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16. Abstract This is the second technical report that describes a series of tasks performed under TxDOT Project 0-4893. The main objectives of this document are to present the findings of the assessment of various asphalt concrete overlay (ACO) projects built in the Bryan, Fort Worth, and Dallas districts. Likewise, it shows the results of the instrumentation of a bonded concrete overlay (BCO) section located in Houston, Texas, where debonding of the overlay was measured and discussed. Finally, the evaluation of a life cycle cost analysis (LCCA) program is evaluated and its use recommended in future overlay projects.		
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Concrete Pavement Overlays and Failure Mechanisms

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Products

This report contains products P4, P5, and P6, according to the deliverables table of Project 0-4893. Product P4, Recommendation on innovative materials for overlay construction, is presented in Chapter 2, Section 2.5. Product P5, Results of field work and test analysis on selected overlays, is presented in Chapter 2, Sections 2.2, 2.3, and 2.4. Product P6, Guidelines for cost analysis comparison according to LCCA and B/C ratio, is presented in Chapter 4, Sections 4.2, 4.3, and 4.4.

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1. Introduction

This report, the second pertaining to Research Project 0-4893, "Performance of Old Concrete under Thin Overlays," documents the activities of the project, including field work on various pavement sections and their findings. It also presents the results of the performance of special materials used in the overlays and guidelines for life cycle cost analysis of overlays.

This project's goal is to evaluate the quality and integrity of original portland cement concrete (PCC) pavements under thin overlays—both bonded concrete overlays (BCO) and asphalt concrete overlays (ACO)—especially those that have been in service for an extended period of time.

The first report of this project, "Preliminary Findings of Performance of Old Concrete under Thin Overlays," presented a review of publications on the design, materials, construction, and performance of concrete and AC overlays. The literature review revealed that the largest concern with BCOs is the occurrence of delaminations and premature failure of the overlay. In the case of ACOs on rigid pavements, the most critical matter is reflective cracking in jointed pavements, stripping, and rutting. A factorial experiment was developed and field evaluations were conducted accordingly. The results of BCO evaluations were described in that report. Four BCO projects in Texas were investigated: two projects in Houston, one in Fort Worth, and one in Wichita Falls. Investigations included a visual condition survey, sounding tests for the evaluation of delaminations, falling weight deflectometer (FWD) testing, and extraction of core samples for materials evaluation. Overall, the BCOs performed well, even though delaminations were observed in some sections. Deflections were within expected range, except for those at delaminated areas, which were quite large. It appears that the compatibility of materials between existing and overlaid concretes, especially the thermal coefficient, plays a role in delamination occurrence. Petrographic evaluations of old concrete cores indicated that no major deteriorations occurred except for one core where pockets of ettringites were observed (Ref 1).

Reporting the continuation of similar type of field work, but focused on ACOs, is one of the subjects in this report. Additionally, a discussion of the failure mechanisms of BCOs and an introduction to the analysis of LCCA of overlays are presented herein.

1.1 Background

Over the course of many years, bonded overlays, both of portland cement concrete (PCC) and asphalt concrete (AC), have demonstrated their value as rehabilitation procedures for continuously reinforced concrete pavement (CRCP), economically providing additional service life to deteriorated pavements.

The Texas Department of Transportation (TxDOT) has more than 35 years of experience rehabilitating CRCP with ACOs. The department started experimenting with BCOs in the early 1980s. Historically, the performance of overlays has been satisfactory. However, little is known about the conditions of the old concrete under the overlays. Once a pavement is overlaid, the main concern is the appearance and performance of the new layer and minimal attention is given to the aging process of the original structure.

TxDOT developed this project to investigate the quality and integrity of the original PCC pavements under thin overlays, especially of those that have been in service over extended periods of time. Intuitively, it could easily be understood that overlays, besides rehabilitating the structure and providing a new riding surface, can work as barriers to prevent the intrusion of moisture and other extraneous elements into the structure and can insulate it from adverse environmental conditions, thus protecting it and making it last longer. There is also anecdotal evidence that overlays provide a higher level of extended service to old pavements than would be predicted by theoretical models. However, the complex rationale of how this occurs has not been fully explained. This project attempts to find more by investigating the conditions of old pavements under thin overlays.

1.2 Objectives

The main purpose of this study is to evaluate the conditions of old PCC pavements under both BCOs and ACOs. The sub-objectives are as follows:

1. to develop guidelines for the selection of overlays
2. to develop guidelines for the design of overlays
3. to assess the strength and durability of overlaid old concrete, as well as the occurrence of alkali-silica reactions (ASR)
4. to investigate pavements and overlays constructed with special materials

The objectives of this report are the following:

1. to present results of the field work conducted on the study sections
2. to present the possible failure mechanism of BCOs
3. to present preliminary guidelines for the selection of BCOs and ACOs

1.3 Methodology and Report Organization

The methodology for this project includes a comprehensive literature search on the use of overlays from a historical perspective and on what has been done recently in both Texas and elsewhere. The search involves revisiting various research projects developed in the past that constitute invaluable knowledge on this subject, which will be useful in the fulfillment of this project's objectives.

The next step in the development of this project was to look for suitable sections in Texas that could be investigated and analyzed by means of field work. The field work was intended to study their performance and assess their adequacy after years of having been constructed. For this purpose, an inventory of both BCO and ACO sections in the state was conducted. Results from the literature search were utilized to compile a list of sections, along with the information provided by the various districts that have used these types of rehabilitation.

With this information, factorials for BCO and ACO were developed, which included factors such as overlay age, thickness, types of aggregate, and construction season. These factors would be used in the selection of the study sections.

Field work involved visiting the sections and performing a series of tests for various evaluations of the overlays and the old pavements. These results of the field work, as well as the literature search, helped on preparing guidelines for overlay selection. The proposed guidelines in this report are preliminary and will help pavement engineers in the decision-making process.

Chapter 2 presents a detailed description of the ACO sections that were investigated and the field work performed in such sections. Chapter 3 presents a discussion of the debonding failure mechanisms possible on BCOs and presents a case study for BCO debonding. Chapter 4 contains the description of a program for LCCA that could be used to determine benefit/cost (B/C) ratios for different pavement types and that could be also used for evaluation of overlays. Chapter 5 features the conclusions and recommendations up to this stage of this research project.

2. AC Overlay Analysis and Results

2.1 Introduction

This chapter presents the work done on various asphalt concrete overlays (ACOs) in different districts in Texas. The study sections were selected from the information provided by the district contacts, as well as from the information available in the literature review and previous research projects. Recommendations from PMC members were also considered for the selection of the sections.

The field work and condition survey conducted included the evaluation of different characteristics of the pavement and sampled materials; such properties included material type, age, thickness, pavement deflection, material strengths, and moduli. In the end, the influence of these variables in the overlays can be linked to the performance of the pavement and recommendations for material use could be made based of the results. The following tests were conducted on the cores:

- compressive strength
- splitting tensile strength
- modulus of elasticity
- coefficient of thermal expansion
- petrographic analysis

The projects that were investigated are located in the Bryan, Fort Worth, and Dallas districts. The main variables that have an effect in the performance of ACOs, such as mix type, age, thickness, use of geotextiles, were considered in the selection process.

2.2 Bryan District

2.2.1 SH 6 in Bryan

Testing was performed for the SH 6 section, southbound, in Bryan on November 15, 2005. The testing started at reference marker 672+1.5. The section evaluated is about 1 mile. The recorded global position system (GPS) coordinates for the beginning of the section were latitude of N 30º 43.195' and a longitude of W 96º 24.470'. The pavement tested consists of an ACO on top of 8 in. thick CRCP pavement built in 1982. The first ACO was placed in 1997 with 1.5-in Type D hot mix, followed by ¾-in microsurfacing in 2003. The AC overlay and CRCP pavement are placed over a 10 in. thick lime-treated subgrade.

In order to simplify traffic control along the testing area, condition survey and coring were performed on the inside lane. Pavement deflections were measured with a falling weight deflectometer (FWD) along the inside wheelpath of the inside lane.

Results

The field work was conducted according to schedule and no problems were experienced. Figure 2.1 shows a panoramic view of the section being studied. As can be seen in this image, the AC overlay has minimum transverse cracking.

Figure 2.1   General view of AC overlay on SH 6

Figure 2.2 shows one of the cores obtained for testing along the inside lane of SH 6. The coring equipment used during testing worked well without any delays. However, only three cores were obtained for testing because of rain that prevented further work.

Figure 2.2   Core obtained from inside lane

The ACO in this section was in very good condition upon inspection and only a few transverse cracks were found. Figure 2.3 below shows an existing deformation along the section, which is mainly due to poor drainage conditions in that area. Deflection values measured in this zone did not show any noticeable increase with respect to the rest of the section, which means that although the pavement is deformed, its structural adequacy withstands the traffic loads.

Figure 2.3   Deformed pavement area along the section

Deflection Testing

Figure 2.4 shows a profile of the measured deflections. The graph shows an overall average deflection value of around 5 mils. The lowest deflection value was about 3.4 mils. The highest deflection value was about 7.4 mils. All these values are for a normalized 9,000 lb load.
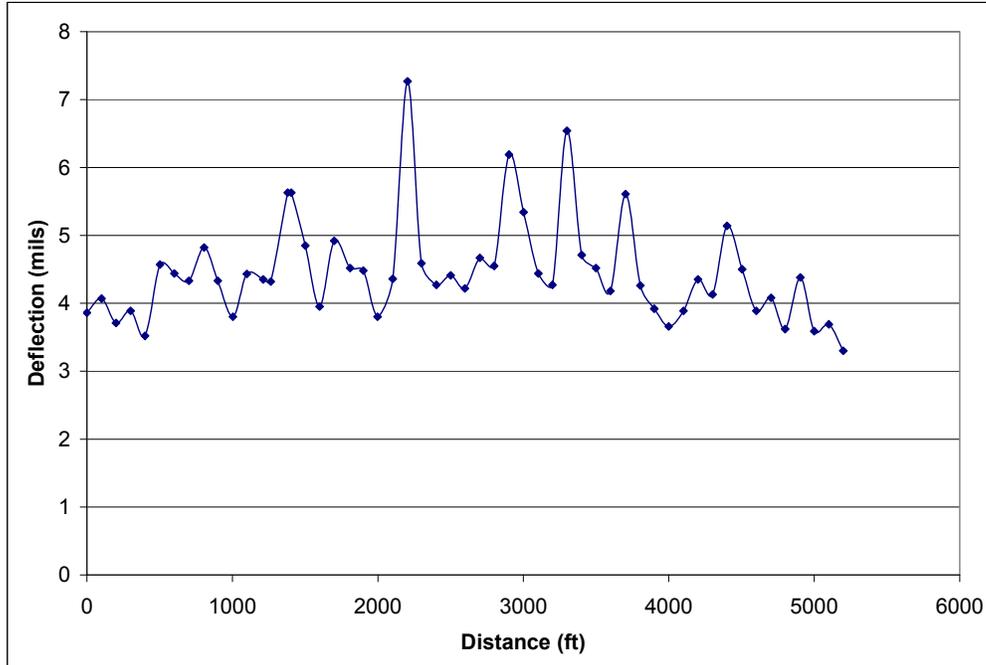
Figure 2.4   Deflection profile obtained for test section

2.3 Fort Worth District

2.3.1 IH-35 W in Fort Worth

The field work was conducted on September 27, 2005; the section analyzed was located on IH-35 W northbound in Johnson County, just south of Burleson. The GPS coordinates for the beginning of the section are latitude N 32º 29.702' and longitude W 97º 17.158'. The outside lane of the section was surveyed from milepost 33 to milepost 34 and cores were taken in between. FWD testing was conducted on the outside wheel path of the lane and also on the middle of the outside shoulder. Additionally, some deflections were taken for some transverse cracks and load transfer efficiency (LTE) was evaluated.

The pavement structure consists of an 8 in. thick CRCP pavement built in 1965 placed on a 6 in. thick lime-treated subbase. The old CRCP was overlaid in 1997 using a petromat followed by 2 in. of asphalt mix built with a coarse aggregate brought from Oklahoma. Current traffic data for this section reveal that the average daily traffic (ADT) is around 46,000 with 21 percent of heavy trucks and the 30-year projected 18 kip-ESALs are 107 million. All field tasks were performed without trouble, except that the company hired to extract the core samples had problems with the coring equipment breaking down. Finally, TxDOT used its coring truck to continue with this task. A general view of the section in question is presented in Figure 2.5.

Figure 2.5   Panoramic view of AC section located on IH-35 W

Results

In general, the AC overlay was in good condition with mild transverse cracking and some longitudinal cracking. Likewise, low-severity raveling was found in isolated areas. Figure 2.6 displays a raveled area.

Figure 2.6   Low-severity raveling found on pavement section on IH-35 W

Although the AC overlay was placed 8 years ago, it is still in good overall condition; only a few of the cracks that were found are severe and caused the AC overlay to completely disintegrate. Figure 2.7 shows a picture of a transverse crack in the AC overlay, which apparently was a transverse construction joint in the CRCP underneath. Contraction and expansion movements of the concrete layer apparently have caused the AC overlay to deteriorate.

Figure 2.7   Deteriorated transverse crack in AC overlay

Figure 2.8 displays the only two medium size (>100 ft^2) AC patches found in the section. The patches looked like they were placed recently or probably replaced older patches.

Figure 2.8   AC patches found in pavement section

Figure 2.9 displays one of the cores extracted from the outside main lane. The top AC layer was 2.5 in. thick and the concrete layer was just above 8 in. thick. The AC layer had a fine transverse crack on the surface that disappeared at about 1 in. deep. The concrete core was intact and only showed scarce segregation. Apparently, the petromat layer placed underneath the AC has protected the old CRCP and has kept its structural integrity.

Figure 2.9   Core sample obtained from section on IH-35 W

After taking out the core samples a dynamic cone penetration (DCP) test was run in most of the cores drilled in the main lanes and also the outside shoulder. The DCP was basically used to evaluate the conditions of the subbase and subgrade layers. Figure 2.10 shows the DCP apparatus being used in the perforation left by Core 6. The estimated modulus of elasticity of the layers underneath the pavement is plotted in Figure 2.11.

Figure 2.10 TxDOT staff conducting DCP test

Figure 2.11 shows that the modulus of elasticity (E) values for the lime-treated subbase, up to 6 in. in depth, lie between 20,000 and 80,000 psi. In the depth between 6 in. and 35 in., the bulk of the modulus of elasticity values fall between 5,000 psi and 25,000 psi. These values correspond to the subgrade layer. As expected, the E values are somehow higher as they approach to the surface, mainly owing to the effect of capillary reaction in the materials, which tend to consolidate.

DCP testing was conducted for Cores 2, 4, 6, and 7, also shown in Figure 2.11. For Cores 2 and 4, both the main lane and shoulder were tested as can be seen in the graph. Cores 6 and 7 only had their main lanes tested. In Core 2, the DCP shows the highest modulus closer to the surface, more so for the main lane than the shoulder. The opposite holds true for Core 4, where the shoulder has the largest modulus in comparison to the main lane. Cores 6 and 7 keep with the overall trend, as their highest modulus values are closer to ground level, and decrease as depth increases. These values are generally smaller than those of Core 2 and 4, despite the fact that Core 6's main lane has the highest batch modulus values for all the cores.
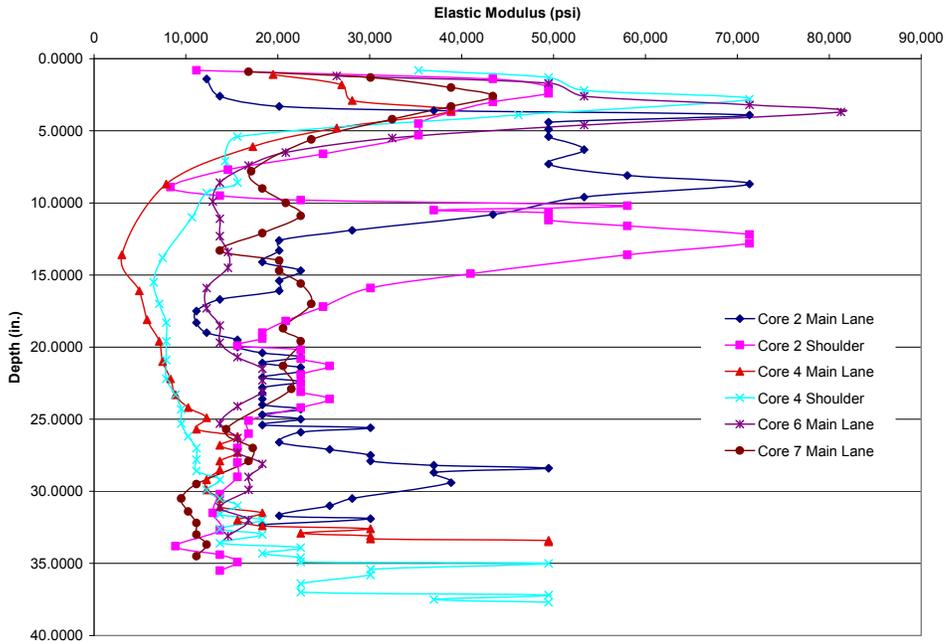
Figure 2.11   Results of DCP testing on IH-35 W

Deflection Testing

Figure 2.12 shows the beginning of test section, where FWD testing started. The FWD testing was conducted only used in the outside lane only.

Figure 2.12   Deflection measurement at test section

Figure 2.13 displays measured deflections versus corresponding distance values. The graph shows an overall mean of about 4.5 to 5 mils and keeps a fairly constant trend. The lowest deflection was about 2.75 mils, while the graph's high peak deflection was around 8.5 mils. A possible reason for the magnitude of the peak deflection could have been the presence of a void between the AC and the PCC layers. The deflections taken for LTE measurement showed that the crack in the ACO was present only in the asphalt layer, which means that the cracks were not reflecting from the concrete pavement underneath.
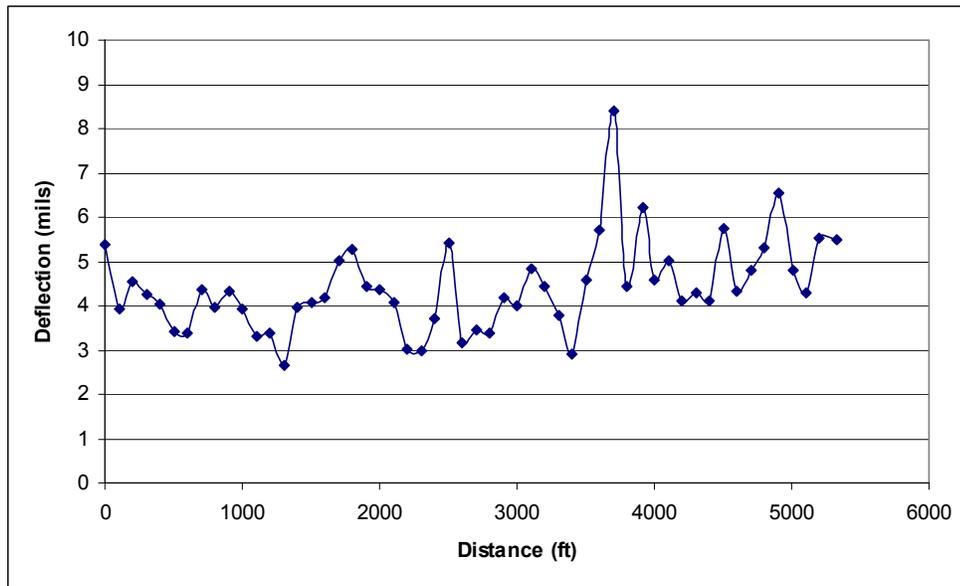
Figure 2.13   Deflection profile obtained for IH-35 W

2.3.2 IH-20 in Fort Worth

Field tasks for this section were conducted on September 28, 2005. The pavement under study is located on IH-20 westbound in Palo Pinto County, just east of US 281. The GPS coordinates for the beginning of the section are latitude N 32º 37.553' and longitude W 98º 04.837'. Tests, condition survey, and coring were done on the outside lane from milepost 389 to milepost 388. Pavement deflections were measured with FWD on the outside wheel path of the lane and also in the middle of the outside shoulder. Load-transfer deflections were measured for some transverse cracks at various locations.

The pavement structure consists of an 8 in. thick CRCP pavement built in 1972 placed over a 4 in. thick asphalt concrete layer and an 8 in. thick lime-treated subgrade. The deteriorated CRCP was then overlaid in 1996 with 2 in. of Type D AC mix and petromat. ADT for this pavement section is around 14,000 with 41 percent of heavy trucks and the 30-year projected 18 kip-ESALs are 54 million. The field work was conducted according to schedule and no problems were experienced. Figure 2.14 shows a panoramic view of the section being studied. As can be

seen in this image, the AC overlay has extensive transverse cracking and also considerable longitudinal cracking.

Figure 2.14   General view of AC overlay on IH-20

Results

The testing program included FWD, coring, and condition survey. Figure 2.15 displays a very distressed area of the pavement. In this particular area, the AC overlay was completely removed by passing traffic. It is believed that the problem probably initiated with the wide crack in the CRCP underneath the AC overlay. Later, maybe the AC layer had reflection cracking, allowing water to get in and down to the subbase. Next, the weakened subbase caused a lack of support of the CRCP, which broke and also caused breaking of the AC layer away from the edge of the pavement, as shown in the upper portion of the picture.

Figure 2.15   Distressed area of the pavement on IH-20

Figure 2.16 shows one of the extracted cores during testing. The pavement was cored at a transverse crack found in the AC layer. The overlay was nearly 3 in. thick and the CRCP layer was 8 in. thick. The asphalt-treated base was found to be separated into two layers, with a total thickness of 3.5 in. In this core location, as well as in the other ones, the petromat layer placed between the AC and the PCC layers has helped keep the concrete layer in good condition.

Figure 2.16   Core sampled from IH-20 westbound

Figure 2.17 shows a full-depth transverse crack in the CRCP, which was reflected on the AC overlay. Usually, reflected cracks on AC overlays are present a few inches away from the crack in the concrete layer; however, this core presented a different scenario.

Figure 2.17   Full depth crack found in core from IH-20

Figure 2.18 shows the FWD testing being conducted at a transverse crack location. The load transfer at this location was found to be 85 percent, which is considered good for the given conditions of the crack.

Figure 2.18   Deflection measurement for LTE at a crack

Figure 2.19 shows TxDOT staff performing the DCP test. The DCP testing performed in this section provided similar results to those obtained from the section located on IH-35W, previously described. In general, it was observed that the capillary effect of the water in the subgrade layer has caused some higher than usual calculated values of E for that layer.

Figure 2.19   DCP testing on IH-20

Deflection Testing

Deflection testing tasks were conducted on time, with no delays. The outside lane and shoulder testing was also completed. LTE calculations at specific locations along this section showed that the transfer efficiency was good with values between 85 and 95 percent. Figure 2.20 shows coring tasks in the mainline while FWD is being conducted on the outside shoulder.

Figure 2.20   Coring and FWD testing on pavement

Figure 2.21 presents measured deflections versus their corresponding distance values. The graph shows an overall average deflection value of around 4 mils. The lowest deflection value was about 2.5 mils. The highest peak deflection value was about 9 mils.
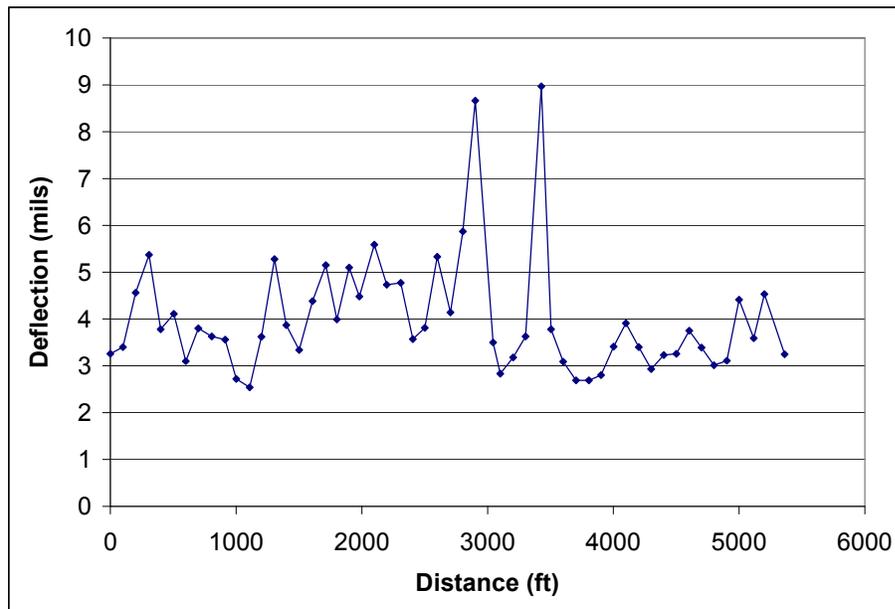
Figure 2.21   Deflection profile obtained for IH-20

2.4 Dallas District

2.4.1 US 175 in Dallas

Testing along US 175 in Dallas was performed on February 6, 2006. During this time, both WB and EB were tested. The testing in the WB started at reference marker 604+0.253. The length of the section evaluated for WB was 1.85 miles, while that for EB was 0.72 miles. The recorded GPS coordinates for the beginning of the WB section are latitude N 32º 39.697' and longitude W 96º 34.372'. The original 9-in jointed reinforced concrete pavement (JRCP) was placed in 1972 and 4 in. of AC overlay project was completed in March, 2004. The JRCP was placed over an 8 in. thick lime-treated subbase. As in the previous tests done in the Bryan District, condition survey and coring were done along the inside lane to make the traffic control process easier and safer. Deflections along US 175 were also measured along the inside wheel path of the lane with FWD.

Results

Figure 2.22 depicts a panoramic view of the section being studied. As can be seen in this image, the AC overlay has almost no transverse cracking and no longitudinal cracking. Figure 2.23 shows location C1, where the first core on the westbound lanes was extracted.

Figure 2.22   Panoramic view of AC overlay, EB lanes

Figure 2.23   Coring of pavement, WB lanes

Figure 2.24 shows the core obtained at C1, WB lanes. As can be seen in the image, the AC overlay is debonded while the JRCP is still in good condition. It can be seen that the AC layer was separated at the mesh's location. Considering the AC overlay was only 2 years old when the evaluation was done, the glass-grid fiberglass mat did not work as intended.

Figure 2.24   Core 1obtained from WB lanes

Figure 2.25 shows core C5, obtained from the EB lanes, where instead of a glass-grid mesh, a strata reflective crack relief system interlayer was used. In this case, the AC layer came

out in one single piece, which showed that strata reflective crack relief system interlayer provided better performance than glass-grid fiberglass mesh, even though this comparison is based on single data point for each system.

Figure 2.25   Core 5 obtained from EB lanes

Deflection Testing

The deflection testing process was conducted without delays. Figure 2.26 shows deflections along both EB and WB lanes. The graph illustrates that the overall deflections in both directions are comparable to each other. The average defections were 3.43 mils for WB and 3.40 mils for EB, with the difference less than 1 percent. As stated above, glass-grid fiberglass mesh was used in WB while strata reflective crack relief system interlayer was used in EB. It appears that the performance difference between the two interlayer systems was not detected by FWD deflections.
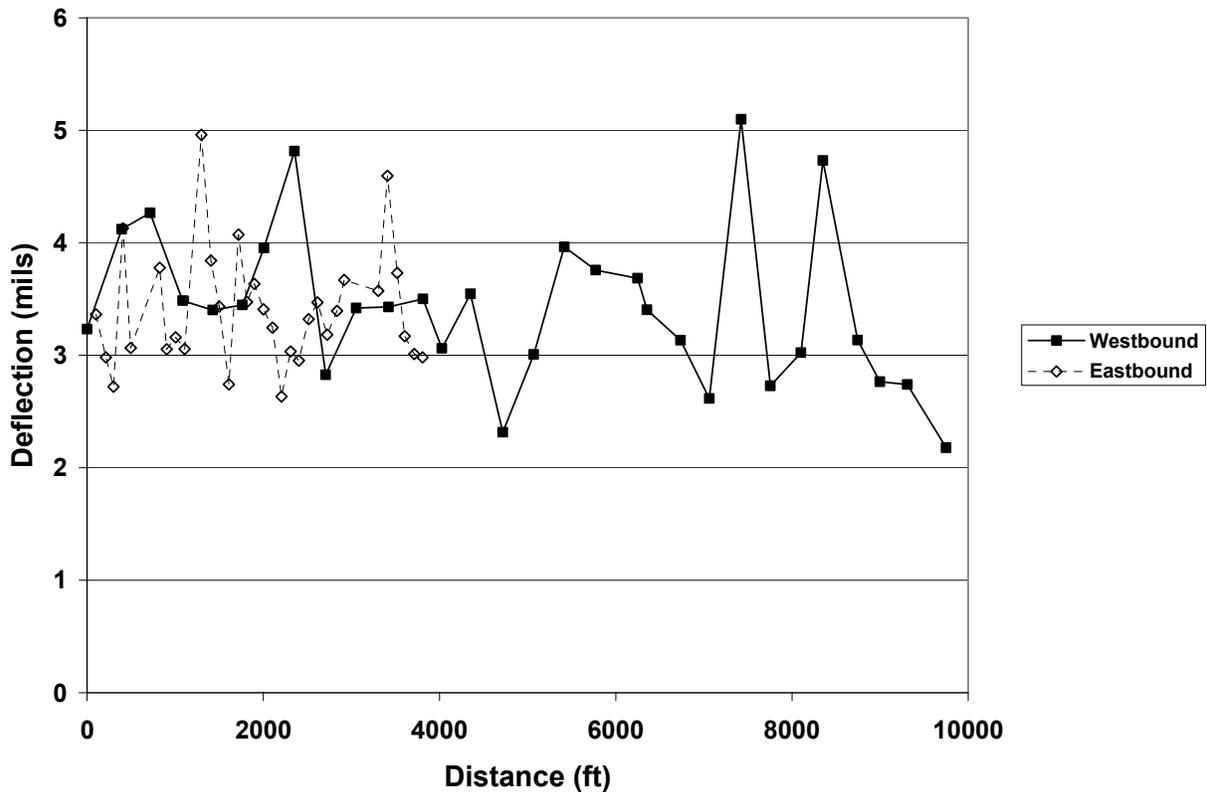
Figure 2.26 Deflection profile obtained for US 175

2.4.2 I-635 in Dallas

Testing for the I-635 section in Dallas was performed on February 7, 2006. The SB lane was tested for this section starting near milepost 2. The length of the section evaluated was about 1 mile. The recorded GPS coordinates for the beginning of the section are latitude N 32º 43.934' and longitude W 96º 36.762'. In order to simplify traffic control and make it safer, tests, condition survey, and coring were done along the inside lane of the section. As for US 175, deflections were measured with FWD on the inside wheel path of the lane. The pavement on I-635 consists of a 4 to 5 in. thick AC overlay that was placed from September to December, 2004, on top of 9 in. thick CRCP that was built in 1982. The CRCP was placed over a 10 in. thick lime-treated subbase.

Results

During field work, problems were experienced with the coring rig, as can be seen below in Figure 2.27. The coring bit was defective and the coring crew had to try coring at different locations. Other testing was performed efficiently with no delays. Figure 2.28 shows a panoramic

view of the section being studied. As can be seen in this image, the AC overlay is in very good condition.

Figure 2.27   Problems during coring on I-635

Figure 2.28   Panoramic view of section on I-635

Figure 2.29 shows the cores taken from I-635. As can be seen, the thickness of the AC overlay varied between 5 in. and 6.5 in. In all cores the AC layer came out as a single piece.

Figure 2.29   Cores obtained from I-635

Deflection Testing

Figure 2.30 below shows measured deflections versus their corresponding distance values. The graph shows an overall average deflection value of around 4 mils. The lowest deflection value was about 2.9 mils with the highest deflection value measured around 5.2 mils.
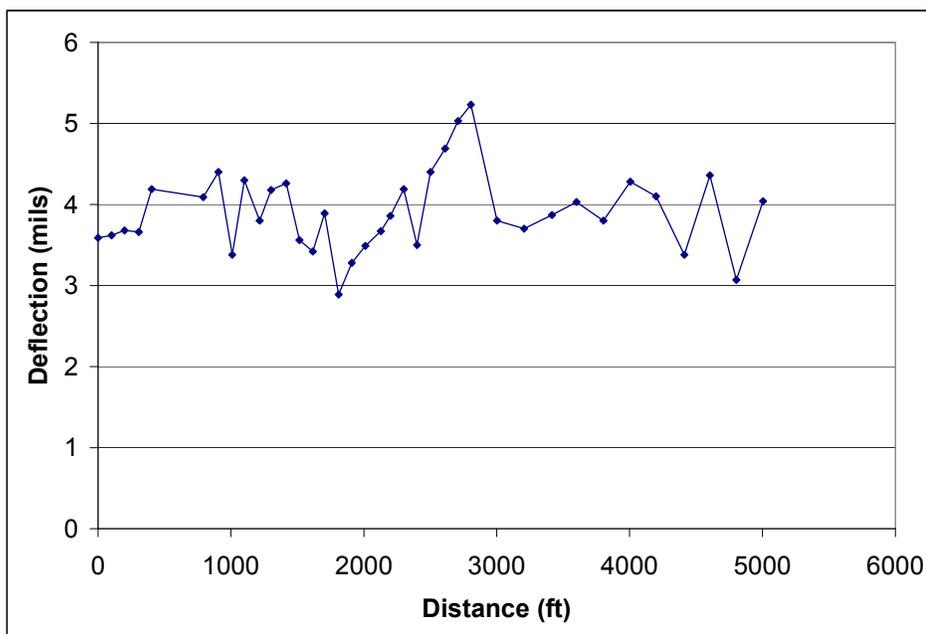
Figure 2.30   Deflection profile obtained for I-635 SB

2.5 Summary of Field Evaluations

This chapter described the work performed for the evaluation of ACOs in the Bryan, Fort Worth, and Dallas districts. Table 2.1 summarizes the ACO sections evaluated in this study.

Table 2.1 ACO sections evaluated in this study

District -Highway	Existing Pavement		AC Overlay	
	Pavement Type	Year Constructed	Thickness	Year Constructed
Bryan – SH6	8-in CRCP	1982	2.25-in	1997
Ft Worth – IH35W	8-in CRCP	1965	2-in with Petromat	1997
Ft Worth – IH20	8-in CRCP	1972	2-in with Petromat	1996
Dallas – US175	9-in JRCP	1972	4-in with Strata (EB) or fiberglass (WB)	2004
Dallas – IH635	9-in CRCP	1982	4 to 5-in	2004

The age of ACO projects when evaluated vary from 2 years (projects in Dallas District) to 9 years (IH20 project in Ft Worth District). Field evaluations indicate the overall performance of AC overlays has been good. Deflection measurements indicate all the pavement sections evaluated are structurally in good condition, which might provide reasons for good performance. In other words, if PCC pavement is in good structural condition and needs functional enhancements such as improving ride quality or skid resistance, ACO can provide a good rehabilitation option. The evaluation of the effectiveness of the interlayer system in ACO was not a primary objective of this study, and the number of projects evaluated in this study is small to draw any general conclusions. However, it appears that fiberglass mat does not appear to provide intended benefits.

3. Field Investigation of Debonding Failure Mechanism

3.1 Introduction

Bonded concrete overlays (BCO) are designed to act monolithically with old concrete pavement so that existing slab and overlay contribute to the maximum extent to the structural capacity of the pavement (Ref 2). It is very important to assure solid bond between old concrete pavement and new overlay. The purpose of this chapter is to identify the dominant debonding failure mode between old concrete pavement and new CRCP overlay. To this end, a field experiment was conducted to investigate the behavior of new CRCP overlay at early age.

3.2 Debonding Failure Mode at Interface between Old and New Concrete

Figure 3.1 shows two different debonding failures that can occur depending on the state of strain or stress at the interface between old concrete pavement and new CRCP overlay. If normal stress at the interface exceeds normal bond strength, Mode-I debonding failure (opening) will occur. On the contrary, Mode-II debonding failure (sliding) will happen when shear stress is more than shear bond strength. To identify debonding failure mode, it is necessary to investigate stress or strain at the interface. Field testing was conducted on a section of pavement in Houston to investigate these failure modes.

Mode I - Opening   **Mode II - Sliding**

New CRCP overlay   New CRCP overlay

Existing pavement   Existing pavement

Normal stress   **Shear stress**
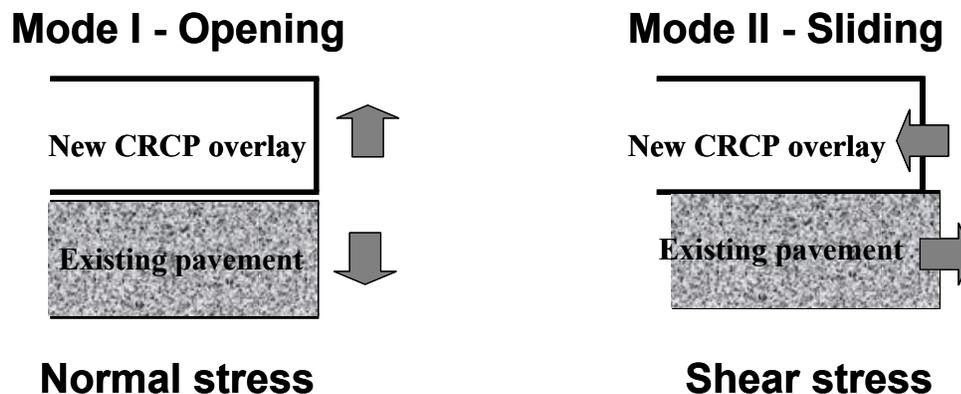
Figure 3.1   Debonding failure model at interface between old concrete and new concrete

3.3 Field Testing

The pavement section instrumented for this experiment is located on Loop 610 between I-45 and US 59 in Houston as shown in Figure 3.2 (Ref 3). The GPS coordinates are latitude N 29º 48.496' and longitude W 95º 21.591'. Concrete was poured at 7:30 a.m. on March 30, 2006. Thickness of both old and new concrete pavements is 8 in.

Figure 3.2　Location of instrumented test section

3.4 Field Measurement Scheme

To investigate the microscopic behavior of new CRCP overlay at early ages, seven vibrating wire strain gages (VWSG) were installed, as shown in Figure 3.3. Six of VWSGs were installed near the crack and one VWSG across the induced transverse crack. Additionally, temperature was measured at top, middle, and bottom of new CRCP overlay to examine the effect of environmental condition on the occurrence of transverse crack and debonding failure. ("Top" is 1 in below the surface, "middle" is at the mid-depth of the slab, and "bottom" is 1 in above the bottom surface of the slab.) A transverse crack was induced at the intended location by reducing the thickness of new CRCP overlay. Figure 3.4 shows the 1 in. deep saw cut that was done 8 hours after concrete placement.

To identify the dominant debonding mode of interface between old concrete pavement and new CRCP overlay, six VWSGs were installed in the vertical and horizontal directions near the interface (Figure 3.3). Two vertical VWSGs, placed at 1 in. and 9 in. from the induced crack, were installed through the interface to detect Mode-I debonding failure. In other words, a half of the VWSG length was embedded in old concrete and the other half in new concrete. Two horizontal VWSGs were installed into old concrete pavement and two in new CRCP overlay at the distance of 5 in. and 13 in. from the induced crack. It was expected that measured differences of horizontal strain at the same location between old and new concrete would provide information on Mode-II debonding failure.
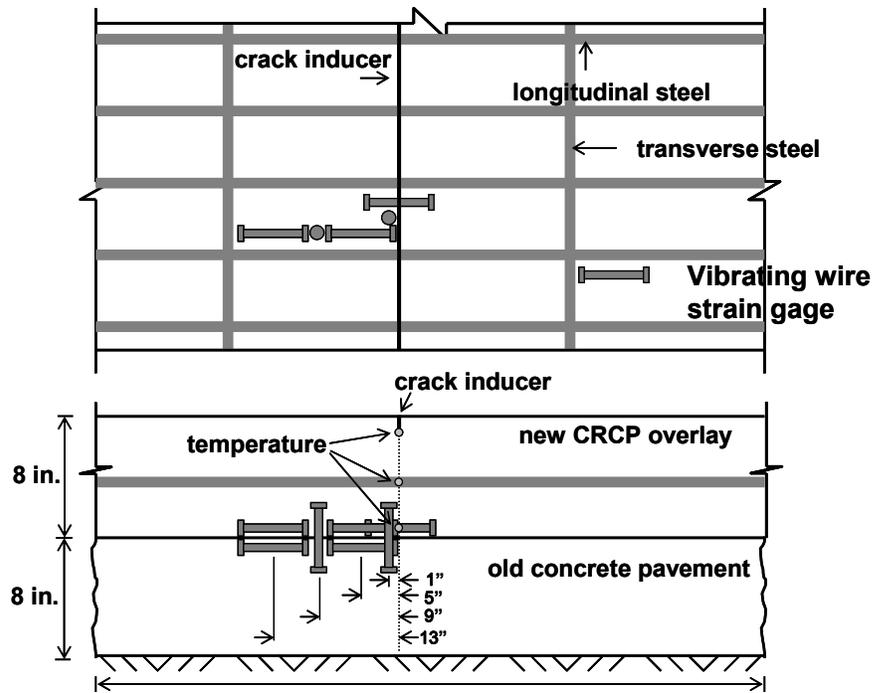
Figure 3.3   Layout of VWSG installation for identification of CRCP overlay delamination

Figure 3.4   Saw cut to induce transverse crack at new CRCP overlay

3.5 Measured Results

3.5.1 Temperature

Figure 3.5 shows the variation of temperature between top, middle, and bottom of new CRCP overlay after placement of concrete. In the figures in this report, time zero in x-axis indicates midnight before the concrete placement. Therefore, day 1 in x-axis represents the first midnight after concrete placement, and the mid-point between day 1 and day 2 indicates noon next day after concrete placement. As expected, the variation of temperature at top was larger than that observed at middle and bottom of the slab. It can be seen that the temperature at day 9 decreased significantly compared to previous days.
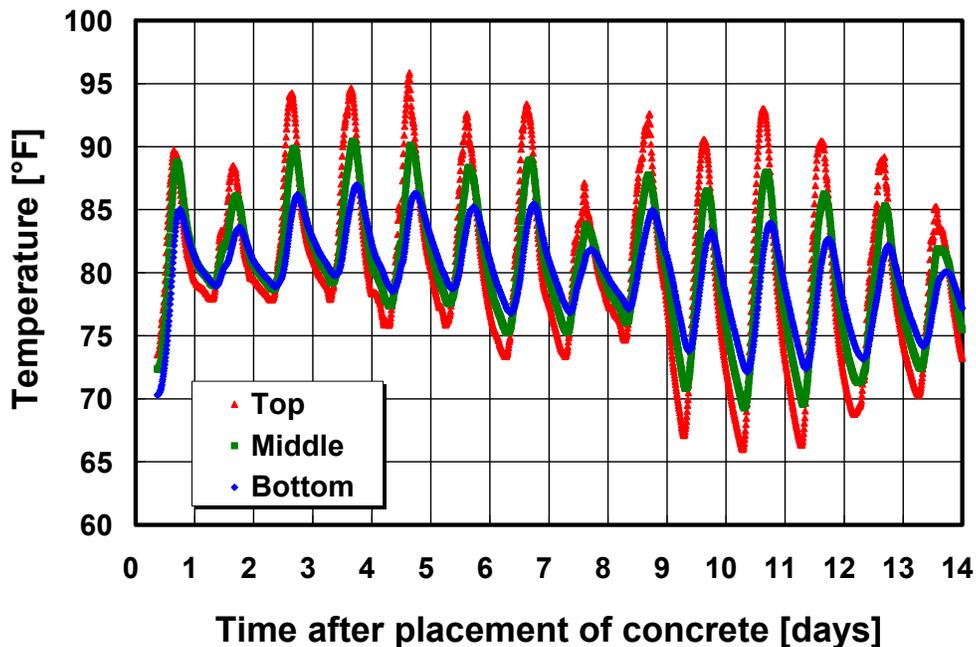
Figure 3.5   Temperature history at top, middle, and bottom depths of new CRCP overlay

3.5.2 Longitudinal Strain of New CRCP Overlay at Transverse Crack

Figure 3.6 shows the measured longitudinal strain of new CRCP overlay evaluated at the induced transverse crack and concrete temperature at the bottom of the overlay. The variations of longitudinal strain are not significant from the beginning of placement until day 5. However, there was a substantial increase in concrete strain at day 6 and it is considered that this change was caused by the development of a transverse crack at the induced crack location. Note that there was a drop of about 2.5 °F in minimum temperature from day 5 to day 6. It is shown that this drop of minimum temperature caused initial transverse crack. It is also noted that there was little difference in concrete temperature for days 6, 7, and 8, and corresponding concrete strains. In the morning of 9th day, there was additional 3.8 °F drop in minimum concrete temperature

from the previous morning and concrete strain increased substantially. This finding exemplifies the importance or significant effect of temperatures on cracking behavior of concrete pavement.
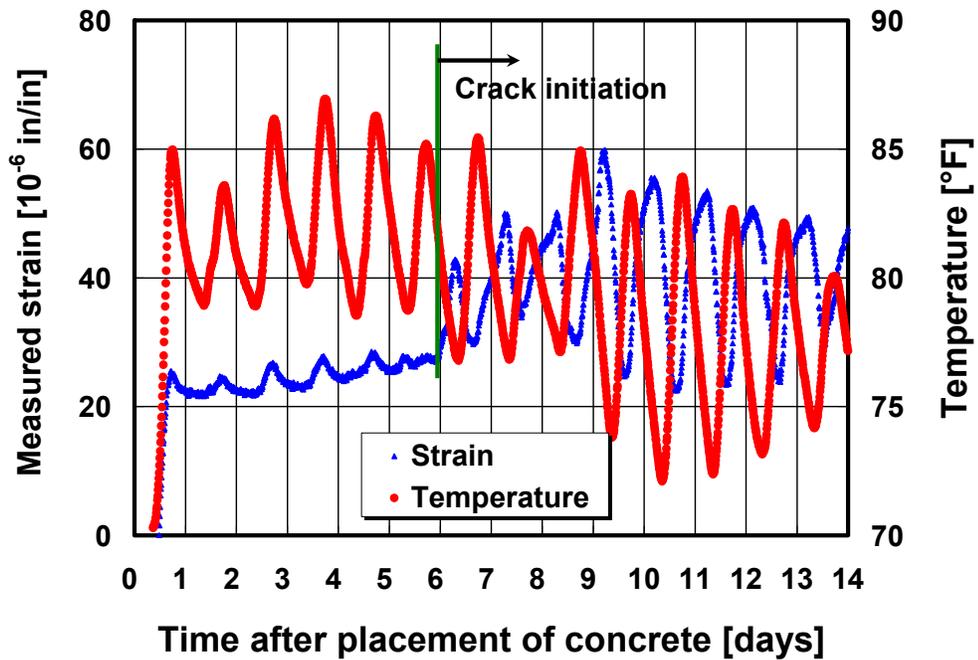
Figure 3.6   Longitudinal strain and temperature at the bottom of new CRCP overlay

3.5.3 Horizontal Strain at Old Pavement and New CRCP Overlay

Figures 3.7 and 3.8 show the measured horizontal strains in old pavement and new CRCP overlay at 5 in. and 13 in. away from the induced transverse crack, respectively. There was little difference in concrete strains between old pavement and new pavement at these two locations. This indicates that there was little debonding or shear failure taking place, if any, at these locations. Therefore, Mode-II debonding failure is not considered to be the primary debonding mode at the interface.

It is noted that the strains increased in the morning of day 9. It is explained by the decrease in minimum concrete temperature in the morning of day 9, as shown in Figure 3.5.

Figure 3.7   Horizontal strain of old pavement and new CRCP overlay 5 in. apart from transverse crack

Figure 3.8   Horizontal strain of old pavement and new CRCP overlay 13 in. apart from transverse crack

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3.5.4 Vertical Strain at Interface between Old Pavement and New CRCP Overlay

Figures 3.9 and 3.10 illustrate measured temperature and strain from VWSGs installed vertically through the interface between old pavement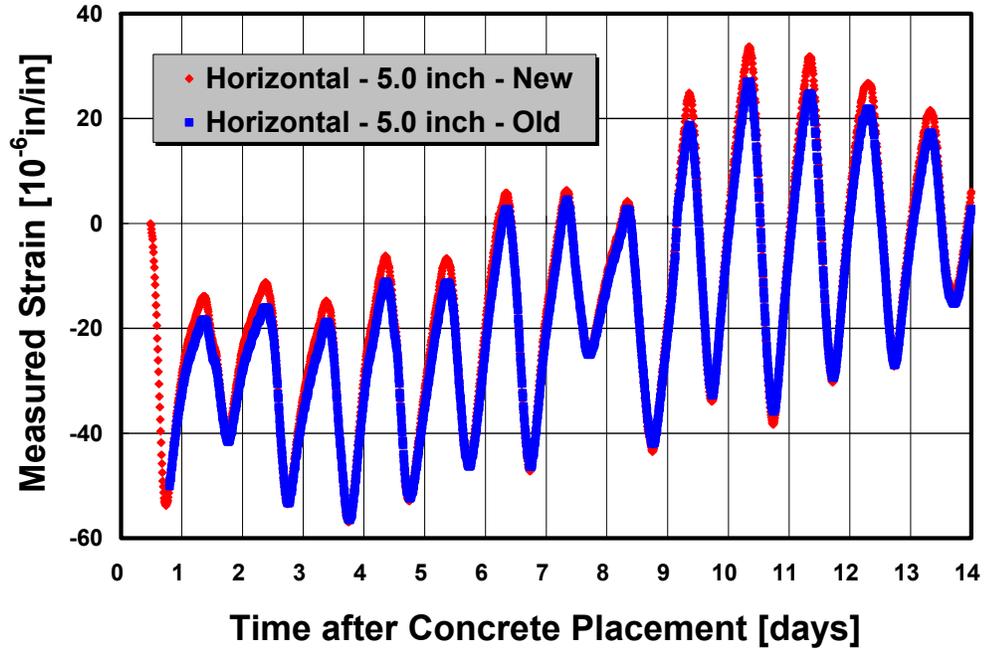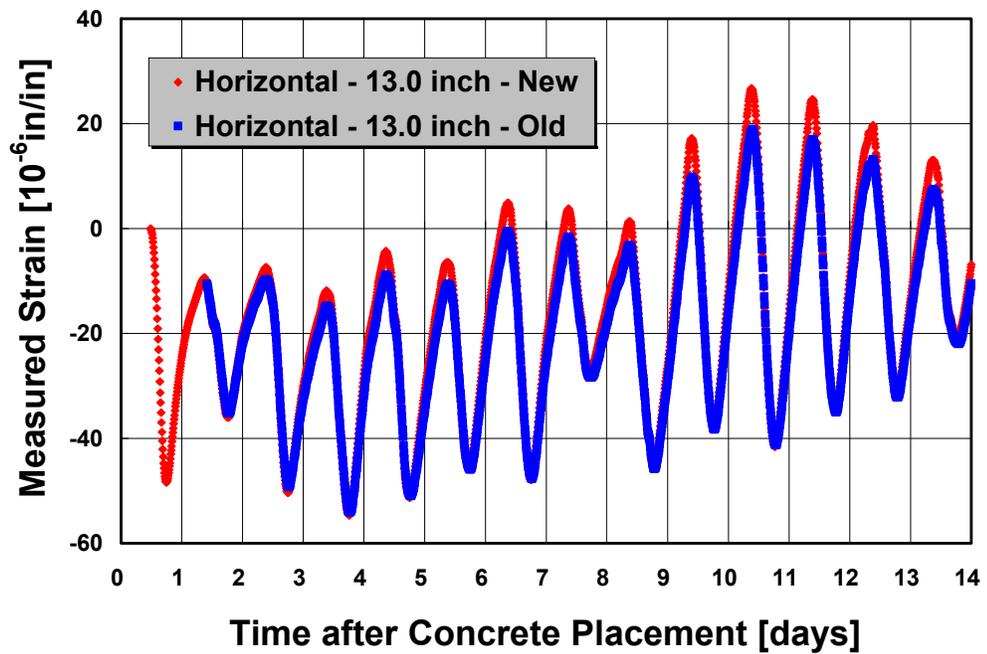 and new CRCP overlay, respectively. The measured temperatures from the two gages are almost identical as expected, since they are at the same depth. Figure 3.10 shows measured strains at the two locations are quite similar until the afternoon of day 4. The strains start diverging from that point, but still maintain the same trend until the morning of day 6. From the morning of day 6, the strains at 1-in location are getting larger than those at 9-in location and the strains have opposite directions – in other words, when the strains are decreasing at 1-in location, they are increasing at 9-in location. This is explained by the fact that a transverse crack started developing in the morning of day 6 (see Figure 3.6). Once the crack occurred, there was curling of the overlaid slab, resulting in larger strains at 1-in location than in 9-in location. Also, curling explains the opposite directions of the strains at the two locations. Figure 3.10 also shows a sudden increase in strains at 1-in location in the morning of day 9. It was shown in Figure 3.6 that there was a larger drop in minimum concrete temperature the morning of day 9 and resulting increase in crack widths. There is a good compatibility between the strains in horizontal and vertical directions. The concrete slab behavior shown in Figures 3.6 and 3.10 indicates that Mode-I failure is the primary debonding mechanism at early ages.
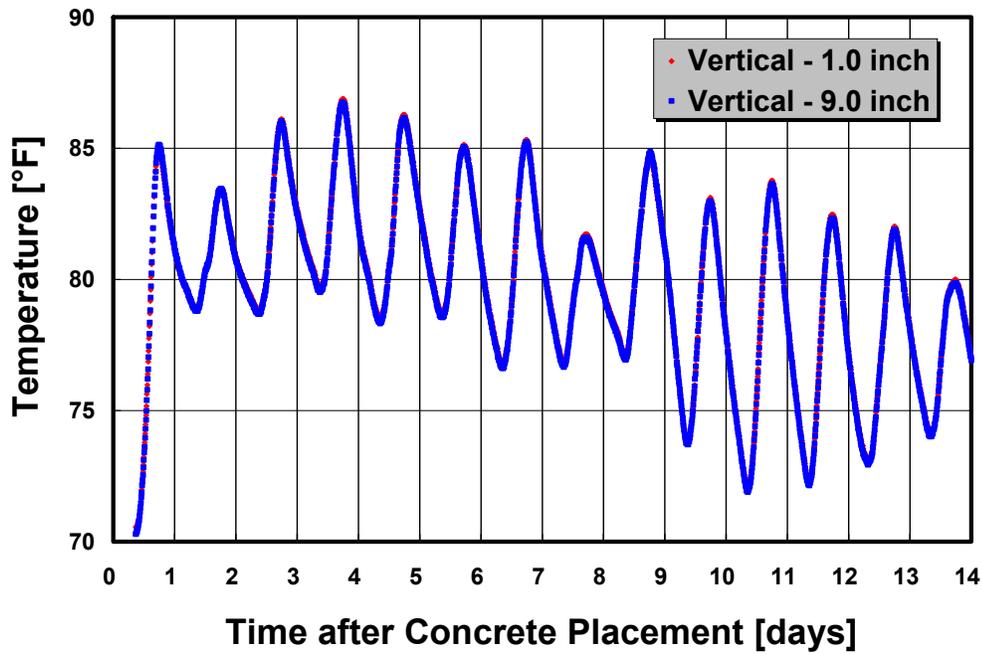
Figure 3.9   Measured temperature from VWSGs installed vertically through the interface between old pavement and new CRCP overlay
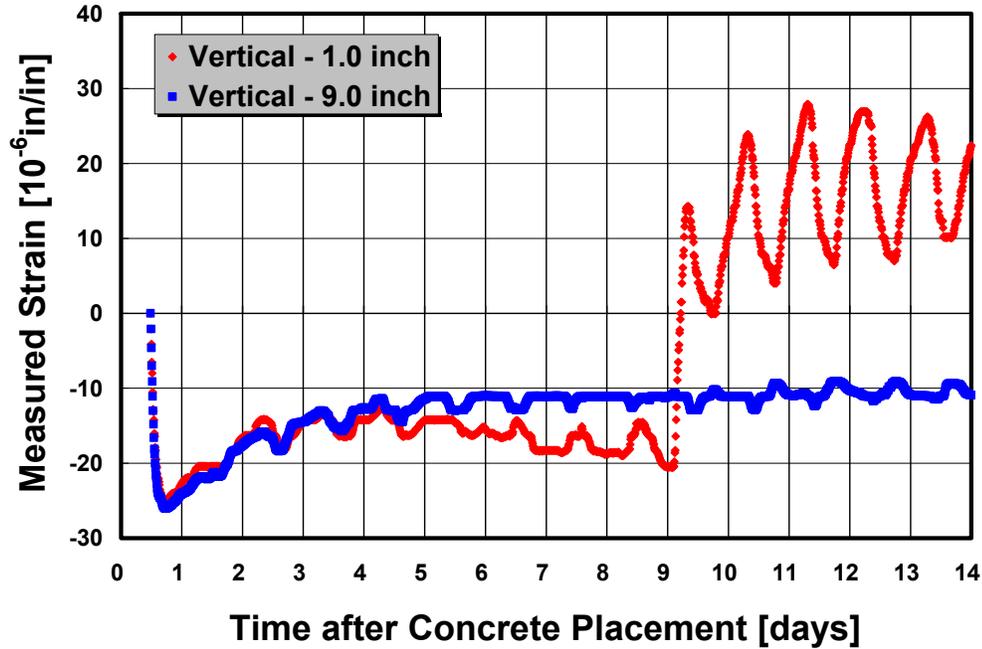
Figure 3.10 Measured strain from VWSGs installed vertically through the interface between old pavement and new CRCP overlay

3.6 Conclusion

Field testing was conducted to identify the primary debonding failure mechanism between old concrete pavement and new CRCP overlay. Concrete temperature had significant effect on cracking and debonding behavior. Horizontal concrete strains measured at just below and above the interface at varying distances from the induced transverse crack were almost identical, indicating that there were practically no differential shear displacements between old and new concrete. On the other hand, vertical strain measurements at the interface showed a significant difference depending on the distance from the induced transverse crack. From this field experiment, Mode-I debonding failure is shown to be a dominant failure mode at early ages between old concrete pavement and new CRCP overlay.

4. Preliminary Cost Analysis and Benefit/Cost Comparison

4.1 Introduction

Among the tasks of Project 0-4893, analyzing life-cycle costs for both BCOs and ACOs placed on rigid pavements was included. For that purpose a previous project conducted at CTR is being revisited, and the computer program that constitutes the main outcome of that project, is reviewed here.

TxDOT research project 0-1739 (Ref 4) developed a LCCA methodology for PCC pavements – one that considers all aspects of pavement design, construction, materials, and maintenance throughout the analysis period – called the Rigid Pavement Life-Cycle Cost Analysis (RPLCCA). It predicts pavement performance using state-of-the-art performance models and reliability concepts, from which it determines maintenance and rehabilitation needs.

LCCA is a process for evaluating the total economic worth of a project by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, and restoration and resurfacing costs, over the life of the project segment.

The program is Windows-based and enables the user to analyze an array of rehabilitation options, allowing various alternatives for input variables, according to the user's availability of information, and providing default values that suit TxDOT's needs for those cases in which the user is unable to come up with values for some variables. The program is comprehensive, as it considers life-cycle costs in depth.

4.2 Components of Life-Cycle Cost Analysis

The components of the LCCA method, as approached by Project 0-1739, are shown below, grouped into categories:

4.2.1 Agency Costs

- Pavement performance and distress
- Construction, maintenance, and rehabilitation

4.2.2 Direct and External Societal Costs

- Travel time delay
- Vehicle operating costs
- Emissions
- Accidents
- Evaluation factors
- Discount rate

- Reliability

The life-cycle cost framework in this program was developed for PCC pavements, but the overlays include both AC and PCC layers, so it can be potentially used for either type of overlay.

4.3 CRCP Performance Models

Transverse Cracking

In this program, transverse cracking model developed by Won et al. (Ref 5) is used for the prediction of transverse stresses caused by wheel loads, which will be used to estimate punchouts. The CRCP-8 computer program used this model was calibrated for the Texas conditions (Ref 6). Therefore, RPLLCA program can use the results of the CRCP-8 program as inputs.

Punchouts

The most commonly used punchout model was developed in 1988 by Won et al. (Ref 5) at CTR. The model uses the fatigue failure model, together with the relationship between crack spacing and the transverse tensile stresses in the pavement. The CTR models assume that no punchouts occur on slabs where the crack spacing is greater than 3.5 feet.

Serviceability

The serviceability model for CRCP used in the program is based upon the present serviceability index calculated using the AASHTO design equation (Ref 7).

Overlays

The first step in determining the rehabilitation needs of a pavement section is to make an estimate of the remaining life of the pavement structure. At the end of each year in the analysis period, an assessment of the condition of the pavement must be made, from which one of the three alternatives must be chosen: do nothing, perform minor maintenance, or perform major rehabilitation. When the decision is a PCCP overlay, the computer program Rigid Pavement Rehabilitation Design System (RPRDS-1) is used.

The RPRDS routine is also used to calculate the remaining life of the pavement with AC overlays. However, AC distresses are determined through other performance models: Reflective cracking is estimated with a model developed for the Federal Highway Administration by ERES Consultants, Inc. (Ref 8), while a model developed for the Strategic Highway Research Program estimates rutting. Because these models require much more information - information that the engineer may only be able to estimate – the asphalt overlay routines included in the framework should be used with caution.

4.4 LCCA Program

The program is Windows-based and is user friendly. For the many inputs, the program offers default options, so if the user does not have information on a certain input variable, there might be a default input that fits the program as well.

The RPLCCA program is capable of considering more than one overlay placed over the span of the facility's life, i.e., the analysis period. Another feature of it is its ability to take inputs from the output files of CRCP-8 or JRCP-6. The program's input values are stored as Microsoft Access files; therefore, values can be changed within MS Access. The program offers the user the option of considering unbonded concrete overlays and asks for trial thicknesses of PCC overlays and AC overlays.

The program does not consider an AC pavement alternative. The variability considered involves materials but not traffic.

The program either asks for maximum distresses values, which, once exceeded, will trigger a rehabilitation option (overlay), or a specified rehabilitation schedule (with pre-determined type of overlays, timing and thicknesses) can be applied.

4.4.1 Program Inputs

In total, there are 138 input variables in the RPLCCA; the data entry is split up into two parts: the first is the alternative-specific data entry mode and the second is the project level data entry mode. Characteristics such as steel reinforcement and concrete properties are specific to each alternative, so they are accessed by pressing the Edit Alternative button. A particular pavement project will also have certain characteristics that are the same, regardless of what type of pavement is constructed, so such elements as loading characteristics, project geometry, and economic factors are all grouped under the Project Inputs portion of the data entry. Figure 4.1 shows the main window of the program and the General Inputs window. The data entry process is easy to accomplish by just clicking on the various tabs that appear in the various pages of the program. A detailed list of the program variables appears in the literature (Ref 4).
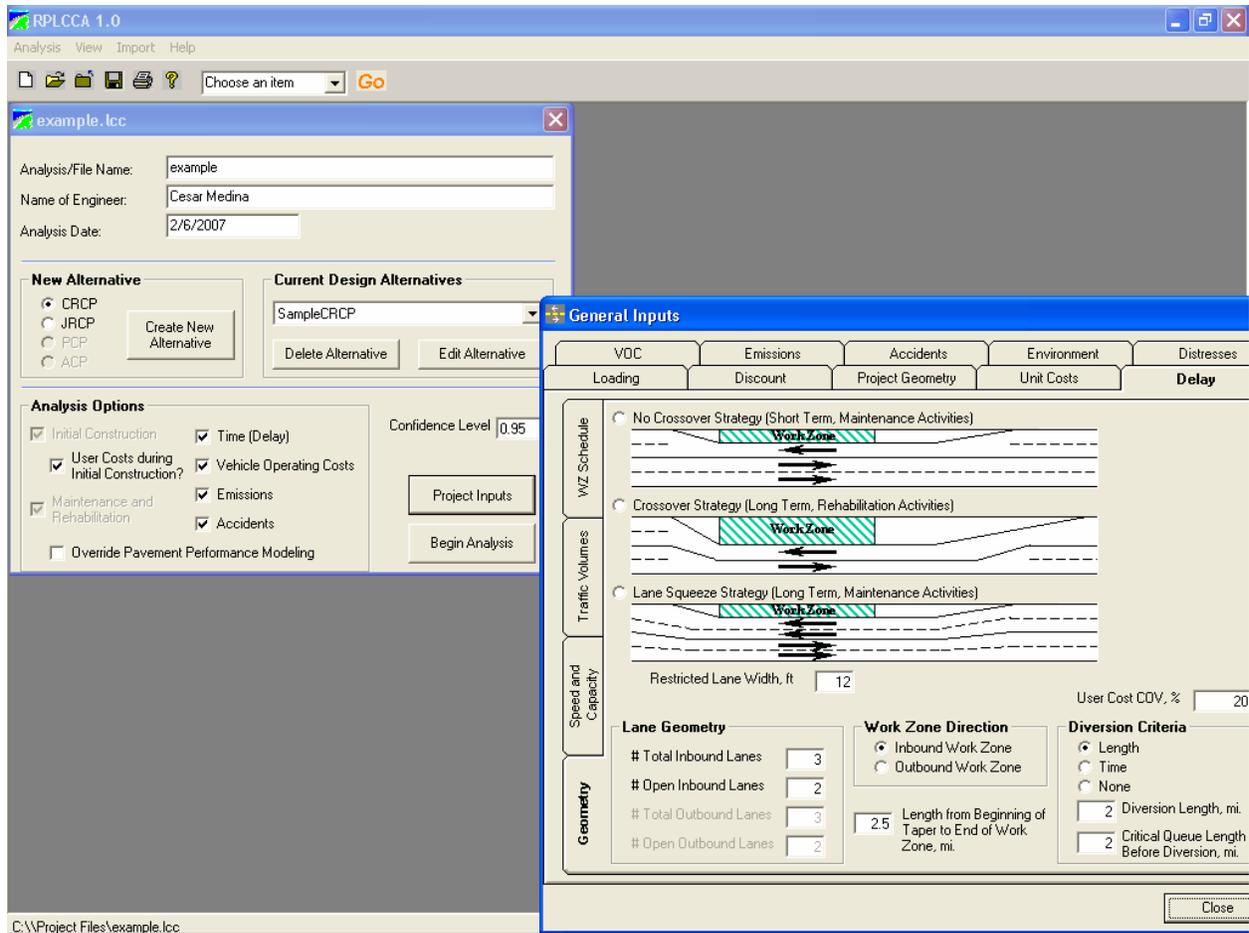
Figure 4.1   Main window and general inputs for RPLCCA program

4.4.2 Materials Database

A material database is included in the RPLCCA computer program to provide a way to organize the different materials that are used for various analyses. The database can be populated with materials available to the local engineer, thus further customizing the RPLCCA program to the local environment.

4.4.3 Program Outputs

The program outputs consist of a series of screens that contain information as follows:

- A list of all the alternatives, with construction and user costs
- Plots of various distresses and present serviceability index (PSI) that are modeled by the RPLCCA program over time for each alternative
- Total life-cycle cost for each design alternative, with rankings, with and without considering user costs

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- Total cost of individual components for each design alternative

Figure 4.2 depicts an example of the output windows that plots the analysis of costs over time for two different alternatives. Figure 4.3 shows a tabular form of the ranking of the different alternatives that includes all the costs at the end of the analysis period. All the output screens can generate reports that could be saved in text format if necessary.
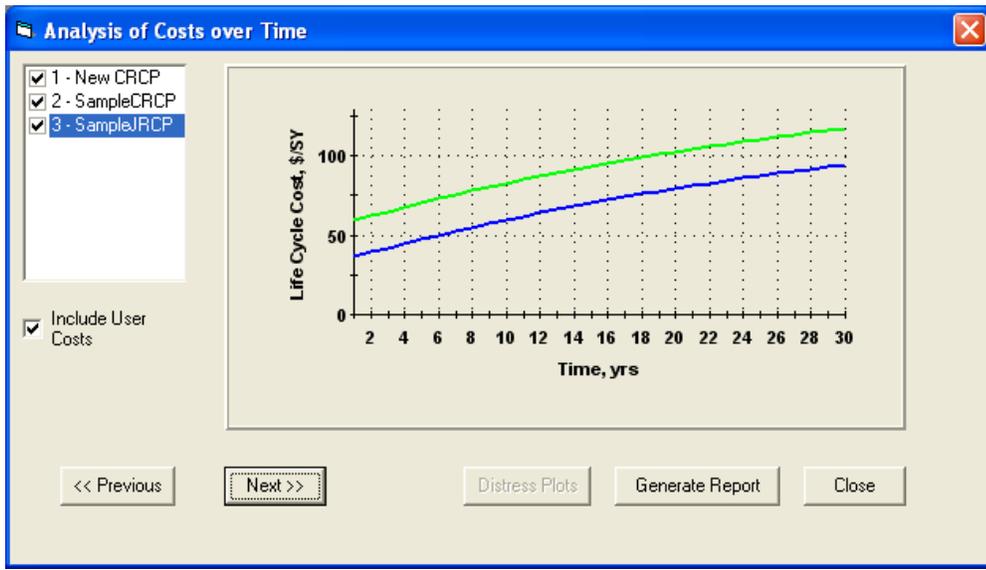
Figure 4.2   Graphical output of analysis of costs over time

Name	Total LCC (NPV)	Total LCC (EUAC)	Agency Costs	Total Time Delay	Tota
New CRCP	$95.51	$4.84	$95.51	$0.00	$0.0
SampleCRCP	$95.51	$4.84	$95.51	$0.00	$0.0
SampleJRCP	$118.43	$6.00	$118.43	$0.00	$0.0

Figure 4.3   Tabular output of LCCA for different strategies

4.5 Summary

RPLCCA software allows the user to perform an analysis that could be very detailed, provided that all the required inputs are available. The results depend heavily on the performance models and the level of confidence that the user places in the distresses predicted by the program. If the user is not satisfied with the predictions provided by the models, a more simplified analysis can be performed by providing preprogrammed maintenance and rehabilitation intervals for specific distresses and by defining the extent of the entire project over which the particular type of maintenance or rehabilitation will be performed. Additionally, there are many default values built within the program, as well as a materials database, which can be expanded and customized.

It is believed that this program could be a very useful tool for the analysis of different overlay alternatives. Although the program was not prepared specifically for overlays, the inputs and outputs could be adjusted to meet this criterion and help pavement engineers make better decisions for the selection of optimum overlay type.

5. Conclusions and Recommendations

5.1 General Conclusions

This report presents the findings of the field studies conducted to evaluate the performance of asphalt concrete overlay (ACO) on PCC pavements, and to identify the debonding mechanism in bonded concrete overlay (BCO). Based on the findings of the field evaluations, the following conclusions are made:

- ACO appears to provide a viable option to extend the life of PCC pavement that is in good structural condition and that needs functional enhancements such as improving ride or skid resistance.
- All the ACO sections evaluated in this study are in good condition. Also, the sections indicate that the structural capacity of the concrete pavement underneath the ACOs was maintained to a good level. The measured deflections in all pavement sections were within acceptable ranges, with no more than 9 mils displacements for a normalized load of 9,000 lb. This implies that, if ACO is applied to PCC pavement that is in reasonable structural condition, good performance of ACO can be achieved.
- Deflections were not available for the concrete pavements before they were overlaid, so it is not feasible to quantify the benefits of ACO on reducing pavement deflections. However, it is believed that thin ACO might not provide the benefits of enhancing the structural capacity of the PCC pavement. Instead, ACO appears to provide benefits of protecting concrete underneath from temperature and moisture variations, and potentially improving ride and skid resistance.
- Due to the small sample size, the effect of special materials used in the ACOs could not be quantified. However, glass-grid mesh does not appears to provide as much benefits as other materials evaluated in this study, such as Strata or Petromat.
- Since all the distresses observed in BCO projects in Texas had debonding problem, a field study was conducted to identify the mechanism of debonding. For this specific case study it was found that the tension generated at the interface between the old concrete and the overlay was the dominant factor for the failure of the bond. Therefore, Mode I was concluded to be the failure mechanism in this experiment. However, because of the complexity of the debonding mechanism and because only one experimental design is not sufficient to draft definite conclusions, it is required that this topic be further researched. Future efforts will be made in this project to investigate debonding issue further.
- The life cycle cost analysis of BCOs and ACOs is something that has not been fully studied yet. At this time, it can be stated that in order to compare both rehabilitation strategies, it will be necessary to build some experimental sections where all incurring costs could be monitored for a

number of years and then compare performances and B/C ratios of the alternatives. The information presented in this report could serve as a starting point for that effort. Further efforts can be made to get full potential of the software described in this report, RPLCCA.

5.2 Recommendations

Considering the mileage of PCC pavement in Texas that is approaching the end of its functional and structural life, BCOs and ACOs could present the most cost-effective ways to extend the life of the existing PCC pavement. Even though guidelines exist on when to use BCOs or ACOs in 1993 AASHTO Guide for Design of Pavement Structure (Ref 7), they are quite general in nature and not specific enough to be useful to TxDOT staff. The development of more detailed guidelines on when to use BCO and ACO will help TxDOT staff make rational decision on the selection of the optimum overlay type. Currently, detailed information on structural condition of continuous reinforced concrete pavement (CRCP) has been collected in TxDOT's research project 0-5445, "Project Level Performance Database for Rigid Pavements in Texas." In that project, deflection information has been collected for CRCPs with various slab thicknesses, and decent correlations obtained between average deflections and slab thicknesses. The information can be used in developing procedures to determine whether BCO or ACO is the optimum overlay type for a given CRCP. It is recommended that further efforts be made to develop comprehensive and detailed guidelines.

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