin began to flow from the adjacent ports. At this point the injection port was capped and the injector nozzle was engaged with the adjacent port and epoxy was again pumped until it flowed from the next port. The procedure was repeated until all ports had been filled or until there was no measurable flow at 280 kPa. The injection process for filling all the unbonded areas of the inside lanes in both eastbound and westbound directions took approximately three weeks to complete.

Although subsequent pullout tests revealed that some areas were not completely filled with epoxy, the great majority of voids were filled, and adequate tensile strengths typically ranging above 1400 kPa were verified. Falling weight deflection testing confirmed that the repair was successful. Figure 3.5 shows the deflection for a 40-kN FWD load, before and after epoxy repairs. Clearly the pavement is responding; it now represents the 37-cm concrete layer it was designed to be. In only two spots (Station number 356+00 and 364+03) there seem to be higher than expected deflections. It is possible that these areas are still unbonded. The repair should, however, extend the structural life of the unbonded sections to that of the bonded sections.

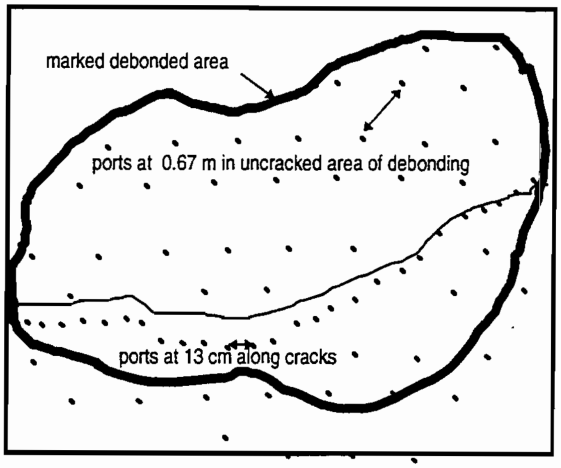


Figure 3.4 Typical port spacing for epoxy injection of debonded overlay areas

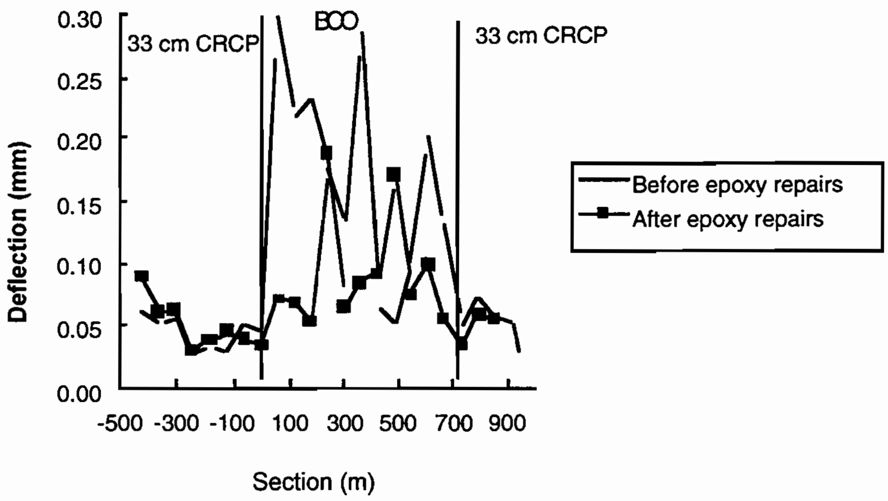


Figure 3.5 FWD deflections on the inside eastbound lane before and after repairs

The high cost of this operation ($597,000) was a result of the unexpected needs of the construction project, the tremendous area of repair (3850 m^2), and the volume of materials (5130 liters of epoxy system). If this cost is spread over the 22,574 m^2 of the total BCO project, however, the total cost of the pavement is $64.90 per square meter, remaining significantly lower than the $83.61 per square meter for the full depth pavement. It is anticipated that costs could be greatly reduced to less than half if bids could be solicited from prequalified contractors and if the contractor had been allowed more time to mobilize and finish the job.

CHAPTER 4. GUIDE FOR EXPEDITED BONDED CONCRETE OVERLAY DESIGN AND CONSTRUCTION

The following guidelines may be used to develop specifications for expedited bonded concrete overlays.

4.1 EVALUATION AND REPAIR OF EXISTING PAVEMENT

Successful long-term performance of a BCO depends strongly on project selection and repair of the existing pavement.

4.1.1 Selection of Rehabilitation Alternative

McCullough and Fowler (Ref 3) outlined a procedure for selecting pavements for bonded concrete overlays. The decision must be made whether to rehabilitate the pavement with a BCO, and if so, when to overlay.

Decision to Rehabilitate with a BCO: The need for pavement rehabilitation may be triggered by an increase or anticipated increase in traffic, or by pavement deterioration indicating that the pavement is approaching the end of its useful life (Ref 3). If the pavement is too badly deteriorated, an unbonded overlay, full depth replacement of the pavement, or other method should be used, because the base pavement distresses are likely to reflect through the overlay.

If applied early enough, a BCO may be significantly cheaper than eventual full depth replacement. Anticipated costs for IH-10 construction were $83.61 per square meter for full depth replacement and $38.53 per square meter for BCO, for the same design life. These estimates do not include user costs, which would increase the economic advantage of the BCO.

When to Overlay: The timing of a BCO rehabilitation is important, inasmuch as the base pavement must not be allowed to deteriorate to the point where the cost of repairs to the base is prohibitive. Repair of the base pavement is important for preventing damage from reflecting through the overlay. The time sensitivity of BCO repairs is illustrated in Figure 4.1. *Functional failure* describes a pavement that has become unsafe or uncomfortable, while the term *structural failure* describes a pavement that has reached a pre-selected level of distress (e.g., cracking or punchouts) (Ref 6). As indicated in the graph, a BCO can be applied after *structural* failure has occurred, but it is generally not feasible after *functional* failure has occurred (Ref 6).

It has been observed in both Houston and El Paso that considerable loss of serviceability can occur during the time between decision and actual BCO construction. This must be considered, particularly since the downward slope of the PSI performance curve may be steep following structural failure.

4.1.2 Evaluation of Existing Pavement

In order to design the BCO, the condition of the existing pavement must be known. The properties of the existing pavement may be measured from cores or by using the falling weight deflectometer (FWD). The properties of interest include the actual pavement thickness, the concrete strength (compressive and splitting tensile), elastic modulus, and coefficient of thermal expansion. None of these properties can be measured directly with the FWD, but the elastic modulus may be estimated.

Cores: Cores provide accurate information about concrete pavement properties (in those areas where the cores were taken). In addition, testing a sufficiently large number of cores (at least 20, or 1 every 200 meters of pavement) can provide an estimate of the variability of concrete properties. For example, testing of IH-10 pavement cores from El Paso indicated a relatively high coefficient of variation (COV) in pavement thickness of 7.2 percent, with COVs in splitting tensile and compressive strength of 8.2 percent to 18.3 percent (Ref 5).

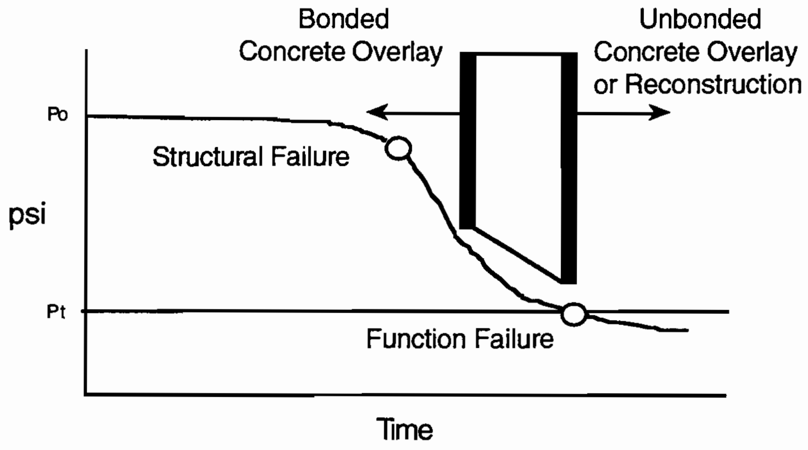


Figure 4.1 PSI performance curve illustrating structural and functional failure and the criteria for bonded or unbonded overlays

Since cores are generally taken only from uncracked sections of the pavement, the reduction of pavement stiffness from cracking cannot be estimated. The stiffness of layers below the concrete cannot be estimated either. Thus, core data should be supplemented and compared with FWD data.

An important concrete property that can only be obtained from cores is the coefficient of thermal expansion. However, if the type of aggregate used to construct the pavement is known, this value may be estimated.

FWD: FWD measurements may be used to calculate pavement stiffness, and use of the FWD is generally more economical than coring. If resources permit, FWD data combined with core testing will provide good estimates of pavement properties and their variability.

Because of time or financial constraints, core testing may not be possible. If only FWD data are available, very conservative values of pavement properties should be used. One example of pavement evaluation using FWD data combined with core testing has been reported by Allison, McCullough, and Fowler (Ref 7).

4.1.3 Repair Requirements

It is important to repair cracks, joints, and spalls so that distress will not reflect through the pavement. Repair requirements have been discussed by McCullough and Fowler (Ref 6).

Cracks and Joints: Load transfer across cracks and joints is very important. Two methods of repairing cracks and failed joints have been discussed by Hoskins, Fowler, and McCullough (Ref 8). If cracking is excessive, a BCO may no longer be an economical solution, and full depth replacement may be necessary.

Spalls: Spalls and other surface distresses that will not be completely removed by the surface preparation must be repaired. These repairs must be completed before the surface preparation.

4.2 THICKNESS AND REINFORCEMENT DESIGN

Design of a BCO requires selection of overlay thickness and reinforcement. The design thickness may depend on whether the BCO is being constructed to remedy a surface or a structural deficiency. If the problem is only the roughness of the pavement, and the stiffness of the structure is not a consideration, then the BCO thickness is governed by the maximum size of the aggregate and by the construction methods used.

Selection of BCO thickness to remedy inadequate pavement structural capacity is discussed below in Section 4.2.1, and selection of reinforcement in Section 4.2.2.

4.2.1 Thickness Design Procedures

Several BCO thickness design methods have been developed (Refs 9, 10). Two methods are currently in use in Texas: the *AASHTO Guide for Design of Pavement Structures* (Ref 11) and the Rigid Pavement Rehabilitation Design System (RPRDS) developed at CTR (Ref 12). The computer program BCOCAD has been developed by CTR for BCO designs using both methods (Ref 13). The current version of BCOCAD should be used for BCO thickness design. Procedures for using BCOCAD may be found in the literature (Ref 13).

A small increase in BCO thickness may substantially increase design life. This should be investigated during design, because the incremental cost of increasing thickness is likely to be a small percentage of overall project costs.

A BCO should be at least 3 times the thickness of the maximum size aggregate (MSA), and preferably thicker. Thus, if 19-mm MSA is used for the BCO concrete, a minimum BCO thickness of 57 mm is required. This may govern the design of thinner overlays. In some cases overhead clearances may present a problem. This should be evaluated early in the project.

4.2.2 Reinforcement Considerations

There are two considerations for selection of BCO reinforcement. First, the percentage of steel of the final pavement structure must be at least as great as that of the original base pavement. Second, cracks in the BCO must be controlled.

Required Steel Percentage: Longitudinal and transverse steel requirements should be developed using the procedures discussed by McCullough and Fowler (Ref 6). The steel is normally provided by reinforcing bars, deformed wire fabric (DWF), or welded wire fabric (WWF). Typical BCO reinforcement is shown in Figure 4.2.

Figure 4.2 Installed shear connectors and reinforcement with formwork

The pavement in this figure also has shear connectors, which will be discussed in Section 4.4.3. The steel is placed directly on the prepared existing pavement surface.

Full-scale test sections were constructed in El Paso to investigate the possibility of replacing the steel with steel fibers distributed through the concrete (steel fiber reinforced concrete, or SFRC). Since this method expedites BCO construction by eliminating the labor and time required to place the steel, it could substantially reduce lane closure times and user costs. The method, however, is still considered experimental, and further investigation with test sections is necessary.

Crack Control: Cracks may occur in the overlay as a result of plastic shrinkage, drying shrinkage, and/or thermal contraction. Plastic shrinkage cracking can be controlled by proper environmental controls, proper curing, and use of synthetic fiber reinforced concrete (SnFRC). Cracking from drying shrinkage or thermal contraction may be addressed by environmental controls, curing, or steel reinforcement, either from bars, DWF, WWF, or SFRC.

Under marginal or severe environmental conditions, SnFRC should be used to reduce the risk of plastic shrinkage cracking. However, SnFRC must also contain steel reinforcement.

4.2.3 Edge Support

The most severe stress conditions for a pavement occur when the edge or corner is loaded (Ref 14). These stresses will be considerably reduced if the edge of the pavement is supported by properly constructed shoulders. If the shoulders are not adequate, consideration should be given to improving them before BCO consideration.

4.3 SURFACE PREPARATION

Proper preparation of the existing pavement surface is important in preventing delaminations. The surface must be rough, clean, and sound enough to achieve bond. The recommended special provisions in Appendix A allow two methods by which to roughen the surface: steel shotblasting and hydrocleaning.

4.3.1 Methods

Commonly used surface preparation methods include shotblasting, sandblasting, and cold milling (Ref 17). The use of hydrocleaning was investigated with the full-scale test sections (Ref 5). A bonding agent is not necessary.

Shotblasting: One type of shotblasting equipment is shown in Figure 4.3. Any equipment that can achieve the required roughness and does not damage the concrete is acceptable. Shotblasting preferentially erodes the weaker component of the base concrete. Generally the paste is eroded, exposing the aggregate.

Figure 4.3 Shotblasting equipment

Hydrocleaning: Field tests verified that hydrocleaning can prepare the base concrete as well as shotblasting, at a similar cost (Figure 4.4). The hydrocleaned surface, however, was more uneven than the shotblasted surface (Ref 5).

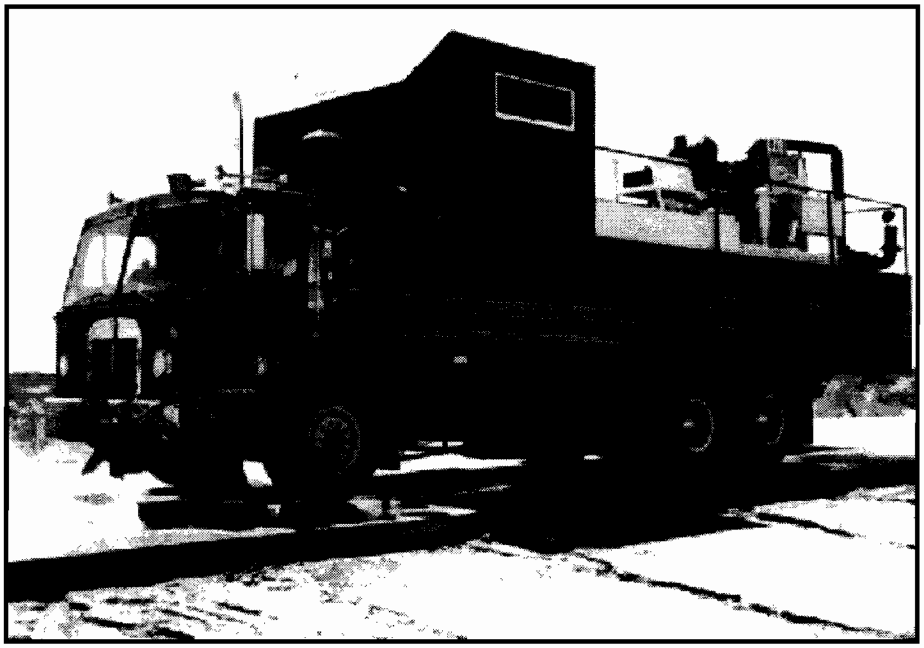


Figure 4.4 Hydrocleaning equipment

Other Methods: Although cold milling has been used for surface preparation in the past, this method does not preferentially erode paste or aggregate, and may cause cracking just below the prepared surface. Therefore, cold milling is not recommended. However, if it is necessary to remove an existing asphalt overlay prior to constructing the BCO, the asphalt overlay should be cold milled off, and then the base concrete should be shotblasted or hydrocleaned. It does not appear that there is any sandblasting equipment appropriate for BCO surface preparation.

4.3.2 Requirements

Results from the full-scale test sections suggest that the roughness and cleanliness requirements proposed in Appendix A are sufficient to achieve bond.

Roughness: The average texture depth of the prepared surface should be at least 2.0 mm, as measured by the sand patch test (ASTM E965-83, test method Tex 436-A, Refs 15, 18). This method is illustrated in Figure 4.5. Test section results showed significantly less delamination at an average texture depth of 1.71 mm versus an average of 1.5 mm (Ref 5). A previous CTR study compared bond strengths at average texture depths of 0.6 mm, 2 mm, and 9.5 mm, among other variables. Use of the roughest texture or an epoxy bonding agent was recommended when environmental conditions posed a severe risk of debonding (Ref 19). A National Cooperative Highway Research Program (NCHRP) study suggested average texture depths of 3 to 6 mm (Ref 17). If severe environmental conditions are anticipated, increasing the average texture depth will provide additional insurance against debonding.

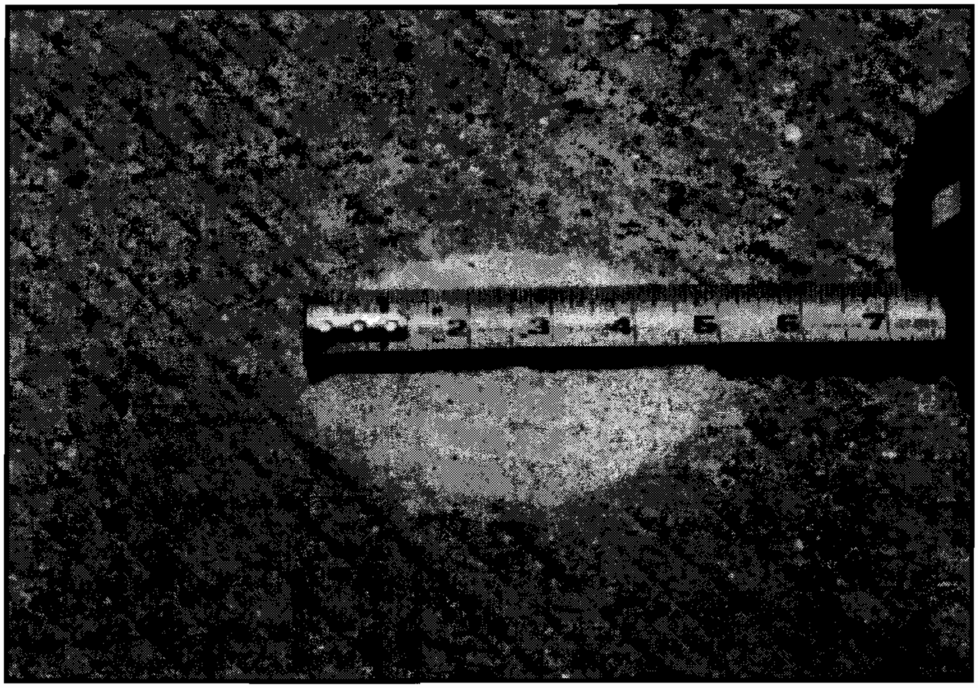


Figure 4.5 Sand patch method

Cleanliness: Contamination of the prepared base concrete could increase the risk of debonding. The suggested special provisions require that all dirt, oil, paint, membrane curing compound, laitance, or loose concrete be removed. The surface may be cleaned by sweeping, air blasting, or by other methods. The BCO should be placed within 24 hours of surface preparation. The base pavement should be air blasted just prior to placing the BCO. The surface should also be saturated surface dry.

Adequacy of surface preparation can be evaluated by determining its bondability according to ACI 5039 Appendix A.1, Field Tests for Surface Soundness and Adhesion. Pull-off values in excess of 200 psi are recommended for BCOs.

4.3.3 Shear Connectors

Shear connectors may be used to reduce the risk of delamination, particularly under severe environmental conditions (Ref 20). Installed shear connectors are shown in Figures 4.2 and 4.6.

The connectors should be placed along all lane edges and on both sides of longitudinal construction joints, at an edge distance of 150 mm and at a spacing of 750 mm.

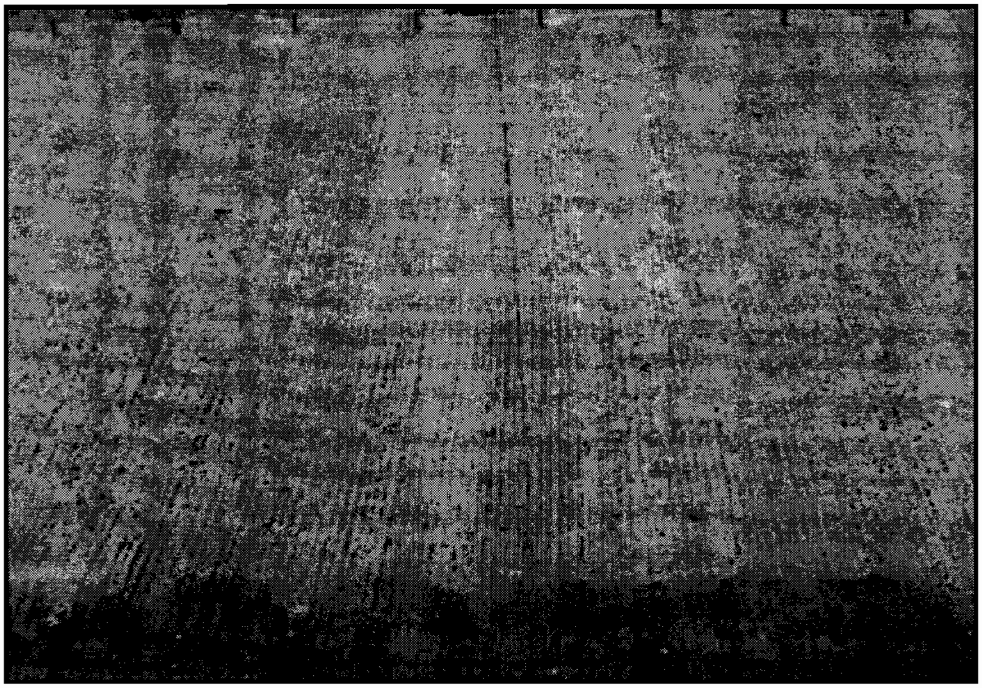


Figure 4.6 Installed shear connectors

On jointed concrete pavement (JCP), shear connectors should be placed on each side of every joint. Thus, each joint in a 3.66 m wide lane will require a total of 10 shear connectors, 5 on each side of the joint.

4.4 MATERIALS

Careful selection of BCO materials is important for optimizing performance. The materials selection and proportioning of the BCO concrete will substantially affect performance. Reinforcement is necessary to resist cracking and to hold cracks to acceptable widths.

4.4.1 Portland Cement Concrete

The goals of specifications and quality control for portland cement concrete are high early strength development and low shrinkage and thermal stresses.

High Performance Concrete: High performance concrete is appropriate for expedited BCO construction (Ref 5). The current TxDOT Standard Specifications list two classes of overlay concrete: concrete overlay (CO) and dense concrete overlay (DC) (Ref 16). While the DC specification will provide highest early strength, the CO specification may be adequate if the BCO will not need to be opened for at least 24 hours.

Materials Selection: Portland cement concrete materials include cementitious materials, aggregates, and admixtures. A more thorough discussion of these may be found in the third report for this project (Ref 5).

1. *Cementitious Materials.* For El Paso conditions, Type II and V cements should be used. Fly ash may be used to replace cement to lower heat of hydration and improve durability, provided that early strength may still be achieved.
2. *Aggregates.* Aggregates should be selected for high strength and low thermal coefficient. The BCO should have a coefficient of thermal expansion lower than the base concrete, if possible, because the BCO will experience greater temperature extremes than the base. In addition, the BCO will undergo drying shrinkage, leading to greater contraction. Aggregates should be selected so that the thermal coefficient of the concrete is not greater than 9.9×10^{-6} mm/mm/°C, tested as outlined in Appendix A. The aggregates should also be sound and non-reactive. The MSA should be less than 1/3 to 1/4 of the overlay thickness. The TxDOT Standard Specification limits MSA to 12.5 mm for CO and DC concrete (Ref 17). This requirement may be relaxed for overlays greater than 50 mm thick.
3. *Admixtures.* High performance BCO concrete requires air-entraining agents and superplasticizers. In hot weather, retarders will also be necessary to prevent premature set.

Mix Design: Mix design considerations include cementitious material content, water-cement ratio, aggregates, and admixtures. These are discussed further in an earlier report for this project (Ref 5).

1. *Cementitious Material Content.* For laboratory testing and the full-scale test sections 520 kilograms of cement per cubic meter of concrete were used, which is higher than the CO (390 kg/m^3) or DC (490 kg/m^3) specification (Ref 5). The lower cement contents may be used if satisfactory early strength can be achieved.
2. *Water-Cement Ratio.* A water-cement ratio of 0.29 was used for laboratory testing and full-scale test sections. For expedited BCO construction, the water-cement ratio should not exceed 0.35.
3. *Aggregates.* Normal procedures for selecting aggregate proportions should be used, except for SFRC. When proportioning SFRC, an intermediate aggregate should be used to improve workability (Ref 21). The coarse and intermediate aggregate combined gradation should meet Grade 9, as outlined in Appendix A. SnFRC does not require intermediate aggregate.
4. *Admixtures.* Admixture dosages should be selected by using trial batches.

4.4.2 Reinforcement

Selection of the required amount of reinforcement was discussed in Section 4.2.2. The requirement may be satisfied by steel bars, DWF, WWF, or steel fibers.

Steel Bars and Fabrics: Often a considerable time and labor savings may be realized by using DWF or WWF, rather than placing and tying together individual reinforcing bars.

Steel Fibers: Commonly used steel fiber contents for SFRC are 1 to 1.5 percent by volume. Excellent results have been achieved with Bekaert Dramix□ fibers (Ref 5). When SFRC is used, local reinforcement at cracks in the base concrete may be provided by sections of DWF or WWF secured to the base concrete with shear connectors.

Synthetic Fibers: Collated fibrillated polypropylene (CFP) fibers 38 mm long at 0.25 to 1 percent by volume should be used for SnFRC (Ref 5). Some type of steel reinforcement should also be used with SnFRC.

4.5 CLIMATIC CONTROLS

High rates of water evaporation from fresh concrete can cause plastic shrinkage cracking, while large ambient temperature differentials within 24 hours after placing bonded concrete overlays can lead to extensive thermal cracking. Both of these conditions are undesirable and can lead to overlay debonding. It is preferable to avoid paving in undesirable or marginal conditions, rather than attempt to apply remedies after the concrete has been placed. Therefore, the weather should be monitored so that BCO construction can be rescheduled or so other corrective measures may be taken when adverse conditions are imminent. A weather station is extremely useful for monitoring the weather conditions (Figure 4.7).

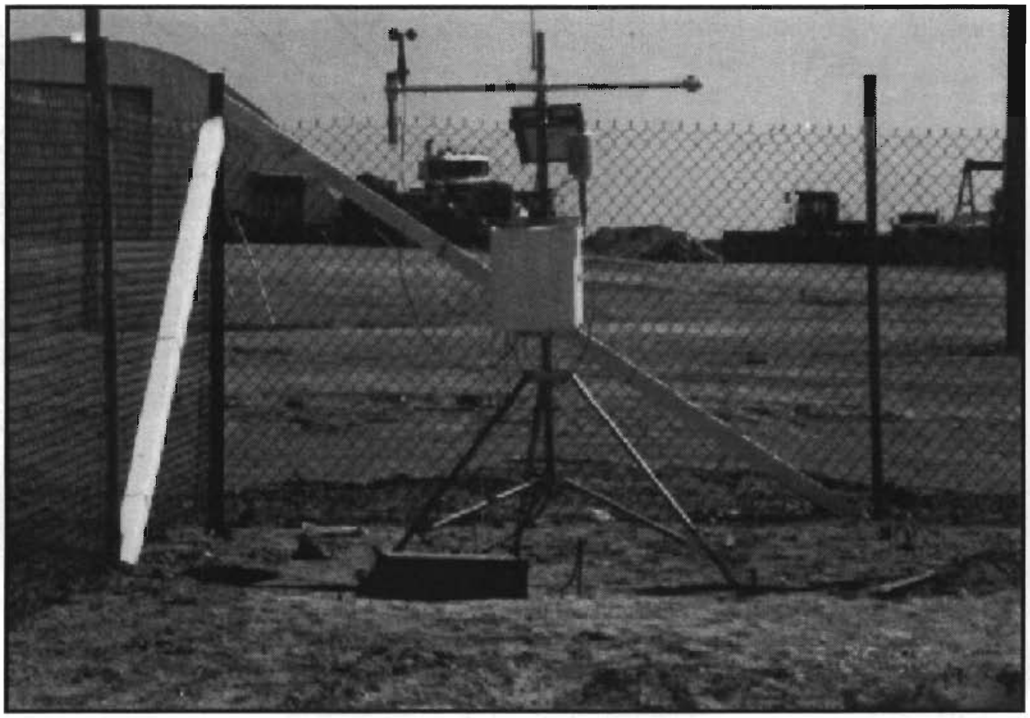


Figure 4.7 Tripod-mounted weather station

4.5.1 Evaporation Rate

The evaporation rate of water from fresh concrete should be limited to 1.0 kg/m^2/hr and preferably should be less than half of that value (Ref 22). Evaporation increases with increasing air temperature, concrete temperature, and wind speed, and with decreasing relative humidity (Ref 23).

Three ways to limit evaporation rate are to schedule construction when evaporation is low, to cure the concrete with wet mats or fogging, and to reduce concrete temperature.

Scheduling: Analysis of available weather records will indicate which time periods pose the highest evaporation risks. For example, by analyzing two years of data from the National Weather Service, Wade et al. determined that the highest evaporation rates in El Paso occurred in May, June, and July (Ref 3). However, further analysis indicated that even during these months, night paving could prevent evaporation problems (Ref 5).

Thus, a useful preliminary step in BCO construction is an analysis of available weather records. If possible, BCO construction should be scheduled during seasons in which evaporation does not pose a problem. If this is not feasible, the BCO should be placed when air temperatures are low, relative humidity is high, and winds are calm. These conditions most often occur at night.

Curing: Curing is addressed in Section 4.6.

Concrete Temperature: The concrete temperature should be limited to 29°C when the concrete is placed. The concrete may be cooled further to reduce evaporation.

The evaporation rate may be calculated using the following equation:

$$w = \left[0.19026(0.253 + 0.06V)\right]\left\{ e^{\left(\frac{17.2694\ T_c}{T_c + 237.30}\right)} - \left[\frac{RH}{100}\right] e^{\left(\frac{17.2694 T_a}{T_a + 237.30}\right)} \right\} \qquad (4.1)$$

where:

W = kilograms of water evaporated per square meter of concrete surface per hour,

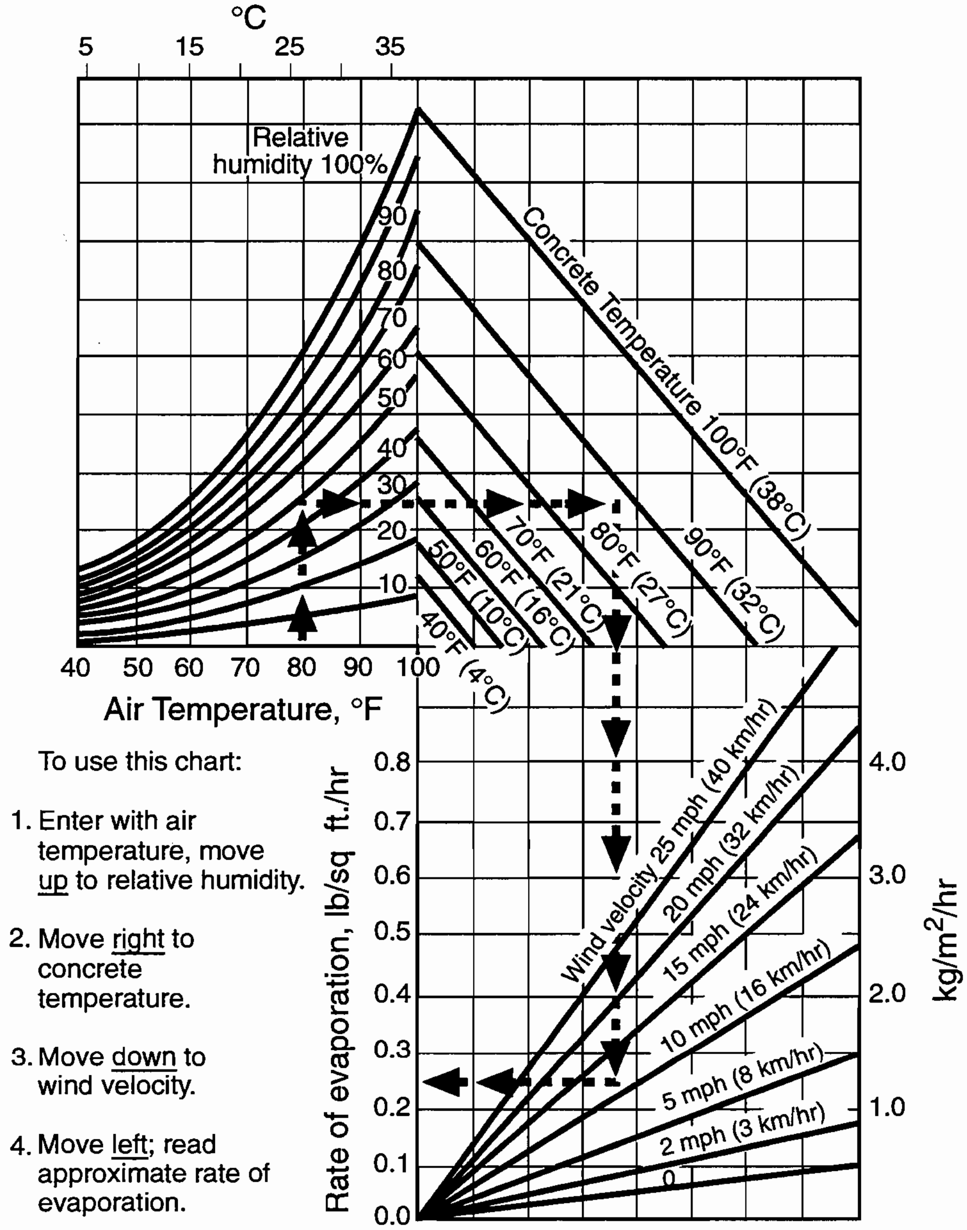
V = wind velocity in kilometers per hour, which should be measured 0.5 m above the evaporating surface,

T_c = concrete temperature in degrees Celsius,

RH = relative humidity, percent, and

T_a = air temperature in degrees Celsius.

This equation may be used to determine if it is economically feasible to cool the concrete sufficiently to meet the evaporation specification. The equation is often presented in the form of a nomograph (Figure 4.8).



To use this chart:

1. Enter with air temperature, move <u>up</u> to relative humidity.
2. Move <u>right</u> to concrete temperature.
3. Move <u>down</u> to wind velocity.
4. Move <u>left</u>; read approximate rate of evaporation.

Figure 4.8 Evaporation prediction nomograph (Ref 22)

4.5.2 Ambient Temperature

To prevent thermal cracking, the BCO should not be placed if the predicted temperature low in the 24 hours following placement is expected to be more than 14°C below the temperature at placement. The engineer and contractor should agree beforehand on the source to be used for the predicted low temperature.

Measures that can prevent problems with ambient temperature differentials include scheduling or covering the entire placement with wet mats at least 36 hours. Obviously, the former will usually be more economical.

As an example of the application of the specification, assume that it is now the morning of 1 June. Predicted highs are 36°C at 4 p.m. on 1 June and 35°C at 3 p.m. on 2 June, and predicted lows are 19°C at 5 a.m. on 2 June and 20°C at 6 a.m. on 3 June (Figure 4.9).

After the temperature drops below 33°C and continues to fall on 1 June (approximately 8 p.m.), the contractor may pave until 5 a.m. on 2 June without wet mats. There are two temperature drops to consider. The low at 5 a.m. on 2 June does not matter as long as the temperature between paving and the drop stays below 33°C. The drop on the night of the 2nd and 3rd of June does not come into play until 24 hours before the drop (6 a.m. June 2). After 6 a.m., paving may proceed with wet mats until noon. After noon on 2 June, paving may not resume until the temperature is no more than 14°C above the predicted low in the following 24 hours, and falling.

As before, weather records should be analyzed to determine the seasons and times of day when the 14°C limit is likely to pose a problem.

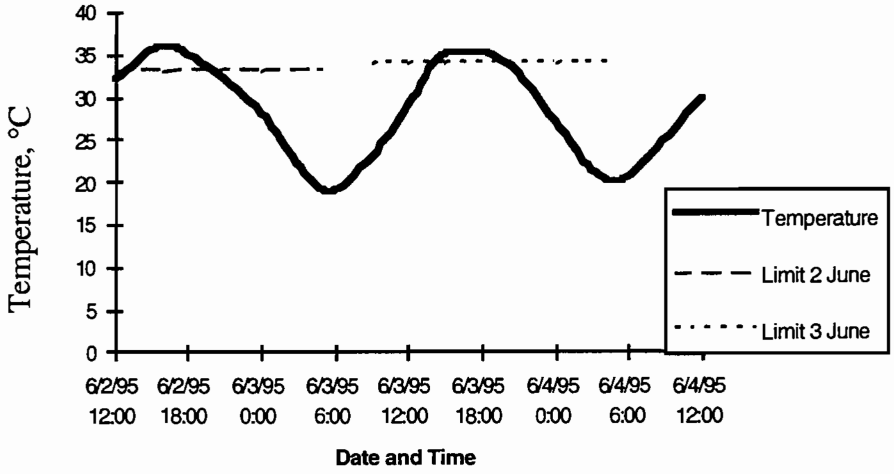


Figure 4.9 Example of ambient temperature differential limit

4.6 CURING

Proper curing must be used to limit moisture loss and temperature gradients in the BCO to promote strength gain and limit thermal and shrinkage stress buildup. Curing methods to be used depend on environmental conditions.

4.6.1 Methods

Many curing methods are available, including wet mats and membrane curing. Evaporation retardant may be used to enhance the effectiveness of these curing methods. The engineer should ensure that proper curing methods are used.

Wet Mats: Wet mats control both moisture loss and temperature. The mats must be kept wet. Evaporation of the water from the mats helps cool the BCO. However, wet mats do not work well for expedited bonded concrete overlays because they must be removed before traffic can be allowed on the pavement.

Membrane Curing: When environmental conditions do not require the use of wet mats, membrane curing at a heavy applications rate (no more than 3.0 square meters per liter, in two applications of no more than 6.0 square meters per liter) may be used. The curing compound should be applied in two passes to ensure that both sides of the tining grooves are coated. Membrane curing is less effective than wet mats for both moisture and temperature control.

Evaporation Retardant: An evaporation retardant such as Master Builders Confilm® may be used to reduce evaporation. Another curing method must be used after the evaporation retardant is sprayed on. Field cylinder tests in El Paso showed that cylinders coated with Confilm® and a light application of curing compound had the same compressive strength as cylinders with a heavy application of curing compound (Ref 5).

4.6.2 Requirements

Curing requirements depend on environmental conditions. Recommended special provisions for curing are summarized in Table 4.1. If both evaporation over 0.5 kg/m^2/hr and a temperature drop of 14°C or more are predicted, the most stringent curing (wet mats) should be used. Under marginal or severe conditions, a rougher pavement surface or shear connectors may also be used.

Table 4.1 Recommended curing for bonded concrete overlays

Condition	Recommendation
Evaporation below 0.5 kg/m^2/hr	Membrane curing
Evaporation above 0.5 kg/m^2/hr but below 1.0 kg/m^2/hr	Membrane curing, plus evaporation retardant or fogging or wet mats, in place for 12 hours
Evaporation over 1.0 kg/m^2/hr	Membrane curing, plus wet mat curing or fogging or other methods approved by the engineer, in place 36 hours
Temperature drop in next 24 hours less than 14°C below temperature at time of paving	Membrane curing
Temperature drop in next 24 hours more than 14°C below temperature at time of paving	Membrane curing plus wet mats for 36 hours, or other methods as approved by the engineer

4.7 OPENING THE BCO TO TRAFFIC

Before the BCO is opened to traffic, it must attain the required tensile, compressive, and bond strength to resist stresses from the traffic loading.

4.7.1 Expedited Construction

Half-scale BCO model tests by Huddleston (Ref 4) showed that a BCO could be loaded as early as 12 hours and with a concrete compressive strength of only 13.5 MPa without compromising its fatigue life. Subsequent tests at 12 hours on the full-scale test sections in El Paso verified this observation (Ref 5).

Time: It is recommended that the BCO be a minimum of 12 hours old before traffic is applied, in addition to attaining to necessary strength requirements. Experience with expedited bonded concrete overlays may allow relaxation of this requirement.

Strength: The following tensile, compressive, and bond strengths should be achieved before the BCO is opened to traffic. It is recommended that a single strength criterion be used, preferably splitting tensile strength.

1. *Splitting Tensile.* A splitting tensile strength of at least 3,450 kPa should be attained.
2. *Compressive.* A compressive strength of at least 24 MPa should be reached.
3. *Bond.* Bond may be measured by either guillotine shear or pull-off tests (Refs 3 and 5). Bond strength of either 1,200 kPa by the pull-off test or 2,400 kPa by the guillotine test should be adequate (Ref 5).

Test Methods: Strength may be based on test specimens, maturity, or a combination of the two. If BCO temperatures are higher than the ASTM C 31-91 Standard of 16 to 27°C (Ref 15), testing cylinders will be conservative; however, if the temperatures are lower they will not be.

Thus, in hot weather, field or laboratory cylinders may be used. In cooler weather, field cylinders or the maturity method (ASTM C 1074-93, Ref 15) should be used rather than laboratory cured specimens.

Bond is highly variable, and coring to remove specimens for bond testing damages the pavement. Therefore, ACI 503 pull-out bond testing should be conducted with two replications only about every 1000 m^2 of BCO, unless problem areas are expected or otherwise apparent. These values should be correlated with splitting tensile or compressive strength based on laboratory testing. Wade found that for the high early strength concrete used for the full-scale test sections, a guillotine bond strength of 2,400 kPa was reached within 24 hours, at a compressive strength of 27 MPa and a maturity of 600°C hours (Ref 3). For the full-scale test sections, the strength of the concrete when accelerated loading was imposed at 12 hours was 25 MPa in compression and 2,800 kPa in splitting tension, and the maturity was approximately 700°C hours (Ref 5). The BCO successfully supported this loading.

Bond testing in the field proved to be time consuming and difficult, particularly with a 165-mm-thick overlay. However, bond testing is recommended for quality control.

1. *Splitting Tension Tests.* The specified opening strength should be based on cylinders tested in splitting tension (ASTM C 496-90, Ref 15). Prior to construction, laboratory tests should be undertaken to ensure that the concrete will have satisfactory compressive and bond strengths when the specified splitting tensile strength is achieved.

2. *Maturity Method.* The BCO may be opened to traffic based on maturity curves developed from laboratory testing. For example, laboratory and field tests suggest that with the concrete used for the full-scale test sections, traffic may be allowed on the BCO at 600 to 700°C hours.
3. *Bond Strength Testing.* After the concrete has developed acceptable strength, the bond to the substrate should be evaluated according to ACI 503R Appendix A.1, Field Test for Surface Soundness and Adhesion. Core specimens of 101.6 mm in diameter are recommended whenever overlay thicknesses exceed 101.6 mm.

4.7.2 Normal Construction

If early opening of the BCO to traffic is not required, the provisions of the TxDOT Standard Specification (Ref 16) are appropriate and conservative. The next chapter summarizes recommendations for project selection, design, and construction.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

5.1 PROJECT SELECTION

The decision whether to construct a BCO and, if so, when, should be based on pavement condition, economic analysis, and overhead clearances.

5.1.1 Pavement Condition

The pavement must be sufficiently sound structurally to construct the BCO without extensive damage reflecting through. If considerable repairs to the base pavement are required, full-depth replacement may be necessary instead.

5.1.2 Economic Analysis

An engineering economic analysis should be used to select from available rehabilitation alternatives. User costs should be considered. The extended pavement life provided by small increases in BCO thickness should be considered.

5.1.3 Overhead Clearances

Construction of a BCO will decrease overhead clearances. This should be considered early in the planning process, because low overhead clearances may make full-depth replacement necessary over part or all of the project.

5.2 DESIGN

BCO design considerations include thickness, reinforcement, and mix design.

5.2.1 Thickness

Design thickness should be selected using BCOCAD.

5.2.2 Reinforcement

Steel requirements should be based on McCullough and Fowler (Ref 6). Steel may be provided by DWF, WWF, or steel fibers. Synthetic fibers should also be used under conditions where plastic shrinkage cracking may occur.

5.2.3 Mix Design

BCO concrete should be based on the TxDOT specification, as modified in Appendix A. The mixture should have the highest water-cement ratio possible that maintains compliance with the strength requirement in order to ensure adequate bond.

5.3 CONSTRUCTION

Construction operations and considerations are discussed below.

5.3.1 Scheduling

Construction should be scheduled to avoid marginal or severe environmental conditions.

5.3.2 Base Pavement Repairs and Shoulder Upgrades

Base pavement spalls and joints having poor load transfer must be repaired. Upgrading shoulders should also be considered to prevent edge loading on the BCO.

5.3.3 Existing Asphalt Overlay Removal

Existing asphalt overlays may be removed by cold milling. All asphalt must be removed, since it is a bond breaker.

5.3.4 Surface Preparation

The base concrete must be shotblasted or hydrocleaned to an average texture depth of 2.0 mm and should be saturated surface dry at placement of the overlay. This may require saturating the overlay sections of the pavement the day before with high pressure water during dry periods.

5.3.5 Reinforcement and Shear Connectors

DWF, WWF, and shear connectors (if required) must be placed after surface preparation. The surface must be cleaned if it becomes contaminated.

5.3.6 Placement and Curing

The prepared surface should be air blasted within an hour before the BCO is placed. Evaporation retardant may be sprayed on the freshly cast BCO. Appropriate curing measures as outlined in Table 4.1 should be taken.

5.3.7 Opening to Traffic

The BCO may be opened to traffic when it is at least 12 hours old and has attained a splitting tensile strength of at least 3,450 kPa, or the corresponding maturity value.

5.3.8 Delaminations

If extensive areas of delamination exist (as identified by cracking, coring, seismic methods and FWD testing), the bond to the substrate must be repaired for the pavement to reach the intended design life. The low viscosity epoxy resin repair system as described in Section 3.4 is an effective bond repair method.

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APPENDIX A: RECOMMENDED BCO SPECIAL PROVISIONS

APPENDIX A: RECOMMENDED BCO SPECIAL PROVISIONS

SPECIAL PROVISION
TO
ITEM 360
CONCRETE PAVEMENT

For this project, Item 360, "Concrete Pavement" of the Standard Specifications is hereby amended with respect to the clauses cited below and no other clauses or requirements of this Item are waived or changed hereby.

Article 360.1. Description is voided and replaced by the following:

360.1 Description. This Item shall govern for the construction of bonded concrete pavement overlay with or without monolithic curbs on a previously placed concrete pavement in accordance with the typical sections shown on the plans, the lines and grades established by the Engineer and the requirements herein.

Article 360.3 Materials, Subarticle (1) Portland Cement Concrete. The first paragraph is voided and replaced by the following:

(1) Portland Cement Concrete. Classification and mix design shall conform to Class "CON", Class "COP", Class "COS", Class "DCN", Class "DCP", or Class "DCS" portland cement concrete as defined in Item 421, "Portland Cement Concrete," unless otherwise shown on the plans.

Article 360.3. Materials. is supplemented by the following :

(7) Steel Fiber. The steel fibers shall be Bekaert Dramix ZC 60/80 applied at the rate shown on the plans.

(8) Polypropylene Fiber. 38 mm collated, fibrillated, polypropylene fibers manufactured by Forta CR or equal applied at a rate of 1.9 kilograms per cubic meter of concrete.

(9) Evaporation Retardant. The evaporation retardant shall be Master Builders Confilm or equivalent.

Article 360.4. Equipment is supplemented by the following:

(15) Existing Concrete Pavement Surface Preparation Equipment. Shot blasting equipment shall be power-operated and shall be capable of propelling steel shot against the pavement surface in a uniform manner so that the entire concrete surface is uniformly prepared. The shot blasting equipment shall include means of collecting used shot which may be reused, and of collecting and disposing of dust. The shot blasting equipment shall be capable of removing all dirt, oil, paint, membrane cure compound, and other foreign material, as well as any laitance or loose concrete from the surface on which the new concrete is to be placed. Hydrocleaning equipment may be substituted for shot blasting equipment providing the required surface texture and cleanness can be achieved.

Article 360.5 Quality of Concrete. is amended as follows:

All references to Flexure Strength are changed to Splitting Tensile Strength.

Article 360.6. Subgrade, Subbase and Forms, Subarticle (1) Preparation of Subgrade or Subbase is supplemented by the following:

Where the existing concrete pavement is covered by an existing asphalt overlay, it must be removed by cold milling. All asphalt must be removed prior to shotblasting or hydrocleaning.

Where shown on the plans, the entire existing concrete pavement surfaces to be overlaid with bonded concrete pavement shall be prepared by shotblasting or hydrocleaning. All dirt, oil, paint, membrane cure compound, laitance and loose concrete shall be removed from the existing surface. The size shot used in shotblasting shall be appropriate for blasting concrete. All foreign material remaining on the existing concrete pavement after operating the shotblasting equipment shall be removed by sweeping, air blasting or by other methods approved by the Engineer. Adequacy of surface preparation will be determined through surface bond pull-off tests as specified in ACI 503R Appendix A.1, Field Test for Surface Soundness and Adhesion. Pull-off values in excess of 200 psi are expected. The entire surface shall be air blasted just prior to the paving operation.

To minimize the possibility of contamination of the cleaned surface, the bonded concrete paving operation shall begin within twenty-four (24) hours following the shotblasting or hydrocleaning operation unless otherwise directed by the Engineer. If for any reason the cleaned surface becomes contaminated, reblasting or recleaning shall be required.

The surface texture of the cleaned, blasted concrete pavement shall have a minimum texture depth of 2.0 mm as measured by Test Method Tex 436-A. The number and location of the tests will be as directed by the Engineer.

The surface of the existing concrete should be saturated-surface dry (SSD) when the BCO is placed.

Article 360.8. Concrete Mixing and Placing, Subarticle (3) Placing is supplemented by the following:

At those times when the evaporation rate exceeds 1.0 kilograms /square meter/hour for a period of time as specified by the Engineer, or greater than 20 minutes, measures shall be taken to control the moisture content of the newly placed bonded concrete overlay. Fogging, wet mat curing, or other approved methods shall be used to control the moisture content. The entire day's placement shall be protected and the protection shall remain in place for 36 hours or until such time as directed by the Engineer. These measures are in addition to the membrane curing required.

At those times when the evaporation rate exceeds 0.5 kilograms /square meter/hour but is less than 1.0 kilograms /square meter/hour for a period of time as specified by the Engineer, or greater than 20 minutes, measures shall be taken to control the moisture content of the newly placed bonded concrete overlay. Evaporation retardant shall be applied in accordance with manufacturer's recommendations after paving but before application of membrane curing to control the moisture content. The entire day's placement shall be protected and the protection shall remain in place for 12 hours or until such time as directed by the Engineer. Wet mats or fogging may be used instead of the evaporation retardant. These measures are in addition to the membrane curing required.

At those times when the difference in the ambient temperature at the time of placement and the expected low temperature in a 24-hour period is expected to exceed 14°C, special measures shall be taken. The bonded concrete overlay shall be placed no later than 12:00 noon the preceding day or a minimum of 18 hours prior to the time the maximum temperature difference is expected. At those times when the difference in the ambient temperature at the time of placement and the expected low temperature in a 24 hour period exceeds 14°C, the entire day's placement shall be protected by wet mat curing or other methods approved by the Engineer. The protection shall remain in place for a minimum of 36 hours, or until such a time as directed by the Engineer.

The Contractor will not be restricted from paving at night.

The temperature of all paving concrete shall not exceed 29°C when placed.

There shall be no free water on the surface of the existing concrete at the time of the placement of the concrete for the bonded overlay pavement.

Article 360.11. Curing, Subarticle (3) Membrane Curing. is voided and replaced by the following:

(3) Membrane Curing. After final finish and immediately after the free surface moisture has disappeared, the concrete surface shall be sprayed uniformly with a Type 2, Class A curing compound in accordance with Article 526.5 except that the membrane curing compound shall be applied in two applications of approximately 5.9 square meters per liter each. A metering device to measure the rate of application shall be required. Should the membrane be damaged from any cause before the expiration of 72 hours after the final application, the damaged portions shall be repaired immediately with additional compound.

Special care shall be taken to ensure that the sides of the tining groves are coated with curing compound.

Article 360.12. Protection of Pavement and Opening to Traffic. Subarticle (2) Opening Pavement to Traffic is voided and replaced by the following:

(2) Opening Pavement to Traffic. The pavement shall be closed to all traffic, including vehicles of the Contractor, until the last concrete placed is at least twelve (12) hours old and has been determined to meet a splitting tensile value of at least 3,450 kPa.

At the end of this period the pavement may be opened for use by vehicles of the Contractor or the public. Such opening, however, shall in no manner relieve the Contractor for his responsibility for the work in accordance with Item 7, "Legal Relations and Responsibilities to the Public." On those sections of the pavement to be opened to traffic, all joints shall first be sealed and the pavement cleaned. Unless otherwise shown on the plans, stable material shall be placed against the pavement edges before permitting vehicles thereon.

SPECIAL PROVISION
TO
ITEM 421
PORTLAND CEMENT CONCRETE

For this project , Item 421, Portland Cement Concrete of the Standard Specifications is hereby amended with respect to the clauses cited below and no other clauses or requirements of this Item are waived or changed hereby.

Table 3, Slump Requirements, A. Structural Concrete (3) Slabs, Concrete Overlay, Caps, Columns, piers, wall sections over 230 mm, etc., and (6) Dense concrete overlay, are voided and replaced by a desired slump of 50 mm for slipformed BCO and 100 mm for formed BCO.

Article 421.2 (7) Materials. Admixtures. is supplemented by the following:

High range water reducer shall be permitted.

Article 421.8. Classification and Mix Design. is supplemented by the following:

Classes of Concrete CON, COP, COS, DCN, DCP, and DCS shall be designed to entrain 4% to 6% air regardless of the grade of coarse aggregate used.

Article 421.9 Quality of Concrete is supplemented by the following:

Unless otherwise directed by the Engineer, 101 mm diameter by 203 mm high cylinders will be required for testing splitting tensile specimens. The splitting tensile test values will be determined according to ASTM C496, Splitting Tensile Strength of Cylindrical Specimens.

Concrete in Classes CON, COP, and COS shall have a thermal coefficient less than 9.9×10^{-6} mm/mm/°C when tested according to Corps of Engineers Test Method for Coefficient of Linear Thermal Expansion CRD C 39-81. The following additional requirements shall also apply:

> Steel studs shall be cast into specimens for determining length measurements.
> Specimens shall have a minimum dimension at least 3 times the nominal size of the coarse aggregate.
> Specimens shall have a minimum aspect ratio of 2:1.
> Specimens shall be tested in a dry condition after curing a minimum of 28 days.

APPENDIX B: LIST OF ACRONYMS

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ASTM	American Society for Testing and Materials
BCO	Bonded Concrete Overlay
BCOCAD	Bonded Concrete Overlay Computer Aided Design
CFP	Collated Fibrillated Polypropylene
COV	Coefficient of Variation
CTR	Center for Transportation Research
CRCP	Continuously Reinforced Concrete Pavement
DWF	Deformed Wire Fabric
FWD	Falling Weight Deflectometer
JCP	Jointed Concrete Pavement
MSA	Maximum Size of Aggregate
NCHRP	National Cooperative Highway Research Program
RPRDS	Rigid Pavement Rehabilitation Design System
SFRC	Steel Fiber Reinforced Concrete
SHRP	Strategic Highway Research Program
SnFRC	Synthetic Fiber Reinforced Concrete
TxDOT	Texas Department of Transportation
WWF	Welded Wire Fabric