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16. Abstract
Little is known about the conditions of old concrete under bonded overlays used in rehabilitation procedures. This project aims at evaluating the quality and integrity of original portland cement concrete (PCC) pavements under thin overlays—both bonded and asphalt concrete (AC)—especially those which have been in service for an extended period of time. Currently, there are no guidelines available for the selection of optimum overlay types. The objectives of this study included (1) the evaluation of the concrete under overlay, (2) the development of guidelines for the selection and design of AC overlays and bonded concrete overlays (BCOs), and (3) assessment of the performance of overlays constructed with special materials. The project began with 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 AC overlays on rigid pavements, the most critical matter is reflective cracking in jointed pavements, stripping, and rutting. In order to achieve the objectives of this study more efficiently, a factorial experiment was developed and field evaluations conducted accordingly. This report presents the results of BCO evaluations. Four BCO projects in Texas have been 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 have 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. The relationship between compressive strength and modulus of elasticity of old concrete cores follows the American Concrete Institute (ACI) equation. Petrographic evaluations of old concrete cores indicate that no major deteriorations occurred except for one core where pockets of ettringites were observed.

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# Preliminary Findings of Performance of Old Concrete Under Thin Overlays

Manuel Trevino
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# Disclaimers



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# Products

This report contains products P1, P2 and P3, according to the Deliverables Table of Project 0-4893. Product P1, Literature Review, is presented in Chapter 2. Product P2, Guidelines for AC and BCO Selection, is presented in Chapter 5, Section 5.2. Product P3, Guidelines for AC Overlay and BCO Design, is presented in Chapter 5, Section 5.3.

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# 1. Introduction

This report, the first pertaining to Research Project 0-4893, "Performance of Old Concrete Under Thin Overlays," documents the initial activities of the project, including literature reviews, inventories of candidate study sections, district contacts, and field work on selected study sections.

## 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 AC overlays. The department started experimenting with bonded concrete overlays (BCO) 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 provided 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, 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 BCO and AC overlays. The sub-objectives are as follows:

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

The objectives of this report are the following:

1. to present the results of review of literature on BCOs and AC overlays
2. to present results on the progress of the fieldwork conducted on the study sections
3. to draft preliminary guidelines and recommendations for the selection of BCOs and AC overlays

## 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 both in 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 is to look for suitable sections in Texas that could be investigated and analyzed by means of fieldwork. The fieldwork is intended to study their performance and assess their adequacy after years of having been constructed. For this purpose, an inventory of both BCO and AC overlay 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 AC overlays 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.

Fieldwork was the next task in the progression of the research activities, which involved visiting the sections and performing a series of tests for various evaluations of the overlays and the old pavements.

With the results of the fieldwork as well as the literature search, recommendations on project selection and design for this type of rehabilitation can be developed. At the present time the fieldwork has not been completed. Therefore, the guidelines in this report are only preliminary. Once all the tasks of the project are completed, final guidelines will be presented in a subsequent report.

Chapter 2 presents the literature synthesis. Chapter 3 is dedicated to the description of the study sections' selection process, as well as the fieldwork performed in such sections. Guidelines and current procedures for BCO and AC overlay design are presented in Chapter 4. Chapter 5 features the conclusions and recommendations up to this stage of this research project.

# 2. Literature Review

## 2.1 Introduction

As a pavement rehabilitation procedure, overlays of portland cement concrete (PCC) and of asphalt concrete (AC) have become a preferred means to restore riding quality characteristics, provide structural improvement, and add service life to the structure. Once a country or a state has constructed a considerable network of roads, its focus turns from new construction to preserving the infrastructure. Overlays serve this purpose ideally because of economical, technical, and practical considerations associated with the nature of overlays. Thereby, an overlay serves not only as a rehabilitation system, but also as a means of protecting and enhancing the infrastructure for the future. Thus, an overlay is an investment.

Both materials, PCC and AC, have proven to be reliable for overlay construction, offering specific advantages and limitations when compared to each other. There is no clear specific guideline as to which material has to be used in any given circumstance, but in general terms, conditions such as structural capacity and functional capacity of the old pavement as well as economics have to be analyzed to make a good engineering decision.

This review of the literature on PCC and AC bonded overlays on continuously reinforced concrete pavement (CRCP) was undertaken from four standpoints, according to the tasks outlined for this project. Those four perspectives, which often overlap, are as follows:

1. review of aspects of bonded concrete overlay (BCO)
2. review of aspects of AC overlay
3. review of project selection strategies
4. review of overlay design methods

## 2.2 Review of BCOs

A general review of BCO aspects is a broad topic. There are, however, a few technical aspects that are of interest for the purpose of this project. Given that the intricacies of project selection and design are addressed in subsequent sections, the most outstanding subjects on BCOs would have to be those related to bonding the overlay to the substrate, such as bonding agents, surface preparation and cleaning, and delaminations, which are critical to the success of any BCO.

The subject of bonding is of paramount importance when dealing with BCOs, because the principle on which this rehabilitation strategy is based states that the BCO and the existing pavement must attain a complete bond, so that their structural behavior is that of a monolithic structure. The added thickness of the BCO with that of the substrate is what provides the enhanced structural capacity to the new composite structure. If the bond between overlay and substrate is not achieved, or not sustained over time, the traffic and environmental loads will impose excessive stresses onto the structure, stresses that a relatively thin overlay is not designed to withstand by itself. Additionally, if delamination occurs, the ensuing increased curling and loading stresses will cause cracks and distresses. As a result, the contribution of the existing structure to the overall strength of the rehabilitated structure is significant.

According to the literature, PCC overlays have been constructed in several states, including California, Illinois, Iowa, Louisiana, New York, Pennsylvania South Dakota, Texas, and Virginia. However, not many have ventured into the construction of thin BCOs on CRCP. Iowa has been a pioneer in BCOs, and Texas has constructed several as well. By far the biggest concerns among state agencies when giving consideration to a BCO project are the occurrence of delaminations and premature failure of the overlay.

In the early 1950s, the Portland Cement Association (PCA) conducted an extensive investigation on the bonding between concrete overlays and old concrete substrates through its Research and Development Laboratories. These early studies, directed by Earl J. Felt (Refs 1 and 2), outlined the fundamentals for attaining a good bond. Felt's research encompassed analyzing many overlays in three different areas: laboratory bond tests, experimental field projects, and existing in-service projects. Surface preparation was identified as the single most important step in the bond strength development process. Good workmanship and quality materials were also recognized as key components of the process. Another finding of the study was that, whenever the old substrate is sound, there is no need for mechanical removal of the concrete surface (Ref 2). He concluded that, in spite of the numerous factors involved in attaining good bond, it is feasible to accomplish it effectively.

In the 1960s R. W. Gillette (Ref 3) studied several BCO projects that were approximately 10 years old. The analysis included overall performance of the overlays as well as factors affecting the bond between old and new concrete. The performance of the BCOs was outstanding. The following summarizes the adequacy and benefits of the BCO utilization:

> *Bonded concrete resurfacing has performed in an excellent manner as a means of strengthening old concrete pavement, providing a new smooth surface, repairing surfaces that have pop-outs, or repairing and patching spalls, scaled areas, etc.*

This study provided important findings, which are discussed herein, on the topic of bonding. These contributions were invaluable for the development of subsequent BCO rehabilitation projects. The study revealed that an adequate bond could be attained with normal construction equipment and materials, without the use of any bonding agents. Core samples from projects indicated that bond strength of 200 psi is adequate for a successful BCO. Whenever delamination occurred, it most likely happened soon after the BCO construction. Free water standing on the pavement surface prior to overlay placement was found to be detrimental to the bond. However, some delaminations were found on almost every project he studied. Most of them occurred in small areas, which did not appear to affect the performance of the BCOs for long-term continuous use. The delaminated areas were located by means of the sounding technique. These findings are consistent with other research projects cited subsequently. On the subject of discontinuities, it was found that existing cracks and joints in the base pavement would reflect through the overlay. Thus, the joints on the overlay should match the existing joints.

### 2.2.1 Application of BCOs in the Unites States

A nationwide trend toward using concrete overlays where traditionally bituminous mixtures were utilized for resurfacing started in the 1970s. Several states implemented concrete overlays on U.S. highways. This was made possible because of the development of new technologies for concrete paving, coinciding with the rise in the cost of asphalt and the variability of the material from region to region. This section contains a brief description of the most relevant findings of some DOTs with regard to the construction of BCOs.

**Iowa**

The Iowa Department of Transportation was the first state agency that experimented with bonded overlays, starting in 1976, and it has constructed many projects ever since. The experience of the Iowa DOT beginning in the mid-1960s using thin, bonded, dense concrete overlays to repair deteriorated bridge decks was later successfully applied to the research and implementation of BCOs. The first of these projects was built in conjunction with the city of Waterloo and the Iowa Concrete Paving Association, on US Highway 20, east of Waterloo. The BCO was 2 inches thick and non-reinforced. A lower than normal water-cement ratio was used in the concrete, with the addition of high range, water-reducing admixtures to provide workability to the mix. The existing substrate was scarified with the Rotomill machine. The aforementioned admixtures were deemed successful, and the bond achieved was excellent. The shear tests at the interface averaged more than 1,000 psi (Ref 4).

This trend of concrete overlay usage continued in the 1980s, aided by external factors such as an emphasis on crude oil conservation and increasingly tighter environmental constraints. Nevertheless, the most persuasive reason encouraging highway engineers and agencies to turn to concrete overlaying rather than bituminous resurfacing was cost. In this decade, pavement engineers started to base their decisions on total-cost economic analysis (i.e., life-cycle costs) which includes initial cost, maintenance and repair costs, and present worth of future rehabilitations during the total life of the structure, including the added life supplied by the rehabilitations (Ref 5). When considering not only the initial cost but all these components of cost, the state transportation agencies realized that concrete overlays may be more economical in the long run than AC overlays.

**Illinois**

Illinois is another state that has constructed its share of BCOs. One of the projects reported in the literature is the construction of a 4-inch-thick BCO located on IH 80 near Moline, Illinois (Ref 6). The original pavement was an 8-inch-thick CRCP built in 1965. Initial testing conducted for the old pavement included falling weight deflectometer (FWD), permeability to chloride, and distress survey. For construction of the BCO, the surface preparation included partial and full-depth patching, asphalt material removal, shot blasting, and sand blasting. The construction procedure was closely monitored, and testing was conducted for the fresh concrete and the pavement.

The BCO was selected as a rehabilitation alternative to AC overlay to increase the old pavement's structural capacity above AC's capabilities. The Illinois Department of Transportation (IDOT) requires that AC overlays for interstate highway resurfacing be 3.25

in. thick, and the observed average life span is around 12 years, which was not considered a long-term solution for Illinois's deteriorating pavements. Thus, BCOs started to be designed for 20 years.

IDOT generally constructs BCOs on a clean rough PCC surface to achieve maximum bond strength. The following observations of the work performed for the construction of the BCO on IH 80 in Moline might apply for any BCO constructed elsewhere:

1. Surface preparation was crucial for an overlay to perform well.
2. Testing showed that bond strength of the overlay did not vary significantly when grout was or was not used as a bonding agent.
3. Grout application slowed down the construction process.
4. Addition of microsilica did not improve the strength of the concrete mixture considerably. Conversely, a rapid water absorption rate resulted in shrinkage cracking, which in turn manifested in delamination problems. Likewise, a greater number of transverse cracks were observed than in the normal concrete mixture.

Recommendations for construction of BCOs include the following:

1. Do not use grout as a bonding enhancement agent.
2. Do not allow shot blasting fines to be piled on the side of the road.
3. Sand blast/shot blast closely to paving operations to keep surface clean. This means removal of foreign materials like oil stains, tire marks, and AC material.

Research conducted by IDOT has shown that edge tensile stresses are reduced 28 percent for 3-inch-thick overlays, and 42 percent for 6-inch-thick overlays when a BCO is used instead of an AC overlay (Ref 6). Bond strength was measured with the guillotine shear test method and in all cases was above the specified 200 psi. No difference was observed when grout was used as bonding agent.

According to IDOT's experience, in monetary terms BCOs are, on average, initially three times more expensive than AC overlays, but their service lives are around 20 years for BCOs and 12 years for AC overlays. For the long-term, life-cycle cost analysis (LCCA) has shown that BCOs are twice as expensive as AC overlays.

A second BCO was constructed on top of another 8-inch-thick CRCP, but this project was built on IH 88 near Erie and the overlay constructed was 3 in. thick. According to observations and testing, this second project has performed much better than the first one and has not developed significant distresses.

For the project built on IH 80, shot blasting was the only surface preparation method used before placing the BCO. For the IH 88 project, two surface preparation methods were used. The eastbound lanes were cold milled and shot blasted, while the westbound lanes were shot blasted only. No grout was used as a bonding agent on the IH 88 project.

Observations have shown that the performance of the section located on IH 80 was poor from the beginning, immediately after construction. In fact, major maintenance tasks were performed just three years following construction. No benefit was observed from either the use of microsilica in the concrete mix or the use of grout as a bonding agent. In contrast, the project on IH 88 showed very good performance with a consistent international roughness index (IRI) for some years. No maintenance work was performed for this overlay at least during the first five years. Based on the performance of these two projects, IDOT does not recommend BCOs for high-volume interstate highways. Likewise, IDOT does not recommend the use of microsilica as an admixture or as a bonding agent.

Research concluded that using microsilica as a bonding agent or an admixture did not add any benefit to the project. Furthermore, it was time consuming to apply as a bonding agent, and concrete strength and bond strength did not improve. Additionally, there was an added cost for using the microsilica. The performance of the concrete overlay with no microsilica was better than the overlay constructed with concrete and microsilica.

For the overlay constructed on IH 88 it was not possible to determine if cold milling plus shot blasting worked better than shot blasting alone. Both approaches showed good results. No maintenance was required after five years of construction.

Additional recommendations by IDOT for BCO construction include using this rehabilitation method only where few major distresses are present in the pavement. Cold milling and shot blasting of the pavement surface seemed to work well for surface preparation. No microsilica or bonding agents are recommended.

### Virginia

A number of BCOs have been constructed in Virginia. A study analyzed two overlays constructed in 1995, placed on top of CRCP to prevent spalling and improve structural adequacy. Mineral admixtures and steel and plastic fibers were used to improve the mechanical properties and durability of the concrete overlays. The overlays were 2 and 4 in. thick.

According to the results obtained from testing, the composite stiffness of the CRCPs was improved with the placement of the overlay (Ref 7). As for bond strength, specimens were tested after one month and then after four years of construction. The results obtained ranked bond strength from good to excellent. All tests indicated that surface preparation during construction was excellent.

The study concluded that concrete overlays can perform successfully. Also, it was recommended that concrete overlays of 2 to 4 inches thick can be used to increase stiffness of CRCPs when the benefits justify the cost, this meaning that the concrete overlay should last at least ten times longer than a conventional asphalt overlay. In another research study 16 concrete overlays were constructed on 28 span bridges in Virginia Beach, Virginia. Thirteen concrete mixtures were used and included a variety of combinations of silica fume, fly ash, slag, latex, corrosion-inhibiting admixtures, shrinkage-reducing admixtures, and fibers. Overlay thicknesses varied between 0.75 and 1.25 in. All the overlays performed well, with the exception of most of the areas adjacent to joints (Ref 8).

A modified version of the Virginia test method (VTM) 92 was used to measure the bond strength of the pavement, and it was classified in five levels:

| | |
|---|---|
| Excellent | ≥ 300 psi |
| Very Good | 250 to 299 psi |
| Good | 200 to 249 psi |
| Fair | 100 to 199 psi |
| Poor | 0 to 99 psi |

For all the overlays, bond strengths were ranked fair to good, with the majority of the failures occurring at the bond interface and in the base concrete close to the bond interface, which indicated that surface preparation could have been better. Bond strengths did not change over a 3-year period and continued to be between 200 and 320 psi.

Prior to construction of the overlays the bridge decks were free of cracks and patches. Later, after the overlays were placed, many of them had minor cracking that was attributed to shrinkage. Delaminations occurred on each side of many joints because they were not adequately prepared. No filler material was placed in the joint. Those problems were repaired, the joints were filled with silicone, and the overlay was patched at joint locations. No additional patching was required in additional locations other than the joints.

The cost of the overlays was around 50 percent higher than the typical overlay project. The bulk of the cost of these overlays was for labor, equipment, mobilization, and traffic control. The materials cost was less than 10 percent of the total cost. It was recommended that this type of overlay be used to extend the life of bridge decks.

Another interesting research study describes the use of special blended cement that was used instead of the common Type I/II cement used in conventional latex-modified concrete (LMC) (Ref 9). The mixing equipment used for this type of mix was similar to that used for conventional concrete mixtures. However, with this special blend contractors have to work faster than usual due to the brief curing period of the concrete, which is around 3 hours instead of 72 hours for conventional concrete.

Tests performed for these mixtures show that roads could be open to traffic in just three hours after pouring concrete. Bond strength and permeability to chloride ions indicated that the constructed overlays were performing satisfactorily and that this special cement mix could be used to extend the life of bridge decks. Likewise, this mix could be used when lane closure time is to be shortened during construction.

During testing and evaluation of the bond strength, it was noticed that failures in the base concrete just below the bond interface typically indicated damage caused by concrete removal operations such as the use of milling machines. Ninety percent of the failures of the bond strength occurred at the base concrete; only a few core samples failed just below the bond line.

The research concluded that LMC can be used for overlays on bridge decks and that the overlays can open to traffic in as early as 3 hours. This type of concrete mix could be used to minimize the inconvenience to users during construction time and to reduce the cost of overlay construction.

### Texas

This section takes a retrospective look at the development of BCOs in Texas, emphasizing the same critical aspects of a successful BCO. It is expected that most of these projects will be the subject of future surveys and investigations for this study. Thus, it is relevant to review some of the noteworthy features of these overlays, many of which include features that have been undertaken from an experimental standpoint. This review presents only the most outstanding characteristics of each project. Further details on these projects can be found in the respective references provided in the following paragraphs.

Most of the BCO research in Texas has been conducted on pavements in the Houston area. Heavy traffic is characteristic of the urban life in this city, which has a sizeable network of concrete pavement roads. The enormous amount of concrete pavement in the Houston area has provided the district with extensive expertise in CRCP rehabilitation with BCOs.

The first BCO project in Texas was implemented in 1983 on IH 610, the urban section known as the South Loop, which is a major freeway encircling downtown Houston. The project was an experimental BCO on a 1,000-ft CRCP segment, developed by the Texas Department of Transportation (TxDOT) under a cooperative highway research program with the Center for Transportation Research (CTR) and the Federal Highway Administration (FHWA). Constructed in July and August of 1983, the BCO has delivered excellent performance and is still in service. It consists of five 200-ft test segments, with several combinations of reinforcement (no reinforcement, welded wire fabric, and steel fibers) and BCO thicknesses (2 and 3 inches), all constructed on the four eastbound lanes between Cullen Blvd. and Calais St. The surface was prepared by cold milling and sand blasting. Portland cement grout was used as a bonding agent for the majority of the section. The existing pavement, built in 1969, consisted of 8-inch-thick CRCP on top of a 6-inch-thick cement-treated subbase. A sounding survey conducted in 1990 on this section revealed some minimal delamination of the overlay (Ref 10). Condition surveys conducted in 1996 showed few distresses on the section and no major performance problems (Ref 11).

The success of this first experience led TxDOT to implement a second BCO project, also on the IH 610 Loop in Houston. The section in question consisted of a 3.5-mile stretch on the northwest part of the loop between East T. C. Jester Blvd. and IH 45. Originally built in the late 1950s, the 8-inch CRCP on a 6-inch-thick cement-stabilized subbase was overlaid with a 4-inch-thick BCO in 1986 (Ref 12).

The project was used to experiment with several variables, including reinforcements, coarse aggregates, bonding agents, and existing pavement conditions (various levels of distress). Within the project limits, ten test subsections were identified, each one including different combinations of the aforementioned variables.

Steel fibers resulted in reduced cracking of the overlay as compared to the sections reinforced with welded wire fabric. During and after construction, some delamination took place between the BCO and the original pavement. Most of the delaminations occurred within the first 24 hours after placement. Delaminations happened in the presence of adverse environmental conditions during overlay placement, such as high evaporation rates and high daily temperature differentials; delaminations were also linked to the sections constructed with siliceous river gravel aggregates, with or without grout. A petrographic study of core samples confirmed the presence of traces of alkali-silica reaction. Even though the delamination was extensive in some segments, it did not continue to deteriorate over time and did not appear to affect performance significantly (Ref 13). A recent condition survey on this section, conducted in November 2000 as part of a CTR project on the condition of several Houston BCOs, revealed that after 15 years of traffic the performance of the BCO has been excellent. Despite the early delamination problem, those areas have not further deteriorated, and the number and severity of distresses is still minimal (Ref 14).

The third BCO rehabilitation in Texas was also implemented on the IH 610 Loop in Houston. In this case, the rehabilitated section was located on the southeast quadrant of the urban interstate loop. Important lessons learned in the IH 610 North project were applied in the construction of this rehabilitation, such as limiting the evaporation rate during construction to less than 0.2 $lb/ft^2$/hour and allowing concrete placement only when the temperature differential expected between placement and the following day is less than 25° F, as adverse environmental conditions surpassing these limits were identified as the primary triggers of the IH 610 North BCO delaminations.

The 8-inch-thick CRCP section is about four miles long, and it includes the aforementioned 1,000-ft experimental BCO constructed in 1983. The approximate project limits are from just east of SH 288 to just west of Telephone Rd. This project started in 1989 and was completed in 1990. It consisted of a 4-inch-thick BCO with two reinforcement types, wire mesh and steel fibers, with limestone as a coarse aggregate. Portland cement grout, epoxy, and latex-modified portland cement grout were used as bonding agents in different sections, and two of the sections were placed with no bonding agent (Refs 10 and 12). The BCO included ten experimental sections, each 400 feet long and four lanes wide, in which several combinations of bonding agents, reinforcements, and surface treatments were implemented.

Substantial early delaminations occurred in some sections of the project where latex-modified portland cement grout was used as bonding agent. The overlay had to be removed from these sections shortly after construction. Apparently, the reason for the delamination was that the grout was being sprayed too far ahead of the paving machine, allowing much of the grout to dry. Before the overlay was placed, the contractor applied new grout over the dried grout, in which the solid latex at the interface behaved as a bond-breaking layer. The BCO was replaced within 30 days, after the sections received the same treatment as the control sections (cold milling and PC grout). Aside from dismissing the use of latex as a bonding agent, another important lesson learned from this BCO project is the finding, on the basis of finite element analyses, that most of the debonding is induced at relatively low stresses (under 50 psi), while the overlay is still new. The experiment's results also emphasized the importance of good surface preparation.

The fourth BCO in Texas was placed on IH 10 in El Paso. This overlay was significantly thicker (6.5 inches) than were previous BCOs in Texas. Also, this project was intended as an expedited BCO. Between Franklin St. Bridge and Missouri St. Bridge in downtown El Paso lies a segment of IH 10 known as the "depressed section" because it goes from four lanes in each direction to three lanes without a decrease in traffic. To say that it is a busy road is an understatement. In a feasibility study, this section was selected for rehabilitation with a BCO in 1993 (Ref 15).

The original section consisted of an 8-inch-thick CRCP built in 1965; 8,000 ft in each direction were overlaid in June and July of 1996. The overlay was planned as an expedited BCO, which means that expedited paving methods were planned to reduce the normal time between placement and the opening of the lanes to traffic. With this, the overall cost of the project would have been reduced (when considering user costs related to traffic delays), and the burden to the public caused by lane closures and detours would have been minimized.

However, despite the planning and research invested in the project, construction mistakes caused the delamination of most of the eastbound and some of the westbound BCO. Shortly after construction, some delaminations were identified during the extraction of core samples from the pavement. Coring and seismic tests confirmed the severity and extension of the delaminations. The comprehensive investigation that followed these events identified the high amount of water lost by the overlay prior to curing compound application as the major cause of the debonding problem. A number of factors contributed to these unusual moisture losses from the concrete. A delay in applying the curing compound, in conjunction with high evaporation rates and inadequate surface preparation, resulted in a stiff, unworkable mix that had lost part of its adhesion. The mix had low water content to begin with, because of the higher strength requirement of an expedited BCO. Then the surface of the existing pavement slab was not dampened before placing the overlay, which caused moisture losses through the bottom of the slab. To prevent these water losses, the substrate surface should have been prepared by spraying water on it before pouring the concrete (Ref 16). This study presents guidelines for expedited BCOs, which include the following:

1. Schedule construction to avoid marginal or severe environmental conditions.
2. The BCO should be at least 12 hours old before traffic is applied, and, in terms of strength, it should have fulfilled one of the following three criteria:
    - splitting tensile strength of at least 500 psi,
    - compressive strength of at least 3,500 psi,
    - bond strength of 175 psi obtained from pull-off tests, or of 350 psi obtained from guillotine tests.
3. Type III cement may be used for construction; otherwise a superplasticizer may be added to the mix.
4. Another type of admixture that may be added is an air entrainment agent to increase workability.
5. The water-cement ratio should not exceed 0.35.

A severely delaminated BCO cannot reach its intended service life, because the delaminations impair its capacity to carry traffic and environmental loads. The BCO had to be repaired by means of injected epoxy. The repair work took three weeks to complete, and falling weight deflectometer (FWD) tests confirmed the success of the remedy. A remarkable fact is that even with the high cost of the repair works added to the original BCO cost, it was still less expensive than a full-depth pavement would have been.

The fifth BCO project in Texas was developed in Houston on Beltway 8, the urban outer loop that surrounds IH 610. The project section, approximately 5.3 miles long, is located between Greenspoint Drive, just east of IH 45, and Aldine Westfield, near Houston Intercontinental Airport. The original 13-inch-thick CRCP structure, built in 1984, experienced a severe spalling problem just a few years after construction. By 1995, when this project was undertaken, the CRCP section was in poor condition. A CTR investigation on that pavement concluded that the spalling was caused by high evaporation rates and high daily temperature differentials that occurred during construction. Deflection tests and core samples were extracted to evaluate the structural integrity of the pavement. The tests showed that the spalling problem was only superficial, and it did not affect the load-carrying capacity of the pavement, making it a good candidate for BCO rehabilitation. Thus, a 2-inch-thick BCO reinforced with steel fibers was designed and placed in 1996 (Ref 11). No problems have been reported on this BCO to date.

The positive experience with the Beltway 8 rehabilitation resulted in a sixth BCO project on IH 610, this time in the west part of the loop. The north end of the project is just south of IH 10 near Memorial Park, and the section extends south for 5.5 miles The original pavement, designed for 20 years, consists of 8 inches of CRCP on 6 inches of cement-stabilized subbase. This section opened to traffic in 1965, and by 1997, when the rehabilitation project started, it had a considerable number of full-depth patches. The extensive repairs that the CRCP had been subjected to over the years prior to the development of this project were due to the heavy traffic volume that this road carries. In 1997 a 5.5-inch-thick BCO was constructed (Ref 17).

The Fort Worth District undertook the seventh BCO project in Texas on IH 30 in the west part of town, near the IH 820 Loop. The original pavement section was built in 1967, consisting of 8 inches of CRCP over a 6-inch layer of lime-stabilized subgrade. This pavement had been overlaid on several occasions with AC because of low skid resistance. A 3.5-inch-thick BCO was placed in the summer of 1998 after the AC overlay was removed. To reduce user costs associated with road closures and delays that happen in high-volume urban highways such as IH 30, an expedited BCO was implemented and traffic was returned to the road about 24 hours after the BCO had been placed. The performance of the overlay was monitored as planned, with condition surveys, in-situ sample testing, deflection measurements, and other tests. In February of 1999, a sounding survey revealed the delamination of most of the eastbound outside lane, whereas the westbound lanes were free of delaminations and remained in good condition. A forensic investigation was conducted with the objective of finding the cause of the delamination problem. The work conducted in the study included the evaluation of the weather conditions at the time of the overlay placement, searching the construction records, and the extraction and testing of cores, including a petrographic analysis, FWD tests, and rolling dynamic deflectometer (RDD) tests.

Those tests showed similar results for both directions; in fact, some of the results of the westbound section, which was not delaminated, were worse than those of the eastbound lanes. The only evidence that led to determining the cause of the eastbound delamination was provided by the petrographic analysis of the cores. The eastbound cores had some debris at the interface between the overlay and the old concrete, whereas the westbound cores were free of debris. Later, meetings with parties involved in the BCO construction revealed that the surface cleaning on the eastbound lanes prior to placement of the BCO was deficient. A great deal of experience was obtained from this project, in which construction mistakes caused the problem, but the concept, appropriateness, and design of an expedited BCO were flawless. The overlay problem areas have been successfully repaired by means of both concrete and asphalt patches, which are performing satisfactorily according to recent surveys.

The aforementioned BCOs in Texas have been designed using the AASTHO 93 and the RPRDS procedures. The designers have found that, because thickness design is not an absolute matter, it is advantageous to not just follow a single approach.

## 2.3 Review of AC Overlays

Just as the subject of delaminations is a critical aspect of BCOs, in the case of AC overlays on rigid pavements, the most critical matters are reflective cracking when the overlay is placed on jointed pavements and stripping and rutting when the overlay is placed on top of CRCP.

### 2.3.1 Reflective Cracking

A reflection crack is initiated by a discontinuity in the underlying layers that disseminates through the AC surface due to movement of the crack. Many state agencies in the U.S. have successfully used AC overlays. Among these, the Arizona Department of Transportation (ADOT) has distinguished itself as a leader in the use of AC overlays on CRCP. One of its studies investigated a large-scale asphalt rubber (AR, also known as asphalt rubber friction course, ARFC) test project in Flagstaff, Arizona, on the very heavily trafficked IH 40 (Ref 18). This section was designed and constructed by ADOT in 1990. The purpose of the test project was to determine whether a relatively thin overlay with AR could reduce reflective cracking. AR is a mixture of 80 percent hot paving-grade asphalt and 20 percent ground tire rubber. This mixture is also commonly referred to as the asphalt rubber wet process, or McDonald process. The overlay project was built on top of a badly cracked concrete pavement. It is reported that the AR overlay has performed well. After nine years of service the overlay was still nearly crack-free, with good ride, virtually no rutting or maintenance, and good skid resistance. This could be attributed to the AR as well as to the good structural quality of the CRCP in which the cracking might have just been superficial.

The ADOT, in cooperation with the Federal Highway Administration and private industry, designed and constructed numerous experimental paving projects from 1993 through 2001.

### 2.3.2 Rutting

A potential problem with AC overlays is the rutting of the overlay itself. Rutting is a surface depression in the pavement's wheel path due to the traffic loads. Pavement uplift may occur along the sides of the rut. However, in many instances ruts are noticeable only after a rainfall, when the wheel paths are filled with water. Rutting stems from the permanent deformation in any of the pavement layers or the subgrade and is usually caused by the consolidation or lateral movement of the materials due to traffic loads. Rutting can be caused by plastic movement of the asphalt mixing in hot weather or by inadequate compaction during construction. Significant rutting can lead to major structural failures and hydroplaning potential. Rutting is measured in square feet or square meters of surface area for a given severity level based on rut depth.

A research study published by the Transportation Research Board (Ref 19) focused on AC overlay behavior under the traffic and environmental conditions of Texas by using the rutting history data on AC overlays on rigid pavement collected by the Center for Transportation Research (CTR). The analysis of the pavement indicated that overlay thickness was one of the significant predictors of rutting in overlays. The study indicates that rut depth is a function of the permanent strain and the layer thickness, and that thicker overlays would rut more than thinner overlays of similar materials. The age of the overlays was not very significant according to this report. This might be attributed to the limited history of rutting data available at that time. The geographic location of the overlaid sections had a significant effect on the rutting as well. Obviously, the construction materials and other related items, which may vary by location, influenced the performance of overlays.

### 2.3.3 Bonding

There are several techniques used to enhance bond between the AC overlay and the existing concrete pavement. Among these the most common are power brooming, power brooming with air blast, cement and water grouting, milling, and applying emulsion tack coat. The last two techniques, milling and application of tack coat, have been found to be the most beneficial in improving bonding.

A strong tack coat guarantees the bond between pavement layers to transfer radial tensile and shear stresses from the overlay onto the entire pavement structure. Insufficient bond strength causes slippage cracking, debonding, and distortion, and reduces the structural capacity and at the same time, concentrates tensile stresses at the bottom of the wearing course, the overlay. Distortion, which results from asphalt layer instability, can take a number of different manifestations, such as shoving, pushing, corrugation, rutting, etc. The development of slippage cracks, crescent or half-moon shaped, is also a result of poor interfacial bond. The major reasons identified for debonding are (Ref 20):

- poor condition of the old pavement—presence of debris, dust, oil, rubber, dirt, water, or any other non-adhesive materials
- use of excessive or inadequate tack coat, or a non-uniform application of it
- highly polished aggregate on the existing pavement, which may be water-sensitive, or use of a tack coat that may not be compatible with the polished aggregates
- use of mixture having a high sand content, especially with rounded particles
- use of improper construction technique and lack of adequate degree of compaction of the AC layer

The debonding may be caused by any one or by a combination of any of the problems listed above. Additionally, the following conditions may contribute to the occurrence of delaminations:

- improper consideration of temperature and field conditions
- excessive load repetitions and dynamic impact loading
- a very thin surface layer thickness

A laboratory study (Ref 21) conducted in Louisiana evaluated the practice of using tack coats and tested their optimum application rates. It examined various tack coats and test temperatures as well. The tack coats included two types of performance-graded AC (PG64-22 and PG 76-22M) and four emulsions—CRS-2P (Cationic Rapid Setting), SS-1, CSS-1, and SS-1h. A statistical analysis of the results indicated that CRS-2P provided significantly higher interface shear strength and was therefore identified as the best performer. Its optimum rate of application was found to be 0.02 gal/yd$^2$. At the lower testing temperature, increasing the application rate resulted in a decrease in interface shear strength. However, at the higher testing temperature, there was no variation of the strength obtained at different application rates. Even the tack coat that performed best during this study, the CRS-2P, which was applied at the optimum rate, only provided 83 percent of the monolithic mixture shear strength. This implies that the use of layers introduces weak zones at the interface, as compared to a non-overlaid pavement (single layer).

The Bryan District reports having success applying hot rubber seal to improve the bonding. AC20-5TR has also been used, as well as tack between the seal coat and the overlay.

New technologies have enabled the development of new mixes to serve as tack coats (Ref 22). The improvement of the rheological properties of bitumens and residual binders provided by the addition of a polymer has resulted in a growing interest in polymer-modified bitumen emulsions. Understanding of the manufacturing process has enabled formulation of polymer-modified bitumen emulsions for various road applications, such as tack coats. One of the major advantages of these emulsions relative to unmodified bitumen emulsions is their applicability as tack coats, providing better interface shear strength, improving the distribution of the stresses, and increasing the resistance to deformation.

Finally, TxDOT Project 0-4398 included a study on AC mixtures and tack coats. The goals of the AC mixture and tack coats experiment were to evaluate the rutting resistance of asphalt mixtures for use as overlays on CRCP and to investigate the interface shear strength of tack coats. The tests indicate that AC mixes with siliceous gravel aggregates delivered the poorer performances when used as overlays. It was recommended that the Superpave, CMHB, and Type C mixes be considered for use as overlays on CRCP pavements. Siliceous gravel aggregates should not be used with these mixes. However, the Houston District reports that Type C mixes segregate badly, and that they have not been able to design a CMHB that works with the available local aggregates.

### 2.3.4 Stripping and Other Moisture-Related Problems

Moisture intrusion has been identified as a particularly harmful occurrence triggering a number of effects that result in AC overlay failure. The primary source of moisture in pavement structures is rainwater, which infiltrates the pavement. Moisture can also enter a pavement from subsurface sources such as:

- cracks in the surface that have not been maintained
- penetration through the surface due to poor density
- poor maintenance, e.g., grass and plants growing on the shoulder acting as a barricade to drainage

Moisture may also enter a pavement from subsurface flow such as from a spring:

- vertical capillary movement of moisture from the subsurface water table
- lateral seepage from high water in a clogged ditch that has not been properly maintained

Stripping is the physical separation of the asphalt cement and aggregate produced by the loss of adhesion between the asphalt cement and aggregate surface, primarily due to the presence of moisture. This is often due to incompatibility between the aggregates and the asphalt. Softening is a general loss of stability of a mixture that is caused by a loss of cohesion due to moisture within the asphalt. These two basic kinds of moisture-induced damage produce various forms of distress at the surface of a flexible pavement, such as shoving, rutting, or bleeding (Ref 23).

The extent of damage caused by moisture depends on the source and the volume of the water. Pavements are exposed to different levels of moisture damage, with the severity of the damage dependent on how quickly the pavement structure drains after experiencing rainwater infiltration. For a given amount of infiltration, drainage time is a function of the type of stone, the gradation of the base, the thickness of the base, the contamination of the base by subgrade intrusion, and the slope of the base layer (Ref 24).

### 2.3.5 Texas Experience

Thin AC overlays on CRCP have been used frequently in Texas with mixed results. Some districts have had good experiences with these overlays, while others have reported premature failure of their overlays. Debonding is often cited as the primary cause of early failure, but slippage cracks, stripping, and softening of the asphalt are occasional problems. Two research projects developed in Texas on AC overlays on CRCP are showcased in this review. Both present interesting findings in terms of the performance of these overlays.

The first one of these projects reports the findings on the long-term performance of the experimental CRCP on IH 45 in Walker County (Ref 25). This section, which is part of the major thoroughfare connecting Houston and Dallas, was the subject of numerous studies. In 1969 an experimental AC overlay of various thicknesses was constructed. Overlays of 2, 4, and 6 inches were placed. Two areas of the investigation are of interest for this project: the variation of deflections with overlay thickness and the reduction of reflective cracking with overlay thickness. From the deflection measurements taken before and after the AC overlay was placed, it was found that there was a deflection reduction of approximately 5 percent for each inch of overlay. In terms of reflective cracking, the condition of the pavement was assessed 5 years after the overlay was constructed, and a percentage of reflective cracking versus overlay thickness was calculated. A very sharp decrease in reflective cracking for thicker overlays was observed. On average, the 2-inch-thick overlay had 20.9 percent reflective cracking, compared to 4.1 percent for the 4-inch-thick overlay, and 1 percent for the 6-inch-thick overlay.

The second research project, conducted on IH 30 in Bowie County (Ref 26), illustrated the achievement of one of the primary benefits of an AC overlay, the reduction of dynamic impact loading. This 10-mile, 8-inch-thick CRCP slab on a cement-treated subbase section was originally constructed in 1972. In April of 1986, an AC overlay was placed to reduce the long wavelength roughness of the CRCP surface caused by swelling clay movements, which produced significant dynamic impact loadings of heavy trucks moving at high speeds, which, in turn, increased the incidence of failures. With the new overlay, the smoother pavement experienced a reduction in the rate of failure development. The study demonstrated that, while the AC overlay increases the service life of the pavement structure by delaying its rate of deterioration, its structural contribution is negligible, and it does little to reverse the development of fatigue in the underlying strata. As an added benefit, it reduces the environmental deterioration of the PCC pavement acting as a protective layer.

Another important finding from this study is that the overlay preserved the integrity of the CRCP as revealed by the back-calculated moduli of elasticity from deflections taken on the overlaid structure.

## 2.4 Review of Overlay Project Selection

Project selection refers to the stage of a project in which a series of decisions are made to assess what alternative to utilize, both from a technical and an economical standpoint. The first decision to be made is whether a pavement needs a rehabilitation of some sort. A pavement may look damaged to the user, but for the engineer, the decision must be based on measurable facts. The best investment at this stage is an investment in information; as much information as possible will provide the design engineer proper knowledge of the deteriorated pavement in order to address the problems appropriately (Ref 27). This reference elaborates on four basic types of data, which are necessary to decide on a rehabilitation alternative:

1. design data
2. traffic data
3. environmental data
4. distress/condition data

Once this information is gathered by means of surveys and other searches, Voigt and Knutson (Ref 27) recommend addressing the following key questions in the ensuing evaluation:

1. Is the pavement structurally adequate for future traffic loadings?
2. Have any of the pavement layer materials deteriorated?
3. Are the drainage conditions adequate?
4. Is the pavement functionally adequate? (ride quality, skid resistance)
5. Is the performance of the pavement uniform, or does it vary between lanes or directions?
6. Has past maintenance been applied or ignored? Could this have contributed to the present condition?

To answer these questions, those factors must be measured and determined from actual testing.

Overlays are just part of the rehabilitation spectrum. Rehabilitation encompasses a series of alternatives, which include overlays as well as other techniques. The American

Association of State Highway and Transportation Officials (AASHTO) Guide (Ref 28) presents a comprehensive list of options in this regard. For CRCP, the subject of this study, the overlay options include BCO, AC, and unbonded concrete overlays. A basic understanding when selecting an option is that there is a general relationship between the existing pavement condition and the required type of rehabilitation. As pavements reach more advanced stages of deterioration, more substantial rehabilitation procedures are necessary.

The ultimate basis for choosing the preferred strategy, once several appropriate options have been considered, is cost. A cost analysis should account for all items, including estimates for scheduled maintenance and repairs over the life of the alternative. In the past, many agencies have based their decision making on initial cost. This, however, did not take into account the long-term performance of pavement alternatives and the effects that economic forces may have on the cost of these alternatives (Ref 27).

## 2.5 Review of Overlay Design

This section is divided in two subsections, each one summarizing the design aspects of each type of overlay studied in this project.

### 2.5.1 BCO Design

The foremost structural feature that differentiates a BCO from other rehabilitation concepts is that, by definition, the overlay behaves as a single unit in conjunction with the existing pavement. Therefore, the structural capacity remaining in the existing substrate is fully utilized. As such, it is accounted for in the design equations, and this contributes to reduce the thickness of the overlay required. This is only attainable if the bond between overlay and substrate is achieved and maintained. This principle is the basis for the most commonly utilized overlay design methods, and is known as the structural deficiency approach to overlay design. It assumes that the overlay satisfies a deficiency between the structural capacity required to support traffic over some future design period, and the structural capacity of the existing pavement.

Some of the design methods for BCO include the Corps of Engineers, the PCA, and the AASHTO. The U.S. Corps of Engineers procedure was originally devised for the design of PCC overlays over PCC airfield runways and taxiways. It was developed using full-scale accelerated test tracks and uses the structural deficiency approach previously described.

The PCA method consists in designing an overlay system that is structurally equivalent to a new full-depth pavement placed on the same subbase and subgrade. Unlike the Corps of Engineers procedure, it uses an evaluation of the existing pavement by means of condition surveys, deflection tests, and in-situ sample testing to take its condition into consideration in the design. The design basis is the analysis of the stresses at the edge of the pavement (Ref 29). If the PCA method is used, then it is assumed that the pavement can withstand an infinite number of applications, as long as those occur under the stress limit established by the method, which is based on plain concrete fatigue tests.

The AASHTO method, the most widely used design procedure among state agencies, uses the aforementioned structural deficiency principle. It is mostly an empirical method, since the design equations for the method were derived from regression analyses performed on the AASHO Road Test data, but it includes a mechanistic part, in the determination of stresses and strains. Like the PCA method, the AASHTO procedure advocates conducting a comprehensive evaluation of the existing pavement conditions, and applying the results as input design parameters for the BCO.

### 2.5.2 AC Overlay Design

The most commonly used approach to structural design of asphalt overlays of concrete pavements is the structural deficiency approach followed by AASHTO. Besides the AASHTO method, TxDOT uses the FPS (Flexible Pavement Design System) 19 procedure, developed by the Texas Transportation Institute (TTI). This is a mechanistic method, which uses back-calculated elastic moduli of pavement layer materials obtained from falling weight deflectometer (FWD) deflections; the main design parameter is the surface curvature index (SCI) computed at the midpoint of a set of dual tires loaded to 9,000 lbs (Ref 30). A computer program has been developed for this design system, and one of the available options is AC overlay design.

## 2.6 Summary

The main differences in performance between thin BCOs and thin AC overlays is that BCOs can usually provide a structural enhancement, whereas thin AC overlays are usually constructed to remedy functional problems, such as riding quality and skid resistance. Structural contributions of thin AC overlays are not significant. AC overlays may reduce dynamic impact loading as a consequence of providing a smoother ride. Likewise, AC overlays are sometimes used to put back other more costly rehabilitation procedures that can be performed at a later time when funding becomes available.

According to the literature findings there is a consensus that BCOs have a longer service life than AC overlays and require less maintenance, but on the other hand their initial cost is higher. The typical range for the service life for a thin AC overlay is between 4 and 8 years, whereas a BCO may last between 15 and 25 years. With regard to costs, it is believed that BCOs could be twice as expensive as AC overlays in the long term. However, the added benefit to the preservation of the highway investment could well justify this expense. Likewise, it has been observed that rather than constructing very thin BCOs (e.g., 1.5 to 2 inches thick) calculated with current design procedures, constructing thicker overlays could greatly enhance the structural capacity of the old concrete pavement at a very minimal increase in cost per inch of thickness of concrete. In other words, labor and mobilization costs have a greater impact on the overall cost of an overlay project as compared to the materials cost that such a thickness increase represents.

It has been concluded that neither a thin BCO nor a thin AC overlay are feasible rehabilitation alternatives when the conditions of the existing pavement (extensive slab cracking or durability problems) dictate substantial removal and replacement, or when durability problems exist. The sensitivity of a thin overlay to underlying pavement condition dictates that exhaustive repair of the existing pavement is necessary before the placement of the overlay to prevent the reflection of distresses in the new layer.

Finally, regarding construction practices, it was observed that in order for any bonded overlay to be successful, the preparation and cleaning procedures of the existing pavement surface are fundamental. It has been observed that the use of bond enhancing agents and admixtures in BCOs does not necessarily have a positive impact on the performance of the reinforced pavement structure. In fact, the use of such materials could be detrimental if used without looking into previous experiences. Furthermore, it has been shown that delaminations occur at very early ages while the concrete is still gaining strength; therefore, in order to minimize the potential for delaminations, the volume changes in concrete need to be tightly controlled by providing prompt curing and minimizing concrete temperature variations, as well as using coarse aggregates with a low thermal coefficient.

# 3. BCO and AC Overlay Study Sections

## 3.1 Introduction

This chapter presents the work done with the sections that are being analyzed as part of this research. 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. This is covered in the first section of this chapter. The second section presents the field work conducted on those sections—first the BCO sections followed by the AC overlay projects.

The purpose of conducting field work on several overlay sections of different characteristics, such as materials, age, thickness, and so forth, is to evaluate their performance, as manifested in condition survey results, deflection tests, strengths, and moduli. Subsequently, the influence of those variables in the overlays can be linked to the performance results to assess their appropriateness and usefulness, and based upon this analysis, guidelines and recommendations on those variables can be made.

## 3.2 Study Sections Selection Approach

### 3.2.1 Design Factorial

For the BCO sections the factorial design was constrained by the limited number of overlays of this type constructed; no more than twenty BCOs have been constructed in Texas in the last two decades. A list of the identified BCO projects in Texas is presented in Table 3.1. Additionally, it should be noted that the scope of this research project includes only thin overlays constructed over old CRCP. The four projects that have been investigated so far are located in the Houston, Fort Worth, and Wichita Falls Districts. The final BCO design factorial for this study is presented in Table 3.2. This factorial includes important variables that have an effect in the performance of BCOs. The variables included in the factorial are age, thickness, use of reinforcement fibers, concrete coarse aggregate type, and BCO placement season.

*Table 3.1 Identified BCO projects in Texas*

| Number | Project | District | Location | Year | Thickness |
|---|---|---|---|---|---|
| 1 | IH 610 South | Houston | Between Cullen Blvd. and Calais St., Houston | 1983 | 2 and 3 in. |
| 2 | IH 610 North | Houston | Between East T. C. Jester Blvd. and IH 45, Houston | 1986 | 4 in. |
| 3 | IH 610 South | Houston | Between Calais St. and M. L. King St., Houston | 1989-90 | 4 in. |
| 4 | IH 10 | El Paso | Between Franklin St. Bridge and Missouri St. Bridge, El Paso | 1996 | 6.5 in. [1] |
| 5 | Beltway 8 | Houston | Between Greenspoint Drive and Aldine Westfield, Houston | 1996 | 2 in. |
| 6 | IH 30 | Fort Worth | Between IH 820 and Las Vegas Trail, Fort Worth | 1998 | 3.5 in. |
| 7 | IH 610 South | Houston | South of IH 10, near Memorial Park, Houston | 1997 | 5.5 in. [1] |
| 8 | IH 10 [2] | Houston | Between IH 45 and Wayside Dr., Houston | 1998 | 6-8 in. [1] |
| 9 | IH 610NE [2] | Houston | Between IH 45 to IH 10E, Houston | 1998 | 4-8.5 in. [1] |
| 10 | IH 610SE [2] | Houston | Between IH 10E and IH 45 South, Houston | 1998 | 6.5-7.5 in. [1] |
| 11 | SH146 [2] | Houston | Between Chambers County line and North Main, Baytown | 1998 | 3 in. |
| 12 | SH225 [2] | Houston | IH 610 to Redbluff, Houston | 1998 | 3 in. |
| 13 | Beltway 8 | Houston | BW-8 West, frontage road, near US 59 S | 1998 | 2 in. |
| 14 | Beltway 8 | Houston | BW-8 West, frontage road, near US 59 S | 2000 | 2 in. |
| 15 | US281 | Wichita Falls | Between Archer and Wichita County line and Holliday Creek Bridge | 2002 | 4 in. |
| 16 | IH 610 South | Houston | Frontage road | 2003 | 2 in. |

[1] These are not thin BCOs

*Table 3.2 Final factorial design for BCO data collection*

| **Overlay Age (years)** | | | | Less than 15 | | | | | | More than 15 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Overlay Thickness (in.)** | | | | 2 | | 2~4 | | >4 | | 2 | | 2~4 | | >4 | |
| **Steel/PP Fibers Reinforcement** | | | | Yes | No | Yes | No | Yes | No | Yes | No | Yes | No | Yes | No |
| **Coarse Aggregate Type** | LS | **Season of Placement** | Hot | 5,13,14,16 | | | 6,15 | | 4 | | | | 3 | | |
| | | | Cold | | | | | | | | | 3 | 2,3 | | |
| | SRG | **Season of Placement** | Hot | | | | | | | | | 1 | 1 | | |
| | | | Cold | | | | | | | | | 2 | 2 | | |

In a similar way, the factorial design for the AC overlays was prepared keeping in mind one of the main objectives of this project, which is the evaluation of the performance of old CRCP constructed under the overlay, either AC or BCO. Similar to BCOs, the variables included in the factorial were geographic location, age, thickness, mixture type, and surface treatment. Table 3.3 presents the AC overlay sections that were identified for this project. Table 3.4 displays the factorial used for AC overlay data collection.

*Table 3.3 AC overlay sections considered for investigation*

| Number | Project | District | County | Location |
|---|---|---|---|---|
| 1 | IH-20 | Fort Worth | Tarrant | From IH 820 to Dallas Co. line |
| 2 | IH-20 | Fort Worth | Palo Pinto | West of Weatherford |
| 3 | IH-20 | Fort Worth | Parker | South of Weatherford |
| 4 | IH-35 | Fort Worth | Johnson | From Burleson to Alvarado |
| 5 | SH-121 | Fort Worth | Tarrant | From IH-35 to IH-820 |
| 6 | US 287 | W. Falls | Wichita | From BU 287 H to Harmony Rd NB lane |
| 7 | IH-20 | Dallas | Dallas | From Co. line to Robinson, SW Dallas |
| 8 | US 175 | Dallas | Dallas | E & W lanes - From Woody Rd. to Seagoville Rd. |
| 9 | IH-635 | Dallas | Dallas | IH-635 - LBJ freeway. NB, SB, shoulder and ramps |
| 10 | IH-636 | Dallas | Dallas | IH-635 - LBJ freeway. NB, SB, shoulder and ramps |
| 11 | IH-10 | Yoakum | Gonzalez | From .135 mi. West of US 90 to Fayette Co. Line |
| 12 | IH-10 | Yoakum | Gonzalez | From Gonzalez Co. Line to 0.056 mi. East of FM 609 |
| 13 | IH-10 | Yoakum | Fayette | US 77 overpass to Colorado Co. Line |
| 14 | IH-10 | Yoakum | Fayette | Fayette Co. Line to Hatterman Lane |
| 15 | FM 1875 | Houston | Fort Bend | From US 90A to LP 540 (CSJ 0527-05-010) |
| 16 | FM 1952 | Houston | Fort Bend | CSJ 0527-01-043 |
| 17 | FM 2759 | Houston | Fort Bend | From FM 762 to Thompsons (CSJ 2817-01-007) |
| 18 | FM 2977 | Houston | Fort Bend | From FM 762 to FM 361 (CSJ 3048-01-011) |
| 19 | SH 6 | Houston | Fort Bend | From Harris Co. Line to US 90 A (CSJ 1685-06-027) |
| 20 | IH 45 | Houston | Galveston | From South of Texas City WYE to Harris Co. Line |
| 21 | FM 1266 | Houston | Galveston | From FM 517 to FM 518 (CSJ 0976-05-022) |
| 22 | FM 1764 | Houston | Galveston | From IH 45 to SH 3 (CSJ 1607-01-048) |
| 23 | FM 1765 | Houston | Galveston | From SH 146 to end of maintenance (CSJ 0686-01-043) |
| 24 | SH 146 | Houston | Galveston | From FM 518 to FM 1764 (CSJ 0389-06-093) |
| 25 | SH 146 | Houston | Galveston | From FM 519 to IH 45 (CSJ 0389-07-032) |
| 26 | FM 521 | Houston | Harris | South of Holmes Rd to South of Anderson Rd |
| 27 | SH 288 | Houston | Harris | South of Reed Rd to North of Sims Bayou (0598-01-073) |
| 28 | IH 45 | Houston | Montgomery | From LP 336 to FM 1097 (CSJ 0675-08-090) |
| 29 | SH 242 | Houston | Montgomery | From San Jacinto River to US 59 |
| 30 | SH6 | Bryan | Brazos | CSJ 0049-12-044 |

*Table 3.4 Final factorial design for AC overlay data collection*

| Geographic Location | 1 | | | | | | 2 | | | | | | 3 | | | | | | 4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Age (yr) | < 5 | | 5-10 | | > 10 | | < 5 | | 5-10 | | > 10 | | < 5 | | 5-10 | | > 10 | | < 5 | | 5-10 | | > 10 | |
| Mixture Type / Thickness (in.) | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 | < 4 | ≥4 |
| Conventional | 7, 8 | | | | | | 11,12, 13,14 | | | | | | | | | | | | 1, 3 | | 2, 4 | | 5 | |
| Interface Treatment | 9,10 | | | | | | | | | | | | | | | | | | | 6 | | | | |

Geographic Locations:

1 - Wet -Freeze
2 - Wet - No Freeze
3 - Dry - No Freeze
4 - Dry - Freeze

### 3.2.2 District Contacts

Several TxDOT districts were contacted to obtain candidate sections to be included in this study. The majority of the districts provided valuable information. Districts contacted included Houston, El Paso, Fort Worth, Wichita Falls, Yoakum, Dallas, Bryan, and San Antonio. As shown in Table 3.3, most of the projects that were selected for analysis fall in a few cells of the factorial, mainly because the age of the AC overlays is lower than 5 years in most of the cases and the thickness of the selected overlays is less than 4 inches.

## 3.3 Evaluation and Analysis of Results of BCOs

As mentioned before, four BCO projects have been investigated, two of them in Houston, one in Fort Worth, and one in Wichita Falls. The fieldwork consisted of a visual condition survey, sounding tests for delaminations, deflection testing with FWD, and extraction of core samples for materials evaluation. The following tests were conducted on the cores:

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

Not all the tests were conducted on the cores; the appropriateness of each test was evaluated according to the appearance and condition of each sample. The subsequent sections are dedicated to the detailed description of the work conducted in each of the pavement study sections and their results.

### 3.3.1 IH 610 S in Houston

The first BCO section that was surveyed was the eastbound frontage road of the loop IH 610 south of downtown Houston, near Reliant Stadium. The field work was conducted on April 20, 2005, on the segment that lies between Almeda Rd. and SH 288. Traffic on this segment during the time of the survey was sparse and consisted mainly of passenger cars. The eastbound frontage road in this area consists of two lanes with adjacent curbs—no shoulders. Several driveways for local businesses are present, which posed some minor limitations for traffic control duties. A general view of the section in question is presented in Figure 3.1.

*Figure 3.1 View of the segment on IH 610 south frontage road*

The pavement in this section consists of a 2-inch-thick BCO with fiber reinforcement placed in May 2003, on top of 6-inch-thick CRCP constructed in 1965. The coarse aggregate for the overlay is limestone, whereas for the old CRCP is SRG.

**Results**

The general appearance of the section is good. The photograph in Figure 3.2 shows a view of the overlay in good condition, which was typical for most of the segment investigated. That image also shows the location of one of the six core samples extracted.

*Figure 3.2    Area in good condition, indicating the location of a core sample*

However, there are some delaminated areas surrounding working cracks and joints that are reflected from the original CRCP. Some other distresses observed occurred where a transverse crack in the curb has propagated to the adjacent overlay as a result of a lack of a separation layer between the curb and the overlay, such as the one illustrated in Figure 3.3, and, in more detail, in Figure 3.4 .

*Figure 3.3    Propagation of transverse crack from the curb to the overlay*

*Figure 3.4 Detail of crack propagation from curb to overlay*

Another common occurrence regarding distresses is the development of spalled areas around working cracks and joints, which have reflected from the old CRCP, such as the one illustrated in Figure 3.5. The reflective characteristic of these cracks is evident in Figure 3.6, which shows the drilled hole after the sample extraction and the crack originated from the old CRCP.

*Figure 3.5 Spalled crack*

*Figure 3.6 Crack reflected from old CRCP to the BCO*

***Deflection Testing***

Figure 3.7 shows the results of the deflection tests, along with the crack spacing, crack, spall, and core locations. These deflections correspond to the first sensor of the FWD and to the second drop, which corresponds to a load of about 9,000 lb. It can be seen that the first segment of the surveyed section was not tested for deflections or coring, and this was because of traffic control constraints. However, the visual survey was conducted on the entirety of the section. A closer view of that plot focusing on the second segment is presented in Figure 3.8.

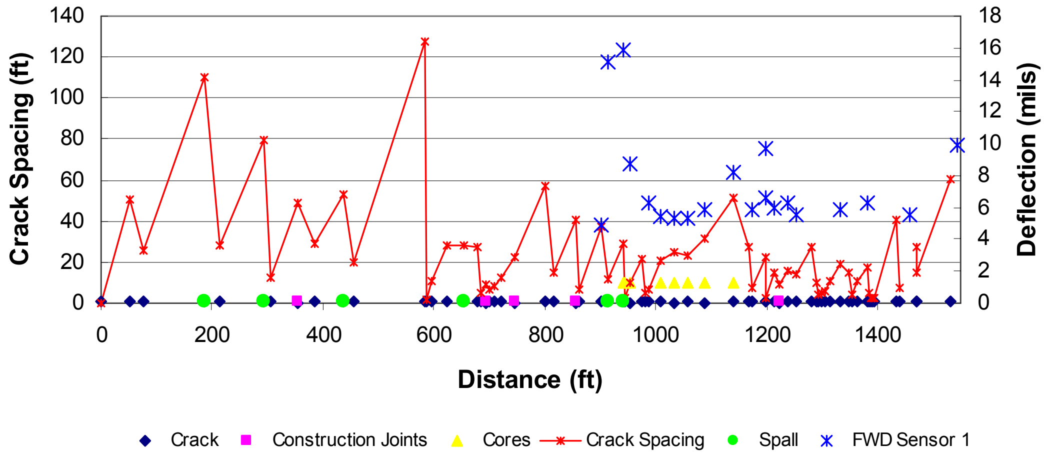


*Figure 3.7 Core locations, condition survey, and deflection testing results*

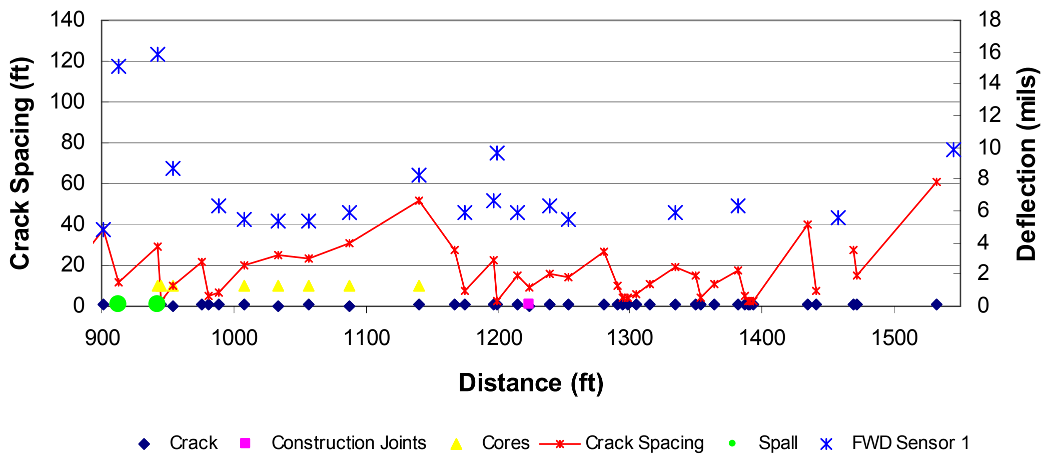


*Figure 3.8 Detailed plot of FWD testing*

The deflections, except for a few outliers that correspond to the spalled cracks were generally low and fairly uniform. The average for the Sensor 1 deflections, using the second drop of the FWD was 7.4 mils, with a standard deviation of 3.1 mils and a coefficient of variation of 42 percent.

Six cores were extracted, from areas in both good and distressed condition. Some of the cores with spalls or delaminations broke during the drilling process, such as the one shown in Figure 3.9.

*Figure 3.9 Delaminated portion of BCO in a core sample broken during drilling operation*

### 3.3.2 IH 30 in Fort Worth

The researchers visited a BCO section located on IH 30 in Fort Worth, between Loop 820 and Las Vegas Trail, in the west part of town. The concrete pavement under study was originally built in 1967 and consists of a 6½-inch-thick CRCP. The section was overlaid with a 3½-inch-thick BCO placed in June and July of 1998. At this stage, only the eastbound lanes were chosen for testing, because even though both directions were constructed as part of the same overlay project, it was part of the eastbound direction that experienced delaminations shortly after construction. Further results of investigation of the westbound lanes will be discussed in upcoming reports.

Field tasks were conducted on May 18, 2005. Data collected included visual inspection of the pavement, sounding testing, and selection of representative locations for FWD testing and core extraction.

#### Results

All field testing was conducted and no contingencies were experienced. The District Pavement Engineer in Fort Worth and Project Director, Andrew Wimsatt, was present during the fieldwork and helped to coordinate all of the tasks. Due to the high traffic volume, traffic control was provided for a stretch of about one mile. The testing was conducted on the outside lane of the main lanes. Traffic control equipment, coring rig, and FWD were provided by TxDOT. A general view of the section under study is presented in Figure 3.10.


*Figure 3.10 Panoramic view of CRCP on IH 30 eastbound*

As shown in Figure 3.11, the coarse aggregate for the old CRCP is a silica-based gravel, while the aggregate used for the overlay was limestone. Five 6-inch-diameter cores were extracted from the pavement, three of which came out unbonded, and two more came out bonded. Figure 3.11 shows one of the samples that came out intact, demonstrating the good bond between the old CRCP and the BCO.


*Figure 3.11 Core obtained from IH 30 in Fort Worth*

The visual inspection conducted for this section showed that the pavement was in fair to good condition, with no major distresses. Only transverse cracks, various AC patches, and very few spalls were found. Figure 3.12 shows one of the AC patches found in the section. It is important to note that the condition of all the patches was very good both visually and structurally, as demonstrated by deflection values measured at those locations. No significant difference was found between deflections measured at AC patches and at the BCO, as described in the following section.


*Figure 3.12 AC patch found in pavement section under study*

***Deflection Testing***

As a general procedure in all the projects, sounding testing was conducted along the test section to detect the presence of delaminations. For this project, only isolated points were found delaminated. Next, the FWD was used to measure deflections at specific locations. In this particular case, the results of the FWD showed that the mean deflection of the pavement measured by Sensor 1 was 3.2 mils for a load of approximately 9,000 lbs, with a standard deviation of 1.6 mils and a coefficient of variation of 50.4 percent. Several deflection locations were picked on AC patches, like the one shown in Figure 3.12. If those deflections were eliminated from the previous calculations, the average deflection would be 3.1 mils, the standard deviation 1.4 mils, and the coefficient of variation 45 percent. These numbers show that the deflections did not vary too much when taken on AC patches. Figure 3.13 shows the deflection profile.

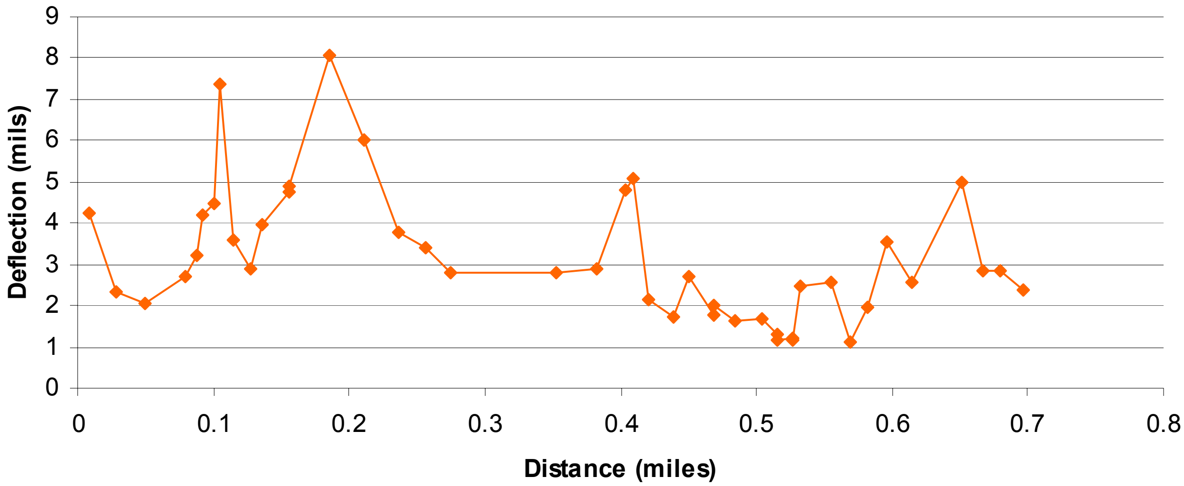


*Figure 3.13 Deflection profile of test section on IH 30 in Fort Worth*

Figure 3.14 shows the FWD test being conducted in one of the most distressed areas of the pavement section studied. Figure 3.15 presents another view of the FWD test. In this image, it can be seen that when the weight of the testing equipment was dropped, water came out through the pavement cracks from the bottom of the slab along with fines from the subbase layer underneath, indicating that the subbase/subgrade is saturated and pumping has occurred.


*Figure 3.14 FWD test of a distressed area of the pavement*


*Figure 3.15 Pumping effect caused by FWD testing in a crack*

The compressive and splitting tensile concrete strengths obtained from core samples were found to be within acceptable limits. The strength and modulus of elasticity values obtained from the testing are presented in Section 3.3.5.

### 3.3.3 Beltway 8 in Houston

CTR researchers visited the BCO section located on the frontage road of Beltway 8 on May 25, 2005. J. A. Tony Yrigoyen, engineer at TxDOT's Waller/West Harris Area Office, guided CTR staff to the site and showed them the pavement section. The original CRCP was 13 inches thick, from which 2 inches were milled off at the time the 2-inch-thick BCO was placed in May 2003. The section in question extends from Westheimer to US 59S. There are actually two different sections within those project limits, and this is because two different contractors participated during the construction of the project. One contractor used tining to provide skid resistance texture to the pavement, while the second contractor used carpet drag only.

Due to maintenance activities being conducted on the southbound roadway, testing was only performed for the northbound lanes. Although traffic volume was not critical during the inspection and testing of the pavement, the Houston District could not provide traffic control for the entire segment that the research team wanted to survey. Thus, TxDOT provided traffic control for a short section at a time, no longer than half a mile, and then moved traffic cones ahead once the work was finished on the segment. This traffic control limitation caused field tasks to advance at a slow pace.

**Results**

The visual inspection performed for this pavement section showed that the pavement was in very good condition with no apparent distresses. Transverse cracks were spaced at 5 to 6 ft from each other. No spalling was found along the tested section. As with previous projects, data collection tasks included a broad visual inspection of the pavement, sounding testing, selection of locations for FWD testing, and core extraction. For this project, as well as for the other project studied on IH 610 in Houston, TxDOT hired a contractor to core the pavement.

Field tasks were performed without problems, except for the coring, as the coring machine lacked power and had difficulty drilling through the entire depth of concrete pavement, causing some delays. Testing was conducted on the outside lane of the frontage road, while the two inside lanes remained open for traffic. However, as mentioned before, the volume of traffic was not an issue at this location. FWD testing equipment was again provided by TxDOT and several locations were tested for the tined and carpet dragged sections. Figure 3.16 shows a general view of the Beltway 8 section under study.

*Figure 3.16 Panoramic view at the beginning of test section*

Figure 3.17 clearly shows that the coarse aggregate of the old CRCP is siliceous river gravel (SRG) and the aggregate in the BCO is limestone.


*Figure 3.17 Hole in the Beltway 8 pavement after a core was drilled*

During the time frame for which traffic control was provided, a total of five 4-inch-diameter cores were obtained from the pavement. Four cores came out unbonded and one came out bonded. Figure 3.18 shows one of cores that came out in two pieces, separated at the interface between the old CRCP and the BCO layer. The image shows that the BCO had a full depth crack which is not a reflection crack and that the bond at the interface was broken. The four unbonded cores taken from the pavement section had a very similar aspect.

*Figure 3.18   Unbonded core taken from BW-8*

The only core that came out intact was taken from the outer third or outside wheelpath of the lane. Figure 3.19 displays the core that was fully bonded. The concrete strength values obtained from core samples were found to be within expected ranges. Strength and modulus of elasticity values for the concrete pavement layer are presented later in this chapter.


*Figure 3.19 Bonded core taken from BW-8 test section*

***Deflection Testing***

As in previous projects, sounding testing was conducted all along the section that had traffic control, that is, the outside lane, and it was noticed that there were widespread delaminated areas, mainly from the left wheel path to the left edge of the lane. In contrast, from the center of the lane to the right edge of the lane, next to the curb, there were no delaminations. The exact cause for this is not known at this point. The results of the FWD showed deflection values ranging from 1.60 to 4.18 mils measured by Sensor 1 at the center of the lane for the load of approximately 9,000 lbs. It can be seen that higher deflections were measured in the second part of the section, which corresponds to the tined segment. For the carpet drag segment, the average deflection was 2.0 mils, the standard deviation was 0.2 mils, and the coefficient of variation was 12.1 percent. For the tined segment, the average deflection was 2.9 mils, the standard deviation was 1.5 mils, and the coefficient of variation was 51.2 percent. It was not possible to conduct FWD testing on the left side of the lane where the debonding areas were detected. This would have required the FWD to encroach to the middle lane, which was open to traffic (only one lane could be closed to traffic). Figure 3.20 displays the deflection profile obtained for the test section on Beltway 8.

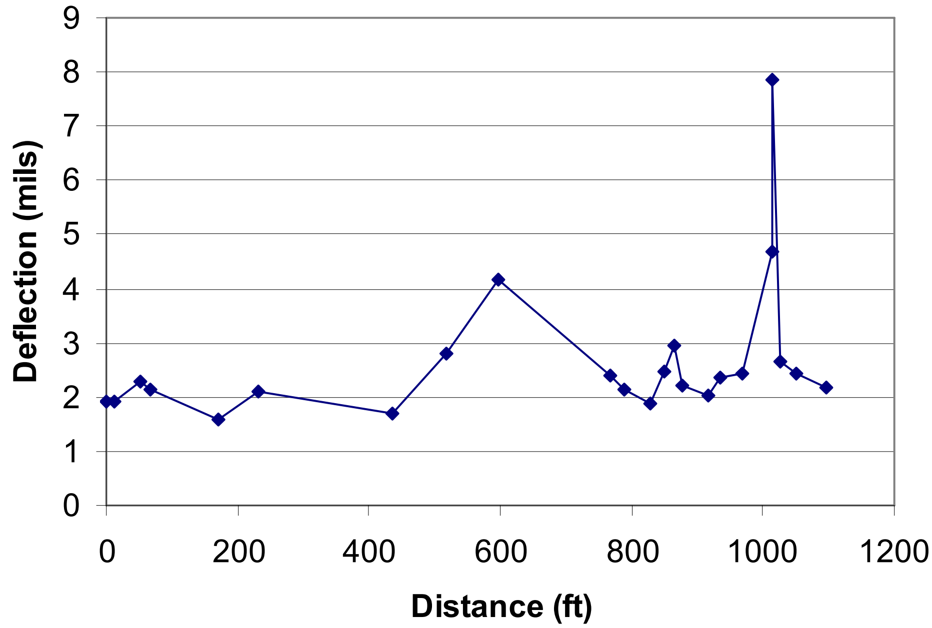


*Figure 3.20 Deflection profile of test section on BW-8 in Houston*

### 3.3.4 US 281 in Wichita Falls

The fourth BCO section visited is located in Wichita Falls, on US 281. This 8-inch-thick pavement was originally constructed in 1969; it was overlaid with a 4-inch-thick BCO in the summer of 2002, for which no bonding agent was used, and for which the surface preparation was accomplished by shotblasting. The coarse aggregate of both the old CRCP and the BCO is limestone. It is important to note that this is the only BCO project of those visited in this study in which the coarse aggregate for both pavement layers is limestone. The project limits for the BCO rehabilitation are the Holliday Creek Bridge on the north end and the county line between Wichita and Archer counties on the south end, for a total of 3.7 miles.

The fieldwork in this section took place on June 9, 2005, and consisted of a visual survey, sounding, FWD deflection testing, and extraction of core samples. The surveyed segment consisted of a stretch of approximately one mile long, on the inside lane of the southbound direction.

**Results**

Overall, the section appears in very good condition. The results of the coring and deflection testing indicate that the section is in good structural condition. No major distresses were observed. The sounding tests revealed that only one spot along the entire segment surveyed could have a minor delamination occurrence, near the edge of the lane, close to the joint with the outside lane. At this location, a core sample was extracted, and the appearance of the core has a good correlation with the audible findings, as will be discussed later in this section.

***Deflection Testing***

The deflections, as shown in Figure 3.21 (corresponding to the first sensor and the second load drop of the FWD), were low in general and fairly uniform, with only one outlier data point (6.2 mils), which happened to be at the most deteriorated of the cracks found. The average deflection of the section was 2.80 mils, the standard deviation was 0.7 mils, and the coefficient of variation was 25 percent.

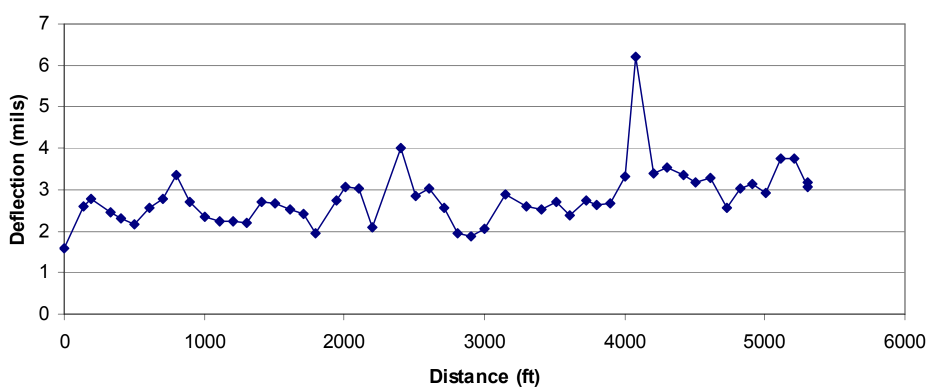


*Figure 3.21 Sensor 1 FWD deflections*

Nine core samples were taken from the section. Figure 3.22 shows one of them, which is in good condition, as were most of the samples extracted.

*Figure 3.22   Core in good condition*

However, some deterioration was found in one of the cores; this is the core that was drilled at the location where the hollow sound was identified with the sounding test. As shown in Figure 3.23, the core had some voids in it, which are in the old concrete layer. The overlay came out delaminated when the drilling was performed. Nevertheless, the overlay part of the core was in sound condition. Thus, the deterioration is confined to the existing CRCP.

*Figure 3.23   Old concrete deterioration in one of the cores*

The deterioration of the pavement can be seen in more detail in Figure 3.24.


*Figure 3.24 Detail of old concrete deterioration in one of the core samples*

### 3.3.5 Concrete Properties Obtained from Testing

Core samples obtained from the four BCO projects previously described were tested, and compressive strength, splitting tensile strength, and free-free modulus of elasticity were obtained. To identify the core samples, they were named with either two or three characters. The first character was a letter: A corresponds to the core samples obtained from the project on IH 610 in Houston, B corresponds to the samples obtained from the section on IH 30 in Fort Worth, C corresponds to the samples obtained from the pavement on Beltway-8 in Houston, and D corresponds to the samples obtained from the section in Wichita Falls on US-281. The second character in the core samples was a number corresponding to the consecutive number when coring a given project. The third character in the sample, when present, shows whether the tested sample corresponded to the top (overlay) or bottom (old CRCP) of the concrete pavement. The letter T and B were used, respectively.

The preparation of the concrete cores started with the trimming, measuring, and weighing of each individual sample. Next, the modulus of elasticity was estimated with the free-free resonance method. This test was performed by researchers at TxDOT's Cedar Park Campus. A summary of the results of this test is presented in Table 3.5, in which the first column represents the core identifier assigned as previously described, the second column represents the estimated modulus of elasticity for each core within a project, and the third column represents the average modulus for each project.

*Table 3.5 Results of free-free modulus of elasticity test*

| Core Identifier | Modulus of Elasticity (ksi) | Average (ksi) |
|---|---|---|
| A8 | **2479.5** | 3580 |
| A7 | **5627.1** | |
| A5 | **4134.8** | |
| A4B | **1878.9** | |
| A3 | **3778.2** | |
| B1B | **5801.8** | 4849 |
| B2B | **4954.9** | |
| B3B | **4906.0** | |
| B4 | **3997.8** | |
| B5 | **4585.1** | |
| C1B | **4748.8** | 4701 |
| C2B | **3503.5** | |
| C4B | **4576.8** | |
| C5 | **5974.2** | |
| D1 | **5137.9** | 4420 |
| D2 | **5024.9** | |
| D3 | **3022.1** | |
| D5 | **4805.4** | |
| D6T | **5513.9** | |
| D6B | **5119.9** | |
| D7A | **4593.8** | |
| D8T | **5328.3** | |
| D9 | **1235.0** | |

Since the modulus values from free-free resonance column testing are measured at initial small strain, they represent initial tangent modulus and are usually higher than those obtained from static modulus testing. The values shown in Table 3.5 are slightly lower than expected, even though there are few apparent outliers. Since the modulus values of these concretes at early ages are not known, it may not be possible to draw any firm conclusions.

After conducting the modulus of elasticity test, the concrete core samples were brought to the materials laboratory located in the basement of the engineering building of The University of Texas at Austin. Preparation of the samples included trimming, weighing, measuring, and sulfur capping. The obtained compressive and split tensile strengths are summarized in Tables 3.6, and 3.7, respectively. Both compressive and tensile strength values are higher than expected.

*Table 3.6 Compressive strength of concrete core samples*

| Core Identifier | Diameter (in.) D | Length (in.) L | Weight (lb) | L/D Factor | Area ($in^2$) | Maximum Load (lbf.) | Compressive Strength (psi) | Correction Factor | Corrected Compressive Strength (psi) |
|---|---|---|---|---|---|---|---|---|---|
| A8 | 3.69 | 7.25 | 3061 | 1.96 | 10.69 | 76710 | 7173 | 1.00 | 7173 |
| C1B | 3.73 | 6.50 | 2735 | 1.74 | 10.93 | 82170 | 7520 | 0.98 | 7369 |
| C4B | 3.70 | 8.00 | 3460 | 2.16 | 10.75 | 79610 | 7404 | 1.00 | 7404 |
| B2 | 5.77 | 5.75 | 5818 | 1.00 | 26.15 | 187800 | 7182 | 0.87 | 6248 |
| D6B | 3.98 | 6.38 | 3173 | 1.60 | 12.44 | 73250 | 5888 | 0.97 | 5711 |
| D8B | 4.00 | 4.75 | 2341 | 1.19 | 12.57 | 87780 | 6985 | 0.92 | 6426 |
| D5 | 3.96 | 7.25 | 3661 | 1.83 | 12.32 | 66060 | 5364 | 1.00 | 5364 |
| C2B | 3.73 | 8.00 | 3463 | 2.14 | 10.93 | 77040 | 7050 | 1.00 | 7050 |

Figure 3.25 shows the relationship between modulus of elasticity and compressive strength by project, after discarding apparent outliers, with the ACI equation. It should be noted that the relationship does not follow the ACI equation well. As discussed earlier, the modulus values obtained in this study are initial tangent moduli while those used for the derivation of the ACI equation are static moduli. Also, there is a large scatter in the data from which the ACI equation was derived, and therefore, it is not unexpected to have slight discrepancy between data obtained in this study and the predictions from the ACI equation.

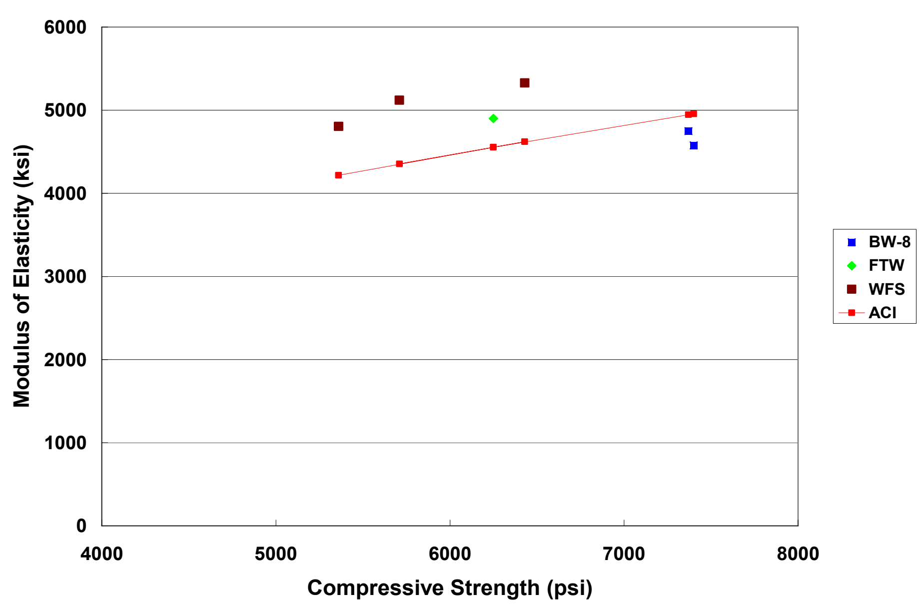


*Figure 3.25 Relationship between compressive strength and modulus of elasticity*

*Table 3.7 Splitting tensile strength of concrete core samples*

| Core Identifier | Diameter (in.) D | Length (in.) L | Weight (lb) | L/D Factor | Maximum Load (lbf.) | STS Strength (psi) |
|---|---|---|---|---|---|---|
| A7 | 3.72 | 7.75 | 3152 | 2.08 | 44400 | 980 |
| A4B | 3.68 | 5.25 | 2116 | 1.43 | 22800 | 751 |
| B1T | 5.76 | 4.38 | 4399 | 0.76 | 25900 | 654 |
| B3B | 5.77 | 5.25 | 5587 | 0.91 | 32500 | 683 |
| C3B | 3.69 | 2.88 | 1175 | 0.78 | 17100 | 1024 |

Another test that was conducted was the estimation of the concrete coefficient of thermal expansion (CTE). Again, this test procedure was run using TxDOT's equipment and facilities. Due to the lengthy process of this test and also because the thermal properties of the aggregates used in Texas' concrete mixes, only two tests were performed. One test was conducted in a concrete core with limestone (LS) coarse aggregate, and the other with a concrete with siliceous river gravel (SRG) aggregate. The results of the tests are presented in Figures 3.26 and 3.27, for the LS and SRG, respectively. As shown in these figures, the values of CTE for both types of aggregates are very typical of the Texas region. The CTE for the concrete with LS was 4.23 m-strain/°F and the CTE for the concrete built with SRG was 6.5 m-strain/°F.

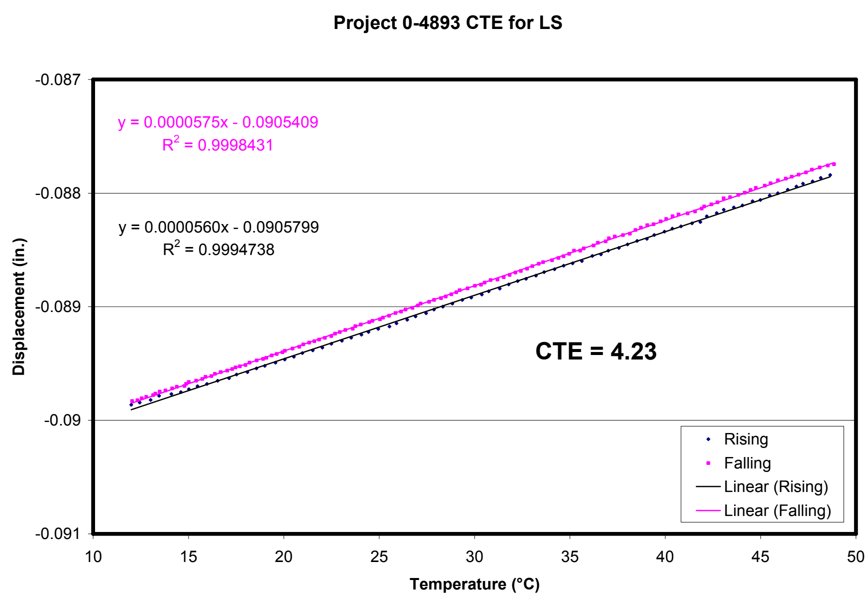


*Figure 3.26 CTE estimated for LS aggregate—US281 Wichita Falls*

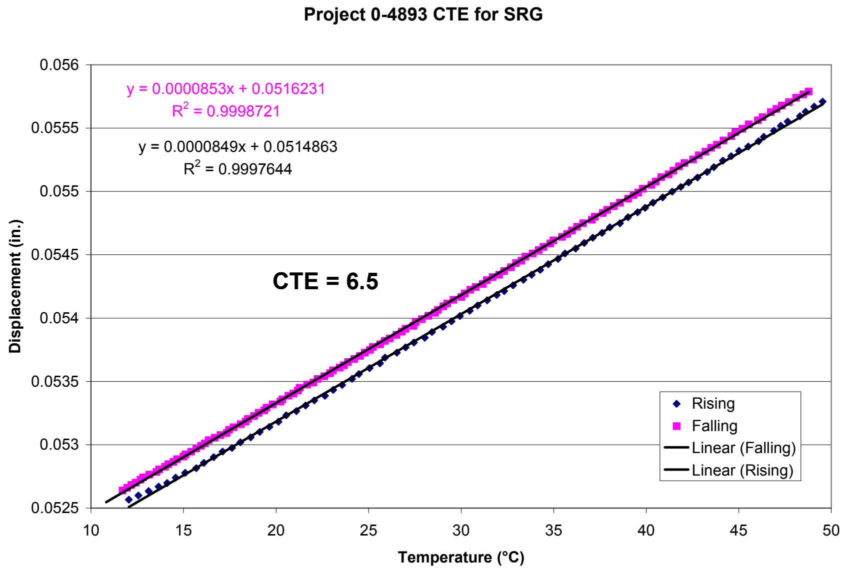


*Figure 3.27 CTE estimated for SRG aggregate—IH 610 Houston*

Petrographic analyses were conducted by Edward Morgan, a geologist at TxDOT, on the cores obtained in the field evaluations. No evidence of ASR or other chemical reactions were observed, with the exception of one core from the IH 610 Houston project where an abundance of ettringite was noted. Figure 3.28 shows an image obtained from a microscope that demonstrates the presence of ettringite. However, in this case ettringite does not appear to have caused distresses in the surrounding concrete.

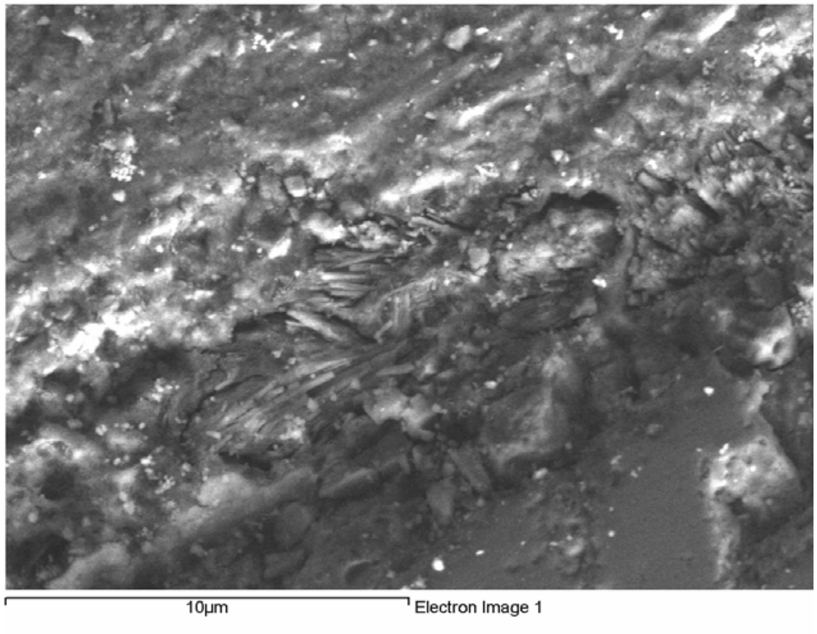


*Figure 3.28 Ettringite deposits in crack adjacent to aggregate revealed by petrographic analysis*

# 4. BCO and AC Overlay Design

## 4.1 Introduction

This chapter is divided in two subsections, each one describing the generally used procedures for designing BCOs and AC overlays. This study does not intend to propose new design approaches for overlays, but rather to summarize what TxDOT and other state agencies use for that purpose.

## 4.2 BCO Design

As it was previously mentioned, the most frequently used design methods for BCO include the Corps of Engineers, the PCA, and the AASHTO. The following paragraphs describe those methods succinctly.

### 4.2.1 Corps of Engineers

This design procedure was originally devised for the design of concrete overlays placed over concrete pavements in airfield runways and taxiways. The design method was developed using full-scale accelerated test tracks and uses empirical coefficients. The required thickness for the overlay is the difference between the thickness required for a new pavement and the thickness of the existing slab. The model used for fully bonded BCOs is represented by Equation 4.1.

$$h_o = h_n - h_e \tag{4.1}$$

where

$h_o$ = required overlay thickness
$h_n$ = required theoretical thickness for the design loading, for a new pavement, and
$h_e$ = existing pavement thickness

This method implies that the existing concrete has suffered no fatigue damage due to traffic or other factors, and it is as sound as the concrete in a new pavement, which contradicts the fatigue damage concept and the idea of remaining life. Besides, it assumes that the failure mechanism of the overlaid pavement is the same as that of a new pavement.

### 4.2.2 PCA Method

The Portland Cement Association (PCA) methodology consists in designing an overlay system that is structurally equivalent to a new full-depth pavement placed on the same subbase and subgrade. Unlike the Corps of Engineers procedure, it uses an evaluation of the existing pavement by means of condition surveys, deflection tests, and in-situ sample testing, to take its condition into consideration in the design. The design basis is the analysis of the stresses at the edge of the pavement (Ref 29). The model equates the edge stress at the bottom of the new full-depth pavement ($\sigma_n$) with that of the overlaid system at the bottom of the existing pavement ($\sigma_e$), as shown in Figure 4.1

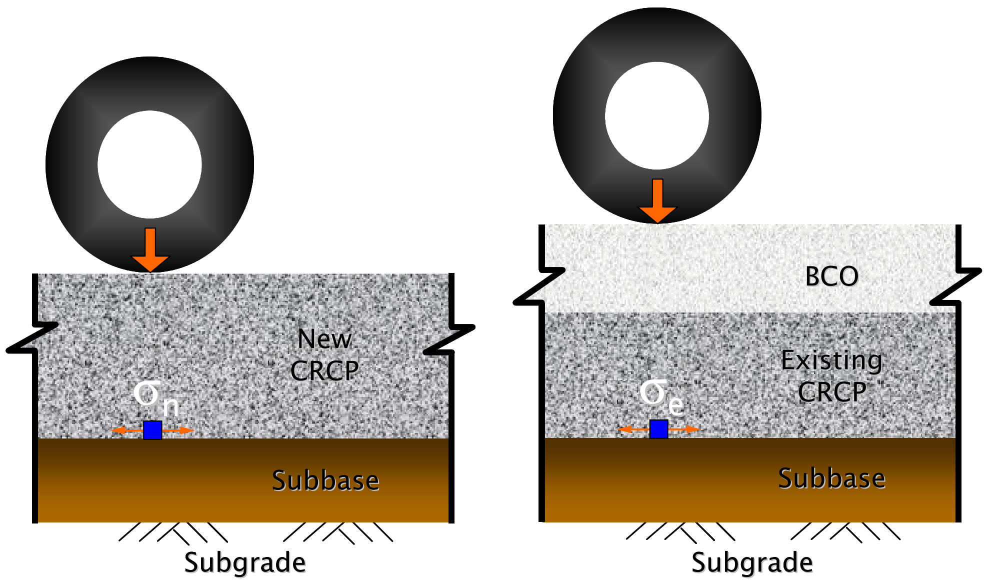


*Figure 4.1 Edge stresses for new and overlaid pavement for PCA method design equivalency*

Since the new full-depth slab and the existing concrete will have different moduli of rupture, Sc, the equivalency is based on the stress ratio to the modulus of rupture. If the stress ratio for the overlaid system is the same as that of the new pavement, both pavements will be structurally equivalent, as shown in Equation 4.2.

$$\frac{\sigma_n}{S_{cn}} \geq \frac{\sigma_e}{S_{ce}} \quad (4.2)$$

where

$\sigma_n$ = critical edge stress in the new pavement
$S_{cn}$ = modulus of rupture of the new concrete
$\sigma_e$ = critical edge stress in the existing pavement
$S_{ce}$ = modulus of rupture of the existing concrete

In developing this method, a finite element program was used to create a design chart in which the critical tensile stresses due to edge loading in both new pavement and the BCO structure are related to the modulus of rupture of the existing concrete, for which three different ranges of moduli are considered.

For the BCO design, the first step consists of calculating the thickness of the new full-depth pavement required for future design traffic, and this can be accomplished by using the PCA design method or other PCC design method. With this thickness and the design chart, the combined thickness of BCO and existing pavement is computed, and the BCO thickness is determined by subtracting the existing slab thickness from this value. The maximum BCO thickness recommended is 5 inches. When the required thickness exceeds this value, the use of an unbonded overlay is preferable.

In this method the fatigue consideration is dependent on the procedure used to arrive at the new full-depth pavement thickness. If the PCA method is used, then it is assumed that the pavement can withstand an infinite number of applications, as long as those occur under the stress limit established by the method that is based on plain concrete fatigue tests.

### 4.2.3 AASHTO Method

The AASHTO method (Ref 28), the most widespread of the design procedures among state highway agencies, uses the aforementioned structural deficiency principle. It is mostly an empirical method, since the design equations for the method were derived from regression analyses performed on the AASHO Road Test data, but it includes a mechanistic part, in the determination of stresses and strains. Like the PCA method, the AASHTO procedure advocates conducting a comprehensive evaluation of the existing pavement conditions and applying the results as input design parameters for the BCO.

The thickness design equation is shown in Equation 4.3:

$$D_{ol} = D_f - D_{eff} \tag{4.3}$$

where

$D_{ol}$ = required thickness of BCO

$D_f$ = slab thickness to carry future traffic

$D_{eff}$ = effective thickness of existing slab

The slab thickness to carry future traffic, $D_f$, is calculated by means of the standard AASHTO rigid pavement design equation, as if it were a new pavement design, as shown in Equation 4.4:

$$\log_{10} W_{18} = Z_R x S_O + 7.35 x \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624 x 10^7}{(D+1)^{8.46}}}$$

$$+ (4.22 - 0.32 p_t) x \log_{10}\left[\frac{S_c' x C_d x (D^{0.75} - 1.132)}{215.63 x J \left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right]}\right] \quad (4.4)$$

where
$W_{18}$ = predicted number of 18-kip ESAL applications
$Z_R$ = standard normal deviate
$S_O$ = overall standard deviation of rigid pavement
D = thickness of pavement slab, in.
ΔPSI = difference between initial serviceability, $p_o$, and terminal serviceability index, $p_t$
$S'_c$ = PCC modulus of rupture, psi
J = load transfer coefficient
$C_d$ = drainage coefficient
$E_c$ = PCC modulus of elasticity, psi
k = modulus of subgrade reaction, pci

The first term ($Z_R x S_O$) corresponds to the reliability. The remaining terms on the first line of the equation are the empirical part of the procedure, derived from the data gathered at the AASHO Road Test. The second line, related to stress computations, is the mechanistic part, which was added to account for changes in strength and stresses owing to physical constants (e.g., $E_c$, k) occurring in conditions other than those that existed during the road test.

The effective thickness of the existing slab, $D_{eff}$, is calculated by applying a condition factor, CF, to the existing slab thickness, D, as shown in Equation 4.5:

$$D_{eff} = CFxD \quad (4.5)$$

The value of CF can be determined in two ways, either by the use of remaining life or by means of the condition survey. The remaining life relationship with the condition factor appears in Figure 4.2 (Ref 28).

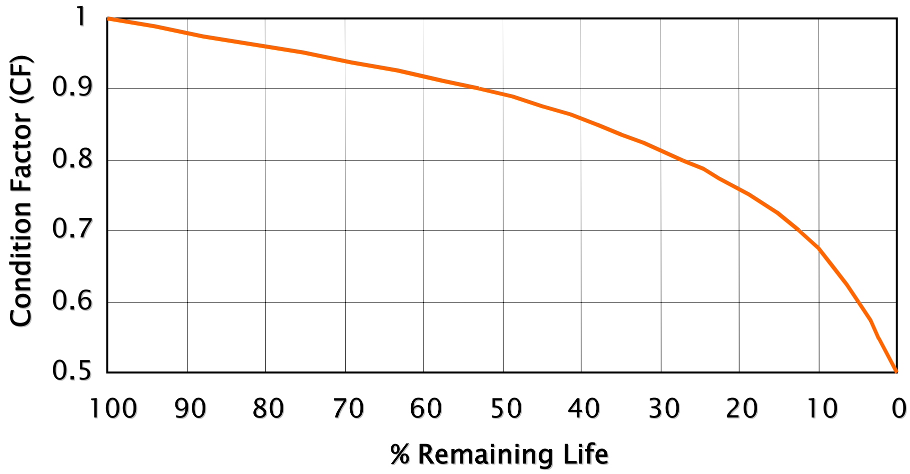


*Figure 4.2 Relationship between condition factor and remaining life*

The other method utilizes condition survey results to determine CF. There are three adjustment factors obtained from condition surveys as follows:

1. Joints and cracks adjustment factor ($F_{jc}$)—adjusts for extra loss in PSI originated by deteriorated reflection cracks that result from unrepaired cracks in the existing pavement prior to overlaying.
2. Durability adjustment factor ($F_{dur}$)—adjusts for extra loss in PSI of the overlay when the existing slab has durability problems like "D" cracking or reactive aggregate distress.
3. Fatigue damage adjustment factor ($F_{fat}$)—adjusts for past fatigue damage that may exist in the slab.

The factors range from 0 to 1. When the pavement condition is satisfactory, these factors take the value of one, which means that the condition of the pavement does not affect the effective thickness. However, as the condition of the slab is more deteriorated, their value decreases. Guidelines for selecting values for the adjustment factors appear in Ref 28. The condition factor is the combination of these adjustment factors as shown in Equation 4.6.

$$CF = F_{jc} x F_{dur} x F_{fat} \tag{4.6}$$

Therefore, the value of $D_{eff}$ can be expressed by Equation 4.7:

$$D_{eff} = F_{jc} x F_{dur} x F_{fat} x D \tag{4.7}$$

## 4.3 AC Overlay Design

The most commonly used approach to the structural design of asphalt overlays of concrete pavements is the structural deficiency approach, exemplified by the 1993 AASHTO procedure, described in the previous subsection.

Of course, for the AC overlay design, Equation 4.4 is replaced by the analogous flexible pavement design equation. Another difference is that, in the last step of the process, the determination of the required overlay thickness is obtained by multiplying the structural deficiency ($D_f$—$D_{eff}$) by an adjustment factor, A, which converts concrete thickness deficiency to the asphalt concrete overlay thickness requirement. A value of 2.5 has traditionally been used for the adjustment factor A. This value was based on the results of accelerated traffic tests conducted by the Corps of Engineers in the 1950's.

# 5. Summary and Guidelines

## 5.1 Summary

The objectives of this study included (1) the evaluation of the old concrete under BCOs and AC overlays, (2) the development of guidelines for the selection and design of AC overlays and BCOs, and (3) assessment of the performance of overlays constructed with special materials. In this reporting period, most of the work consisted of a review of the literature, the evaluation of the concrete under overlay, and the analysis of the performance of the various BCOs. The following summarizes the findings made so far:

The literature review reveals that the largest concern with BCOs is the occurrence of delaminations and premature failure of the overlay. In the case of AC overlays on rigid pavements, the most critical matter is reflective cracking in jointed pavements, stripping, and rutting.

The concrete under overlays appears to be in good condition with no deleterious chemical reactions. The only exception is the ettringite found in a concrete core from the Loop 610 South overlay in Houston; however, the ettringite is near the air voids, innocuous, and has not caused any damage.

Delaminations were observed in several projects; however, some delaminated sections appear to perform well. Even though the amount of data is very limited, it appears that the material compatibility in terms of thermal coefficient between existing and overlaid concretes plays a vital role in the occurrence of delaminations. This is especially true when limestone is used for both concretes, which appears to minimize this incidence. It is not known whether the same is true when siliceous river gravels are used for both concretes. Debonding has been observed on BCOs over existing CRCP constructed with siliceous river gravel, whereas it has not occurred when the existing CRCP contained limestone coarse aggregates, i.e., the Wichita Falls BCO.

The mechanical properties of concrete under the overlay evaluated in this study—strength and modulus of elasticity—are within expected range, indicating that further deterioration of concrete due to age has not occurred.

FWD deflection information is not available for pavements before overlay and it is not feasible to draw any conclusions on the contribution of overlay to the reduction in deflections. However, FWD evaluations show that the structural capabilities of the overlay sections are satisfactory.

## 5.2 Guidelines for Overlay Selection

A BCO contributes to the structural capacity of the overlaid pavement system while an AC overlay does not, if any. For the rehabilitation of old CRCP, it is important to identify the deficiencies of CRCP, i.e., whether the need for rehabilitation arises from a structural or a functional deficiency. If it is a structural deficiency, a BCO provides a corrective solution. On the other hand, if it is a functional deficiency, such as poor riding quality or skid resistance, an AC overlay will provide an economical and reasonable solution. Therefore, the first step is to evaluate the structural capacity of the existing CRCP. Not much field and analytical evaluations have been done so far in this study. Nevertheless, the following steps are provided as an interim guideline for the selection of proper overlay system for CRCP, which will be further refined and presented in the final report.

1. Evaluate the structural capacity of the CRCP using FWD.
2. Evaluate the structural capacity of the CRCP using condition surveys. The rate of occurrence of failures can be used to determine where the pavement is in relation to its service life-span. As such, it can be used as an intrinsic indicator of the feasibility and the timeliness of not only an AC overlay, but of different types of rehabilitation, namely, a BCO and an unbonded concrete overlay. The failure rate, computed from historic condition survey information, establishes two threshold values of failures per mile per year, which have been derived from previous experiences (Ref 31). The threshold values are 2 and 3 failures per mile per year, respectively, and are applied in the following manner. If a CRCP approaches a rate of failure development of 2 failures per mile per year, an AC overlay is likely to remedy the situation and deliver good performance. However, if the rate approaches 3 failures per mile per year, a BCO represents a better technical and economical strategy. If the deterioration rate has reached beyond 3 failures per mile per year, the best solution is an unbonded concrete overlay; in this case, the section is already too damaged to be repaired by a BCO in an economic way.

## 5.3 Guidelines for Overlay Design

### 5.3.1 Guidelines for AC Overlay Design

AASHTO procedures for the AC overlay over rigid pavement are reasonable, and it is recommended that AC overlay over CRCP be designed using these procedures. Additionally, it is recommended that the AASHTO procedures be adopted as TxDOT's design methods in TxDOT's online design manual.

### 5.3.2 Guidelines for BCO Design

AASHTO procedures for the BCO over rigid pavement are reasonable, and it is recommended that BCO over CRCP be designed using the procedures. Additionally, it is recommended that the AASHTO procedures be adopted as TxDOT's design methods in TxDOT's online design manual. BCOs in Texas have been successfully designed following this procedure, as well as RPRDS. The few failures that have occurred in some of the BCOs can be attributed to construction flaws, and not to design.

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