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16. Abstract

This report follows through design, construction and pavement evaluation of an experimental thin-bonded concrete overlay pavement placed on the south Loop 610 freeway in Houston, Texas, during the summer of 1983.

The body of knowledge gained from this experiment and laboratory work conducted at the Center for Transportation Research, The University of Texas at Austin, is reported. Specifically, surface preparation techniques which will result in good and durable bond between the concrete overlay and pavement, construction techniques which would provide a high level of serviceability and an assessment of cost and structural value are included herein.

This report is arranged so as to provide a framework for information exchange between those people and agencies contemplating the use of Bonded Concrete Overlay as a pavement rehabilitation alternative.

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AN EXPERIMENTAL THIN-BONDED CONCRETE OVERLAY PAVEMENT

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Research Report Number 357-2F

Experimental Thin-Bonded Concrete Overlay
Research Project 3-8-83-357

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

November 1985

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

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

PREFACE

This is the second and final report which documents work done under Project 3-8-83-357, "Experimental Thin-Bonded Concrete Overlay." The project was conducted as part of a cooperative highway research program between the Center for Transportation Research, the Texas State Department of Highways and Public Transportation, and the Federal Highway Administration.

Many people have contributed their help toward the completion of this study. The authors would like to thank the Center for Transportation personnel for their assistance and support throughout the study, in particular Jim Long and Eduardo Ricci for technical assistance, Lyn Gabbert and Rachel Hinshaw for typing the manuscript, and Bob Gloyd and Jeannette Garcia for assistance with the computer systems.

Thanks are also extended to the Texas State Department of Highways and Public Transportation and the Federal Highway Administration personnel who made the South Loop 610 experiment a reality, especially Mr. W. V. Ward, formerly of the Houston Urban Office and now of the Center for Transportation Research.

LIST OF REPORTS

Report 357-1, "A Study of the Effects of Interface Condition on Thin-Bonded PCC Overlay," by Kandiah Kailasananthan, B. F. McCullough, and D. W. Fowler, presents the findings of the laboratory experiments on thin-bonded overlay which were conducted as a prelude to completing the Houston 610 Loop experimental section and the results of the experiments on the field cores obtained from the test sections. October 1984.

Report 357-2F, "An Experimental Thin-Bonded Concrete Overlay Pavement," by Moussa Bagate, B. Frank McCullough, D. W. Fowler, and M. Muthu, describes the design, construction, and pavement monitoring program on the South Loop 610 project in Houston and presents various data analyses which evaluate two years of performance. November 1985.

ABSTRACT

This report follows through design, construction, and pavement evaluation of an experimental thin-bonded concrete overlay pavement placed on the south Loop 610 freeway in Houston, Texas, during the summer of 1983.

The body of knowledge gained from this experiment and laboratory work conducted at the Center for Transportation Research, The University of Texas at Austin, is reported. Specifically, surface preparation techniques which will result in good and durable bond between the concrete overlay and pavement, construction techniques which would provide a high level of serviceability and an assessment of cost and structural value are included herein.

This report is arranged so as to provide a framework for information exchange between those people and agencies contemplating the use of Bonded Concrete Overlay as a pavement rehabilitation alternative.

SUMMARY

The use of thin-bonded concrete overlay pavement is rapidly emerging as a viable means to rehabilitate concrete pavements. In recent years, several projects have been constructed, and valuable information has been gathered, with the Iowa Department of Transportation leading the way.

However, a survey of the available literature reveals that the information is scattered and in most cases, difficulty arises when it comes to making statistical inferences, simply because the information was not collected for that purpose (i.e., not task-oriented) or there has been no prior well-defined experiment design.

During the summer of 1983, an experimental 1,000 feet of thin bonded concrete overlay pavement was placed in IH-610, an eight-lane divided freeway in Houston, Texas. The original pavement structure is an eight-inch-thick continuously reinforced concrete pavement. Five design sections were constructed. Two main factors (concrete reinforcement and overlay thickness) were used at three and two levels, respectively.

This report discusses several aspects of Bonded Concrete Overlay (BCO) construction using the South Loop 610 experiment. First, design considerations, construction aspects and pavement evaluation surveys are presented followed by extensive data analyses in an effort to ascertain pavement performance. Second, interpretation of the analyses is presented. The report ends with conclusions derived from this study and various laboratory investigations of BCO.

IMPLEMENTATION STATEMENT

Based on this study and the previous laboratory investigation, the following are recommended for implementation:

(1) The thin-bonded concrete overlay scheme used in the South Loop 610 experiment is a viable rehabilitation alternative, and thus should be included in the future project level Pavement Management System decision making process in Texas.

(2) During BCO construction, the same grade control requirements which were used during construction of the existing pavement should be used. This is particularly important since the BCO is expected to provide many years of service life.

(3) Until further information is known of the cost effectiveness of other bonding agents, a mixture of water, cement, and plasticizer should be used. This will deliver the expected bond performance.

(4) The use of steel-mat-reinforced BCO design is warranted in areas of high traffic level and intensity or high existing pavement deflection.

(5) The use of fiber-reinforced BCO design is warranted when cracking is the prime concern.

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CHAPTER 1. INTRODUCTION

This report is concerned with the use of a thin layer (2 to 4 inches) of Portland cement concrete (PCC) to rehabilitate an existing concrete pavement. This chapter presents background information, the objectives, and the organization and scope of the report.

BACKGROUND

In recent years, the highway industry in the United States has shifted its attention from construction of new pavements to maintenance, repair, and rehabilitation of the existing infrastructure. This shift has occurred primarily due to two factors:

(1) The Interstate Highway program is nearing completion. The basic highway network is now in place, and future activities will be directed towards preserving this initial investment of public funds through resurfacing, restoring, rehabilitating, or reconstructing these highways.

(2) Most of the pavements now in service were built with a theoretical twenty year design life. They are reaching the end of this period, and rehabilitation of these pavements is needed.

In addition to these factors, there are financial, environmental, and ecological factors contributing to the trend toward maintenance and repair (Ref 6). In Houston, the highway and street network comprises many miles of continuously reinforced concrete pavements (CRCP). Overall, these pavements are in good structural condition. However, pavement condition and evaluation surveys indicate the need for rehabilitation in the near future.

This report is the second in a series of reports on a study of thin-bonded concrete overlay (BCO) pavements conducted under a cooperative highway research program between the Center for Transportation Research, The

University of Texas at Austin, the Texas State Department of Highways and Public Transportation, and the Federal Highway Administration. The report specifically covers an experimental highway rehabilitation project constructed on South Loop 610, a busy freeway in Houston. The South Loop 610 experiment was constructed in July and August 1983 and is performing excellently as of the latest pavement evaluation survey, in November 1985.

The rehabilitation of concrete pavements with BCO is desirable because of thermal and structural compatibility between the overlay material and the overlaid pavement. Although concrete has been used for over thirty years for the rehabilitation of concrete pavements (Ref 11), thin-bonded concrete overlay pavement is only now emerging as a viable rehabilitation alternative. This is primarily due to the availability of high production milling machines and pavers and the introduction of new, energy efficient highway construction materials, mainly concrete admixtures (synthetic and natural fibers, super plasticizers). Theoretical studies have shown that a BCO will substantially increase the structural capacity of an existing concrete pavement and, therefore, could buy additional fatigue life for the structure. The Loop 610 experiment provides a good opportunity to test the theory under high traffic loadings.

Successful use of BCO would permit optimum use of resources available for rehabilitation of the pavement network and allow the rehabilitation of many more miles of pavement in the system.

OBJECTIVES

The objectives of this report are the following:

(1) Describe the design, construction and pavement monitoring program for the South Loop 610 project in Houston.

(2) Report on the initial pavement performance as determined by periodic evaluation surveys.

(3) Interpret the data collected during two years of observation.

ORGANIZATION AND SCOPE OF THE REPORT

Chapter 2 highlights the design and construction of the South Loop 610 experiment in Houston. Concepts and design considerations that led to the construction of a 1,000 foot stretch of BCO are reviewed and discussed.

Chapter 3 presents field measurements, including Dynaflect deflections, concrete movement measurement, collection of concrete cores to test in the laboratory, and concrete quality control data during construction.

Chapter 4 is concerned with performance data from periodic pavement evaluation surveys.

Chapter 5 attempts to estimate the total cost of the project from the viewpoints of the users and the Houston Urban Office.

Chapter 6 discusses the results of the experiment and underscores its achievements and weaknesses overall.

Finally, concluding remarks and recommendations derived from the study are presented in Chapter 7.

It should be noted that this report does not seek to be exhaustive or authoritative on the subject of rehabilitating concrete pavements with BCOs; the approach is rather selective and inferential in that immediate and related answers could not be found but could be calculated or derived from the wealth of data available to the authors. Again, the South Loop 610 experiment constitutes the centerpiece of the report, and the primary concern is for highway pavements; nonetheless the methodology and techniques used could equally well apply to airport pavements. Laboratory investigations were summarized in Ref 5 and more theoretical considerations will be presented in a subsequent report, which will also address the mechanistic design of BCOs and related issues.

CHAPTER 2. BACKGROUND ON EXPERIMENTAL TEST SECTIONS

This chapter introduces the field experiment in Houston, which uses various types of thin-bonded concrete overlay pavements. The design and construction of the test sections are discussed.

DESIGN CONSIDERATIONS

The South Loop 610 experiment was designed using the principles of statistics. Main factors which were thought to have a significant effect on the performance of BCOs were first identified. These were (1) type of concrete reinforcement and (2) overlay thickness (see Table 2.1).

The following design sections were actually built in the field.

(1) Two-inch thick plain concrete overlay.
(2) Two-inch thick steel reinforced (welded wire fabric) concrete overlay.
(3) Three-inch thick steel reinforced (welded wire fabric) concrete overlay.
(4) Three-inch thick steel fiber-reinforced (Bekaert's Dramix ZP 50/50) concrete overlay.
(5) Two-inch thick steel fiber-reinforced (Bekaert's Dramix ZP 50/50) concrete overlay.

Note that the factorial experiment design did not include a 3-inch-thick plain concrete section and is, therefore, only a partial factorial.

It was desired to assess the effects of the main factors and their interactions, if any. At the same time, an effort was made to factor out possible confounding of undesirable secondary effects. Two such effects that were factored out are traffic level and temperature differential for the overlay and the original pavements attributable to coarse aggregate types. To overcome traffic effect, the project location was selected so that no

TABLE 2.1. FACTORIAL DESIGN FOR THE SOUTH LOOP 610, HOUSTON EXPERIMENTAL PROJECT

Overlay Thickness \ Concrete Reinforcement	Non–Reinforced	Steel-Mat Reinforced	Steel-Fiber Reinforced
2 in.	X	X	X
3 in.		X	X

X = Test Sections

entry nor exit ramp existed for the entire length of the project (1,000 feet). Therefore, if we assume that only a few lane changes occur on the 1,000 foot section and that weaving is also at a minimum, we can accept that a given design section receives the same number of load applications as the section next to it within a given lane. The analysis of performance data therefore can be conducted as a two-way design where lane is the blocking variable. We shall return to this in a subsequent chapter. As can be seen, the physical layout is here coupled with an intended purpose, that of assessing the main effects of significant factors. To avoid the temperature differential effect, not only was the same type of coarse aggregate specified but also the same source, i.e., the Colorado River; the gravel was a quartzite.

Since the type of coarse aggregate has a significant effect on concrete strength and coefficient of thermal expansion, it affects temperature induced movement and thus CRCP-BCO system performance. When the same source of coarse aggregate is used, only the inherent variability within the borrows remains. Since this is conceivably of the same order of magnitude as existed when the original CRCP was constructed, the chances of differential movement between the original and overlay pavements are considerably reduced after a good bond has been achieved; therefore possible debonding due to interface shear failure is reduced.

Finally, a noteworthy feature of the experimental design was simplicity. It was thought that any concrete paving contractor with reasonable experience could handle this project without specialized equipment, and the materials selected would be readily available.

PROJECT INFORMATION

The Loop 610 experiment consisted of overlaying a 1,000 foot section of IH-610, a major urban freeway which encircles downtown Houston. The site selected for the experiment is on South Loop 610 between Cullen Boulevard and Calais Street, approximately 3.5 miles east of the AstroWorld/WaterWorld amusement park complex. At this location, the roadway is an 8-lane divided highway with four through lanes in each direction, and a concrete median barrier. Main lane widths are 12 feet and shoulders are 10 feet wide (Fig 2.2). Only the four eastbound lanes were overlaid in this experiment.

Figures 2.1(a) and 2.3 show the plan view and the longitudinal profile of the roadway, respectively. As can be seen in Fig 2.3, the 3-inch steel-reinforced, 3-inch fiber-reinforced, and 2-inch fiber-reinforced sections are all on a slight upward grade (+ 3.60 percent). Figure 2.1(a) shows the location and the horizontal alignment; on the eastbound lanes no entry nor exit ramp exists for the length of the project (cross-hatched area). Figure 2.1(b) shows the details of the arrangement of the test sections.

The original pavement structure is a continuously reinforced concrete pavement (CRCP) with 0.5 percent longitudinal steel and 5 sacks per cubic yard cement factor. The CRCP rests on a 6-inch thick cement treated subbase. The natural material comprising the subgrade is a silty clay (Fig 2.2). Construction was completed on this section of roadway on 4 June 1969; it now carries an estimated average annual daily traffic of 113,000 vehicles per day with 8 percent trucks.

To date, the original CRCP has performed well in general. At the site of the experimental project, the types of surface defects present were primarily closely spaced transverse cracks, spalled transverse cracks, longitudinal cracks, and asphalt and polymer concrete patches. Figures 2.4 and 2.5 illustrate a few of these distress manifestations.

PROJECT SPECIFICATIONS

Special specifications were written for this project. They covered six items, as follows:

(1) description,
(2) materials,
(3) equipment,
(4) construction method,

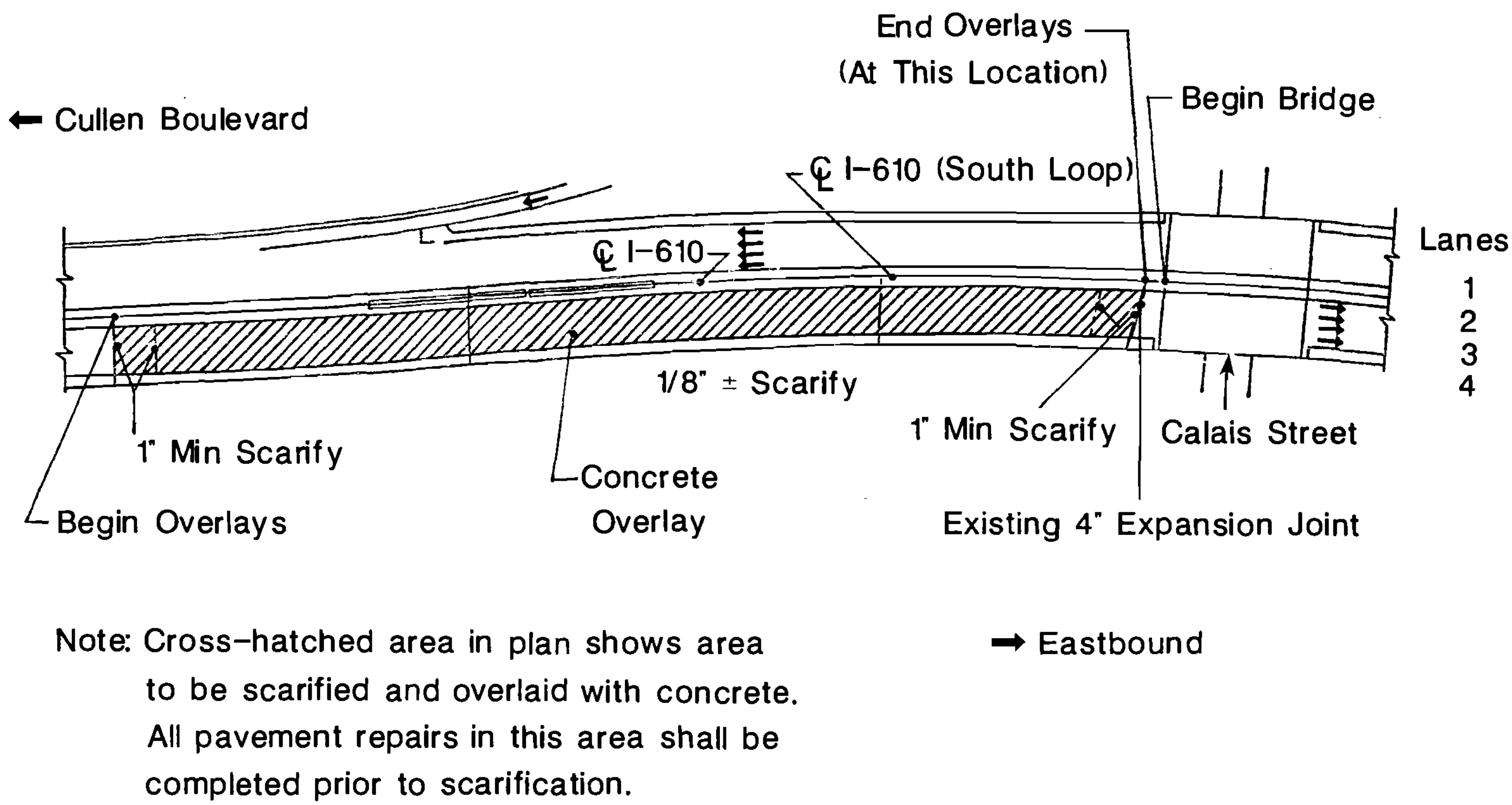


Fig 2.1(a). View showing the Houston Loop 610 project location, horizontal alignment, and depth of scarification.

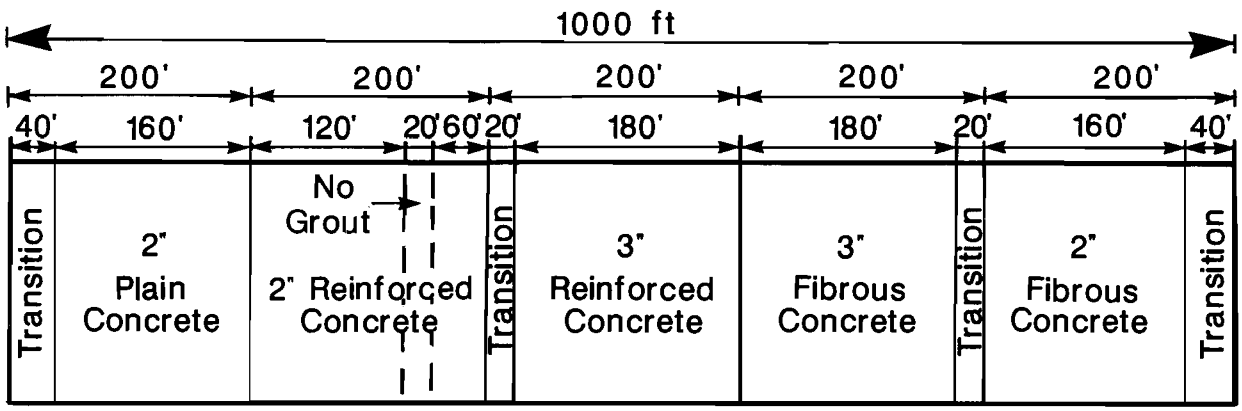


Fig 2.1(b). Plan view of the Loop 610, Houston test sections, showing details of design and layout.

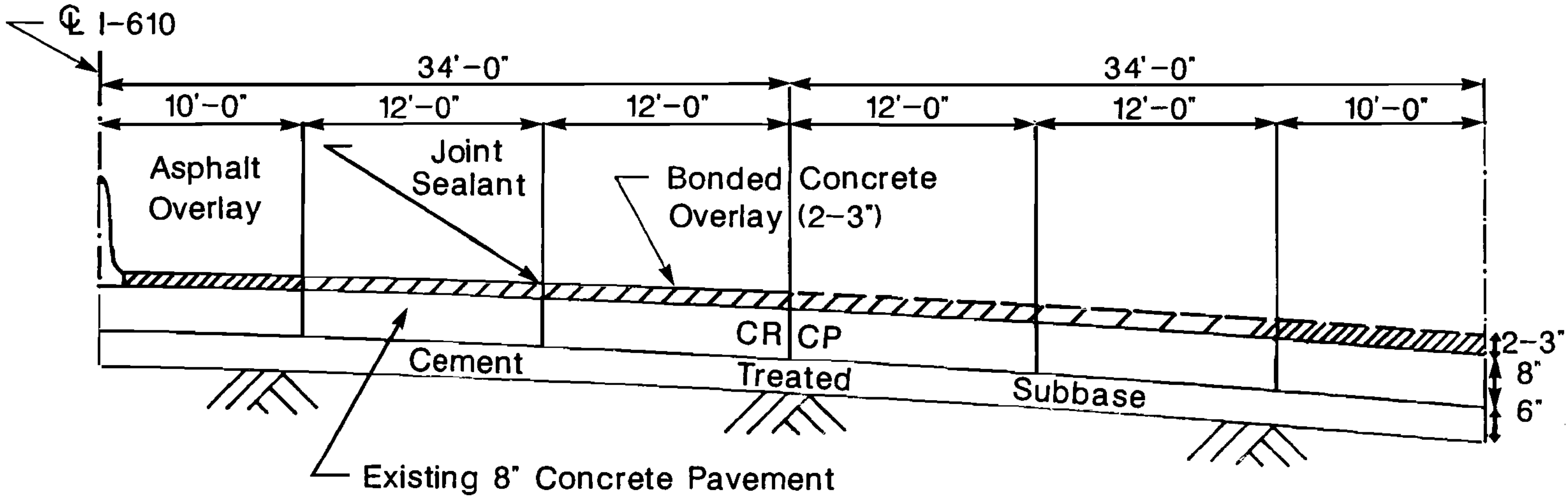


Fig 2.2. Typical cross section showing detail elements and their dimensions.

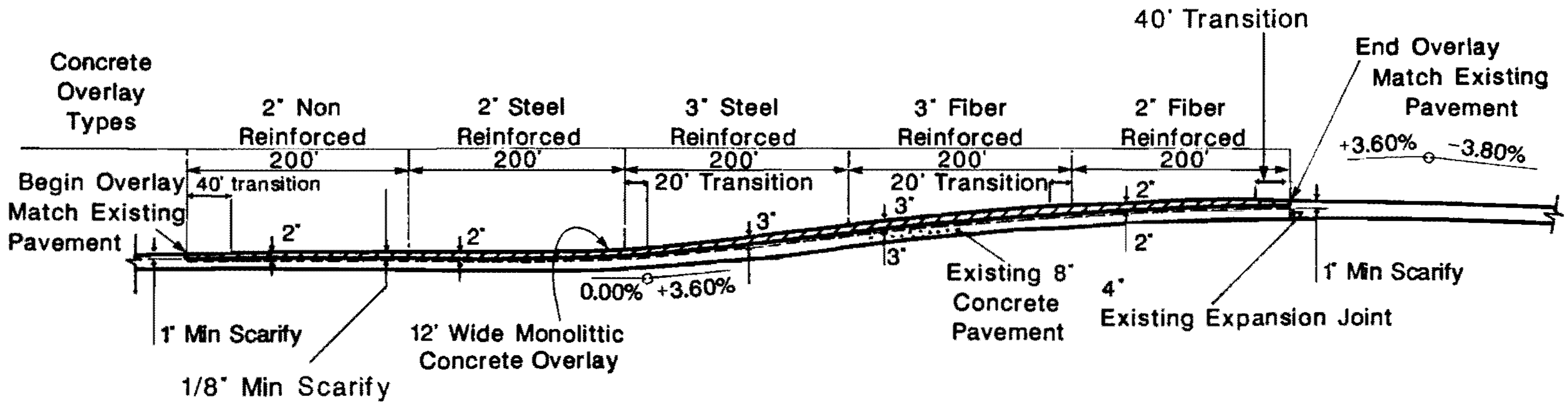


Fig 2.3. Profile of Experimental Section.

Fig 2.4. Transverse cracks -- original pavement.

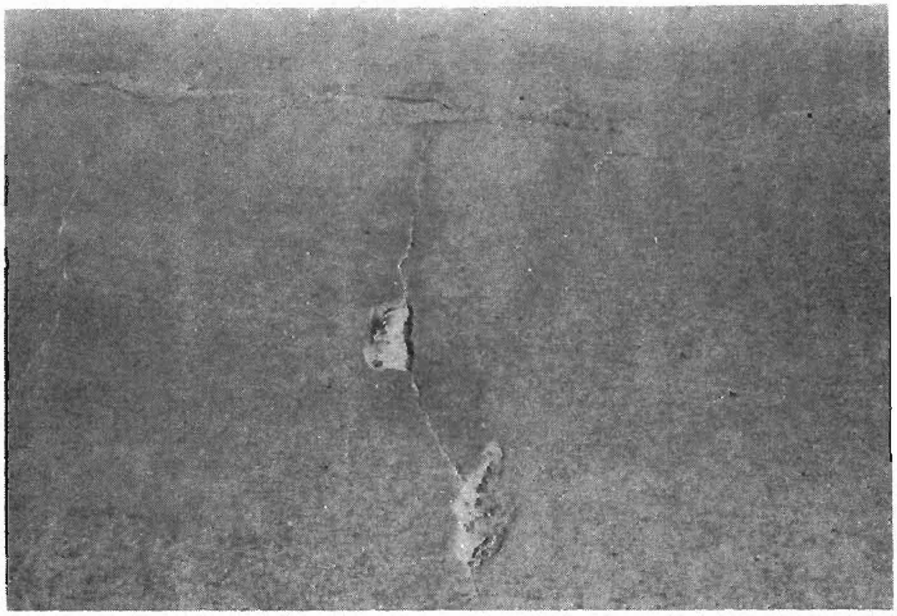


Fig 2.5. Spalled cracks -- original pavement.

(5) measurement, and

(6) payment.

The special specifications are included in Appendix A. Note that the concrete mix designs under Item 2 were different for fiber and no-fiber (i.e., plain concrete and steel reinforced concrete) sections. The fiber sections were designed with a higher cement factor (8 sacks versus 7 sacks per cubic yard) and a higher water factor (5 gallons versus 4.5 gallons per sack of cement).

The specifications on the BCO project were to be in accordance with the details shown on the plans; from these, the wire fabric sizes for the steel-reinforced sections were specified as follows:

(1) 3-inch overlay -- 6 x 12 -- D12 x D4.2

(2) 2-inch overlay -- 6 x 12 -- D8 x D4

(3) permitted end lap -- 12-inch minimum, and

(4) permitted edge lap -- 6-inch minimum.

Finally, Table 2.2 affords a comparison of the special specifications for the Loop 610 project with those for various BCO projects constructed in recent years.

MEASUREMENTS PROGRAM

Measurement of several variables was considered on this experimental project. They can be thought of as response variables, CRCP-BCO system output variables, or performance variables.

A modified Nikon camera was mounted on a horizontal pole attached to a truck for photologging. Photologging allowed a pictorial record of pavement surface conditions before and after overlay construction.

The Dynaflect is widely used for measuring pavement surface deflections. In pavement engineering practice, surface deflections are used for many purposes (e.g., characterization of materials, detection of voids

TABLE 2.2. COMPARISON OF TBCO SPECIFICATIONS USED BY VARIOUS AGENCIES

	Agency				
Specification	Iowa	Louisiana	New York	Texas	U.S. Navy
One Facility type where used	Interstate Highway	Primary; rural highway	Interstate Highway	Urban Freeway	Parking Apron
Project Location and Date	I-80, West Iowa, Summer, 1979	US-61 May, 1981	I-81 North of Syracuse, April-October, 1981	South IH-610, Houston July-August 1983	Naval Air Station, Norfolk, VA
Length/Area	4-1/2 miles x 24 ft lanes	0.8 mile x 2 lanes	3 miles x 6 lanes (12 ft wide)	4 lanes x 1,000 ft	4,000 square yards
Original Pavement Type	CRCP (8-inch) JRCP (10-inch) 76-1/2 ft joint spacing	JRCP (9-inch) 20 ft joint spacing	JRCP (9-inch) 43 ft joint spacing	8-inch CRCP	25 x 25 ft slabs
Surface Preparation	Scarification and joint blasting	. Patching . Transverse joints cleaned and resealed . "Blastrac" slab cleaner . Air blasting	. 3-inch milling at deteriorated joints . Scarification . Sand blasting . Cleaning	. Scarification (1/4-inch) . Sand blasting . Air blasting	
TBCO Depth	3-inch Nominal	4-inch Average	3-inch Nominal	2-3 inches	2-12 inches
Unique TBCO Design	Yes	Yes	Yes	No	Yes
Maximum Size of Coarse Aggregate	3/4-inch	1-inch	1-inch	3/4-inch	1/2-inch
Slump (inch)	1-1/2 ± 1/2 inch	1 - 2-1/2 inch	2-1/2 inch	3 - 4 inches	4-inch maximum

(continued)

TABLE 2.2. (CONTINUED)

	Agency				
Specification	Iowa	Louisiana	New York	Texas	U.S. Navy
Cement Factor	595 lbs/cy	545.2 lbs		658 or 752 lbs/cy	600 lbs
Water/Cement Ratio	0.43 (.489)	0.48	0.44	0.40 or 0.44	.38 (including fly ash)
Air Content Percent	6.0	5 ± 2	5.5 - 9.5	4 - 6	4.5 ± 1.5
Bonding Agent	Water-Cement Sand-Grout	Water-Cement Grout	Water-Cement Sand-Grout	Water-Cement Grout	
Surface Finishing	Burlap Drag or Broomed Finish	Transverse Metal Tine Finish	Motor Driven Tine Rake	Tine Finish	. Transverse Finishing Machine . Hand Finishing in Emergencies or Inaccessible Areas . Longitudinal Floating . Straight Edge Finishing
Type of Concrete Curing	Curing Compound at 10 sq. yd per gallon	White Pigmented Curing Compound	White Pigmented Curing Compound at .75 SF per gallon	Membrane Curing at 120 SF per gallon for 4 days above 40°F	. Wet Burlap Mats, 7 days . Waterproof Paper, 7 days Blanket . Impervious Sheeting, 7 days
Unit of Measurement and Payment for TBCO Placed	Square Yard	Square Yard	--	Square Yard	--

underneath slabs, evaluation of load carrying capacity of pavement structures). In this case, the latter application was sought. Specifically, it was desired to know how surface deflections were affected by the various thin-bonded concrete overlay designs.

The General Motors Research (GMR) digital profilometer was used to record road profiles before and after overlay construction. By using roughness data, the profilometer permits the engineer to estimate serviceability index, a user-oriented performance measure of the roadway.

Visual condition surveys were conducted before and after overlay construction. The detailed method used in this case is called the "small sections" method. A crew walked the pavement and recorded any visible distress manifestations. Cracks were mapped and spalls were counted and classified as minor or severe. A condition survey is the single most important item of the pavement monitoring activities and will usually dictate the course of action (routine maintenance or major repair) to be taken.

Concrete movement across cracks and, therefore, crack width is a major factor contributing to the performance of CRCP. A mechanical strain gauge was used in this project to monitor concrete movement after overlay placement. To this end, metallic boxes with removable metal tops were inserted at quarter points within each of the five design sections; gauge plugs were placed in the boxes on the original CRCP and above the boxes across the same cracks on the BCOs. Prior to the overlaying, crack widths were read with a graduated microscope. The data appear in Table 2.3.

During construction, field tests were performed. They included concrete and air temperatures, concrete air value, slump test, and for the flexural strength test on beams.

After construction, 4-inch field cores were taken for laboratory testing. The tests were CRCP-BCO interface shear strength, using a modified shear collar, and splitting tensile strength.

TABLE 2.3. SELECTED CRACK WIDTH MEASUREMENTS WITH MICROSCOPE AT QUARTER POINT WITHIN EACH SECTION, PRIOR TO ROTO MILLING*

Location	Distance From Outside Edge (in.)	Microscope Reading ** (div.)	Crack Width (in.)
1	18	7	0.014
2	39	17	0.034
3	37	12	0.024
4	34	21	0.042
5	32	15	0.030
6	25	6	0.012
7	32	8	0.016
8	39	10	0.020
9	37	13	0.026
10	34	14	0.028
11	34	8	0.016
12	35	11	0.022
13	31	12	0.024
14	39	10	0.020
15	31	8	0.016

* Same cracks were instrumented for Berry strain gauge measurement.

** 1 division on microscope equals 0.002 inch.

Average temperature was 80'F.

CONSTRUCTION

Construction began July 22, 1983, and was completed August 27, 1983. After a six-day curing period for the last pour, all four lanes were opened to traffic. Much of the delay incurred is attributable to waiting out hurricane "Alicia," which struck the Houston-Galveston area August 18, 1983, and the subsequent lack of ice, used to control concrete placement temperature.

Construction proceeded in two phases:

(1) Phase 1, the placement of overlays on lanes 1 and 2, the inside two lanes, and

(2) Phase 2, the placement of overlays on Lane 3 and Lane 4, the outside two lanes.

Traffic Handling

For about a mile in advance of the project location, high visibility flashing signalization was used in addition to appropriate traffic signs to notify the drivers of the closure of two lanes and portable arrows to indicate which lanes to use. Portions of the existing 10-foot asphalt shoulders were temporarily used. Barrels partially filled with sand, often surmounted by caution flags, effectively closed off three lanes at a time to traffic. Removable 4-inch white lane delineators were used and speed limits posted. Traffic lanes were reduced from 12 feet to 10 feet.

In phase 1, the inside two lanes were closed to traffic and an additional lane was used to separate and protect workers from traffic. This lane was also useful in expediting construction. In this way, about a 25-foot width of pavement was available for construction.

In phase 2, the outside two lanes were closed to traffic. Traffic was rerouted on part of the inside asphalt shoulder and the completed overlay pavement. No accident was reported during the construction. A similar traffic handling scenario was used later for monitoring the test sections.

Sequence of Construction Operations

Surface preparation consisted of Roto milling to a nominal depth of 1/4 inch, which proved to be the minimum attainable, given the equipment and pavement material. Dust control was a problem when it was windy. An estimated three passes on average was required to cover the width of pavement to overlay. After milling, the pavement surface was broomed with a stiff bristle broom to remove all chippings. Thereafter, the longitudinal joint sealing material was removed using jack hammers. Finally, the surface was thoroughly sand blasted to remove all contaminants.

At this stage, clean sound concrete was exhibited. Transverse cracks which had a bad appearance at the surface now looked tightly closed; this was a sign that the original CRCP was structurally adequate. It was also revealed that the polymer concrete patching material had indeed penetrated deeply into the cracks.

The last phase of the pavement surface preparation consisted of air blasting as close as possible to the grouting and paving operations. Following air blasting, double polyethylene sheet protection was spread in the middle of the two lanes to be overlaid; ready-mix concrete trucks were backed up on these sheets so that the prepared pavement surface was free from their tire imprints and engine and transmission oil drippings. It should be noted that no repair work (e.g., joint or crack sealing, deep patching, slab jacking) was necessary on the prepared CRCP surface, which appeared to be in excellent condition.

Immediately prior to paving, a water and cement grout was uniformly broomed onto the full width of the prepared CRCP surface. The grout consisted of water, cement, and a water reducing plasticizer. The water-cement ratio was about 0.62 by weight or seven gallons of water per sack of cement. The plasticizer used gave the bonding grout a creamy aspect. The concrete was batched at a central plant and hauled in ready-mix trucks to the construction site. The trucks were loaded at six cubic yard or less than 80 percent of capacity.

The concrete was dumped onto the grouted pavement surface and spread manually. A transverse concrete finisher guided by rails was used to consolidate and finish the concrete to grade. The inspector took frequent readings to insure that the nominal specified thicknesses were obtained. Surface texturing consisted of transverse metal tine finish (i.e., wire combing), and was accomplished by hand from a working bridge.

Following surface texturing, a white pigmented impervious curing component was spread uniformly onto the overlay surface from a second working bridge.

Within 24 hours of a pour, the pavement edge and centerline longitudinal joints were saw cut. The centerline longitudinal joints were cut to a nominal one inch depth and sealed with a hot-poured asphaltic material.

In phases one and two of the construction, the last pour was allowed to cure for a minimum of six days before the lanes were opened to traffic.

CHAPTER 3. FIELD MEASUREMENTS

This chapter presents field data collected as part of the Loop 610 experiment; various analyses of the data are conducted in an effort to ascertain the responses of interest. Specifically, Dynaflect deflection data, concrete movement data, and quality control/quality assurance data are collated and interpreted. This constitutes the basic purpose of the experimental project.

During the course of the study, five periodic pavement evaluation surveys were conducted by Center for Transportation Research personnel as follows:

(1) May 11, 1983: Before overlay.
(2) September 8, 1983: First survey immediately after overlay.
(3) February 15-16, 1984: Second survey after overlay.
(4) November 7-8, 1984: Third survey after overlay.
(5) May 7-8, 1985: Fourth and final survey after overlay.

Note that overlay construction was completed August 27, 1983. The various activities conducted were as shown in Table 3.1 over a two year period before and after overlay construction.

PAVEMENT DEFLECTION

The Lane-Wells Dynaflect device was used throughout this study to measure pavement deflections. Dynaflect deflections were taken during all five pavement evaluation surveys.

Test Points Location

The Dynaflect test points were located with reference to the expansion joint at the approach slab of the Calais Street overpass bridge; as can be

TABLE 3.1. PERIODIC PAVEMENT EVALUATION SURVEY BY YEAR

	Pavement Evaluation Survey			
Survey Date	Visual Condition Survey	Dynaflect Deflection Measurements	Longitudinal Profile Roughness Measurements	Photologging
May 1983	Yes	Yes	Yes	Yes
September 1983	No	Yes	Yes	No
February 1984	Yes	Yes	Yes	No
November 1984	Yes	Yes	Yes	No
May 1985	Yes	Yes	Yes	Yes

seen in Fig 2.1, the Calais Street overpass bridge is at the end of the test sections. Nine to twelve points were selected approximately on the centerline of each lane within each design section for both the crack condition (i.e., Dynaflect loading wheels close to a designated transverse crack) and the midspan condition (i.e., Dynaflect loading wheels midway between two consecutive transverse cracks). Crack and midspan points were alternated, before and after overlay construction. Once selected, the test points were marked with spray paint and labelled C (for crack) or M (for midspan). In general, the paint endured the traffic remarkably well. Also, a rolling tape was used before and after overlay to reference all test points marked to the expansion joint; the measurements obtained were recorded for possible future use.

Methodology

The methodology adopted calls for repeat measurements of the same test points before and after overlay construction. Although the stated objective was to test ten points per design section for crack condition and ten more points for midspan condition, a drift occurred during actual testing as can be seen on Table 3.2, which shows the total number of points actually tested by section, lane, and date. However, since this drift resulted in the loss of observations in some cells of the experiment design in an essentially random manner (i.e., not directly related to the experimental variables) the analysis is conducted by the method of unweighted means; this approach is in conformity with the views expressed by Winer (Ref 12).

Note that because interior loading was used and Dynaflect testing was usually finished before the hottest part of the day (i.e., the pavement still curled upward or was at full contact with the subbase in the center), no temperature correction was used in the analysis of the Dynaflect data. Further, since relative comparisons were the primary goal and temperature correction would not necessarily provide more accurate results, raw data was used throughout and served the intended purpose quite well.

Dynaflect data have been used in a number of studies to evaluate the structural adequacy of pavements. Many state highway departments

TABLE 3.2(a). NUMBER OF DYNAFLECT DEFLECTION POINTS TESTED BY DESIGN SECTION AND DATE

Design Sections	May 1985	November 1984	February 1984	September 1983	May 1983
2" NR	76	76	48	74	74
2" R	92	92	58	92	92
3" R	84	83	54	82	80
3" F	92	90	54	88	88
2" F	71	74	46	76	76
Total	415	415	260	412	410

TABLE 3.2(b). NUMBER OF DYNAFLECT DEFLECTION POINTS TESTED BY LANE NUMBER AND DATE

Lane* Number	Date				
	May 1985	November 1984	February 1984	September 1983	May 1983
1	105	104	104	100	100
2	104	104	52	104	104
3	104	102	52	104	104
4	102	105	52	104	102
Total	415	415	260	412	410

*Note: Lanes are numbered outwardly, i.e, the innermost lane (closest to the median barrier) is labeled Lane 1 and the outermost lane (closest to the outside shoulder) is labeled Lane 4.

currently use Dynaflect deflections or other dynamic deflection sampling and measurements as part of their overlay design methods. Dynaflect sensor measurements and other deflection parameters (e.g., Surface Curvature Index, Base Curvature Index, Deflection Basin Slope, and Spreadability) have been correlated, with mixed success, to the performance of various types of pavements.

Also, it has been found that the sensor No. 5 deflection (W_5) could be used to accurately predict the Young's modulus of the subgrade and that the sensor No. 1 deflection (W_1) was better correlated with the surface layer modulus and, in addition, provided a good indication of the overall pavement structural capacity.

In this report, deflection fitting techniques are used to obtain the elastic constants of the various layers of the South Loop 610 pavement structure at the experimental project site. In this manner, test section remaining lives and structural benefits of BCOs can be assessed.

SUMMARY AND CONCLUSIONS FOR THE DEFLECTION STUDY

Three methods of analysis have been used: univariate analysis of variance, multiple classification analysis, and multivariate analysis of variance. Details of the analyses are given in Appendix B.

The univariate analysis of variance revealed that the main effects lane and section were significant at a 5 percent confidence level. The interaction lane by section was also significant. The effect of sensor 1 position for the base CRCP and all other two-way interactions for all four Dynaflect data sets corresponding to testing dates May 1985, November 1984, September 1983, and May 1984 were not significant.

The February 1984 data set was found ill-conditioned and probably in error. Rather than attempt to reorder the data (by increasing the order of magnitude corresponding to the sensor layout) or other such manipulation, this data set was removed from further analysis.

The multiple classification analysis allowed for ordering of lane and section effects for a given survey date.

Before overlay, the 2"F section had the lowest mean deflection and the 2"R the highest. Lane 1 had the lowest mean deflection and Lane 3 the highest.

Immediately after overlay, the differences between the mean lane deflections were negligible (about one-tenth their initial values) and differences between mean section deflections varied depending on the sensor number.

After overlay, the 3"F section had the lowest mean deflection and the 2"NR the highest. The difference between the mean lane deflection varied depending on the sensor number.

The before minus the after Dynaflect data allowed for an assessment of the structural benefit of the five BCO design sections. This immediate effect was analyzed using univariate analysis of variance, multiple classification analysis, and multivariate analysis of variance. It was found that significant effects were lane, section and their interaction. The position of sensor 1 was significant for sensor 1 and sensor 2 measurements only.

Again, it was found that the 3"R section induced the greatest reduction in pavement deflection. Lane 3, the lane with the worst deflection characteristics, showed the largest improvement after overlay. In fact, the order in lane deflection characteristics improvement remained unchanged (i.e., 2nd worst, 2nd largest improvement, etc.).

In the multivariate analysis of variance, three effects were studied: survey date effect, section effects for each survey date, and immediate section effect after BCO construction. The analysis of the date effect revealed that even if the before overlay data set is not considered, the data sets after overlay were significantly different; thus, these data sets could be studied on a date basis.

The section effect study showed that all other sections had significantly different deflection basins from the 3"R, the section which had the largest reduction in deflection after overlay, on all survey dates but May 1985 and November 1984, when the 3"R and the 2"R had statistically the same deflection characteristics. Therefore, the thickness effect varied by survey date (i.e., there is a date by thickness interaction).

The immediate section effect study revealed that thickness effect is significant for a high level and intensity of traffic and that this effect appears sooner for the fiber sections than for the steel reinforced sections.

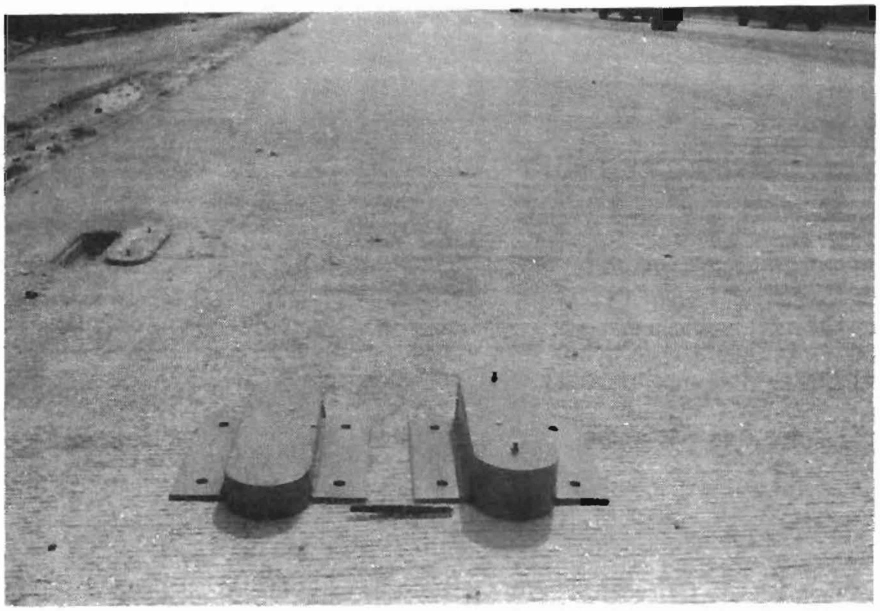
For a level of traffic the fibers were more effective in reducing the deflection of overlaid CRCP.

CONCRETE MOVEMENT AT CRACKS

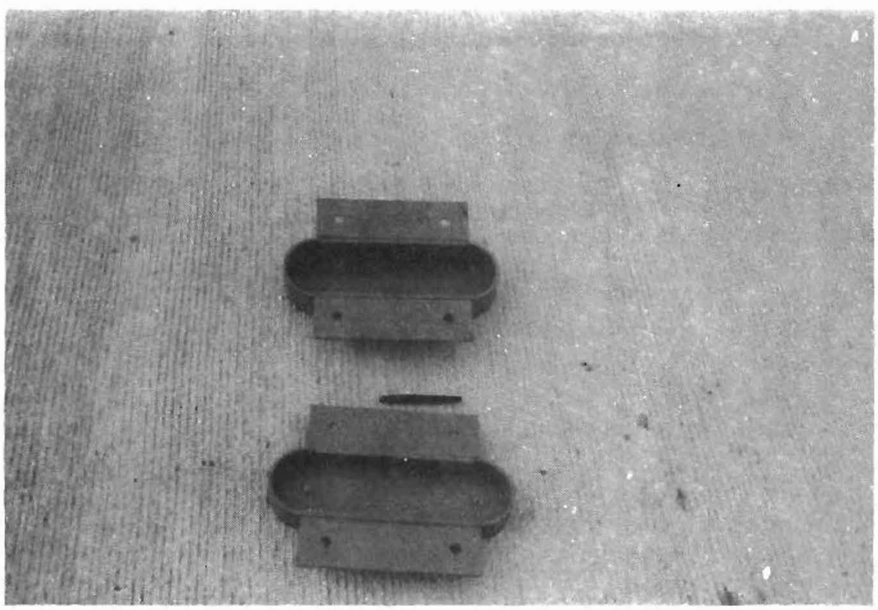
Experiment Design

As part of the measurement program on the South Loop 610 BCO project, it was proposed to study for a period of time immediately following construction the movements of the CRCP and the five overlay sections across designated cracks. It was felt that three typical cracks at quarter points within each design section would provide representative data to be extended to the entire section in question. The main issue to address at that point was how to maintain contact with the original CRCP after overlay placement. To this end, 15 metal boxes were fabricated at the Center for Transportation Research. These were to be fastened onto the milled CRCP surface so that their tops would be flush with the overlay surface. Accordingly, nine 2-inch-high boxes and six 3-inch boxes were required. Figure 3.1 shows typical measurement boxes used at the site. Note that all boxes were coated with a multilayer of paint to inhibit rusting.

The measuring equipment selected was a Whittemore type multi-position strain gauge developed by Soil Test, Inc., Evanston, Illinois. It is a high precision mechanical strain gauge capable of "measuring movements through a range of 0.2 inch with dial gradation of 0.0001 inch" (Ref 15).



(a) Box tops.



(b) Box bottoms.

Fig 3.1. Typical two and three inch high concrete movement measurement boxes used in Lane 4.

For a period of two to three weeks immediately following overlay construction, concrete movement was measured along with air temperature. The measurements were taken three times daily: morning, afternoon, and night. An outdoor thermometer with glass casing was first used during the experiment. It was hung on a string and swung in the air above the pavement to obtain an average air temperature at the time of concrete movement measurement. During the experiment, this thermometer broke and was replaced by a fresh concrete thermometer with a metal probe. Air temperature was measured in an identical manner.

Two sets of gauge plugs were installed on the CRCP (inside the boxes) and on the BCO (outside the boxes), respectively, as part of the Phase II construction operations encompassing the overlaying of the outside two lanes, 3 and 4.

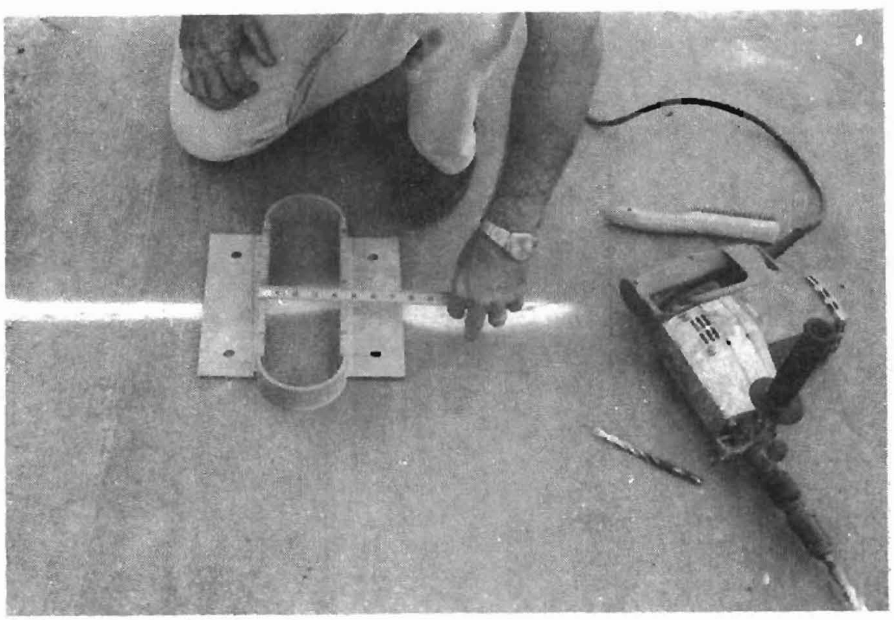
The inside dimensions of the measurement boxes were approximately 4 x 14 inches (Fig 3.2). These boxes were installed at 18 inches on center from the outside shoulder edge. The outside gauge plugs were installed at 12 inches from the boxes or a total of 30 inches from the pavement edge (Fig 3.3). All concrete movement measurements were confined to Lane 4, the outermost lane.

The installation procedure for the two sets of plugs was not the same; the inside plugs were epoxied down on the milled CRCP surface whereas the outside plugs were mounted on brass inserts that were first drilled into the "green" concrete and then epoxied down to the proper elevation.

The sequence of the box and gauge plug installation is illustrated in Figs 3.4 through 3.7. The finished product is illustrated in Fig 3.8, and Fig 3.9 shows a typical measurement.

Finally, it must be said that the shape and the dimensions of the boxes were designed to sustain traffic loading while allowing for easy access to the gauge plugs. By and large, this objective was achieved as revealed by the periodic condition surveys.

(a) Half length at 7 inches.



(b) Width at 4 inches.

Fig 3.2. Dimension of concrete movement measurement boxes.

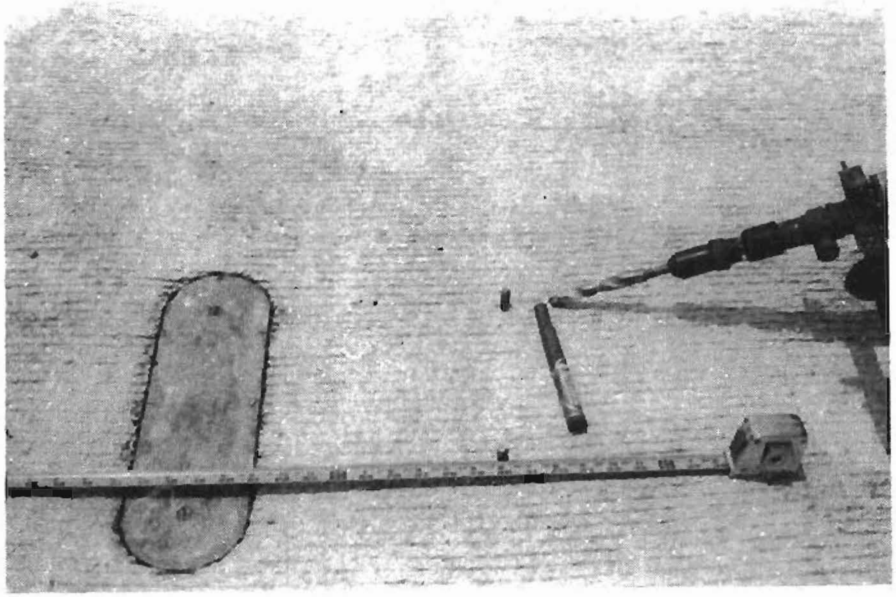


Fig 3.3. Location of gauge plugs with respect to outside shoulder; inside plugs at 18 inches on center and outside plugs at 30 inches.

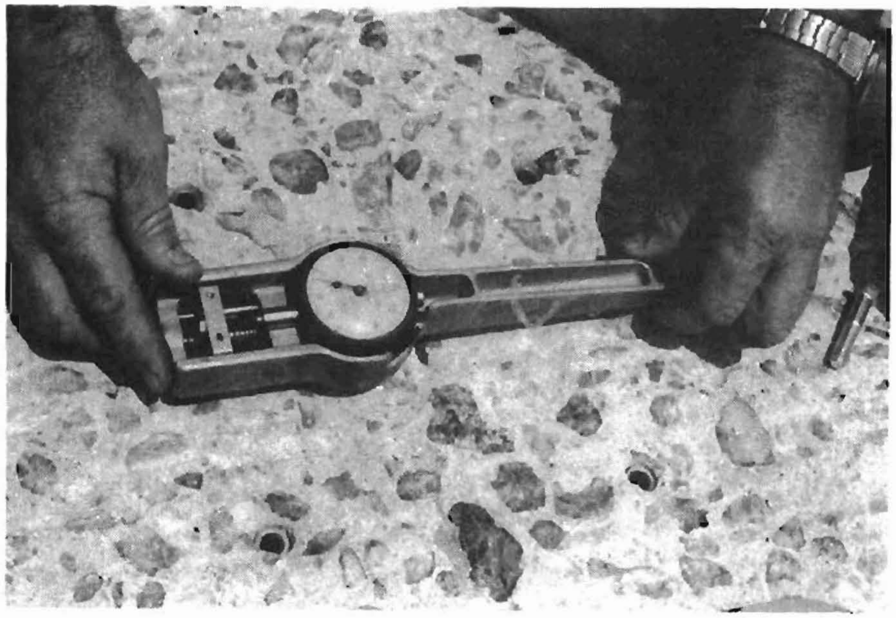


Fig 3.4. Installation of inside gauge plugs on surface of CRCP at 8 inches gauge length. Note crack location.

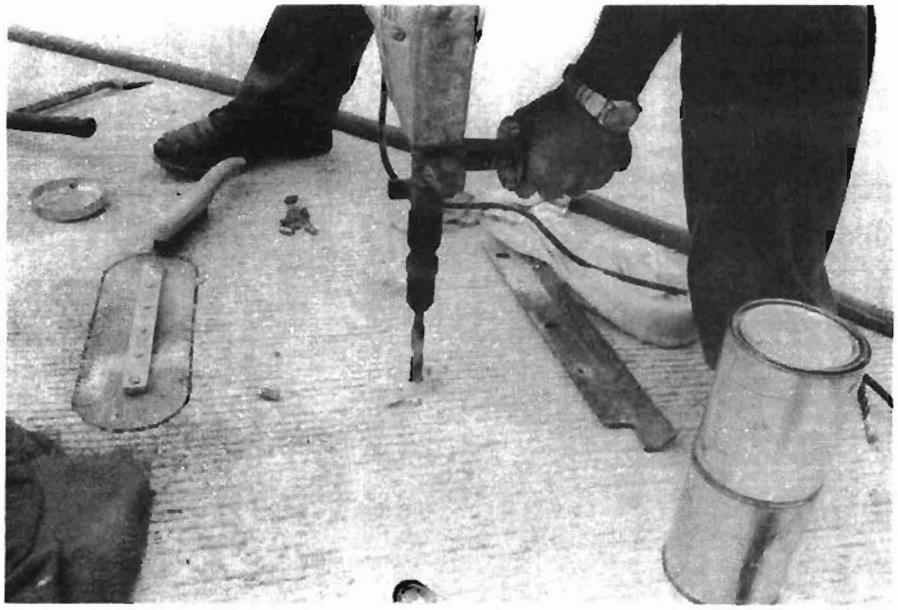


Fig 3. 5. Installation of outside gauge plugs; drilling of "green" overlay concrete.

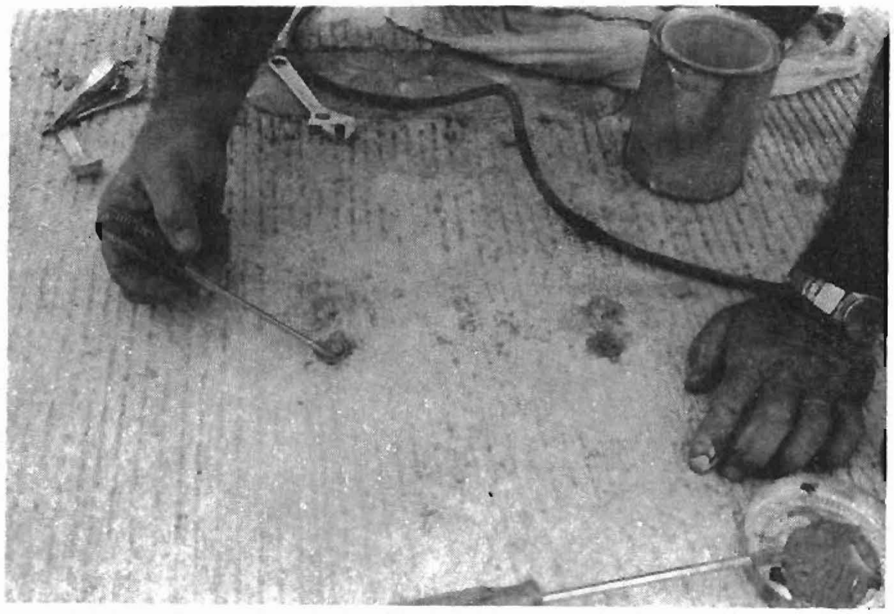


Fig 3. 6 . Installation of outside gauge plugs; plugs being epoxied down to proper elevation.

Fig 3.7. Installation of inside gauge plugs; sealing bottom of a measurement box with slicone compound.

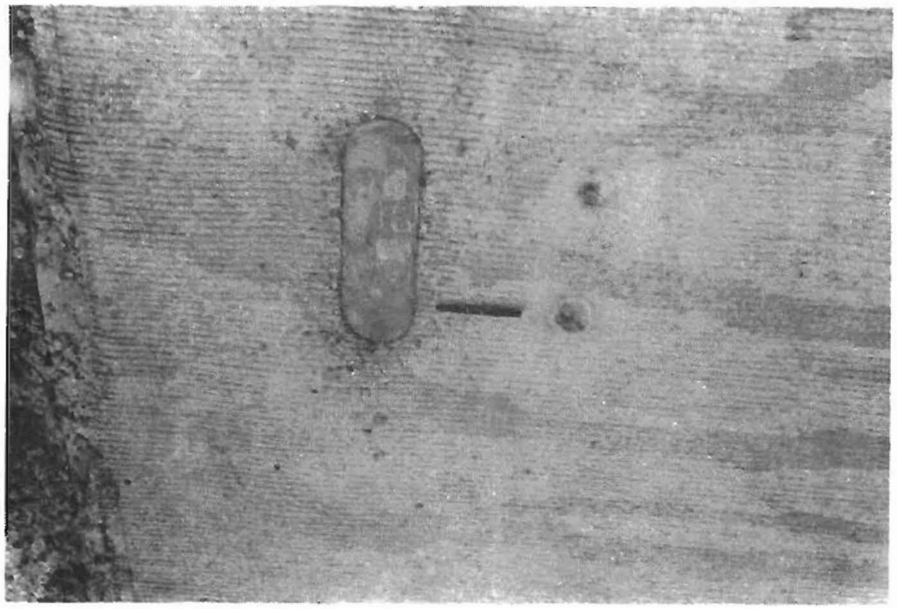


Fig 3. 8 . Final appearance of concrete movement measurement box; note how it is flush with BCO surface. Also note outside plugs. Marker is for scale.

Fig 3. 9. Typical concrete movement measurement on inside plugs. Note easy access and position of hands. Also note standard bar on BCO surface.

Testing Procedure

A gauge length of 8 inches was used throughout for both inside plugs and outside plugs. On each test run, the top covers of the boxes were removed to give access to the inside gauge plugs. A reading was taken on the inside plugs followed by a reading on the outside plugs, and this sequence was repeated all over again. If the two measurements related to either set of plugs differed by a significant amount, then additional measurements were called for. Otherwise, the operators proceeded to the next set of plugs. This procedure allowed for true replicates of measurements. Figure 3.10 shows the form used in the field to record the data. It was specifically laid out to be easy to use in the field as well as practical.

Recorded Concrete Movement

First, the concrete movement, X_G or successive readings was calculated as follows:

$$X_G = C_i - C_o$$

where

C_o = initial difference between bar reading, A_o and gauge plug reading, B_o; and

C_i = subsequent difference.

Therefore, $C_i = A_i - B_i$; $i = 0, 1, 2, \ldots$; and i is an index that denotes the incidence of measurements over time.

C_o is also called the reference constant. Its algebraic value is subtracted from all subsequent measurements to obtain the relative movement of concrete across a crack, X_G (i.e, crack opening and closing). This relative movement can be related to many variables. In this study, however, temperature and time after overlay construction in 1/2 hour increments (a substitute variable for shrinkage) were used as explanatory variables.

CONCRETE MOVEMENT DATA FORM
Experimental Thin-Bonded Concrete Overlay Project
Loop 610, Houston

Section Number: ______________ Box Number: __________
Operator's Name: ______________ Agency: ______ Position: ______
Starting Date: ____/____/____ Air Temperature: ______°F
Finishing Date: ____/____/____ Air Temperature: ______°F

Run No.	Date (mo/day/yr)	Time (hr:min)	Air Temp (F)	Bar Reading No. 1	Gauge Plug Reading No. 1	Bar Reading No. 2	Gauge Plug Reading No. 2	Comments
	INSIDE GAUGE PLUGS							
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
	OUTSIDE GAUGE PLUGS							
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
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15								
16								
17								
18								

Fig 3.10. Concrete movement data form.

Next, summary statistics of the data collected at all 15 cracks are tabulate and presented in Table 3.3. In this table, negative values correspond to elongation/expansion from initial reading, and positive values to contraction. Thus, it can be seen that, on an average, the type of concrete movement experienced by the inside and outside gauge plugs (i.e., CRCP and BCO) is the same; in other words, the behavior of the pavement system is monolithic. A few exceptions are noted however in the fiber sections (Box 11, 13, and 14).

The probable implication here is that, over the measurement period, no significant debonding had occurred.

Another observation concerns the order of magnitude of the movement. The mean value for the BCO gauge plugs is in general several orders of magnitude smaller than it is for the underlying CRCP.

The implication in this case is that in most likelihood, the cracks monitored in the CRCP had not reflected through the BCO or that if they had, they were even more tightly closed in the BCO than in the CRCP. A few exceptions are noted in the steel mat reinforced sections (e.g., Boxes 5 and 9).

CONCRETE FIELD TESTS

During overlay construction, a number of tests were conducted for concrete quality control. These included the slump test, determination of concrete air content, determination of minimum overlay depth, concrete temperature, and 7-day flexural strength test of beams. The results of these tests are presented in Table 3.4 for both phase 1 of the construction, involving Lane 1 and Lane 2 (the inside two lanes), and phase 2 of the construction, involving Lane 3 and Lane 4 (the outside two lanes). Note that lanes are numbered outwardly from the median; thus, Lane 1 is the lane adjacent to the median and Lane 4 is adjacent to the outside shoulder.

TABLE 3.3. SUMMARY STATISTICS FOR CONCRETE MOVEMENT DATA

		Inside ($\times 10^{-4}$ in.)			Outside ($\times 10^{-4}$ in.)		
Design Section	Box Number	Median	Mean	Standard Deviation	Median	Mean	Standard Deviation
2"NR	1	32	30	16	5	5	4
	2	- 23	- 26	13	- 14	- 13	6
	3	13	12	10	13	13	6
2"R	4	2	-0.3	9	7	8	5
	5	- 3	- 3	14	- 38	- 36	18
	6	3	4	22	3	2	5
3"R	7	12	9	9	- 8	- 8	4
	8	4	5	18	0	4	12
	9	4	4	7	14	13	6
3"F	10	- 5	- 7	8	- 3	- 3	3
	11	- 83	- 87	9	7	6	4
	12	3	- 62	242	-0.5	-0.4	2
2"F	13	9	9	5	- 9	- 9	5
	14	- 7	- 5	8	2	1	3
	15	4	3	5	88	58	49
Expansion Joint					- 80	- 89	146

TABLE 3.4. CONCRETE QUALITY CONTROL DATA DURING OVERLAY CONSTRUCTION

Phase	Lanes	Section	Average Slump (in.)	Average Flexural Strength (PSI at 7 days)	Average Chace Air Value (percent)	Range of Concrete Temperature (°F)
1	1 and 2	2"NR	3.6	889	4.1	75 - 82
		2"R	4.3	878	2.4	76 - 78
		3"R	5.5	992	3.0	79 - 85
		3"F	5.2	870	5.3	79 - 85
		2"F	5.1	920	4.6	79 - 83
2	3 and 4	2"NR	3.4	730	3.8	77 - 82
		2"R	4.1	798	4.2	78 - 83
		3"R	3.7	840	3.1	75 - 82
		3"F	5.0	838	4.9	72 - 78
		2"F	4.3	898	5.1	80 - 84

As can be seen, the flexural strength of concrete for the 7 days test is well above the 700 psi specified for the entire population; the mean flexural strength is $\bar{f}$ = 864 psi with a standard deviation σ_f = 75 psi. Although no durability test (e.g., freeze - thaw) was performed, it can be inferred from the Chace air values (2.4 to 5.3 percent) that this concrete property would most likely be adequate.

Workability, as measured by the concrete slump, varied between 3.4 and 5.5 inches. This made for a concrete that could easily be placed. The fiber sections did not present any particular difficulty in that respect. In general the fiberous concrete was easily cast and surface finished. The metal tine finish adopted was particularly appropriate in that it would rearrange the steel fibers at the surface in a direction perpendicular to traffic, thus effectively eliminating any potential for damage to rolling tires caused by the steel fibers used in the paving concrete mix.

CHAPTER 4. ANALYSIS OF PERFORMANCE DATA

In this chapter, performance of the test sections is evaluated in terms of the condition survey variables (e.g., cracking and spalling) and ride quality (i.e., longitudinal profile roughness data).

CONDITION SURVEY DATA

Condition survey data were collected in May 1983 (before overlay construction), February 1984 (first condition survey after construction), November 1984 (second condition survey after construction), and May 1985 (third condition survey after overlay).

The method used is called the small sections method. It is a detailed procedure used for CRC pavements when complete information is desired and is particularly appropriate for roadways that are experimental in nature (Ref 16). At the Houston site, two lanes at a time were blocked off to traffic. To conduct the survey, a team walks onto the pavement in the lane to be surveyed. Any visible distress is noted and referenced with a rolling tape to some fixed highway element (e.g., milepost). In particular, longitudinal and transverse cracks are mapped, and spalling is counted and classified as either minor or severe spalling.

Subsequently, the data are entered on a computer file and processed through the computer program CONSMS. The purpose is to store the data so they can be easily accessed or manipulated at a later stage. The output from CONSMS is summary information from all previous surveys. For the south Loop 610 experiment, the condition survey information derived from the CONSMS output is presented in Tables 4.1 through 4.4. The data are first aggregated by section, then by lane.

Tables 4.1 through 4.4 are derived from Tables 4.5 through 4.8, which are three-way classifications of longitudinal cracking (Table 4.5), transverse cracking (Table 4.6), minor spalling (Table 4.7), and severe spalling (Table 4.8). The classification factors are lane (4 levels),

TABLE 4.1. CRACKING SUMMARY IN THE VARIOUS DESIGN SECTIONS

Cracking	Design Section	Survey Before Construction, May 1983	First Survey After Construction, February 1984	Second Survey After Construction, November 1984	Third Survey After Construction, May 1985
Longitudinal (ft)	2" NR	323	245	475	276
	2" R	200	202	552	122
	3" R	291	247	595	316
	3" F	489	4	124	0
	2"F	348	60	74	53
Transverse (Actual Count)	2" NR	264	81	143	49
	2" R	305	116	249	131
	3" R	289	223	374	130
	3" F	288	28	99	44
	2"F	119	11	28	4

TABLE 4.2. SPALLING SUMMARY IN THE VARIOUS DESIGN SECTIONS

Spalling	Design Section	Survey Before Construction May 1983	First Survey After Construction February 1984	Second Survey After Construction November 1984	Third Survey After Construction May 1985
Minor	2" NR	17	0	0	0
	2" R	18	0	0	0
	3" R	9	0	0	0
	3" F	15	0	0	0
	2" F	4	0	0	0
Severe	2" NR	109	0	0	0
	2" R	82	0	0	0
	3" R	103	0	0	0
	3" F	87	0	0	0
	2" F	17	0	0	0

TABLE 4.3. CRACKING SUMMARY IN THE VARIOUS LANES

Cracking	Lane Number	Survey Before Construction, May 1983	First Survey After Construction, February 1984	Second Survey After Construction, November 1984	Third Survey After Construction, May 1985
Longitudinal (ft)	1	149	102	147	118
	2	498	363	535	428
	3	602	146	229	169
	4	402	147	309	52
Transverse (Actual Count)	1	283	118	228	89
	2	319	108	203	87
	3	344	121	245	109
	4	319	112	217	73

TALBE 4.4. SPALLING SUMMARY IN THE VARIOUS LANES

Spalling	Lane Number	Survey Before Construction May 1983	First Survey After Construction February 1984	Second Survey After Construction November 1984	Third Survey After Construction May 1985
Minor	1 (Innermost)	11	0	0	0
	2	12	0	0	0
	3	19	0	0	0
	4 (Outermost)	21	0	0	0
Severe	1 (Innermost)	139	0	0	0
	2	131	0	0	0
	3	51	0	0	0
	4 (Outermost)	77	0	0	0

TABLE 4.5. LONGITUDINAL CRACKING BY DATE, SECTION AND LANE (FT)

Date	Section	Lane Number 1	2	3	4	Total
May 1983	2" NR	25	112	121	65	323
	2" R	66	46	24	64	200
	3" R	30	49	152	60	291
	3" F	12	153	183	141	489
	2" F	16	138	122	72	348
Total		149	498	602	402	
February 1984	2" NR	16	101	94	34	245
	2" R	53	59	29	61	202
	3" R	33	143	23	48	247
	3" F	0	4	0	0	4
	2" F	0	56	0	4	60
Total		102	363	146	147	
November 1984	2" NR	51	175	160	89	475
	2" R	219	157	29	147	552
	3" R	277	243	23	52	595
	3" F	0	4	3	117	124
	2" F	0	56	14	4	74
Total		547	635	229	409	
May 1984	2" NR	46	133	89	8	276
	2" R	20	26	72	4	122
	3" R	52	216	8	40	316
	3" F	0	0	0	0	0
	2" F	0	53	0	0	53
Total		118	428	169	52	

TABLE 4.6. TRANSVERSE CRACKING BY DATE, SECTION AND LANE (ACTUAL COUNT)

Date	Section	Lane Number 1	2	3	4	Total
May 1983	2" NR	59	65	76	64	264
	2" R	71	82	75	77	305
	3" R	62	71	77	79	289
	3" F	65	72	82	69	288
	2" F	26	29	34	30	119
Total		283	319	334	319	
February 1984	2" NR	6	17	33	25	81
	2" R	5	15	49	47	116
	3" R	103	54	38	28	223
	3" F	2	17	1	8	28
	2" F	2	5	0	4	11
Total		118	108	121	112	
November 1984	2" NR	15	27	53	48	143
	2" R	41	43	87	78	249
	3" R	136	98	76	64	374
	3" F	30	27	21	21	99
	2" F	6	8	8	6	28
Total		228	203	245	217	
May 1983	2" NR	11	10	14	14	49
	2" R	20	16	57	38	131
	3" R	42	48	24	16	130
	3" F	14	11	14	5	44
	2" F	2	2	0	0	4
Total		89	87	109	73	

TABLE 4.7. MINOR SPALLING BY SECTION AND LANE, MAY 1983

		Lane Number				
Date	Section	1	2	3	4	Total
May 1983	2" NR	5	3	3	6	17
	2" R	0	4	6	8	18
	3" R	2	2	4	1	9
	3" F	1	3	5	6	15
	2" F	3	0	1	0	4
Total		11	12	19	21	

TABLE 4.8. SEVERE SPALLING BY SECTION AND LANE, MAY 1983

		Lane Number				
Date	Section	1	2	3	4	Total
May 1983	2" NR	32	30	22	25	109
	2" R	24	28	13	17	82
	3" R	37	36	11	19	103
	3" F	39	29	5	14	87
	2" F	7	8	0	2	17
Total		139	131	51	77	

section (5 levels) and date (4 levels). In Tables 4.5 and 4.6, the information is presented for four time periods (one before overlay and three after overlay); in Tables 4.7 and 4.8, the information is presented only for the before overlay survey, because no spall had occurred when the last three condition surveys were taken. Thus, in February 1984, November 1984, and May 1985 table entries for both minor and severe spalling categories are all zeros. Tables 4.5 through 4.8 are presented to give the reader insight into the level of aggregation which is not evident from an examination of Tables 4.1 through 4.4. The latter set of tables summarizes the distress manifestation under consideration.

Table 4.1 presents cracking in the various design sections for the four time periods when condition survey data were collected. Two types of cracking were recorded: longitudinal cracking and transverse cracking. Longitudinal cracking is measured in units of lineal feet whereas transverse cracking is measured as number of occurrences (i.e., actual count).

As can be seen, a significant decrease in the amount of both types of cracking was noted six months after overlay placement, and the harshest winter on record in the recent past in Houston (February 1984 data), followed by a tremendous increase for the November 1984 data and, finally, a sudden decrease. The history of cracking is as would normally be expected, except for the last change. The recorded decrease in the amount of cracking is best explained by a combination of factors, but most importantly a change in survey team. In addition, weather condition (the tightly closed cracks in a CRCP are best seen shortly after a light to medium rain when the pavement is still wet) and seasonal effect (e.g., pavement temperature at the time of the condition survey) may have influenced the visual condition survey. However, the trend in Table 4.1 still indicates that the fiber sections exhibit the best performance with respect to cracking, and the 3-inch steel reinforced section the worst.

Table 4.2 presents the number of spalled cracks by section for before and after overlay conditions. As can be seen, virtually no spall has occurred after almost two years of thin bonded concrete overlay placement.

Table 4.3 presents the cracking information by lane. Again, the units of measurement are lineal feet for longitudinal cracking and number of occurrences (i.e., actual count) for transverse cracking. In this form of presentation, the data primarily indicate the effect of traffic. Basically, after overlay construction in February 1984, the amount of longitudinal and tranverse cracking was halved in the various lanes. At the next survey date, the amount of cracking had almost returned to the original level. Finally, a significant decrease is noted at the May 1985 survey. The effect of BCO on cracking is evident in all lanes in February 1984. In November 1984, the increase in cracks is most likely due to reflection cracking of the base CRCP. The survey team effect manifested itself in the difference between November 1984 and May 1985 data.

Transverse cracking across the four lanes seems to occur more uniformly than longitudinal cracking. Most likely, transverse cracks reflect through the BCO earlier and more systematically than longitudinal cracks.

Overall, Lane 1 has the least amount of cracking and Lane 3 the most. Therefore, an informal observation that the second right most lane on south Loop 610 is the most heavily trafficked lane is confirmed.

Table 4.4 presents spalling by lane. Notice that no cracks showed evidence of spall after overlay until May 1985 (twenty months after overlay construction).

ROUGHNESS DATA

The new GMR digital profilometer was used in at least two consecutive runs within each of the four lanes of the test sections. The data obtained were subsequently processed through the VERTAC computer program at the Center for Transportation Research. The VERTical ACceleration (VERTAC) program computes road profile statistics and estimates serviceability index, a user-oriented performance measure, based on combined information obtained under both trailing wheels of the profilometer.

The Serviceability Index (SI) values are presented in Table 4.9 by lane, design section, and date. Because short sections, approximately 200 feet

TABLE 4.9. SERVICEABILITY INDEXES BY LANE, SECTION AND DATE

Lane Number	Design Section	May 1983	September 1983	February 1984	November 1984	May 1985
		Date				
1	2" NR	2.37	3.49	3.36	3.37	3.24
	2" R	3.66	3.35	3.45	2.89	3.19
	3" R	2.67	2.78	2.99	2.56	2.62
	3" F	3.57	2.44	2.24	2.13	2.12
	2" F	4.21	2.36	2.28	2.06	2.32
2	2" NR	3.70	3.66	3.76	3.58	3.33
	2" R	3.57	2.96	3.08	2.78	2.70
	3" R	3.71	3.23	3.46	3.43	3.00
	3" F	3.76	3.33	3.33	3.06	3.17
	2" F	4.41	3.03	3.07	2.06	3.03
3	2" NR	4.11	3.06	3.07	3.00	3.03
	2" R	3.92	3.22	3.46	3.32	3.32
	3" R	3.89	3.44	3.61	3.50	3.14
	3" F	4.08	2.61	2.64	2.45	2.62
	2" F	4.44	3.25	3.59	3.45	3.22
4	2" NR	3.30	3.19	3.09	2.77	3.13
	2" R	3.62	3.40	3.70	3.27	3.44
	3" R	3.94	3.11	3.11	2.80	2.96
	3" F	3.95	2.70	2.82	2.58	2.54
	2" F	3.93	3.23	3.25	2.86	2.14

long, were used, roughness data by section which could be derived from Table 4.9 would not be meaningful. Therefore, only SI values by lane are presented in Table 4.10 for the various survey dates.

As can be seen in Table 4.10, after overlay construction a general decrease in SI values occurred. This, it appears, resulted from a lack of grade control during construction, and shorter "as-constructed" transitional sections than the design originally called for.

Finally, surface finishing was achieved by wire combing. This may have had a negative impact. To sum it up, it seems roughness was built in to all four lanes. However, the SI values are about 3.0 in most cases, and little change is evident over the two year pavement monitoring period, indicating an overall good riding pavement. Also, the decrease of SI value right after overlay by no mean reflects negatively on the structural benefit obtained by placing the various BCO design.

SUMMARY AND CONCLUSIONS FOR THE ANALYSIS OF PERFORMANCE DATA

After BCO construction, the amount of surface cracking decreased signficantly. Both longitudinal and transverse cracking showed this trend by section and by lane. Subsequent surveys show a substantial increase first followed by a decrease. At the last survey, the level of the observed distress is decreased but the relative rankings are not changed. This is mainly due to a change in the survey team. If one averaged data for the last two survey dates and compared the result to the February data, a modest increase would be noted, which most likely correspond to the actual field conditions.

All in all, the 3-inch fiber section has the least amount of longitudinal cracking and the 3-inch steel reinforced the most, and the 2-inch fiber section has the least amount of transverse cracking and the 3-inch steel reinforced section the most.

A comparison by lane indicates that overall Lane 1, the lane next to the median barrier, has the least amount of cracking and Lane 3, the second rightmost lane, the most.

TABLE 4.10. SERVICEABILITY INDEX BY LANE AND DATE

Lane Number	Date				
	May 1983	September 1983	February 1984	November 1984	May 1985
1	3.1	2.9	2.9	2.6	2.7
2	3.8	3.2	3.3	3.0	3.0
3	4.1	3.1	3.3	3.1	3.1
4	3.7	3.1	3.2	2.9	2.8

After almost two years of BCO placement, virtually no crack showed evidence of spalling.

The reader should recall that longitudinal cracking and transverse cracking are counted in different units and thus are not directly comparable. Also, no distinct relationship is evident between the two types of cracking (e.g., the most amount of longitudinal cracking, the least of transverse cracking). Another point deserves serious consideration: although the numbers in Tables 4.1 and 4.3 are close for the before construction and second after construction conditions, the methodology used for the condition survey reveals nothing of the severity of the observed distress. Any visible surface defect that could be seen was recorded and counted. For transverse cracking, for example, the crack width or length was not relevant. Therefore, it is desirable that some measure of severity be included. If the exact length of transverse cracks would be too time consuming to record and process, then at least transverse cracks could be classified in two groups: those which extend to one-half the lane width or more, and those which do not. Also, labels, such as close, normal, or open, could be attached to both types of cracks to denote severity.

The serviceability indexes estimated from the GMR profilometer have only slightly varied over the two-year monitoring period.

Overall, Lane 3 has the highest serviceability index and Lane 1 the worst. Compare this result with the amount of cracking: the smoothest lane has the most cracking.

The trend in serviceability index is in keeping with the before construction condition, as of May 1983. Therefore, it can be hypothesized that this parameter has reached a natural level and ranking (compare for example the change in Table 4.10 for the last three survey dates). Thus, only minor changes can be expected in the next few years (i.e., the duration of BCO service life before fatigue occurs).

CHAPTER 5. OVERLAY COST INFORMATION

The purpose of this chapter is to provide cost information which can be used at the planning stage when various rehabilitation alternatives are being considered. Cost to the agency and to the user of the facility are estimated and reported herein.

The reader should keep in mind the implications on cost analysis of the experimental nature of this project; even if precise cost figures could be determined, these would not be representative of typical jobs in urban areas, let alone rural Texas. Therefore, the cost figures reported herein should be viewed as best estimates within the realm of the assumptions made, and as guidelines for future projects utilizing BCOs.

AGENCY COST

The experimental BCO sections were part of a larger roadway repair program comprising 13.882 miles of south Loop 610. The prime contractor for the overall project was Simonsen Co., Inc., the lowest bidder. The subcontractor involved in actual construction of the five test sections was Stan Forde Construction Co., Inc. A summary of the material cost bid by Simonsen is presented in Table 5.1 along with the average of the three lowest bid and the engineer's estimate.

As would be expected, the unit price increased with thickness; note that the most expensive material is fibrous concrete and that the unit price for 2-inch fiber concrete is about the same as the unit price for 3-inch steel-mat-reinforced concrete. Scarification of the base CRCP is about one-quarter the average unit price for material.

The detailed cost on this experiment was obtained from the subcontractor. It is informative to see the breakdown of these costs so that efficiency may be sought on future projects. The subcontractor broke down his costs as follows:

TABLE 5.1. SUMMARY OF MATERIAL UNIT PRICE ON THE SOUTH LOOP 610 EXPERIMENTAL TBCO

Section	Simonsen, Inc.	Average Three Lowest Bids	Engineer's Estimate
2"NR	$ 18.00/SY	$ 16.30/SY	$ 9.00/SY
2"R	20.00/SY	19.04/SY	12.00/SY
3"R	23.00/SY	21.57/SY	16.50/SY
3"F	29.00/SY	25.35/SY	16.50/SY
2"F	25.00/SY	21.48/SY	12.00/SY
Average	23.00/SY	21.00/SY	13.00/SY
Scarification of Base CRCP Surface	7.00/SY	5.82/SY	3.50/SY

(1) material,

(2) labor,

(3) tax and miscellaneous,

(4) equipment, and

(5) indirect cost.

The material cost included concrete, fibers, water reducer, curing compound, joint sealant, saw blades, scarification teeth, sand (for sand blasting), and grout mix. Indirect costs included project superintendent, engineering, time keeper and office personnel, office expenses, utilities, sanitation, ice, field supplies, insurance, bond, licenses and permits, mobilization, subsistence allowance, special freight, miscellaneous repairs, and safety supplies.

The subcontractor summed up his cost to arrive at the following unit bid price.

2"NR	$16.97/SY
2"R	18.85
3"R	21.68
3"F	27.33
2"F	23.56
Average	22.00
Scarify Base CRCP + Sand Blasting	6.60

With all other cost items included, the total construction cost was about $29.00/SY.

The last cost item of interest to the agency is the cost for handling traffic during concrete overlay construction and subsequent curing. This was informally estimated at approximately $1,000 per day for this size project by the Houston Urban Office engineers. Since total construction time was 36 days (July 22 - August 27, 1983) and 6 days were allowed for the curing period, the unit cost for handling traffic can be estimated at $8/SY.

USER COST

The cost to the user of a facility during rehabilitation includes delay costs, costs associated with changes in vehicle operational characteristics, and accident costs. However, of all these costs, only delay and vehicle operation costs have been studied and little is yet known of the relationship between rehabilitation and accidents (i.e., no convincing data have shown that certain rehabilitation practices cause traffic accidents).

The traffic delay cost model used in this study was extracted from the Rigid Pavement System - Version 3 (RPS-3) and incorporated in a computer program called USER-CST. The USER-CST program is well documented elsewhere (Ref 17).

Basically, USER-CST differentiates between asphaltic concrete and Portland cement concrete overlays because of the longer curing period required for PCC overlays. This was the case on the Loop 610 project. The program accumulates costs on a twenty-four hour basis, distinguishing between vehicle operational mode during construction time and time of the day when construction does not occur. Subsequently, costs are accumulated for the whole construction period and the specified curing period.

Input to the program includes traffic, traffic delay, overlay, material, construction, and interest rate. Output is in terms of present worth cost per square yard.

Five traffic handling models are built into the program. The model used in this study assumes that two lanes are merged in the vicinity of the work zone for the overlay direction but that the traffic flow is not affected in the non-overlay direction (i.e., model III). By and large, this scheme reflects the practice followed throughout construction and evaluation survey for the Loop 610 project. However, the model fails to recognize that users of the facility could choose alternate routes after an initial learning period. No effort was also devoted to keeping traffic count or change in traffic count during overlay construction and curing periods versus periods when the traffic flow was unrestricted (i.e., either before or after construction and curing period). For this reason, the program may over estimate actual user cost on this experimental project.

Figure 5.1 presents the relevant input data, including the assumptions made, and output from the program. Note that the current ADT is the result of a recent traffic count at the experiment site. The four lane highway was treated as two lanes (24 feet each) highway, to be compatible with the traffic models inherent in the program. Finally, the construction rate was back calculated to correspond to the 36-day construction period actually needed for this experiment (this period includes waiting out hurricane Alicia and the subsequent unavailability of ice used to control concrete temperature).

Within the realm of these assumptions, the total user cost is estimated at \$77.40/SY or approximately 2.7 times the construction cost. Note that the user costs were actualized to 1978 figures in the USER-CST model. A more rigorous analysis would bring these costs to 1983 figures or bring the construction cost back to 1978 figures. In either case, the relative magnitude of user and agency costs would be of the order of 3:1.

CONCLUSIONS FOR THE COST STUDY

In this study, the total cost of BCO placement was estimated for the south Loop 610 experiment. The unit construction cost was approximately \$29/SY and the traffic handling cost was \$8/SY, for an agency cost of \$37/SY. The user cost estimated in 1978 figures by the USER-CST model (Ref 17) was \$77.40/SY, which becomes after adjustment for inflation, say 3 percent per year, \$90/SY.

Therefore, the best estimate of the total cost for the experiments BCO is \$127/SY, of which 30 percent is agency cost and 70 percent user cost. This shows that, once started, BCO construction must proceed without delay in order to keep the total cost down and make it a more competitive rehabilitation alternative.

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PROGRAM USERCST - FOR THE DETERMINATION OF TRAFFIC DELAY COSTS TO THE USER
LATEST REVISION - 3/28/78

***** PROBLEM NUMBER     1 *****
CTR REP. 357-2: ASSESSMENT OF USER COST DURING THE S. LOOP 610 CONSTR.


          *********************************************
          *                                           *
          *              TRAFFIC INPUTS               *
          *                                           *
          *********************************************


INITIAL ONE DIRECTION ADT EXPECTED                            56523.00

ADT GROWTH RATE (PERCENT PER YEAR)                                3.00

DIRECTIONAL DISTRIBUTION FACTOR (PERCENT)                        50.00


          *********************************************
          *                                           *
          *           TRAFFIC DELAY INPUTS            *
          *                                           *
          *********************************************


DISTANCE OVER WHICH TRAFFIC IS SLOWED (MILES)
                           IN OVERLAY DIRECTION                   2.00
                       IN NON-OVERLAY DIRECTION                    .50

DETOUR DISTANCE AROUND OVERLAY, MODEL 5 ONLY (MI)                -0.00

AVERAGE APPROACH SPEED OF VEH. TO OVERLAY ZONE (MPH)             45.00

AVERAGE SPEED THROUGH RESTRICTED ZONE (MPH)
                           IN OVERLAY DIRECTION                  30.00
                       IN NON-OVERLAY DIRECTION                  45.00


NUMBER OF OPEN LANES IN RESTRICTED ZONE
                           IN OVERLAY DIRECTION                      1
                       IN NON-OVERLAY DIRECTION                      2

PROJECT LOCATION (1=RURAL,2=URBAN)                                   2

PERCENT VEHICLES STOPPED BY ROAD EQUIPMENT AND PERSONNEL
                           IN OVERLAY DIRECTION                   0.00
                       IN NON-OVERLAY DIRECTION                   0.00

AVERAGE DELAY PER VEH. STOPPED IN RESTRICTED ZONE (HRS)
                           IN OVERLAY DIRECTION                   0.00
                       IN NON-OVERLAY DIRECTION                   0.00

MODEL DESCRIBING THE TRAFFIC SITUATION                               3
```

(continued)

Fig 5.1. User cost model used in the study.

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*******************************************
*                                         *
*             OVERLAY INPUTS              *
*                                         *
*******************************************

LENGTH OF OVERLAY, MILES                                      .30

NUMBER OF LANES OVERLAID                                        2

AGE OF EXISTING FACILITY AT TIME OF OVERLAY, YEARS          14.00

WIDTH OF EACH LANE, FEET                                    24.00

*******************************************
*                                         *
*             MATERIAL INPUTS             *
*                                         *
*******************************************

OVERLAY MATERIAL (AC=1,PCC=2)                                   2

NUMBER OF DAYS CONCRETE IS ALLOWED TO CURE                     6.

*******************************************
*                                         *
*           CONSTRUCTION INPUTS           *
*                                         *
*******************************************

MILITARY TIME OF DAY OVERLAY CONSTRUCTION BEGINS               10

MILITARY TIME OF DAY OVERLAY CONSTRUCTION ENDS                 15

NUMBER OF HOURS PER DAY OVERLAY CONSTRUCTION OCCURS             5

CONSTRUCTION RATE, HOURS PER SQUARE YARD OF OVERLAY        .00375

*******************************************
*                                         *
*           INTEREST RATE INPUT           *
*                                         *
*******************************************

INTEREST RATE OR TIME VALUE OF MONEY                         5.00

PROGRAM USERCOST - FOR THE DETERMINATION OF TRAFFIC DELAY COSTS TO THE USER
LATEST REVISION - 3/[illegible]/78
```

(continued)

Fig 5.1. (continued).

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***** PROBLEM NUMBER     1 *****
CTR REP. 357-2: ASSESSMENT OF USER COST DURING THE S. LOOP 610 CONSTR.


          *********************************************
          *                                           *
          *              PROGRAM RESULTS              *
          *                                           *
          *********************************************


TOTAL PRESENT WORTH TRAFFIC DELAY COST
(DOLLARS PER SQUARE YARD OF OVERLAY)                            77.399
```

Fig 5.1. (continued).

Finally, note that these costs are indicative and should not be taken as absolute.

CHAPTER 6. DISCUSSION OF RESULTS

This chapter discusses experience gained on the South Loop 610 experiment and contrasts it with other rehabilitation alternatives that may have been considered. An assessment of the additional life resulting from the placement of the five design sections is made, along with the number of years it will take to exhaust the fatigue life that is now added to the remaining life of the old CRC pavement.

Results from laboratory experiments conducted during this study are also presented and discussed.

OVERALL OBSERVATION

Three concrete paving materials and two overlay thicknesses were used in the BCO experiment on South Loop 610, Houston. The three materials were fibrous concrete, steel mat reinforced concrete, and plain concrete. The two thicknesses were 2 and 3 inches. Periodic evaluation surveys of the test sections indicate good performance on most of the variables measured. However a site inspection revealed that, unquestionably, the current condition of the test sections is far superior to that prior to May 1983. For example, the recorded cracks are in many cases hairline cracks. From that perspective, the experiment can be gauged as successful.

Fibrous concrete and steel-mat-reinforced concrete performed differently with respect to cracking and deflection reducing capabilities. Fibrous concrete is a more resilient material than steel mat reinforced concrete. Although more brittle, steel-mat-reinforced concrete is stronger. Fibrous concrete is tougher. Therefore, when spalling does occur on the five test sections, one would expect it to occur earlier on the steel-mat-reinforced sections than on the fiber sections. This inference is based on field observation which revealed the prevalence of microcracking (D-cracking) along longitudinal saw-joints in the steel mat reinforced sections but found virtually none along the same joints in the fiber sections. It is expected that the material inside the D-cracking will eventually chip off, resulting in a spall.

The data in Table 3.4 indicate that average slumps and Chace air values were higher in the fiber sections than in the no-fiber sections. There is a concern that these tests may not be relevant for quality control or quality assurance of fibrous concrete under field paving conditions and thus, other avenues should be explored (e.g., flow table for workability).

The base pavement for the South Loop 610 experiment is an 8-inch CRCP. The reader should keep in mind this important factor when examining the performance of the BCO sections. Other important factors to consider are environment and traffic loadings. The information obtained on this project can be extended to cover other conditions through more experimentation.

In the 2-inch thick steel-mat-reinforced section, approximately 20 feet were tried without a bonding grout, and no adverse effect seems to have resulted. Note that laboratory testing has shown that the use of a bonding agent, cement grout in this case, resulted in a marginal increase in the interface shear strength when the pavement was dry, and that the most benefit of using a bonding grout was achieved when the pavement surface was wet.

Other important results from the laboratory study include the following:

(1) Scarifying the base pavement yields a roughened surface which allows for a better bond between the old and new pavements.
(2) The reinforcing steel position in the thin overlay has little impact on the strength as measured in a bond pullout test. Whether the reinforcing steel was at the interface between the original slab and the overlay or at middepth within the overlay pavement, the steel failed in tension before the bond strength was reached. Therefore, from the view point of practical considerations, time and money saved, it is better to lay the reinforcing steel flat on top of the prepared base pavement when the steel mat reinforced design is adopted in BCO construction without any fear of bond failure.

(3) As a bonding agent, cement grout proved to be a better material than the epoxy used.

(4) The use of a bonding grout reduces the coefficient of variation of shear strength at the interface of pavement and overlay.

(5) Overlay placement temperature is not a factor in interface shear strength over the range of temperatures investigated.

ESTIMATION OF PAVEMENT FATIGUE LIFE AFTER OVERLAY

In addition to correcting a minor grade problem, a BCO can add fatigue life to an existing rigid pavement. In this section, an estimate is made of the load-induced fatigue life that is likely to result from the placement of the South Loop 610 BCO sections.

Concept of Fatigue

The concept of fatigue simply stated stipulates that a material subjected to repetitive load applications, each of a magnitude far below its strength will nevertheless break; a fatigue failure is of a brittle nature. This phenomenon has been well documented as it applies to pavement structures.

The fatigue equations used in this study have been developed by Taute et al (Ref 22). They relate the number of repetitions to failure of a simulated half 18 kips S.A.L. to the tensile stress developed at the underside of a concrete layer and the concrete flexural strength; analytically,

$$N_{18} = 43,000 \left(\frac{f}{\sigma_c} \right)^{3.2} \qquad (1)$$

for overlaid pavements, and

$$N_{18} = 46,000 \left(\frac{f}{\sigma_c}\right)^{3.0} \qquad (2)$$

for non-overlaid pavements, where

N_{18} = number of 18-kip single axle load, repetitions to failure
σ_c = tensile stress at the underside of the concrete layer (psi)
f = flexural strength of concrete (psi)

Let's note in passing that the failure criteria inherent in these equations corresponds to a cracking index of 50 ft. per 1000 ft and that the flexural strength of the concrete used is the average 21 days strength developed at the AASHO Road Test (i.e., 690 psi).

Finally, note that (1) the mean flexural strength obtained from beam tests by the Houston Urban Office for the Loop 610 Experimental project is $\bar{f}$ = 864 psi with a standard deviation, σ_f = 75 psi; (2) the aggregate source used is the same for the original CRCP and the BCO construction; (3) the BCO has a finer gradation; (4) however, it has been shown that aggregate source is a major influencing factor of concrete flexural strength; (5) the Loop 610 CRCP is 14 years older than the BCO and flexural strength increases with concrete age. Therefore, considering $\bar{f}-2\sigma_f$ =714 psi, the use of the AASHTO's $\bar{f}$ = 690 psi will leave us with yet a reasonable margin of safety.

<u>Concepts of Damage and Remaining Life</u>

Damage is defined as the proportion of fatigue life used up after a given number of loads repetitions at a specified stress level. Damage to pavement structures is cumulative in accord with Miner's Law; analytically, damage,

$$D = \sum_{\ell=1}^{m} \left(\frac{ni}{Ni}\right)_{\ell} \qquad (3)$$

where

ni : actual number of load applications at stress level

Ni : number of load applications at stress level to reach failure

m : number of stress levels considered.

Remaining life, R is defined as R = 1.0 - D and can also be expressed in percent. Remaining life is used in this study because it has been shown that remaining life is well correlated with condition survey variables.

Application of the Concepts to the Determination of Added Fatigue Life

For our purpose, let us assume that there will be only one overlay until the failure condition is reached. The total cumulative damage, D_T can then be written as:

$$D_T = 1.0 = \frac{n_1}{N_1} + \frac{n_2}{N_2} \tag{5}$$

where $\frac{n_1}{N_1}$ is the damage incurred prior to overlay, and

$\frac{n_2}{N_2}$ the damage after overlay.

The methodology used is the same as related in Ref 19. First, moduli of elasticity are back calculated from deflection data within each design section for before overlay (May 1983) and immediately after overlay (September 1983) conditions. The computer program RPEDD1 (Ref 20) was used for the computations. The results appear in Table 6.1, columns A2 through A4 and B2 through B5, respectively.

Second, elastic layer theory is used to calculate wheel load stresses at the underside of the CRCP pavement. The computer program ELSYM-5 (Ref 21) is used for this purpose. Critical stresses are then used in fatigue equations (1) and (2) to arrive at a theoretical number of repetitions to failure, N_1 and N_2. A stress modifying factor of 1.2 is considered for CRCPs (after Ref 22).

Therefore, the number of load applications the system can sustain after overlay, n_2, is such that,

$$n_2 = (1.0) - n_1/N_1) \times N_2 \qquad (6)$$

where the expression in parenthesis represents the remaining life of the original pavement at the time of overlay, i.e.,

$$r_L = 1.0 - n_1/N_1 \qquad (7)$$

and N_2 is the theoretical number of applications to failure of the pavement-overlay system.

Note that N_2 is calculated using the fatigue equation for overlaid pavements and that the stress is taken to be the stress at the bottom of layer 2. The reason for this is apparent from Fig 6.1.

After overlay, the remaining life of the BCO decreases rapidly until it reaches that of the original pavement primarily due to reflection cracking.

Thus,

$$N_1 = 46{,}000 \left(\frac{690}{\sigma_{Col\ A.5}{}^{*} \times \text{stress factor}} \right)^{3.0} ; \text{ and}$$

$$N_2 = 43{,}000 \left(\frac{690}{\sigma_{Col\ B.6}{}^{*} \times \text{stress factor}} \right)^{3.2}$$

(*Column A.5 refers to column 5 in Table 6.1(a); column B.6 refers to column 6 in Table 6.1(b)) and finally,

$$n_2 = r_L \times 43{,}000 \left(\frac{690}{\sigma_{Col\ B.6} \times \text{stress factor}} \right)^{3.2} \qquad (8)$$

As can be seen from this expression, the number of load repetitions to failure after overlay, n_2 is directly proportional to the remaining life of the original pavement at the time of overlay. This suggests that more benefit will be achieved if the BCO is placed when r_L is still high.

To calculate remaining life at the time of overlay placement, damage is first estimated under the following assumptions:

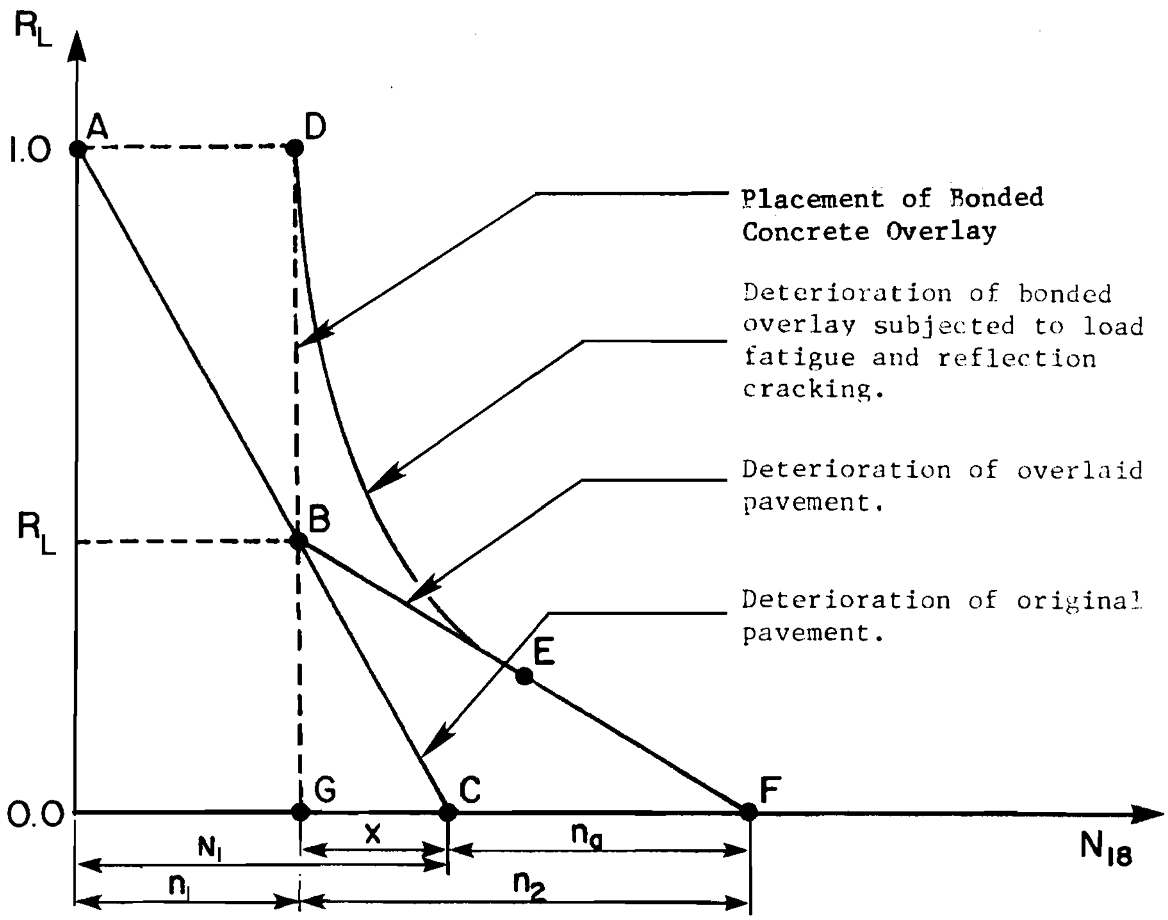

Fig 6.1. Conceptual graph showing relationship between original concrete pavement and bonded concrete overlay deteriorations as a function of 18-kip SAL applications (after Ref 22).

(1) average daily traffic, ADT = 113,000

(2) directional distribution factor, DDF = 0.50

(3) lane distribution factor, LDF = 0.60

(4) truck factor, T = 0.08

(5) average number of 18-kip ESAL per truck, A = 0.70

(6) constant traffic growth, i = 0.04.

Other assumptions intrinsic to this method are that linear elastic theory applies; distress is measured only in terms of cracking index, AASHTO definition, and is solely due to traffic loading; and the terminal condition is a cracking index of 50 feet per 1000 ft^2. Finally, only one overlay is considered over the design period and the effects of routine maintenance are not accounted for.

Values of damage appear in column 7 of Table 6.1(a) for the five sections. They range from 0.67 to 0.79. Corresponding values of remaining lives in the next column are calculated using Eq 7.

The additional life, n_a, resulting from the placement of a BCO is as follows (also see Fig 6.1):

$$n_a = n_2 - X \tag{9}$$

where n_2, as given by the above expression and X is calculated from similar triangles OAC and GBC

$$\frac{X}{N_1} = \frac{r_L}{1.0} \; ; \quad X = r_L \cdot N_1 \tag{10}$$

X represents the number of load repetitions to failure left, had the original pavement not been overlaid.

Equation (9) becomes:

$$n_a = n_2 - r_L \cdot N_1$$

TABLE 6.1. DETAILS OF ADDED FATIGUE LIFE ANALYSIS

(A) BEFORE OVERLAY

Section	Moduli (psi) E_1	E_2	E_3	Max Wheel Load Stress (psi)	Theoretical Repetitions To Failure N_1	Damage n_1/N_1	Remaining Life
2"NR	5,218,000	459,700	13,530	95.8	9,946,375	0.75	0.25
2"R	4,369,000	352,200	13,840	96.1	9,853,515	0.76	0.24
3"R	3,647,000	305,700	14,040	92.3	11,121,318	0.67	0.33
3"F	4,836,000	369,500	15,870	97.3	9,493,423	0.79	0.21
2"F	5,301,000	478,100	15,250	93.7	10,630,228	0.70	0.30

(B) AFTER OVERLAY

Section	Moduli (psi) E_1	E_2	E_3	E_4	Max Wheel Load Stress (psi)	Theoretical Repetitions To Failure N_2	Added Fatigue Life n_a	Years to Exhaust Life n_{years}
2"NR	5,717,000	5,198,600	459,700	12,620	74.3	30,008,297	5,015,480	7.33
2"R	5,214,000	5,697,200	352,200	14,320	80.0	14,283,639	3,320,135	5.23
3"R	5,931,000	4,592,300	305,700	15,300	64.7	21,136,402	11,747,885	15.66
3"F	5,204,000	4,927,400	369,500	15,650	65.3	19,004,959	7,532,209	10.44
2"F	4,871,000	5,354,400	478,100	15,470	70.6	17,717,091	7,412,052	10.29
							Average =	9.79

and substituting n_2 and N_1 by previous expressions:

$$n_a = r_L \times 43{,}000\left(\frac{690}{\sigma_{Col\ B.6} \times SF}\right)^{3.2} - r_L\, 46{,}000\left(\frac{690}{\sigma_{Col\ A.5} \times SF}\right)^{3.0}$$

finally,

$$n_a = r_L \times \left\{43{,}000\left[\left(\frac{690}{\sigma_{Col\ B.6} \times SF}\right)^{3.2} - 46{,}000\left(\frac{690}{\sigma_{Col\ A.5} \times SF}\right)\right]^{3.0}\right\} \tag{10}$$

The results of the added fatigue life n_a are presented in Table 6.1. This represents the additional fatigue cracking life that is "bought" by placing a BCO.

The values for n_a are in column 8 of Table 6.1(b). The next and final column represents the estimated values of fatigue life in years, n_{years} that it will take under prevailing traffic conditions (i.e., current traffic and assumed growth rate of 4 percent) to consume the additional lives, n_a. This comes to be 9.8 years on average for this section of roadway on South Loop 610. In other words, after the time required for the prevailing traffic to cause failure of the original CRCP, and additional 9.8 years will be available. The life of the overlaid pavement can be estimated by summing the life remaining in the existing pavement (X) and that provided by the overlay (N_a). This results in an expected life of over 13 years assuming no maintenance.

WARRANTS OF BONDED CONCRETE OVERLAYS

At a recent symposium held at the Balcones Research Center of The University of Texas at Austin with highway engineers from Texas, contractors and industry representatives, the following known and potential advantages of bonded concrete overlays were mentioned at the symposium:

(1) The use of a bonded concrete overlay has the potential to reduce user cost; to reduce delays during construction, and to reduce operating costs due to a smoother riding surface.

(2) A bonded concrete overlay placed on a pavement in good condition will extend its fatigue life.

(3) A bonded concrete overlay is warranted on the basis of faster construction than complete reconstruction; the technology does now exist for bonded concrete overlays. However, the use of a BCO must be justified if it is to be the appropriate solution.

(4) The use of bonded concrete overlays would allow a pavement agency to utilize the cost savings for other rehabilitation projects because the operation is less costly than, say, complete restoration.

(5) Bonded concrete overlays can be warranted on the basis of friction/skid resistance and riding quality of the existing pavement.

(6) A bonded concrete overlay would correct under-design (in cases where an unexpected increase in traffic volume or load limit occurs).

(7) Physical facilities and roadway geometry such as bridges, grade control may warrant bonded concrete overlays, over unbonded (hence thicker) overlays over unbonded overlays.

(8) The use of a bonded concrete overlay is warranted if it can be shown that it is a competitive alternative. Length of pavement and total bonded concrete overlay quantity that may be placed at one time (e.g., total square yardage) before the method is cost-effective must be examined.

CHAPTER 7. GENERAL CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the principal results reported throughout the study are assembled and organized for conciseness. Conclusions stemming from the study are presented first, followed by recommendations for this project and future research in the use of BCOs.

CONCLUSIONS

This study warrants the following conclusions:

(1) The constructibility of the various thin-bonded concrete overlay designs has been amply demonstrated; with current paving materials and equipments, it is possible to build BCO of rigid pavements as a viable rehabilitation alternative.

(2) In BCO construction, a mixture of water, cement, and plasticizer is an adequate bonding agent.

(3) BCO design sections, lane number, and survey dates had a significant effect on the observed variation of the Dynaflect deflections in the South Loop 610 experiment.

If lane number is considered a surrogate variable for traffic loading (the heavy trucks are usually in the right lanes, and weaving is at a minimum over the 1,000-foot-long test sections) then an equivalent statement is that traffic level and intensity, BCO thickness, and concrete reinforcement influenced the load-carrying capacity of the pavement structure.

(4) The observed variation in the Dynaflect deflections cannot be explained by the combined, additive effects of section, lane, and survey date alone. These factors interact. For example, the variation of Dynaflect deflections explained by the sections depends on the lane number.

(5) Immediately after overlay construction, it was found that the 3-inch thick, steel mat reinforced section was the most effective design in reducing Dynaflect surface deflections.

(6) After overlay construction, the effects of cracking indicator were no longer significant. A different formulation of this statement is to say that (at least for sensor 1) the construction of BCO re-establishes load transfer across the CRCP cracks.

(7) For a low level of traffic loading, 2- and 3-inch thick BCO resulted in statistically the same reduction of Dynaflect deflections.

(8) For a high level of traffic loading, 2- and 3-inch BCO performed differently in reducing surface deflections.

(9) The level and intensity of traffic for which the BCO thickness effect becomes significant is lower for the fiber sections than for the steel mat sections.

(10) For 2-inch thick BCO, fiber-reinforced and steel-mat-reinforced sections performed differently in their ability to reduce surface deflections.

(11) For 2-inch-thick BCO, the inclusion of fiber in the paving concrete mix, resulted in a significant change in the deflection basins irrespective of past traffic loadings.

(12) For 2-inch-thick BCO, the inclusion of steel mat in the paving concrete mix resulted in a significant change in the deflection basins only when past traffic level and intensity had been high.

(13) For 3-inch-thick BCO, the two materials investigated performed the same in reducing surface deflections, except when past traffic loading had been high.

(14) Overall, the type of movement across cracks experienced by the BCO sections and the underlying CRCP is the same (i.e., expansion or contraction); the BCO and CRCP seem to act as a monolithic structure.

(15) Two to three years after BCO placement no significant debonding seems to have occurred.

(16) The fiber sections proved to be far superior in their ability to control longitudinal and transverse cracking.

(17) After almost two years of BCO service virtually no crack showed evidence of spalling.

(18) For the successive survey dates, only a modest decrease of serviceability index was noted in all four lanes.

(19) Unit construction cost was estimated at $29/SY on this experimental project, and agency cost at $37/SY including traffic handling. Agency cost was about 30 percent of total cost.

RECOMMENDATIONS

(1) The five test sections on South Loop 610 have been monitored for approximately two years. During this period, satisfactory performance has been noted on most of the pavement response variables. However, the long term performance still needs to be established. Therefore, careful periodic evaluation surveys need to be conducted in order to meet this important objective. Only in this way can the state-of-the-art be advanced.

(2) Short of test tracts or a full-scale road test, experimental projects such as constructed on South Loop 610, Houston, will provide invaluable information at relatively low cost for the design and construction of BCOs. Thus, such experiments should be carefully designed and constructed so as to yield definitive answers. The area of past and future traffic loadings of these projects deserves particular attention. A new methodology which is now emerging, the weigh-in-motion technique (Ref 18), could be used to advantage to gather lanewise data on traffic level and intensity.

(3) To improve the quality of ride as measured by the GMR profilometer, stringent grade control requirements should be included in the

specifications for construction of BCO and/or equipment capable of delivering the desired pavement smoothness specified.

(4) Areas of future research which could be investigated in experimental projects include evaluation of various surface preparation techniques for type, amount, and cost effectiveness (e.g., compare scarifying, shot blasting, and acid etching) and experimentation with various "exotic" materials (polypropylene fibers, latex modified concrete, super plasticized concrete, etc.).

(5) Still, field work on BCO needs to address mode of failure of overlay pavement structures. Also, whether the interface bond endures over the service life of the BCO or whether it fatigues and fails along with the base slab and the overlay needs further research.

(6) It is recommended that the nature of bond failure be studied carefully. Whether loss of bond is localized or generalized by lane and how to remedy either situation (e.g., BCO anchorage or special end treatment) should be considered during long term evaluation surveys of BCO experiments.

(7) Debonding in South Loop 610 should be checked in subsequent surveys. The Delamtech machine, which has been used in Iowa, could be used for this purpose. Other avenues which hold promise include wave propagation and thermography techniques.

(8) The two levels of BCO thickness used in this experiment may have been too close together. Trying extreme values (e.g., 2 and 5 inches) with suitable transition sections is recommended.

(9) Along with field testing, laboratory work and theoretical analyses should be conducted to advance the state-of-the-art in BCO design and construction.

(10) A laboratory experiment should evaluate suitable tests for quality control/quality assurance of fiber reinforced concrete in its application for BCO in the field.

(11) Theoretical analyses of BCO should include mechanistic design, predict fatigue life, and find optimum overlay thickness and interface bond strength requirements.

REFERENCES

1. "Innovative Highways: A New Era Begins," Transportation Research News, No. 113, Transportation Research Board, July-August 1984.

2. Haas, Ralph C., and W. R. Hudson, Pavement Management Systems, McGraw Hill Book Co., New York, 1978.

3. "Pavement Management Guide," Roads and Transportation Association of Canada, Ottawa, Canada, 1977.

4. "Pavement Management System Development," NCHRP Report 215, Transportation Research Board, November 1979.

5. Kandiah, Kailasananthan, B. Frank McCullough, and D. W. Fowler, "A Study of the Effects of Interface Condition on Thin Bonded PCC Overlays," Research Report 357-1, Center for Transportation Research, The University of Texas at Austin, Austin, Texas, October 1984.

6. Knutson, M. J., "Introduction to Concrete Overlays," 15th Annual ICPA Workshop, Des Moines, Iowa, February 15, 1979.

7. Bergren, V. Jerry, "Bonded Portland Cement Concrete Resurfacing," Division of Highways, Iowa Department of Transportation, Ames, Iowa.

8. Federal Highway Administration, "Highway Statistics," U. S. Government Printing Office, Washington, D. C., 1980.

9. Walpole, Ronald E., and Raymond H. Myers, Probability and Statistics for Engineers and Scientists, 2nd Edition, MacMillan Publishing Company, Inc., New York, 1978.

10. Nie, Norman H., et al, Statistical Package for the Social Sciences, 2nd Edition, McGraw-Hill Book Company, New York, 1975.

11. "1977 Condition Survey Concrete Resurfacing Plain and Reinforced Concrete," Portland Cement Concrete Association and American Concrete Pavement Association, Skokie, Illinois, 1978.

12. Winer, B. J., Statistical Principles in Experimental Design, Second Edition, McGraw-Hill Book Company, New York, 1971.

13. Rohlf, John G., and Ramey O. Rogness, "Multivariate Analysis of Pavement Dynaflect Deflection Data," 64th Annual Meeting of the Transportation Research Board, Washington, D. C., January 1985.

14. Morrison, Donald F., Multivariate Statistical Methods, McGraw-Hill Book Company, New York, 1967.

15. "Operating Instructions Multi-position Strain Gauge," Soil Test, Inc., Evanston, Illinois, March 1979.

16. Gutierrez de Velasco, Manuel, and B. Frank McCullough, "Rigid Pavement Network Rehabilitation Scheduling Using Distress Quantitites," Research Report 249-5, Center for Transportation Research, The University of Texas at Austin, August 1983.

17. Daniel, James I., "A Methodology to Determine an Optimum Time to Overlay", Master's Thesis, The University of Texas at Austin, December 1979.

18. Izadmehr, Bahman and Clyde E. Lee, "Evaluation and Applications of Vehicles Weigh-in-Motion," Research Report 1024-1F, Center for Transportation Research, The University of Texas at Austin, 1985 (in preparation).

19. Bagate, Moussa, "Theoretical Study of Added Fatigue Life and Shear Stress," Technical Memorandum 357-22, Center for Transportation Research, The University of Texas at Austin, May 1984.

20. Uddin, Waheed, A. H. Meyer, and W. Ronald Hudson, "A User's Guide for Pavement Evaluation Programs RPEDD1 and FPEDD1," Research Report 387-2, Center for Transportation Research, The University of Texas at Austin, July 1985.

21. Ahlburn, Gale, "ELSYM-5 3/72-3, Elastic Layered System with One to TEn Normal Identical Circular Uniform Loads," Institute of Transportation and Traffic Engineering, University of California at Berkeley, 1972.

22. Taute, Arthur, B. F. McCullough, and W. R. Hudson, "Improvements to the Materials Characterization and Fatigue Life Prediction Methods of the Texas Rigid Pavement Overlay Design Procedure," Research Report 249-1, Center for Transportation Research, The Univeristy of Texas at Austin, November 1981.

APPENDIX A. SPECIAL SPECIFICATION

EXPERIMENTAL THIN BONDED CONCRETE OVERLAY, LOOP 610, HOUSTON

APPENDIX A. SPECIAL SPECIFICATION*

EXPERIMENTAL THIN BONDED CONCRETE OVERLAY, LOOP 610, HOUSTON

1. Description. This item shall govern for the materials to be used, for the scarifying of the existing concrete pavement, and for the furnishing and the placing of the thin bonded concrete overlay at the location shown, in accordance with the details shown in the plans, the requirements of Item 360, "Concrete Pavement (Water Cement Ratio)" except as noted herein, and with these specifications.
2. Materials. Materials and concrete design mix shall be as follows:

(1) Fibrous concrete mix design:

Cement Type I or II	--	8 sacks per cubic yard
Fine Aggregate (SSD)	--	1320 pounds per cubic yard
Coarse Aggregate (natural or crushed gravel) 3/8 inch maximum (SSD)	--	1335 pounds per cubic yard
Water Factor	--	5 gallons per sack cement
Bekaert Dramix fiber ZP 50/50 or equal	--	85 pounds per cubic yard
Water Reducer	--	as directed by manufacturer
Entrained Air	--	4 to 6 percent
Slump	--	3 to 4 inches

(2) Steel reinforced and non-reinforced concrete mix design

Cement Type I	--	7 sacks per cubic yard
C.A.F.	--	0.60

*Source: Houston Urban Office, SDHPT, Houston, Texas

Coarse aggregate gradation of natural or crushed gravel as follows:

Sieve Size	Percent Retained
3/4 inch	0
1/2 inch	0 - 15
3/8 inch	15 - 40
No. 4	40 - 98
No. 8	98 - 100

Water Factor -- 4.5 gallons per sack cement

Entrained Air -- 4 to 6 percent

(3) The temperature of the overlay concrete at the time of placement on the slab shall not exceed 85°F. When a retarding admixture is required, it shall meet the requirements of the item "Concrete Admixtures", except for measurement and payment.

(4) The concrete shall have a minimum 7 day flexural strength of 700 psi.

(5) Cement grout shall consist of 1 bag portland cement and 7 gallons water. It may contain a water reducing plasticizer at the option of the engineer.

(6) Membrane curing shall be at the rate of 120 S.F. per gallon and shall meet the requirements of Special Specification Item 5431, except for measurement and payment.

(7) When specified, steel reinforcing shall meet the requirements of Item 440, "Reinforcing Steel", except for measurement and payment.

3. Equipment. Equipment shall be subject to the approval of the engineer.

(1) Sand blasting equipment shall be capable of removing rust, oil, and concrete laitance from the existing surface of the pavement.

(2) Scarifying equipment shall be a power-operated, mechanical scarifier capable of uniformly scarifying or removing the old

surface to the depths required in a satisfactory manner. Other types of removal devices may be used if their operation is suitable and if they can be demonstrated to the satisfaction of the Engineer.

(3) Transit mixers shall be loaded no more than 80 percent capacity when fibers are to be added to the mix at the job site. Enough mixers shall be provided to permit the intended pour to be placed without interruption.

(4) Placing and finishing equipment to be used shall be at the option of the contractor subject to the approval of the engineer.

4. Construction Method. The contractor shall furnish to the engineer, for his approval, a work plan including equipment and manpower before work is started on the overlay.

The existing concrete pavement surface shall be scarified to the depth shown in the plans, followed by sand blasting. Sand blasting shall be of such an extent as to remove all dirt, oil, and other foreign material, as well as any laitance or loose concrete from the surface and edges against which new concrete is to be placed. The entire surface shall then be air blasted just prior to the grouting - paving operation.

The prepared surface shall be dry to allow absorption of the bonding grout. Bonding grout may be scrubbed or pressure sprayed at the option of the contractor. Care shall be exercised to insure that all parts receive a thorough, even coating and that no excess grout is permitted to collect in pockets. The rate of progress in applying grout shall be limited so that the grout does not become dry before it is covered with new concrete.

During delays in surfacing operations, should the surface of the grout indicate an extensive drying, additional grout shall be brushed on the areas as directed by the engineer. In areas where the grout becomes thoroughly dried, the grout shall be removed by sand blasting, or other methods as approved by the engineer.

When fibers are to be added to the mix at the job site, fibers are added in 66 lb. bags at the rate of 2 bags per minute. After all fibers have been added, the batch should be mixed for another 2 minutes at 16 rpm prior to placement.

The slump to be used on the job shall be as specified by the engineer from the results of trial batches. When this slump has been established, all concrete shall be delivered with a consistency of $\pm$ 1 inch from that designated.

Reinforcing steel type and placement will be as shown on the plans.

The concrete overlay shall receive a tine finish as shown on the plans.

The concrete overlay shall cure for a period of four days.

The surface temperature shall be maintained above 40'F for the curing period.

5. Measurement. Scarification as described herein and in the plans will be measured by the square yard of "Scarify Concrete Surface (1/8 inch)."
6. Payment. Payment for "Scarify Concrete Surface (1/8 inch)" measured as described above will be paid for at the unit price bid per square yard, which price shall be full compensation for removing all material to the depth shown, loading, hauling, unloading and disposing of all cuttings; for all sand blasting and air blasting; and for all labor, tools, equipment, manipulation, and incidentals necessary to complete the work.

Payment for the type of overlay placed as described above will be paid for at the unit price per square yard of "Concrete Overlay", of the depth specified, and with or without reinforcing steel, which price shall be full compensation for placing grout on the existing concrete slab; for furnishing, hauling, mixing, placing, finishing and curing of the concrete overlay; for sawing and sealing of joints; for all labor, tools, equipment and incidentals necessary to complete the work.

APPENDIX B

DYNAFLECT DEFLECTION DATA ANALYSIS

APPENDIX B. DYNAFLECT DEFLECTION DATA ANALYSIS

Analysis Of Variance (ANOVA)

ANalysis Of VAriance (ANOVA) is a statistical method whereby the total variation within a data set is decomposed into meaningful components (Ref 9), and the components are assigned to the factors of classification or their interactions. Usually, factors are non-metric (i.e., categorical) variables; otherwise the analysis is termed an analysis of covariance (Ref 10). For the South Loop 610 Dynaflect data, section, lane, sensor 1 position (at crack or between cracks), sensor and survey dates are considered as factors.

The study of variation is summarized in analysis of variance tables; evaluation of significant effects is then made possible. The level of significance = 0.05 is used throughout the remainder of this chapter.

The setup used to collect Dynaflect data in the South Loop 610 experiment resulted in a multi dimensional structure which can be described in simple terms as follows:

Factors	Levels
(1) Lane	4
(2) Section	5
(3) Sensor 1 Position	2
(4) Sensors	5
(5) Dates	5

This results in 1,000 non-empty cells. Therefore, a computer is required for the analysis.

To analyze the data, first a three-way cross-tabulation of the results was generated within subprogram ANOVA of the SPSS Library available on the University computer systems. Tables B.1 through B.10 are extracted from ANOVA output. They present Dynaflect data collected at the South Loop 610 experiment. Tables B.1 and B.2 show mean deflections at midspan and at the crack, respectively, in May 1985 (the fifth Dynaflect test); the next pair of

TABLE B.1. MEAN DEFLECTIONS (1/100 MILS) AT MIDSPAN - MAY 1985

Lane Number	Design Section	Sensor Number				
		1	2	3	4	5
1	2"NR	51.6	48.3	43.1	40.5	37.7
	2"R	48.3	45.0	39.3	36.1	32.9
	3"R	46.8	43.4	38.2	35.0	32.2
	3"F	49.0	45.6	39.7	36.2	33.3
	2"F	46.8	43.7	38.1	35.6	33.0
2	2"NR	53.1	48.6	44.9	40.6	38.4
	2"R	52.9	48.6	42.8	37.6	34.2
	3"R	52.3	47.8	41.4	36.6	33.3
	3"F	50.8	46.8	40.7	36.5	33.4
	2"F	51.8	48.1	42.3	38.6	36.0
3	2"NR	56.1	51.9	50.0	44.7	43.0
	2"R	51.7	47.4	44.1	39.6	37.5
	3"R	52.1	47.6	46.4	41.0	39.6
	3"F	47.4	43.6	41.7	37.5	36.0
	2"F	50.1	46.6	45.1	40.9	39.6
4	2"NR	57.5	53.5	50.4	45.4	43.0
	2"R	55.7	50.9	47.9	42.2	39.8
	3"R	49.1	45.2	43.3	38.3	36.4
	3"F	41.2	38.0	37.5	33.8	32.6
	2"F	43.7	40.3	39.1	35.6	34.2

TABLE B.2. SUMMARY OF MEAN DEFLECTIONS (1/100 MILS) AT CRACKS -- MAY 1985.

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2"NR	53.6	49.8	43.6	40.7	38.0
	2"R	50.1	45.6	39.6	35.5	32.8
	3"R	49.8	44.9	38.8	35.3	32.4
	3"F	51.0	45.8	39.3	35.4	32.6
	2"F	47.5	42.5	38.2	34.9	32.4
2	2"NR	54.0	49.8	44.9	40.4	38.2
	2"R	52.1	47.4	41.8	36.9	33.6
	3"R	49.9	45.7	39.6	35.1	32.1
	3"F	52.2	47.1	41.1	36.7	33.8
	2"F	53.0	48.8	42.8	39.4	36.8
3	2"NR	54.0	51.0	47.8	43.4	42.7
	2"R	51.4	47.2	44.7	39.5	37.4
	3"R	52.3	48.5	46.6	41.0	39.1
	3"F	47.3	44.4	42.8	38.3	36.3
	2"F	50.4	46.4	44.3	40.3	38.9
4	2"NR	57.6	53.8	50.9	46.8	43.8
	2"R	53.8	49.7	46.8	41.5	38.7
	3"R	50.6	46.3	44.2	38.6	35.6
	3"F	40.7	37.5	36.3	32.8	31.8
	2"F	41.9	40.0	38.8	35.2	34.2

TABLE B.3. MEAN DEFLECTIONS (1/100 MILS) AT MIDSPAN - NOVEMBER 1984

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2" NR	49.9	47.7	42.3	40.2	38.9
	2" R	50.1	47.0	40.8	37.1	33.9
	3" R	46.2	44.2	38.2	36.0	33.8
	3" F	47.2	45.6	39.6	36.6	33.6
	2" F	43.7	42.0	37.7	35.9	33.7
2	2" NR	49.6	47.5	41.0	40.1	38.4
	2" R	51.9	49.2	40.7	37.4	34.4
	3" R	50.8	48.2	40.9	37.7	34.9
	3" F	50.6	47.9	40.9	38.3	35.0
	2" F	49.0	47.4	42.2	40.3	37.9
3	2" NR	52.8	49.6	46.1	42.0	39.8
	2" R	53.2	49.8	45.3	40.4	37.2
	3" R	55.2	51.7	47.4	41.6	39.7
	3" F	51.5	48.6	43.9	39.4	37.6
	2" F	54.6	52.8	48.1	44.4	41.6
4	2" NR	60.1	57.3	52.0	46.9	43.8
	2" R	58.6	56.5	50.0	44.0	40.6
	3" R	53.1	50.5	44.5	39.8	36.0
	3" F	44.9	43.1	38.9	35.8	33.7
	2" F	45.9	44.2	41.3	37.8	36.1

TABLE B.4. MEAN DEFLECTIONS (1/100 MILS) AT CRACKS - NOVEMBER 1984

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2" NR	56.8	52.1	43.9	41.9	40.3
	2" R	49.6	45.6	38.6	35.8	33.3
	3" R	51.0	46.3	39.0	36.6	33.9
	3" F	50.7	46.0	39.1	36.1	33.1
	2" F	46.4	42.8	37.2	35.3	32.8
2	2" NR	50.3	47.6	41.6	40.4	38.5
	2" R	49.8	46.0	40.2	37.1	34.7
	3" R	50.2	46.7	39.4	37.2	34.5
	3" F	50.2	47.0	40.3	37.8	35.2
	2" F	52.7	49.1	42.1	39.9	37.5
3	2" NR	54.1	50.8	47.3	43.2	41.1
	2" R	51.4	48.6	44.0	39.7	37.2
	3" R	51.0	48.3	43.6	39.2	36.6
	3" F	48.4	46.4	41.8	37.8	35.6
	2" F	54.1	51.3	46.0	41.6	39.4
4	2" NR	60.6	56.9	51.6	46.4	43.4
	2" R	56.4	53.3	48.8	42.5	39.2
	3" R	51.6	49.8	44.5	39.7	37.2
	3" F	43.9	42.3	38.4	35.3	33.4
	2" F	46.6	45.2	40.7	38.3	35.7

TABLE B.5. MEAN DEFLECTION (1/100 MILS) AT MIDSPANS - FEBRUARY 1984

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2" NR	50.6	60.3	50.7	55.8	45.5
	2" R	49.8	58.7	48.4	51.6	41.0
	3" R	47.9	51.9	44.2	47.4	37.6
	3" F	55.0	47.8	44.8	48.1	38.5
	2" F	49.8	43.2	40.6	45.6	36.6
2	2" NR	59.8	51.6	48.8	54.2	42.8
	2" R	58.8	50.3	47.2	50.5	40.0
	3" R	61.4	53.0	47.4	50.4	39.6
	3" F	53.3	46.5	43.2	47.7	38.5
	2" F	56.8	50.0	47.3	52.0	42.5
3	2" NR	62.0	53.8	49.4	54.0	43.0
	2" R	63.5	55.2	50.3	53.3	41.5
	3" R	62.3	53.3	49.5	52.2	40.8
	3" F	62.8	52.8	49.0	51.4	40.0
	2" F	63.3	54.8	51.8	57.0	46.0
4	2" NR	72.0	63.3	58.3	60.8	48.0
	2" R	73.5	62.7	57.0	59.8	47.5
	3" R	62.0	53.3	49.2	51.5	40.2
	3" F	53.2	46.0	43.8	46.6	37.8
	2" F	52.4	45.6	43.6	48.4	38.5

TABLE B.6. MEAN DEFLECTIONS (1/100 MILS) AT CRACKS - FEBRUARY 1984

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2" NR	58.2	65.1	52.9	56.9	46.2
	2" R	53.0	60.2	48.4	50.8	40.5
	3" R	52.1	55.4	45.0	47.0	37.0
	3" F	63.6	52.2	47.4	50.7	39.4
	2" F	56.0	46.9	42.4	45.8	36.6
2	2" NR	60.4	51.0	48.4	53.4	43.6
	2" R	62.2	53.3	49.3	52.8	41.8
	3" R	62.6	53.2	48.8	51.6	40.6
	3" F	56.5	48.2	44.0	46.8	38.2
	2" F	63.0	52.8	47.8	51.5	41.3
3	2" NR	59.4	52.4	48.0	52.6	43.0
	2" R	65.5	55.8	51.3	54.8	43.0
	3" R	64.7	54.2	49.8	52.8	41.0
	3" F	64.8	53.2	48.4	50.0	40.4
	2" F	67.7	57.8	52.0	55.5	44.0
4	2" NR	72.0	62.8	58.5	63.3	49.8
	2" R	70.3	61.5	56.0	58.8	46.0
	3" R	64.0	55.0	50.5	52.8	42.0
	3" F	55.4	47.6	43.4	47.0	38.4
	2" F	54.4	47.2	44.2	47.8	38.6

TABLE B.7. MEAN DEFLECTIONS (1/100 MILS) AT MIDSPAN - SEPTEMBER 1983

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2" NR	48.0	45.6	42.8	40.1	36.1
	2" R	49.3	46.3	42.1	38.4	33.9
	3" R	47.0	43.8	39.6	37.0	31.4
	3" F	46.9	44.8	40.7	37.7	32.6
	2" F	44.4	42.8	39.9	37.2	33.9
2	2" NR	49.8	47.5	43.8	41.7	37.6
	2" R	46.2	44.0	39.8	37.2	32.6
	3" R	44.9	43.1	39.1	36.8	31.7
	3" F	46.7	44.5	40.4	37.1	32.4
	2" F	41.9	39.9	37.1	34.7	31.0
3	2" NR	51.8	49.7	46.0	44.0	39.4
	2" R	48.5	46.2	42.2	39.6	34.3
	3" R	47.2	45.1	41.3	38.6	33.9
	3" F	45.1	43.6	40.1	37.8	33.4
	2" F	45.7	44.3	41.0	39.3	34.6
4	2" NR	55.2	52.0	48.3	44.2	39.6
	2" R	54.3	51.2	46.9	42.8	37.3
	3" R	46.0	43.0	39.7	37.0	32.1
	3" F	39.6	37.6	34.9	33.2	29.3
	2" F	41.6	39.9	37.3	35.8	31.0

TABLE B.8. MEAN DEFLECTIONS (1/100 MILS) AT CRACKS - SEPTEMBER 1983

Lane Number	Design Section	Sensor Number				
		1	2	3	4	5
1	2" NR	47.6	44.8	41.9	39.1	35.4
	2" R	46.9	44.1	40.5	37.3	32.7
	3" R	47.9	44.3	39.8	36.9	31.6
	3" F	47.6	44.2	39.8	36.9	32.0
	2" F	44.8	42.3	38.6	36.3	32.0
2	2" NR	50.5	47.7	43.8	41.5	37.3
	2" R	47.9	44.6	39.9	37.0	32.5
	3" R	46.8	43.4	38.8	35.9	31.1
	3" F	50.1	45.6	40.6	37.7	31.7
	2" F	46.3	42.7	38.4	35.2	31.4
3	2" NR	48.6	46.7	42.9	40.9	35.9
	2" R	48.3	46.0	42.1	39.3	34.6
	3" R	48.2	45.7	41.8	39.3	34.4
	3" F	45.2	43.4	39.9	37.4	32.8
	2" F	48.3	46.4	43.0	40.9	36.3
4	2" NR	54.1	51.3	48.2	44.4	40.0
	2" R	52.3	49.2	44.8	41.3	35.8
	3" R	46.1	42.8	38.9	36.1	31.4
	3" F	38.8	37.2	34.5	33.0	29.4
	2" F	41.1	39.3	36.6	35.0	30.7

TABLE B.9. MEAN DEFLECTIONS (1/100 MILS) AT MIDSPAN - MAY 1983

		Sensor Number				
Lane Number	Design Section	1	2	3	4	5
1	2" NR	50.7	47.9	42.8	40.3	35.7
	2" R	52.8	49.4	43.6	39.5	34.0
	3" R	50.6	47.4	42.0	38.0	31.6
	3" F	50.7	47.6	41.7	37.4	30.9
	2" F	43.2	40.1	36.4	34.0	29.3
2	2" NR	52.7	49.0	44.4	41.7	36.3
	2" R	57.6	53.8	46.6	42.7	35.6
	3" R	56.2	52.4	45.1	41.3	34.2
	3" F	54.2	50.9	44.3	39.9	33.5
	2" F	50.2	47.2	43.3	39.7	34.9
3	2" NR	60.7	57.4	49.7	46.3	39.2
	2" R	64.0	60.5	53.1	48.4	40.7
	3" R	66.6	61.6	52.9	47.1	39.2
	3" F	57.3	54.4	47.5	43.1	36.8
	2" F	54.6	51.1	46.8	42.9	37.6
4	2" NR	63.2	58.7	51.8	47.1	40.1
	2" R	64.3	60.0	52.4	47.1	39.4
	3" R	58.6	54.1	47.0	41.9	34.8
	3" F	48.1	44.5	39.9	36.6	30.8
	2" F	47.6	45.5	41.3	38.6	33.2

TABLE B.10. MEAN DEFLECTIONS (1/100 MILS) AT CRACKS - MAY 1983

Lane Number	Design Section	Sensor Number 1	2	3	4	5
1	2" NR	54.2	49.1	43.2	39.8	35.0
	2" R	57.8	51.0	44.0	39.7	33.5
	3" R	58.0	50.8	43.7	39.0	32.0
	3" F	53.6	48.0	41.0	36.8	31.2
	2" F	49.5	45.2	39.7	36.4	31.6
2	2" NR	53.8	49.3	44.1	41.1	36.3
	2" R	59.0	53.8	47.2	42.6	36.5
	3" R	58.4	53.1	45.3	40.7	33.7
	3" F	56.7	51.8	44.5	40.4	34.0
	2" F	52.2	47.7	42.5	39.7	34.4
3	2" NR	60.4	56.4	48.9	45.0	38.2
	2" R	64.1	59.8	51.5	47.3	39.7
	3" R	69.6	64.2	54.7	48.7	40.3
	3" F	58.8	54.6	47.5	42.6	36.3
	2" F	56.2	50.8	45.2	41.3	35.2
4	2" NR	63.8	59.0	53.0	48.0	41.2
	2" R	64.3	59.8	51.8	46.8	39.2
	3" R	61.2	55.9	47.8	42.4	35.1
	3" F	48.5	45.6	39.9	36.7	31.0
	2" F	47.7	45.2	41.2	38.3	33.1

tables (Tables B.3 and B.4) shows the November 1984 data (the fourth Dynaflect test), etc.

As can be seen, the range of deflections is 30 to 70 x 10^{-2} mils, except for the February 1984 data (the third Dynaflect test). At this point, the following remarks can be made concerning this set of data:

(1) The raw data show many instances of series of sensor readings having no particular order to their magnitudes. For example, the sensor 4 deflection might be greater than the sensor 2 deflection, which in turn might be greater than sensor 1 and finally sensors 3 and 5 deflections. Furthermore, no definable trend exists in the raw data of 260 observations. This lack of trend is also reflected in Tables B.5 and B.6 of weighted averages (e.g., lines 1 and 6, Table B.5).

(2) The Dynaflect operating system and the physical layout of the five sensors dictates that the sensor 1 deflection be greater than the sensor 2 deflection, etc., since sensor 1 is the closest to the loading wheels.

(3) This lack of order of the sensor readings was not observed either before or after February 1984 in any single measurement (sensors 1 through 5 deflections).

(4) The February 1984 data set contains half as many observations as the other four sets. Deflection measurements were taken "every other point" out of a concern for lane closure downtime.

(5) The equipment and crew used for this particular test were different from those for all other Dynaflect tests of the project, leaving the distinct possibility there was equipment and/or human error.

(6) Finally, communications with the Texas State Department of Highways and Public Transportation technicians revealed that low voltage may have affected the sensor readings in February 1984.

For these reasons, the February 1984 data is excluded from further analyses.

Tables B.1 through B.10 exhibit noticeable variations between sections and lanes on a given test date. To determine whether these variations are statistically significant, one must examine the ANOVA tables. Table B.11 displays a summary from many runs of ANOVA. The following remarks are in order:

(1) The main effect "lane" is significant in all cases for all sensors, except for sensor no. 1 immediately after overlay construction (September 1983).

(2) The main effect "section" is significant in all cases for all sensors.

(3) The main effect "cracking" is never significant, except at sensor no. 1 before overlay construction (May 1983).

(4) The only two-way interaction which is consistently significant is the lane by section interaction.

Multiple Classification Analysis

In this analysis, the effects of the various factors are displayed in a (MCA) table. The effects are presented under two forms: (1) unadjusted and (2) adjusted for all other factors. Thus, the net effect of each factor can be determined while differences in the other factors are controlled.

The MCA scores for the Dynaflect data indicate which level of the various factors had the lowest deflections for all 5 sensors taken individually. This information is compiled by survey date in Table B.12.

Only the lane and section effects appear in this summary of MCA tables. These effects are adjusted for all other factors. The variation of grand means indicates that the general level of deflections decreased significantly after overlay placement (compare May 1983 with September 1983 data) and that this level is increasing but at a decreasing rate (e.g., see November 1984 and May 1985 data, and compare with September 1983 data).

If the data is considered on a date basis, the following remarks can be made:

TABLE B.11. DYNAFLECT DATA ANALYSIS - SOUTH LOOP 610 EXPERIMENT: SIGNIFICANT FACTORS (α = 0.05)

Date	Source of Variation	Sensor Number				
		W_1	W_2	W_3	W_4	W_5
May 1985	Main Effects					
	Lane	X	X	X	X	X
	Section	X	X	X	X	X
	Cracking	-	-	-	-	-
	2-way Interactions					
	Lane X Section	X	X	X	X	X
	Lane X Cracking	-	-	-	-	-
	Section X Cracking	-	-	-	-	-
November 1984	Main Effects					
	Lane	X	X	X	X	X
	Section	X	X	X	X	X
	Cracking	-	-	-	-	-
	2-way Interactions					
	Lane X Section	X	X	X	X	X
	Lane X Cracking	X	-	-	-	-
	Section X Cracking	-	-	-	-	-
September 1983	Main Effects					
	Lane	-	X	X	X	X
	Section	X	X	X	X	X
	Cracking	-	-	-	-	-
	2-way Interactions					
	Lane X Section	X	X	X	X	X
	Lane X Cracking	X	-	-	-	-
	Section X Cracking	-	-	-	-	-
May 1983	Main Effects					
	Lane	X	X	X	X	X
	Section	X	X	X	X	X
	Cracking	X	-	-	-	-
	2-way Interactions					
	Lane X Section	X	X	X	X	X
	Lane X Cracking	-	-	-	-	-
	Section X Cracking	-	-	-	-	-

X = Significant Effect

TABLE B.12. MULTIPLE CLASSIFICATION ANALYSIS OF THE DYNAFLECT DATA BY DATE

Date	Source of Variation	Sensor Number				
		W_1	W_2	W_3	W_4	W_5
May 1985	Grand Mean	50.5	46.5	42.6	38.4	36.0
	Adjusted Effects					
	Lane 1	- 1.0	- 1.0	2.9	- 1.9	- 2.4
	Lane 2	1.7	1.3	- 0.5	- 0.7	- 1.2
	Lane 3	0.6	0.8	2.5	2.1	2.8
	Lane 4	- 1.3	- 1.1	0.8	0.5	0.9
	* Beta	.21	.20	.41	.36	.49
	Section 2"NR	4.0	4.1	4.2	4.3	4.5
	Section 2"R	1.6	1.3	0.8	0.3	- 0.2
	Section 3"R	- 0.0	- 0.3	- 0.3	- 0.7	- 0.9
	Section 3"F	- 3.0	- 2.9	- 2.8	- 2.5	- 2.3
	Section 2"F	- 2.4	- 2.0	- 1.6	- 0.9	- 0.5
	* Beta	.44	.46	.48	.54	.56
	Multiple R^2	.24	.25	.39	.42	.54
November 1984	Grand Mean	51.0	48.2	42.7	39.2	36.7
	Adjusted Effects					
	Lane 1	- 1.9	- 2.3	- 3.0	- 2.2	- 2.1
	Lane 2	- 0.5	- 0.6	- 1.8	- 0.7	- 0.7
	Lane 3	2.4	1.3	2.5	1.5	1.7
	Lane 4	1.0	1.6	2.3	1.3	1.1
	* Beta	.20	.27	.47	.36	.37
	Section 2"NR	3.2	2.9	3.0	3.4	3.8
	Section 2"R	1.6	1.3	0.9	0.1	- 0.4
	Section 3"R	0.1	- 0.0	- 0.5	- 0.7	- 0.9
	Section 3"F	- 2.8	- 2.5	- 2.4	- 2.2	- 2.1
	Section 2"F	- 2.0	- 1.5	- 0.8	- 0.1	0.1
	* Beta	.34	.32	.34	.43	.49
	Multiple R^2	.15	.18	.34	.31	.37

(continued)

TABLE B.12. (CONTINUED)

Date	Source of Variation	Sensor Number W_1	W_2	W_3	W_4	W_5
September 1983	Grand Mean	47.2	44.7	40.9	38.2	33.6
	Adjusted Effects					
	Lane 1	- 0.1	- 0.3	- 0.3	- 0.6	- 0.5
	Lane 2	- 0.1	- 0.4	- 0.7	- 0.8	- 0.8
	Lane 3	0.4	1.0	1.0	1.4	1.2
	Lane 4	- 0.3	- 0.3	0.1	- 0.0	- 0.0
	* Beta	.05	.11	.15	.21	.21
	Section 2"NR	3.5	3.5	3.8	3.8	4.1
	Section 2"R	2.1	1.8	1.4	0.9	0.6
	Section 3"R	- 0.4	- 0.8	- 1.0	- 1.1	- 1.4
	Section 3"F	- 2.2	- 2.1	- 2.1	- 1.9	- 1.9
	Section 2"F	- 2.9	- 2.4	- 1.9	- 1.5	- 1.0
	* Beta	.45	.46	.50	.51	.57
	Multiple R^2	.21	.22	.27	.31	.37
May 1983	Grand Mean	56.5	52.3	45.8	41.8	35.4
	Adjusted Effects					
	Lane 1	- 4.2	- 4.5	- 3.9	- 3.6	- 2.9
	Lane 2	- 1.2	- 1.3	- 1.0	- 0.7	- 0.5
	Lane 3	4.9	5.0	4.1	3.6	3.0
	Lane 4	0.3	0.6	0.8	0.6	0.4
	* Beta	.39	.46	.49	.52	.50
	Section 2"NR	0.9	1.0	1.4	1.9	2.3
	Section 2"R	4.1	3.8	3.0	2.6	2.0
	Section 3"R	3.6	2.8	1.6	0.7	- 0.2
	Section 3"F	- 3.0	- 2.6	- 2.5	- 2.5	- 2.3
	Section 2"F	- 6.2	- 5.6	- 3.7	- 2.8	- 1.7
	* Beta	.47	.47	.44	.45	.45
	Multiple R^2	.40	.44	.45	.49	.46

(1) In May 1985, section 3"F (i.e., the 3-inch-thick fibrous concrete section) exhibited the lowest deflections at all five sensors, and section 2"NR (i.e., the 2-inch-thick non reinforced section) the highest deflections. On the same testing date, the lane effect varied at the different sensors.

(2) In November 1984, section 3"F again exhibited the lowest deflections and section 2"NR the highest. On the same testing date, lane 1, the innermost lane, exhibited the lowest deflections, and lane 4, the outermost lane, the highest. These inferences apply at all five sensors.

(3) In September 1983, right after overlay placement, the significance of section effects varied at the five sensors. The lane effects were negligible and the significance also varied at all five sensors.

(4) In May 1983, before overlay, the 2"F section had the lowest deflection and the 2"R section had the highest deflection at all but sensor 5 where the lowest was 3"F and the highest 2"NR. At that time, lane 1 had the lowest deflection and lane 3 the highest. These inferences on the lane factor are made for all five sensors.

In the MCA table, two descriptive statistics are used throughout: β and multiple R^2. The R^2 represents that proportion of the total variation in the deflection data which is explained by the lane or section factors. The R^2 represents the combined (additive) proportion of the total variation explained by all factors (lane, section, and cracking indicator).

As can be seen, multiple R^2 ranges from 0.15 to 0.54; this is for real life, raw data and suggests good performance of the analysis of variance method for Dynaflect data analysis.

Effects of Overlay Placement on Pavement Deflections

Dynaflect deflections were taken before and immediately after overlay placement. This provides an opportunity to evaluate the immediate effect of overlay placement on pavement deflections. Table 3.2 indicates that virtually the same points were tested in May 1983 and September 1983. Therefore, the difference in deflections, the before overlay minus that after overlay, is analyzed using analysis of variance and the multiple classification analysis. The results are summarized in Tables B.13 and B.14 respectively. From these tables, the following remarks can be made:

(1) Lane and section effects are significantly different at $\alpha = 0.05$.
(2) Cracking is significant for sensor 1 and sensor 2.
(3) Lane by section interaction is significant at all five sensors.
(4) The weighted average deflection difference (i.e., grand mean in Table B.14) decrease with radial distance from the loading wheels (i.e., from sensor 1 to sensor 5).
(5) Section 3"R exhibits the highest reduction in deflection at all sensors. The lowest reduction in deflection varied for the various sensors.
(6) Lane 3 has the highest reduction in deflection and lane 1 the lowest.

The R^2 ranges from 0.25 to 0.40 in this analysis. To illustrate the fluctuation of average deflection basins with survey date Figs B.1 through B.4 were drawn in accordance with the cell means and the analysis of variance results for the 3"R section where the highest reduction in deflection occurred. Thus, the lane, section and date effects are not confounded in these graphs because they were all found to be significant. The four figures are self explanatory. From the figures, it is apparent that the deflection basins became much shallower (i.e., the structure became much stiffer) after BCO placement (September 1983 data). This is especially noticeable at sensors 1, 2, and 3 in all the figures. Sensor 5 deflections, reflective of the subgrade properties, did not change significantly over the two years of observations. Finally, with successive survey dates, the deflections basins are approaching their before construction condition.

TABLE B.13. FACTORS SIGNIFICANTLY AFFECTING DYNAFLECT DEFLECTION DIFFERENCES BEFORE AND AFTER OVERLAY

Source of Variation	Sensor Number				
	1	2	3	4	5
Main Effects					
Lane	X	X	X	X	X
Section	X	X	X	X	X
Cracking	X	X	-	-	-
2-way Interaction					
Lane X Section	X	X	X	X	X
Lane X Cracking	X	-	-	-	-
Section X Cracking	-	-	-	-	-

X = Significant at $\alpha = 0.05$.

TABLE B.14. MULTIPLE CLASSIFICATION ANALYSIS OF DEFLECTION DIFFERENCES BEFORE AND AFTER OVERLAY

Source of Variation	Sensor Number				
	W_1	W_2	W_3	W_4	W_5
Grand Mean	9.3	7.7	4.9	3.5	1.8
Adjusted Effects					
Lane 1	- 4.1	- 4.2	- 3.6	- 3.1	- 2.5
Lane 2	- 1.2	- 0.9	- 0.3	0.1	0.3
Lane 3	4.5	4.0	3.0	2.3	1.7
Lane 4	0.6	0.9	0.7	0.6	0.4
* Beta	.44	.47	.47	.45	.39
Section 2"NR	- 2.6	- 2.5	- 2.4	- 1.9	- 1.7
Section 2"R	2.0	2.0	1.6	1.7	1.3
Section 3"R	4.0	3.6	2.6	1.8	1.2
Section 3"F	- 0.8	- 0.5	- 0.5	- 0.7	- 0.4
Section 2"F	- 3.3	- 3.1	- 1.8	- 1.4	- 0.7
* Beta	.39	.40	.38	.36	.30
Multiple R^2	.37	.40	.38	.34	.25

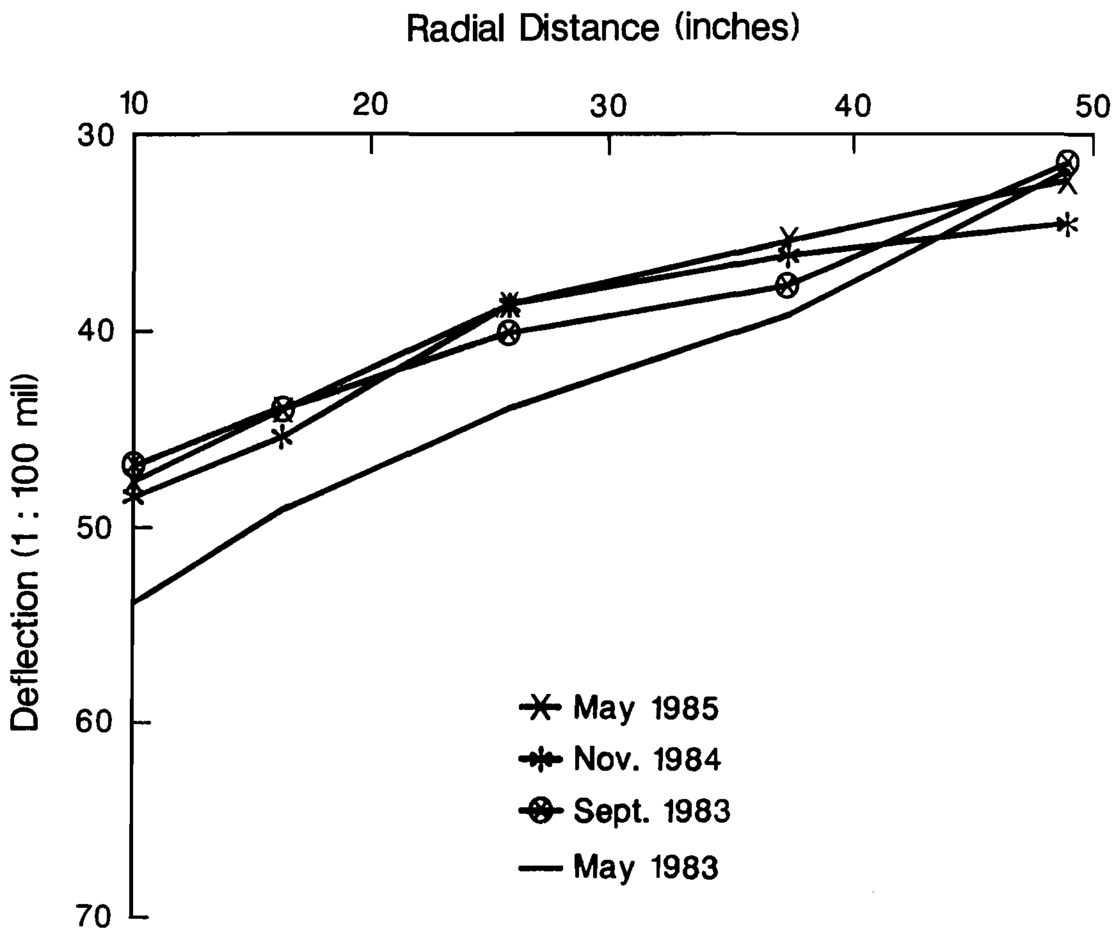

Fig B.1. Deflection basin by date: Section 3"R, Lane 1.

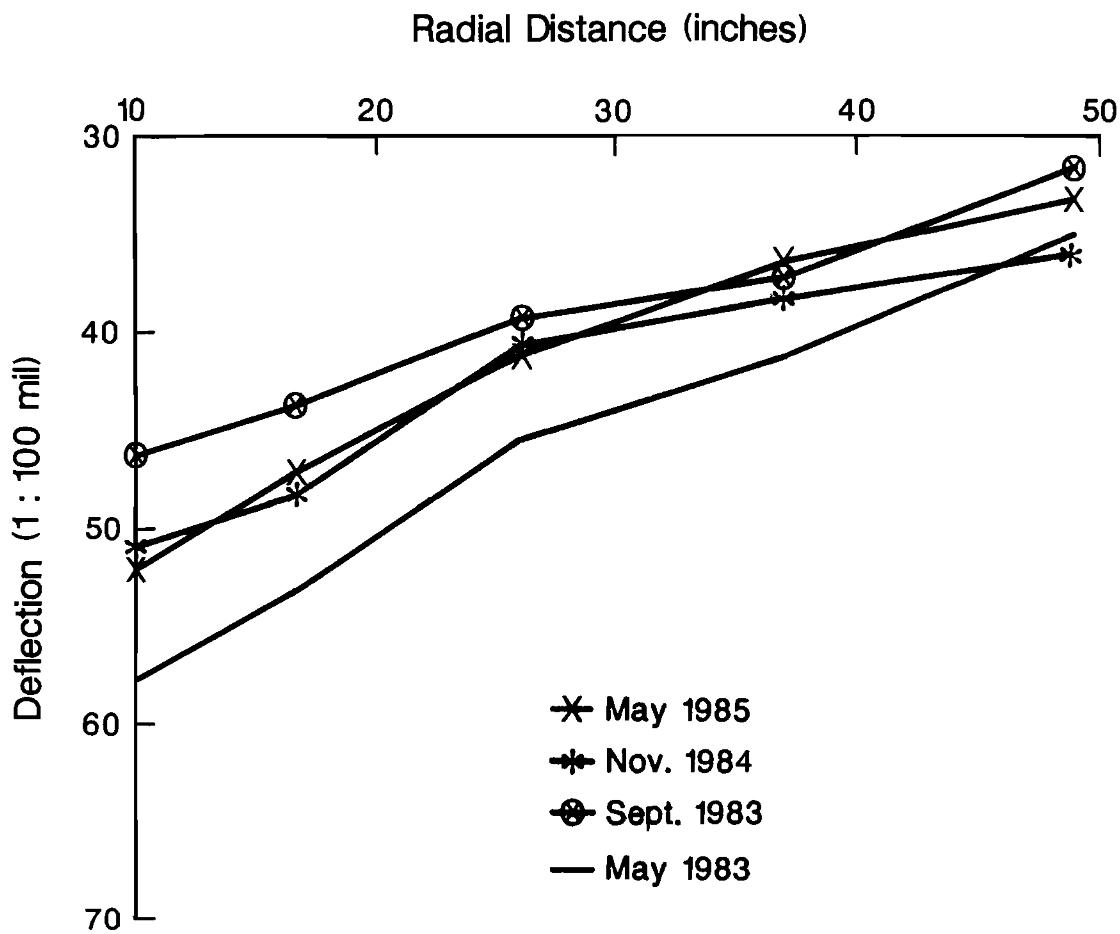

Fig B.2. Deflection basin by date: Section 3"R, Lane 2.

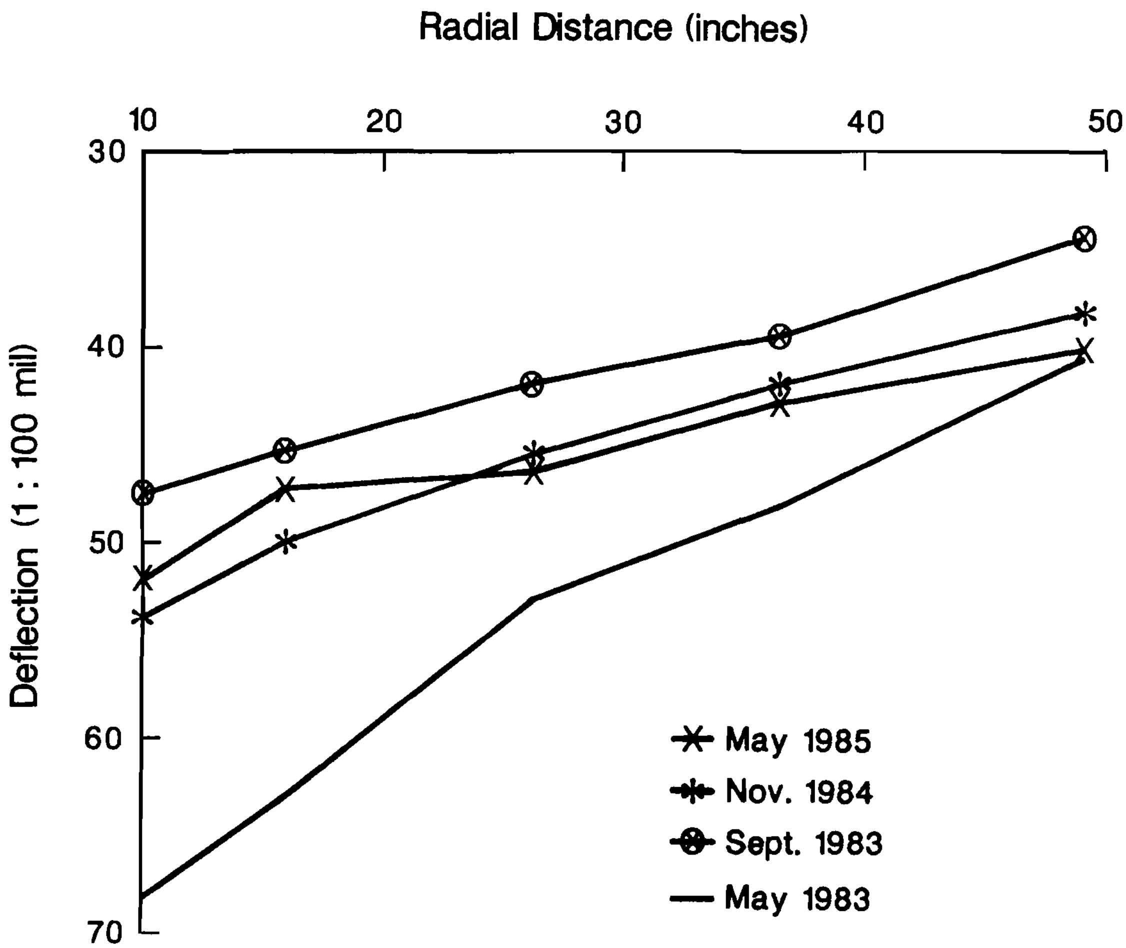

Fig B.3. Deflection basin by date: Section 3"R, Lane 3.

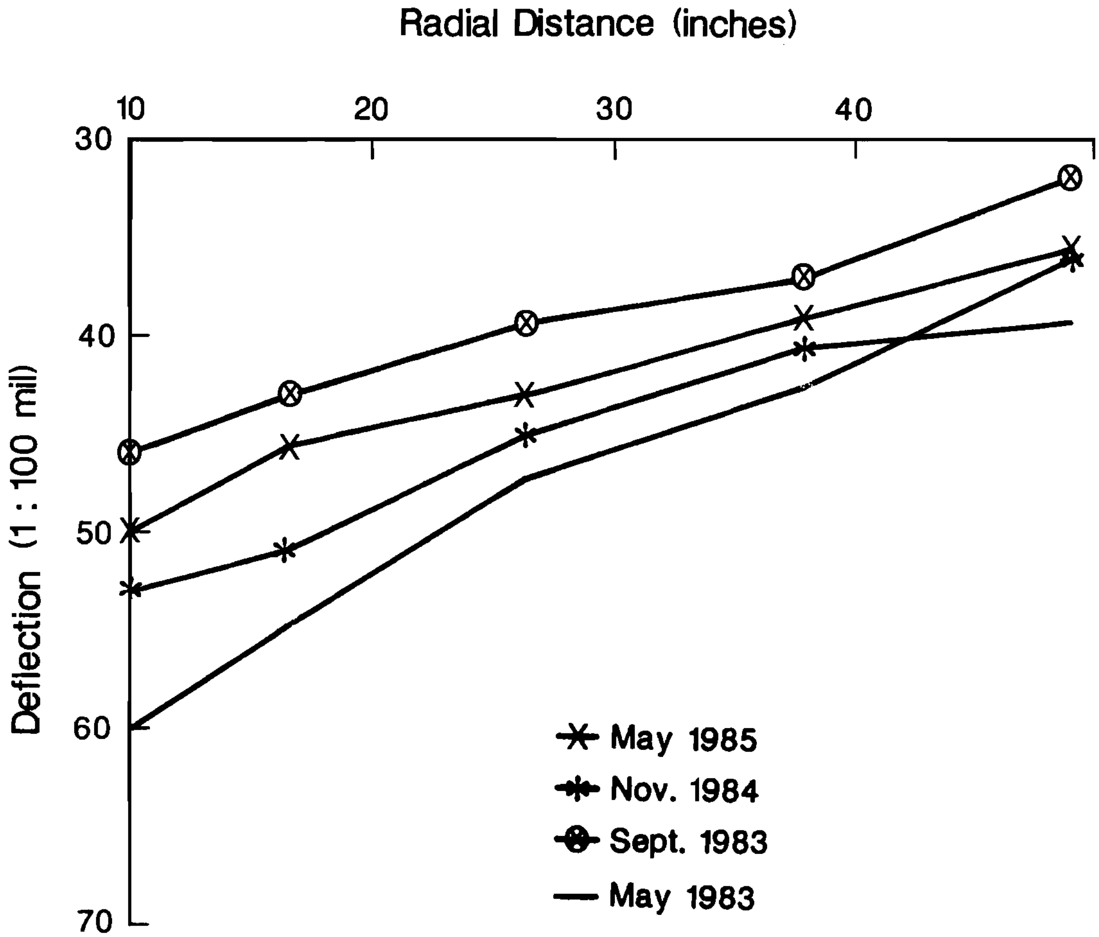

Fig B.4. Deflection basin by date: Section 3"R, Lane 4.

Multivariate Analysis of Variance (MANOVA)

Multivariate ANalysis Of VAriance (MANOVA) is used to complement the univariate analysis of variance. In MANOVA, the information contained in the deflection basin taken as a whole (i.e., sensor 1 through 5 readings) is used to make inferences. The use of MANOVA affords the study of lane and section contrasts (i.e., the comparison of mean deflections) for all five sensor readings simultaneously. It may also be argued that the five sensor readings on every test are correlated because of Dynaflect operational mode and condition, and therefore that MANOVA is required in order to make appropriate use of the total information collected (Ref 13). However, when the inferences previously made vary for the five sensors, MANOVA will provide more definitive answers.

Sample input and output for subprogram MANOVA of the SPSS library are presented in Fig B.5. The analysis starts by checking the homogeneity of variance for the data set; this is required for the analysis to be valid. The following were analyzed with MANOVA.

(1) Survey date effect (after overlay); whether or not, after the initial significant reduction due to the various BCO designs, the deflection basins were statistically different.

(2) Section effects by survey date; whether or not the results obtained from the previous univariate analysis still hold when the multivariate approach is used, and whether or not the inferences on section effects can be made when these varied for the various sensor readings.

(3) Immediate section effects nested in lane effects: whether or not the immediate response of pavement after BCO exhibited a definite and consistent trend within each lane (i.e., traffic level).

Table B.15 presents a summary of the multivariate Dynaflect data analysis for the date effect. Four test statistics are used in subprogram MANOVA of the SPSS library to make multivariate tests of significance:

TABLE B.15. MULTIVARIATE ANALYSIS FOR THE DATE EFFECT

(A) MULTIVARIATE TEST OF SIGNIFICANCE

	Significance of F-Test Less Than $\alpha = 0.05$		
Test Name	September 1983 Versus November 1984	November 1984 Versus May 1985	September 1983 Versus May 1985
Pillais	Yes	Yes	Yes
Hotellings	Yes	Yes	Yes
Wilks	Yes	Yes	Yes
Roys	Yes	Yes	Yes

(B) UNIVARIATE TEST OF SIGNIFICANCE

	Significance of F-Test Less Than $\alpha = 0.05$		
Variable	September 1983 Versus November 1984	November 1984 Versus May 1985	September 1983 Versus May 1985
W_1	Yes	No	Yes
W_2	Yes	Yes	Yes
W_3	Yes	No	Yes
W_4	Yes	Yes	No
W_5	Yes	Yes	Yes

```
                                                              04 OCT 85    17.55.37.
 ***************************************
 *          COMPUTATION CENTER          *
 *    UNIVERSITY OF TEXAS AT AUSTIN     *
 ***************************************

 S P S S - - STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES

 CDC 6000/CYBER VERSION 9.0  -  LOCAL RELEASE 1.2

 370000 CM MAXIMUM FIELD LENGTH REQUEST


            RUN NAME          LOOP 610 DYNAFLECT DEFLECTION DATA
            FILE NAME         UMANOVA
            COMMENT           THE PURPOSE OF THIS COMPUTER RUN OF SUBPROGRAM MANOVA
                              ON SPSS IS TO PERFORM THE N-WAY ANALYSIS OF VARIANCE
                              RECOMMENDED IN TECH-MEMO 357-14. BASICALLY, A FEW LANES,
                              SECTIONS,AND CRACKING CONDITION CONTRASTS ARE STUDIED.
                              THE STATISTICS (MEANS,STANDARD DEVIATIONS) OF THE
                              TECH-MEMO ARE ALSO CHECKED.
            VARIABLE LIST     W1 TO W5,CRACKING,SECTION,LANE,
            N OF CASES        UNKNOWN
            INPUT FORMAT      FREEFIELD
            INPUT MEDIUM      CARDS
CPU TIME REQUIRED..       .005 SECONDS

            MANOVA             W1 TO W5 BY LANE(1,4) SECTION(1,5) CRACKING(1,2) /
                               CONTRAST(SECTION)=SIMPLE(3)/
                               PRINT= HOMOGENEITY(BARLETT,COCHRAN)/
                               PRINT=CELLINFO(MEANS)/
                               PRINT=DESIGN(SOLUTION)/
                               METHOD=SSTYPE(UNIQUE)/
                               PARTITION(SECTION)/
                               DESIGN=LANE SECTION(1) SECTION(2) SECTION(3) SECTION(4)
                                      CRACKING LANE BY SECTION/
            OPTIONS            10
            STATISTICS         ALL
            READ INPUT DATA



END OF FILE ON FILE MANSECT
AFTER READING     415 CASES FROM SUBFILE UMANOVA

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

LOOP 610 DYNAFLECT DEFLECTION DATA                            04 OCT 85    17.55.37.

FILE   UMANOVA  (CREATION DATE =  04 OCT 85)

* * * * * * * * * * * * * * * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * *
```

Fig B.5(a). Sample input to subprogram MANOVA of the SPSS library.

LOOP 610 DYNAFLECT DEFLECTION DATA 04 OCT 85 17.55.37.

* A N A L Y S I S O F V A R I A N C E * * * * * * * * * * *

EFFECT .. SECTION(4)

MULTIVARIATE TESTS OF SIGNIFICANCE (S = 1, M = 1 1/2, N = 184 1/2)

TEST NAME	VALUE	EXACT F	HYPOTH. DF	ERROR DF	SIG. OF F
PILLAIS	.06150	4.86257	5.00	371.00	.00025
HOTELLINGS	.06553	4.86257	5.00	371.00	.00025
WILKS	.93850	4.86257	5.00	371.00	.00025
ROYS	.06150				.00025

- -

EIGENVALUES AND CANONICAL CORRELATIONS

ROOT NO.	EIGENVALUE	PCT TRACE	CUM. PCT	CANON. COR.	SQUARED COR.
1	.06553	100.00000	100.00000	.24800	.06150

- -

DIMENSION REDUCTION ANALYSIS

ROOTS	WILKS LAMBDA	F	HYPOTH. DF	ERROR DF	SIG. OF F
1 TO 1	.93850	4.86257	5.00	371.00	.00025

- -

UNIVARIATE F TESTS WITH (1,375) D. F.

VARIABLE	HYPOTH. SS	ERROR SS	HYPOTH. MS	ERROR MS	F	SIG. OF F
W1	370.95579	7882.05214	370.95579	21.01881	17.64876	.00003
W2	288.10970	6632.59792	288.10970	17.68693	16.28941	.00007
W3	260.46539	4377.56101	260.46539	11.67350	22.31254	3.28028E-006
W4	129.72803	2907.71143	129.72803	7.75390	16.73069	.00005
W5	81.88603	2324.75325	81.88603	6.19934	13.20883	.00032

- -

- -

LOOP 610 DYNAFLECT DEFLECTION DATA 04 OCT 85 17.55.37.

Fig B.5(b). Sample output of subprogram MANOVA of the SPSS library.

(1) Pillai's criterion,
(2) Hotelling's trace,
(3) Wilk's λ , and
(4) Roy's largest root criterion.

The definition and limitations of these statistics are beyond the scope of this report. Suffice it to say that approximate F-values can usually be calculated for each and that the significance of the F-test (i.e., the area in the tails of the distribution function) can be calculated and interpreted as in the familiar univariate Fisher's F-test. In Table B.15, these values do not appear as such but are compared to a fixed significance level $\alpha = 0.05$. It is such that all the four test statistics show that the date effects are significant.

Since, "at the present time, little is known of the comparative power of the (first) three test criteria" (Ref 14), it is important to ascertain that the criteria are all in agreement (Table B.15).

From the analysis of the date effects, it can be said that pavement response to dynamic loads as measured by the five Dynaflect sensor readings varied significantly from one testing date to the next over the period when the South Loop 610 BCO experiment was monitored in Houston.

The contrasts for individual sensor readings (i.e., linear combination of means) varied in absolute value from 0.2 to 3.8 and the associated standard errors from 0.19 to 0.33.

Finally, it can be seen that the univariate results agree reasonably well with the multivariate results.

Table B.16 is a summary of the section effect analysis. The following contrasts were studied:

(1) section 2"NR versus 3"R,
(2) section 2"R versus 3"R,
(3) section 2"F versus 3"R, and
(4) section 3"F versus 3"R.

TABLE B.16(a). MULTIVARIATE ANALYSIS FOR THE SECTION EFFECT - MAY 1985 SURVEY

(A) MULTIVARIATE TEST OF SIGNIFICANCE

Date	Test Name	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
May 1985	Pillais	X	X	-	X
	Hotellings	X	X	-	X
	Wilks	X	X	-	X
	Roys	X	X	-	X

(B) UNIVARIATE TEST OF SIGNIFICANCE

Date	Variable	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
May 1985	W_1	X	X	X	X
	W_2	X	X	X	X
	W_3	X	X	X	X
	W_4	X	-	X	X
	W_5	X	-	X	X

X = Significant Effect at $\alpha = 0.05$

TABLE B.16(b). MULTIVARIATE ANALYSIS FOR THE SECTION EFFECT - NOVEMBER 1984 SURVEY

(A) MULTIVARIATE TEST OF SIGNIFICANCE

Date	Test Name	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
November 1984	Pillais	X	X	-	X
	Hotellings	X	X	-	X
	Wilks	X	X	-	X
	Roys	X	X	-	X

(B) UNIVARIATE TEST OF SIGNIFICANCE

Date	Variable	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
November 1984	W_1	X	X	-	X
	W_2	X	-	-	X
	W_3	X	-	X	X
	W_4	X	-	-	X
	W_5	X	X	-	X

X = Significant Effect at $\alpha = 0.05$

TABLE B.16(c). MULTIVARIATE ANALYSIS FOR THE SECTION EFFECT - SEPTEMBER 1983 SURVEY

(A) MULTIVARIATE TEST OF SIGNIFICANCE

Date	Test Name	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
September 1983	Pillais	X	X	X	X
	Hotellings	X	X	X	X
	Wilks	X	X	X	X
	Roys	X	X	X	X

(B) UNIVARIATE TEST OF SIGNIFICANCE

Date	Variable	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
September 1983	W_1	X	X	X	X
	W_2	X	X	X	X
	W_3	X	-	X	X
	W_4	-	-	X	X
	W_5	-	-	X	X

X = Significant Effect at α = 0.05

TABLE B.16(d). MULTIVARIATE ANALYSIS FOR THE SECTION EFFECT - MAY 1983 SURVEY

(A) MULTIVARIATE TEST OF SIGNIFICANCE

Date	Test Name	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
May 1983	Pillais	X	X	X	X
	Hotellings	X	X	X	X
	Wilks	X	X	X	X
	Roys	X	X	X	X

(B) UNIVARIATE TEST OF SIGNIFICANCE

Date	Test Name	Significant Effects			
		3"F Versus 3"R	2"F Versus 3"R	2"R Versus 3"R	2"NR Versus 3"R
May 1983	W_1	X	X	-	X
	W_2	X	X	-	-
	W_3	X	X	X	-
	W_4	X	X	X	X
	W_5	X	X	-	X

X = Significant Effect at α = 0.05

The reader may recall that the 3-inch steel-mat-reinforced section (i.e, 3"R) had the greatest reduction in deflection immediately after overlay. For this reason, it is compared to all other sections for the four dates when deflection data were collected.

From Table B.16, the following remarks can be made:

(1) The multivariate tests are all significant for the contrasts studied except for the 2"R versus 3"R contrast in May 1985 and November 1984. For these two data sets, it follows that if one accounts for the random variation due to lane, cracking indicator of the base CRCP and lane by section interaction, then the 2"R section exhibits statistically the same deflection characteristics as the 3"R section; this inference can be made with 95 percent confidence. All other sections have deflection characteristics statistically different from the 3"R section.

(2) The univariate tests of significance obtained from MANOVA are presented to indicate which sensor reading may have influenced the multivariate results. They are otherwise essentially the same as was reported at the start of the study (i.e., univariate ANOVA).

Finally, the immediate effect of BCO placement is studied again from the multivariate vantage point. Two main effects are examined corresponding to the main factors of the experiment design: (1) materials and (2) overlay thickness.

Specifically, the contrasts studied are as follows:

(1)	2"NR versus 2"R	material
(2)	2"NR versus 2"F	
(3)	2"R versus 2"F	
(4)	3"R versus 3"F	overlay thickness
(5)	2"R versus 3"R	
(6)	2"F versus 3"F	

Since, the univariate ANOVA had revealed a significant lane by section interaction, the nested design feature of subprogram MANOVA is used to assess the effects of the six contrasts above.

In essence, lane becomes the blocking variable: the variations between lanes are not investigated as such but rather the variation within each lane.

This analysis is summarized in Table B.17. From Table B.17, the following remarks can be made:

(1) The 2"F and 3"F sections are statistically different in lane 3 and lane 2 only.

(2) The 2"R and 3"R sections are statistically different in lane 3 only.

Recalling that before overlay placement, (May 1983 data set) lane 3 had the highest deflection at all 5 sensors (see Table B.12) followed by lane 4, lane 2 and lane 1, it can be said that the thickness effect as revealed by the two contrasts above is a function of traffic level where lane number is a substitute variable for traffic level. In other words, for a low level of traffic loading, the thickness effect is negligible. As traffic level increases, thickness effect becomes significant; therefore, there seems to be a threshold of traffic beyond which thickness of overlay becomes important for the two materials used in the South Loop 610 experiment, and the threshold is reached for the fiber before the steel mat.

(3) The 3"R and the 3"F sections have significantly different deflection basins in lane 3 only.

(4) The 2"R and the 2"F sections have significantly different deflection basins in lane 3, lane 4, and lane 1.

(5) The 2"NR and the 2"F sections have significantly different deflection basins in lane 3, lane 4, and lane 2.

(6) The 2"NR and the 2"R sections have significantly different deflection basins in lane 3 and lane 2.

TABLE B.17(a). MULTIVARIATE ANALYSIS FOR THE IMMEDIATE SECTION EFFECT WITHIN A LANE - LANE 1

(A) MULTIVARIATE TEST OF SIGNIFICANCE

Lane	Test Name	Significant Effects					
		2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
1	Pillais	-	-	-	X	-	-
	Hotellings	-	-	-	X	-	-
	Wilks	-	-	-	X	-	-
	Roys	-	-	-	X	-	-

(B) UNIVARIATE TEST OF SIGNIFICANCE

Lane	Variable	Significant Effects					
		2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
1	W_1	-	-	-	X	-	-
	W_2	X	-	-	X	X	-
	W_3	-	-	-	X	-	-
	W_4	-	-	-	X	-	-
	W_5	-	-	-	X	-	-

TABLE B.17(b). MULTIVARIATE ANALYSIS FOR THE IMMEDIATE SECTION EFFECT WITHIN A LANE - LANE 2

(A) MULTIVARIATE TEST OF SIGNIFICANCE

		Significant Effects					
Lane	Test Name	2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
2	Pillais	X	-	-	-	X	X
	Hotellings	X	-	-	-	X	X
	Wilks	X	-	-	-	X	X
	Roys	X	-	-	-	X	X

(B) UNIVARIATE TEST OF SIGNIFICANCE

		Significant Effects					
Lane	Variable	2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
2	W_1	-	-	X	X	X	X
	W_2	-	-	X	X	X	X
	W_3	-	-	X	-	X	X
	W_4	-	-	-	-	X	X
	W_5	-	-	-	-	X	X

TABLE B.17(c). MUTLIVARIATE ANALYSIS FOR THE IMMEDIATE SECTION EFFECT WITHIN A LANE - LANE 3

(A) MULTIVARIATE TEST OF SIGNIFICANCE

		Significant Effects					
Lane	Test Name	2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
3	Pillais	X	X	X	X	X	X
	Hotellings	X	X	X	X	X	X
	Wilks	X	X	X	X	X	X
	Roys	X	X	X	X	X	X

(B) UNIVARIATE TEST OF SIGNIFICANCE

		Significant Effects					
Lane	Variable	2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
3	W_1	X	X	X	X	-	X
	W_2	X	X	X	X	X	X
	W_3	X	-	X	X	-	X
	W_4	X	-	X	X	-	X
	W_5	X	-	X	X	-	X

TABLE B.17(d). MULTIVARIATE ANALYSIS FOR THE IMMEDIATE SECTION EFFECT WITHIN A LANE - LANE 4

(A) MULTIVARIATE TEST OF SIGNIFICANCE

		Significant Effects					
Lane	Test Name	2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
4	Pillais	-	-	-	X	X	-
	Hotellings	-	-	-	X	X	-
	Wilks	-	-	-	X	X	-
	Roys	-	-	-	X	X	-

(B) UNIVARIATE TEST OF SIGNIFICANCE

		Significant Effects					
Lane	Variable	2"F Versus 3"F	2"R Versus 3"R	3"R Versus 3"F	2"R Versus 2"F	2"NR Versus 2"F	2"NR Versus 2"R
4	W_1	-	-	X	X	-	-
	W_2	-	-	X	X	-	-
	W_3	-	-	X	-	-	-
	W_4	-	-	X	-	-	-
	W_5	-	-	-	-	-	-

These results reflect on the structural value of the two types of materials investigated; results (3) and (4) indicate that for the low level of overlay thickness (i.e., 2 inches) the fiber and steel mat material performed significantly differently in their ability to reduce pavement deflection. At the high level of thickness (i.e., 3 inches) the two materials performed the same except when traffic level was high.

Results (5) and (6) indicate that for the low level of thickness, the inclusion of fiber in the paving concrete resulted in a significant change in the deflection basins whereas the inclusion of steel mats in the paving concrete resulted in significant change only when the traffic level or intensity had been high.

To sum it up, within the realm of the variables investigated, the most structural benefit is obtained by using fibrous concrete in BCO construction when traffic level and intensity are low and steel-mat-reinforced concrete when traffic level and intensity are high.