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16. Abstract

Bonded concrete overlays are a new method of pavement rehabilitation and the effect of long-term repeated loadings is not yet known. A laboratory study, using accelerated repeated loadings, was performed to enable a prediction of long-term results in a relatively short time period.

In the laboratory, four model pavement slabs, designed to simulate conditions on Loop 610 in Houston, Texas, were tested. Each slab consisted of a base slab and a bonded PCC overlay. Each base slab was cracked transversely at the midspan and then loaded in fatigue to a distress condition before the overlay was placed. The overlay was cracked and fatigue loaded in the same manner. Both continuously reinforced and jointed pavements were studied. The data taken from the laboratory were analyzed and a study on remaining life was done.

Results from the study showed differences in the behavior of CRCP and JCP slabs. JCP slabs had larger deflections and shorter fatigue lives. CRCP slabs failed by cracking with no other signs of distress while JCP slabs failed by punch-out; following loss of shear strength and delamination. In general, for both the CRCP and JCP slabs, placement of a BCO decreased deflections, increased load transfer, and increased the fatigue life of the pavement structure.

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A Laboratory Study of the Fatigue of Bonded PCC Overlays

by

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Chhote Saraf
B. Frank McCullough
D. W. Fowler

Research Report 457-2

Thin-Bonded Overlay Implementation
Research Project 3-8-86-457

conducted for

Texas State Department of Highways
and Public Transportation

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

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September 1986

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.

PREFACE

This is the second report which documents work done under Project 3-8-86-457, "Thin Bonded Overlay Implementation." 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.

The authors would like to thank all of the people who assisted in the laboratory phase of the project, in particular Mark Wickham and Jim Long for their help at the start; Rouault Ray Buvia, James Stewart, Tex Rushing, and Paul Walters for their many contributions throughout; and David Whitney and all of the work-study students who were always willing to help.

In addition, thanks are extended to all who assisted in the preparation of this report, in particular to Lyn Gabbert and Rachel Hinshaw for typing; Michele Mason Sewell for drafting; and Matt Loeffler for photography. Special thanks are also due to Alberto Mendoza Diaz for his time taken in discussion of the research.

LIST OF REPORTS

Report 457-1, "Preliminary Design of a Testing Facility to Subject Full Scale Pavement Sections to Static and Cyclic Loading," by Mark D. Wickham, B. Frank McCullough and D. W. Fowler, defines the problems and presents possible solutions for the design of a testing facility to cyclicly load full scale pavement sections.

Report 457-2, "A Laboratory Study of the Fatigue of Bonded PCC Overlays," by Karen T. Reilley, Chhote Saraf, B. Frank McCullough, and D. W. Fowler, presents the findings of laboratory fatigue experiments which simulate the field conditions of IH-610 in Houston, Texas.

ABSTRACT

Bonded concrete overlays are a new method of pavement rehabilitation and the effect of long-term repeated loadings is not yet known. A laboratory study, using accelerated repeated loadings, was performed to enable a prediction of long-term results in a relatively short time period.

In the laboratory, four model pavement slabs, designed to simulate conditions on Loop 610 in Houston, Texas, were tested. Each slab consisted of a base slab and a bonded PCC overlay. Each base slab was cracked transversely at the midspan and then loaded in fatigue to a distress condition before the overlay was placed. The overlay was cracked and fatigue loaded in the same manner. Both continuously reinforced and jointed pavements were studied. The data taken from the laboratory were analyzed and a study on remaining life was done.

Results from the study showed differences in the behavior of CRCP and JCP slabs. JCP slabs had larger deflections and shorter fatigue lives. CRCP slabs failed by cracking with no other signs of distress while JCP slabs failed by punchout; following loss of shear strength and delamination. In general, for both the CRCP and JCP slabs, placement of a BCO decreased deflections, increased load transfer, and increased the fatigue life of the pavement structure.

KEYWORDS: Continuously reinforced concrete pavement, jointed concrete pavement, bonded PCC overlay, remaining life, fatigue.

SUMMARY

The use of bonded concrete overlays is becoming an accepted method of rehabilitation for portland cement concrete pavements. Progress in the design and construction of bonded overlays and the success thus far of several BCO projects have led to this acceptance. However, the long-term success of bonded overlays is still unknown. The primary goal of this study is to examine the effects of long-term loadings on bonded concrete overlays.

This study involves the simulation of the field conditions of IH-610 in Houston, Texas, and the fatigue-testing of both continuously reinforced and jointed concrete pavements. The effect of placing overlays on pavements at varying levels of distress is also examined. Results from the laboratory tests include data on deflections, cracking, and shear strength. The laboratory results are presented and analyzed in the study.

IMPLEMENTATION STATEMENT

The laboratory fatigue tests produced results which are applicable in the field. Recommendations for implementation include:

(1) Repair failures before placement of the bonded concrete overlay - laboratory tests demonstrate that repairing the existing pavement adds life.

(2) Weld cracks with low load transfer (measured by deflections taken in the field) together before overlaying - load transfer influences pavement fatigue life and this will extend the life of the pavement structure.

(3) Overlay before the pavement condition deteriorates - laboratory results indicate that overlaying an existing pavement with a higher remaining life yields a pavement structure that will have a longer fatigue life.

(4) Laboratory studies on surface preparation types should be done prior to field experiments because failure of the bonded concrete overlayed structure can occur at the interface.

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CHAPTER 1. INTRODUCTION

This report presents the findings of a laboratory study on the fatigue of bonded concrete overlays. This chapter presents the background, objectives, and scope of the study.

BACKGROUND

Bonded concrete overlays (BCO) are rapidly becoming an accepted method of rehabilitation for portland cement concrete (PCC) pavements. This is due in part to the progress in design and construction; for example, the high production scarifying, sandblasting, waterblasting, and shotblasting machines used in surface preparation. The success, thus far, of several BCO projects has also helped make bonded concrete overlays a viable resurfacing alternative.

In 1973, a research project involving bonded, unbonded, and partially bonded fibrous-reinforced concrete overlays was conducted in Greene County, Iowa. In the sections that were bonded, little bonding occurred because the method utilized for bonding consisted of spreading cement on the surface and adding water. Since then, new methods of surface preparation (discussed later) have been perfected and the success of bonded overlays has followed.

There have been four additional bonded concrete overlay projects in Iowa. The first, in 1976 on U.S. 20 in Black Hawk County, was a demonstration project. The second, in 1977, in Clayton County was 1.6 miles long and the third, in Woodbury County in 1978, was a 0.5-mile-long project. The fourth Iowa project, completed in 1979, on I-80, was 4.5 miles long. In 1981 Louisiana constructed a 0.8-mile-long BCO and New York, a 3.0-mile-long BCO.

Bonded concrete overlays have also been constructed near Atlanta, Georgia in 1975, near Minneapolis, Minnesota in 1978, and in Louisiana, New York, and California in 1981. In 1983, a BCO was constructed in Wyoming on I-25 and a 1,000 foot experimental project was constructed on south IH-610 in Houston, Texas (Ref 1). The success of this project led to the 1985 BCO on north IH-610 in Houston. Also in 1985, near Sioux Falls, South Dakota, a BCO was constructed on State Route 38A.

The success of a BCO may depend on the success of the pavement surface preparation. Full-depth PCC patches are placed before the surface preparation if total failure has been experienced. Partial-depth repairs may also be made as part of the overlay placement. Scarification is done by milling machines to remove the old surface to a certain depth. Shotblasting of the surface is now being used as an alternative to scarification. The pavement surface is then airblasted to clean the surface. A bonding agent (grout) may then be applied immediately prior to the overlay placement.

Proper surface preparation and other improved construction methods have contributed to the success of the bonded concrete overlay. However, the long-term success of a bonded concrete overlay is still unknown. The mode of failure is also unknown. The pavement may fail by debonding or in a manner similar to the original pavement. This study will examine the effects of long-term loadings on bonded concrete overlays.

OBJECTIVES OF THE STUDY

In the laboratory, pavement models can be loaded in an accelerated manner. Results that would take years or decades to occur in the field take days or weeks to simulate in the lab. In this way, fatigue can be studied in the laboratory and results applied in the field. Since bonded concrete overlays are a relatively new method of rehabilitation, what actually happens with long term repeated loadings will not be known for some time. This laboratory study hopes to predict what will occur, long term, with bonded concrete overlays. Specifically, the objectives are

(1) to simulate the field conditions in Houston, Texas, on IH-610,
(2) to accomplish fatigue testing of continuously reinforced and jointed concrete pavements,
(3) to study the effect of placing overlays on pavements that are at varying levels of distress, and
(4) to implement the results in the laboratory in field design and construction.

SCOPE OF THE REPORT

Chapter 2 presents the design variables that were tested in the laboratory and explains how field conditions were simulated in the lab.

Chapter 3 explains the preparation necessary to cast the four laboratory slabs and the quality control involved. Procedures for simulating a temperature crack and loading the slabs, and a description of the instrumentation used, are also presented.

Chapter 4 presents the data obtained from testing the laboratory slabs. The data include loading history, average deflections, load transfer, cracking development, and interface shear test results.

Chapter 5 examines the relationship between remaining life and applied load repetitions. A remaining life analysis is done using the laboratory data.

Chapter 6 discusses the trends of the laboratory data and the results of the remaining life analysis.

Chapter 7 summarizes the conclusions of the study and presents recommendations for field implementation and further studies.

CHAPTER 2. LABORATORY EXPERIMENT DESIGN

This chapter presents the experiment design variables that were tested in the laboratory. It also shows how field conditions were simulated in the lab. Four model pavement slabs were tested. Each slab consisted of a base slab and overlay. Each base slab was cracked transversely at the midspan and loaded before the overlay was placed. The overlay was then placed, cracked, and loaded in the same manner. The procedures for construction, cracking, and loading the slabs are the same as those used in earlier studies (Refs 2 and 3). However, these earlier studies tested 4-inch CRCP slabs only, while this study, in addition to CRCP slabs, tested JCP slabs and CRCP and JCP overlays.

LABORATORY FACTORIAL DESIGN

A factorial design (Fig 2.1) was used to outline the design variables that were to be tested in the laboratory. The design variables included type of pavement (for base slab and overlay) and remaining life. The factorial design includes numbers which indicate the priority of testing. Because the laboratory experiment was designed to simulate conditions in Houston on IH-610 (a CRC pavement), CRCP slabs were tested first (Slab Nos. 1 and 2) and JCP slabs (Slab Nos. 3 and 4) were tested next.

Types of Pavement

The base slabs modeled either a CRCP (continuously reinforced concrete pavement) or a JCP (jointed concrete pavement). These represent the primary types of Portland Cement Concrete (PCC) pavements used in the field. The CRCP slabs were reinforced with a welded deformed steel wire fabric. No reinforcement was used in the JCP slabs, but dowels were used at the joint in the JCP base slab to transfer load. On the CRCP, a CRCP overlay was placed, and on the JCP, a JCP overlay was placed. It was necessary to place a JCP overlay on a JCP base

	Type of Base Slab and Type of Overlay	
Remaining Life of Base Slab	CRCP	JCP
High	1	4
Low	2	3

Fig 2.1. Slab testing factorial. Numbers indicate priority of testing.

slab to prevent high stresses which could cause reflective cracking, spalling, or loss of bond (Ref 4). Thus, the joint in the base slab was reproduced in the BCO (Figs 2.2 and 2.3).

Because two types of pavements were being tested (CRCP and JCP), it was possible for different modes of failure to occur. Debonding could occur at a joint in a JCP or at a crack in a JCP or CRCP. If debonding did not occur, another type of failure was possible. Testing two types of pavements allowed more modes of failure to be studied.

Remaining Life

The concept of remaining life is discussed in detail in Chapter 5. After a pavement has been subjected to cyclic loading, a certain amount of distress has occurred. If failure is defined in terms of damage, remaining life can then be defined as the amount of damage left in the pavement that the pavement can experience before failure. The deterioration of the bonded overlay is related to the remaining life of the existing pavement at the time of overlay placement. If a pavement has a low remaining life, many cracks will exist and high stress concentrations will occur when a BCO is placed. The BCO may then deteriorate at a faster rate than if placed on a pavement with a higher remaining life. In this laboratory study, the base slabs were loaded until either a relatively high or low life remained before overlay placement. The first base slab (a CRCP) was loaded in the same manner as previous laboratory studies (Refs 2 and 3)... that is for two million cycles at a load intensity of 5 kips. Because little distress had occurred, this base slab was considered to have a high remaining life. The second base slab (also a CRCP) was loaded until more distress (cracking) had occurred and this was defined as low remaining life.

The third base slab (a JCP) was loaded until a punch-out occurred (defined in this study as failure or zero remaining life). The fourth and final base slab (JCP) was loaded with approximately 70 percent as many repetitions as the third base slab. Less distress had occured and thus this base slab was defined as having a (relatively) high remaining life.

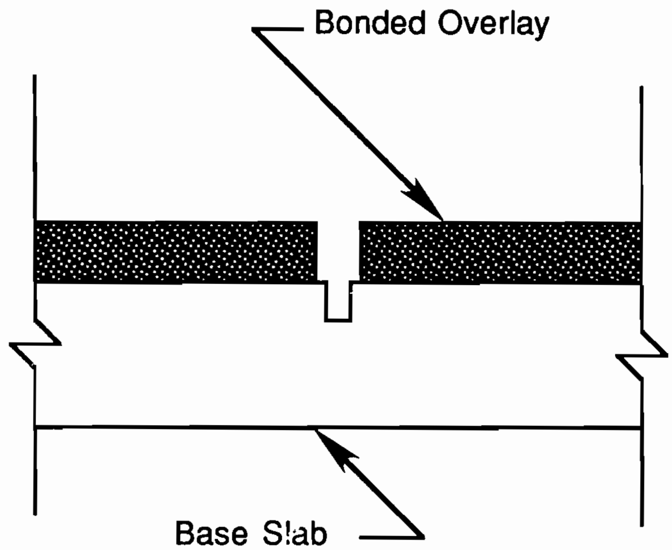


Fig 2.2. Reproduction of transverse joint in overlay.

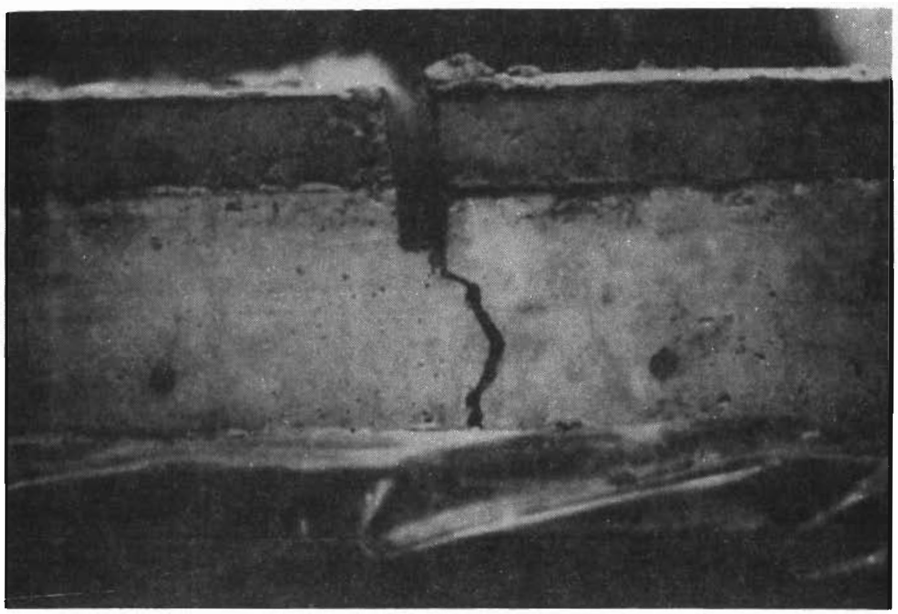


Fig 2.3. Joint in laboratory slab.

SIMULATION OF FIELD CONDITIONS

In the laboratory, a half-scale model of Houston's Loop 610 pavement was designed. Loop 610 had a base pavement of 8 inches and the test sections (Ref 1) had overlay thicknesses of 2 and 3 inches. The pavement system was modeled (Ref 5) using the Loop 610 8-inch base pavement with 3-inch overlay as the prototype. For similar stresses to occur (with a 5-kip loading in the lab), the thickness of the base slabs was 4 inches and of the overlays 1-1/2 inches. In addition to modeling the depth of the base slab and overlay, several other factors had to be taken into account to simulate field conditions. These factors included the concrete mix design, simulation of pavement continuity, cracking of a slab due to temperature changes, and simulation of a wheel load. The basis for the simulation of these factors is described in the following sections.

Mix Design

The mix design for the bonded concrete overlays in the laboratory was the same as used on the Loop 610 BCO (Ref 6). For steel reinforced and for plain concrete mix, 7 sacks per cubic yard of Type I cement, a course aggregate factor of 0.60, and a water factor of 4.5 gallons per sack of cement were used. In addition, the entrained air was 4 to 6 percent and the slump 2 to 4 inches.

Simulation of Pavement Continuity

Due to space limitations in the laboratory, it was impractical to have a slab longer than 6 feet. A slab size of 3 feet by 6 feet was chosen, using discrete element analysis techniques (Ref 2), to allow for a two-dimensional bending model and still meet the laboratory space requirements. A W6x12 beam was placed at each end of the slab. The ends of the beams were tightened with bolts which extended through the ends of the beams and were then attached to the test bed floor. These beams (Fig 2.4) served to model a pavement by simulating the weight of additional slab length.

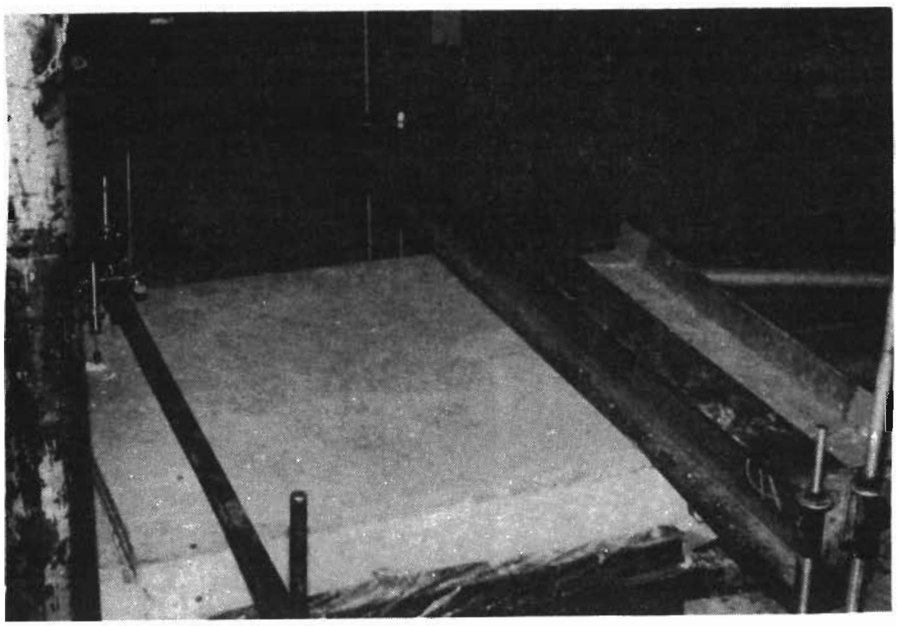


Fig 2.4. Simulation of a continuous pavement using hold-down beams.

Temperature Crack

To simulate a crack formed in the field due to temperature changes, the laboratory slab was put in tension by pulling it horizontally. Pulling bars were embedded into the concrete to help accomplish this. The pulling bars extended 31-1/2 inches into the slab. This embedment length helped simulate field conditions; i.e., movement started at the crack and thus maximum stress occurred at the crack, as in the field. In addition, the first embedded 6 inches of each leg of the pulling bars were covered with polyethylene which served as a bond-breaker to encourage the greatest movement at the center of the slab (at the crack).

Simulation of Wheel Load

The load was transmitted from the load cell to the slab by two steel plates. A 6x6x1 inch plate was fastened on top of a 6x11x1 inch plate and the plates were then placed next to the crack at the midspan. The smaller plate helped to distribute the load to the larger plate, which was approximately the size and shape of a truck tire.

SUMMARY

The procedures used for the construction and loading of the laboratory slabs are similar to those used in earlier studies. However, in addition to testing 4-inch CRCP slabs, with an 1-1/2 inch CRC BCO, 4-inch JCP slabs with an 1-1/2-inch JCP bonded overlay were tested. The laboratory slabs modeled the pavement structure of Loop 610 in Houston. Factors that were taken into account to simulate field conditions included slab size, concrete mix design, pavement continuity, cracking due to temperature changes, and wheel loads.

The primary types of PCC pavements used in the field, CRCP and JCP, were represented in the laboratory. Different modes of failure could be studied by testing these two different types of pavements. Each base slab had either a high or low remaining life at the time of overlay placement. This was done in an attempt to support the hypothesis that an overlay placed on a pavement with a lower remaining life will fail more rapidly than if placed on a pavement with a higher remaining life.

CHAPTER 3. LABORATORY TEST SET-UP AND PROCEDURES

This chapter explains the preparation necessary to cast the four half-scale model slabs and the quality control involved. The procedures for simulating a temperature crack and loading the slab as well as the instrumentation used are also presented in this chapter.

SLAB PREPARATION

Preparing the slabs included everything done prior to cracking and loading the slab. Roughening the surface of the slab after concrete placement was the last step in the slab preparation.

Slab Size

The half-scale model slabs were 3 feet wide and 6 feet long. The base slabs were 4 inches deep while the overlays were 1-1/2 inches deep.

Forms

The forms for the concrete were made of steel and wood and were reusable. The steel part of the base slab forms consisted of 4-inch-deep channels. The channels were then bolted to pieces of wood of the same depth. The forms for the overlay were steel angles, 1-1/2 inches in depth, also bolted together. Before placing the concrete, the forms were oiled to allow for easy removal after the concrete had set.

A piece of wood, 1 inch deep, 1/2 inch wide, and 3 feet long was used to form the joint in the base slab of the jointed model. The wood was placed transversely at the midspan of the slab. To reproduce the joint in the overlay, a piece of wood having a depth of 1-1/2 inches (equal to the depth of the overlay), also 1/2 inch wide and 3 feet long, was used as a form. It was placed on top of the old joint of the base slab to continue the joint in the overlay.

Roadbed

Neoprene mats, 1-inch thick and with a durometer of 50, were used as the roadbed. The first and second slabs were tested on 4 inches of neoprene mats. To allow a slab to be brought to failure more quickly, 6 inches of neoprene, a weaker subgrade (Ref 2), was used for the third and fourth slabs. To reduce friction between the neoprene roadbed and the concrete slab, a thin sheet of polyethylene was used as a bond-breaker. This reduced friction allowed the slab to be pulled from each end forcing a crack at mid-span.

Steel Placement

The test slabs modeled either CRCP or JCP. Pulling bars, used to form the simulated temperature crack, were placed in both the CRCP and JCP slabs. Steel for the CRCP slabs also included a metal strip as well as the reinforcement (Fig 3.1). The JCP slabs had dowels to transfer load, but no reinforcement.

Pulling Bars. Four Grade 60, #6 rebars were used as the pulling bars. The pulling bars were placed in the base slab. Each had an inner diameter of 5-1/4 inches. The pull bars penetrated 31-1/2 inches into the slab, keeping 4-1/2 inches clear on either side of the crack at midspan.

Reinforcement. A welded deformed steel wire fabric (4 x 15-D8 x D4 for the base slab and 4 x 24-D4 x D4 for the overlay) in a flat sheet was used for the CRCP. The slabs as well as the overlays were each reinforced 0.50 percent longitudinally. The steel was placed at mid-depth of the base slab, using 2-inch chairs. Before pouring the overlay, the steel was placed at the top of the base slab. In the first slab, grout was used, and the steel was placed after the grout had been brushed on. No grout was used on the remaining slabs. The steel was supplied by Ivy Steel & Wire Co. and conformed to ASTM Standards 496 and 497.

Metal Strip. A 20-gauge metal strip, with a 1-inch height, was positioned transversely at the mid-span of each of the CRCP base slabs. The purpose of this strip was to form a weak section in the concrete, and thus, force a crack to form at the desired place in the slab. The metal strip was not necessary for the JCP slabs since the joint provided a weakened cross-section.

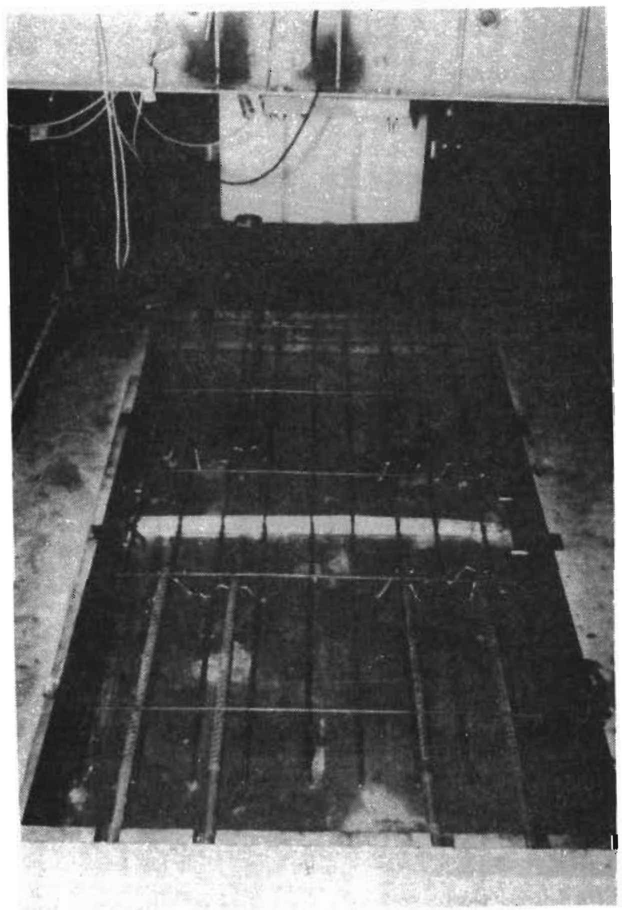


Fig 3.1. CRCP base slab prior to concrete placement. Note metal strip at midspan, pulling bars, and welded wire fabric.

Dowels. The dowels had a diameter of 1/2 inch and were 9 inches long. Each dowel was placed at 6 inches center-to-center at the midspan of the slab (where the joint was formed). Five dowels were used in each JCP base slab.

Concrete Mix Design

The mix specifications for the base slab were

(1) Type I Cement - 5 sacks/cubic yard, supplied by J & J Masonry,

(2) Aggregate - 1335 lb/cubic yard, 3/4 inch max (first and second slabs) or 1/2-inch max (third and fourth slabs),

(3) Sand - 1320 lb/cubic yard,

(4) Slump - 2 to 4 inch, and

(5) Air entrainment - 3 to 6 percent.

The 3/4-inch aggregate used initially was difficult to work with on the 1-1/2-inch overlay. Thus the aggregate was changed to a 1/2-inch max.

The mix specifications for the overlay were the same except that 7 sacks/cubic yard of the Type I cement was used. When grout was needed, the ratio of 1 sack of cement to 7 gallons of water was used. The grout was brushed on immediately before the overlay was placed.

Roughening the Surface

About 3 hours after the base slabs were placed, the surfaces were roughened (Fig 3.2) with a trowel to simulate the scarified base slab. This prevented the need for scarifying the dry concrete surface before placing the overlay.

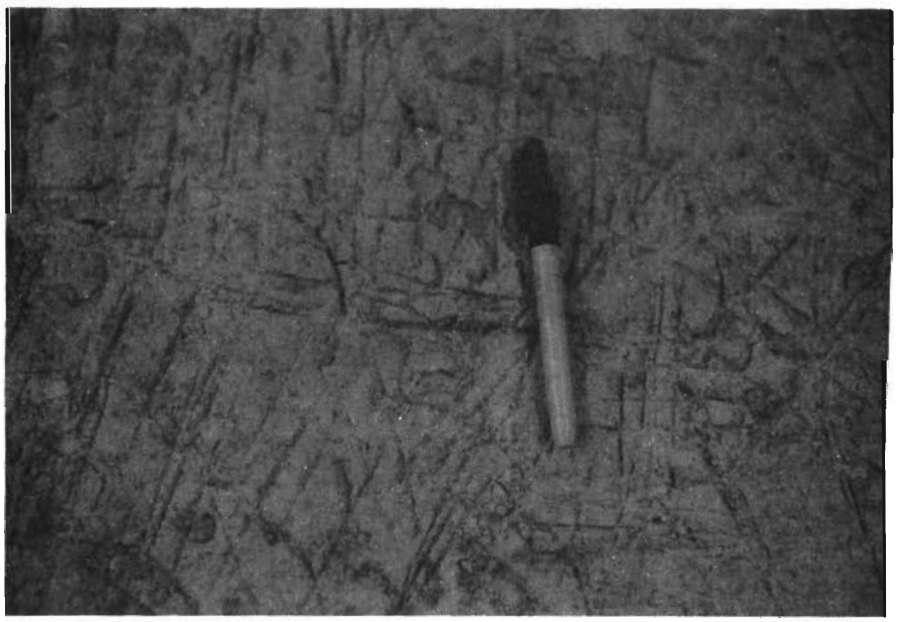


Fig 3.2. Roughened surface of base slab.

QUALITY CONTROL

After mixing the concrete, slump tests and air entrainment tests were performed. In addition, test specimens were made for both the base slab and the overlay. The specimens included three each of compression cylinders, flexural beams, and splitting-tensile cylinders.

These specimens were then evaluated at 7 days (Tables 3.1 and 3.2). Results shown are the average of three tests.

CRACKING THE SLAB

The slabs were cracked within a maximum of 24 hours after placing the concrete. The pulling mechanism (Fig 3.3) used to crack the slab and overlay consisted of the following parts:

(1) Dead Ends: There were two dead ends, each having two L8 x 8 x 1 sections welded together and supported on structural tubing secured to the floor by 14 high-strength bolts. The dead end at the fixed end (Fig 3.4) had four slots cut through it to accomodate the pulling bars, which were anchored in place by half-round sections. The pulling dead end had one slot to accomodate the pulling bolt.

(2) Pulling Frame: The pulling frame included two channels such that the pulling bars could slide between the channels. The pulling bars were anchored by half-round sections.

(3) Wire Rope: A 1-inch wire rope was looped through a connecting section (attached to the pulling frame) and the pulling bolt. The wire rope was held together by seven 1-1/8-inch Crosby cable clamps (Fig 3.5).

(4) Pulling Bolt: The 1-1/2-inch diameter heavy threaded pulling bolt was fitted through the slot in the pulling dead end. Several washers were placed before the large nut that was attached to the pulling bolt. This nut was tightened with a large wrench (Fig 3.6) so that the horizontal forces necessary to crack the slab would be placed on the slab.

The test set-up for cracking the slab is similar to the set-up used by Randall (Ref 2). Further details of the set-up can be found in Reference 2.

TABLE 3.1. RESULTS OF QUALITY CONTROL TESTS FOR BASE SLABS

Base Slab No.	Slump (Inches)	Percent Air Entrained	7-Day Compressive Strength (psi)	7-Day Flexural Strength (psi)	7-Day Tensile Strength (psi)
1	3	6	2310	520	280
2	3 1/2	4 1/2	2370	460	280
3	2 1/2	6	3030	780	320
4	2 1/2	5	3200	600	360

TABLE 3.2. RESULTS OF QUALITY CONTROL TESTS FOR OVERLAYS

Overlay No.	Slump (Inches)	Percent Air Entrained	7-Day Compressive Strength (psi)	7-Day Flexural Strength (psi)	7-Day Tensile Strength (psi)
1	3 1/2	6	2540	540	350
2	2 1/2	5 1/2	4400	690	500
3	3 1/2	6	3680	920	350
4	3	4	4210	800	290

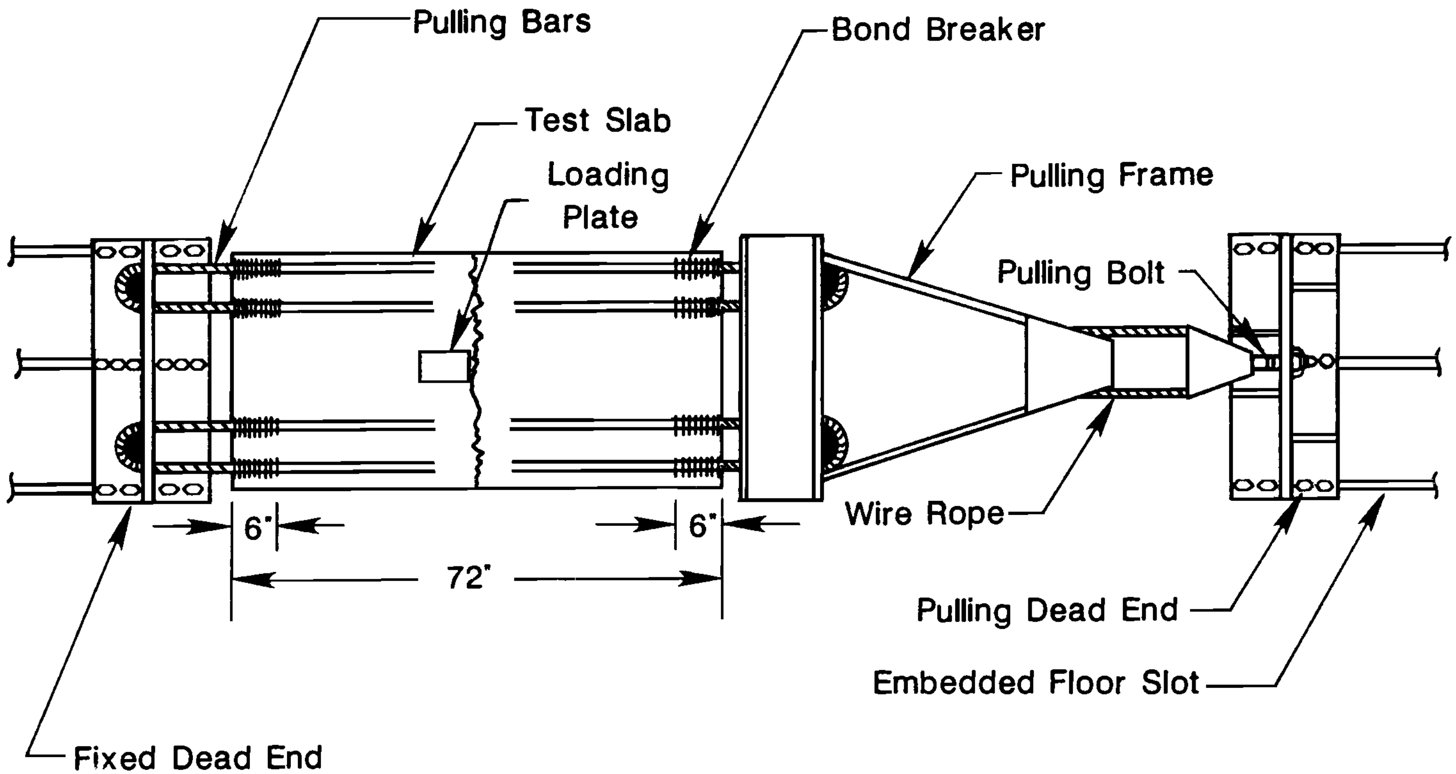


Fig 3.3. Schematic of the pulling mechanism used to form the simulated temperature crack at midspan.

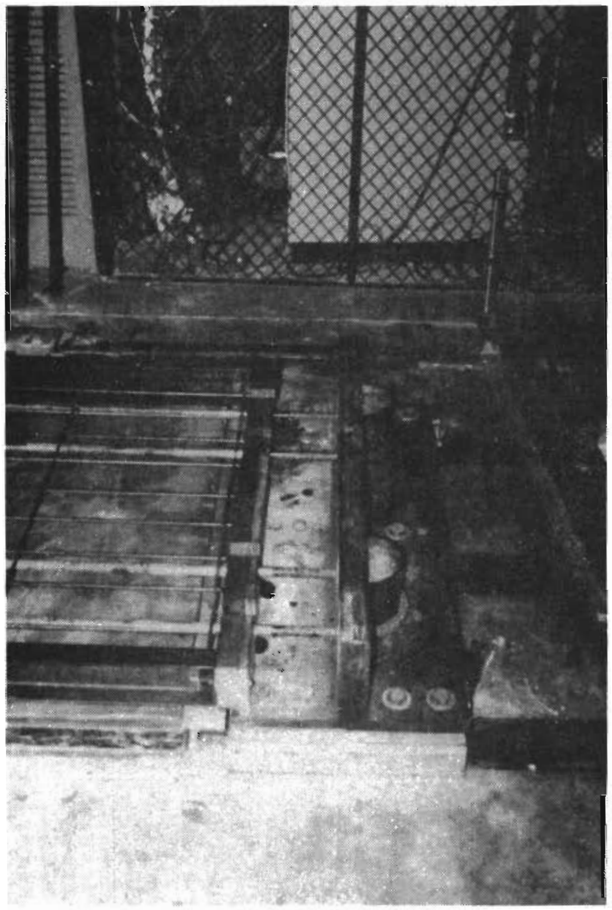


Fig 3.4. Fixed dead end of the pulling mechanism used to crack each base slab and overlay.

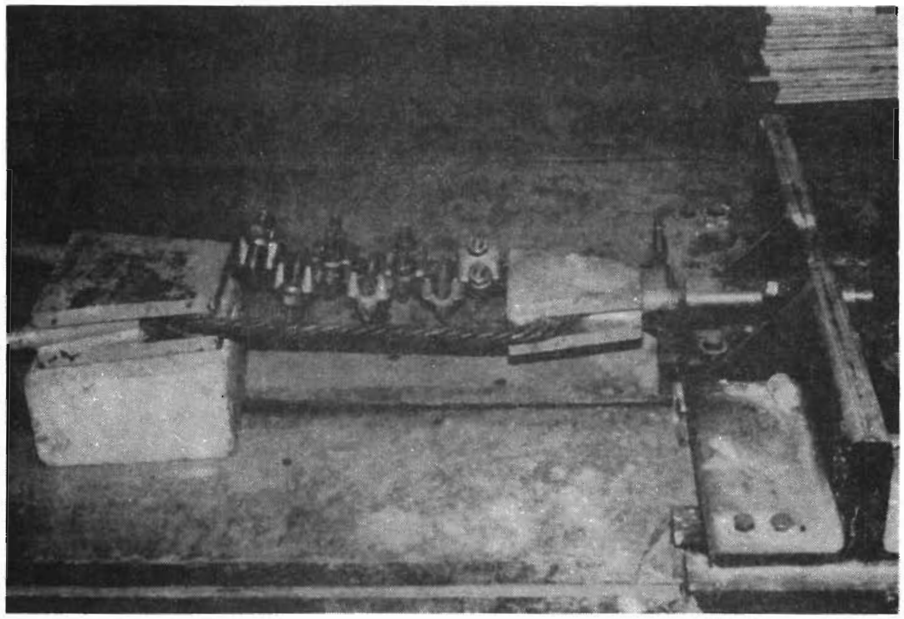


Fig 3.5. Wire rope and clamps at pulling end.

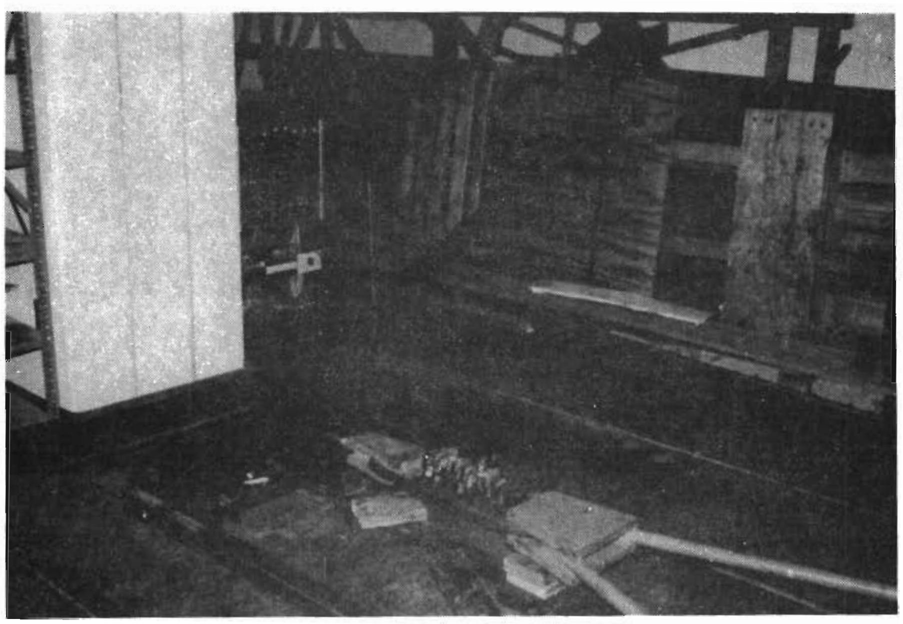


Fig 3.6. Wrench used at pulling end to crack slab.

INSTRUMENTATION

Each slab and overlay was monitored for crack width and deflection. Berry strain gauges were used to measure crack widths, and direct current displacement transducers (DCDTs) were used to record vertical deflections.

Berry Strain Gauge

For each slab and overlay, several pairs of gauge plug points were placed in the concrete before the concrete had hardened. A pair of gauge plug points consisted of one point on either side of the crack, and thus the crack width could be measured with the Berry strain gauge (Fig 3.7). The gauge plug points were placed 8 inches apart. Initial readings, before the slab had been cracked, were taken. Readings after the slab had been cracked were also taken. The crack width was found by taking the difference between the readings taken after the slab had been cracked and the initial readings.

The Berry strain gauge has an accuracy of $\pm$ 0.001 inch. For each measurement, three readings were taken and the average value was used in calculating the crack width (Table 3.3).

DCDTs

Four DCDTs were placed in a line parallel to and approximately one inch away from the loading plate (Fig 3.8). The DCDTs were numbered and placed in the following manner:

DCDT #1 - 3 inches from the crack on the non-loaded side
DCDT #2 - approximately 1/4 inch from the crack on the loaded side
DCDT #3 - 8 inches from the crack on the loaded side
DCDT #4 - 16 inches from the crack on the loaded side.

TABLE 3.3. AVERAGE CRACK WIDTHS.

Base Slab No.	Base Slab with Overlay No.	Average Crack Width (Inches)
1	--	0.037
2	--	0.030
3	--	0.079
4	--	0.086
--	1	0.012
--	2	0.016
--	3	0.047
--	4	0.034

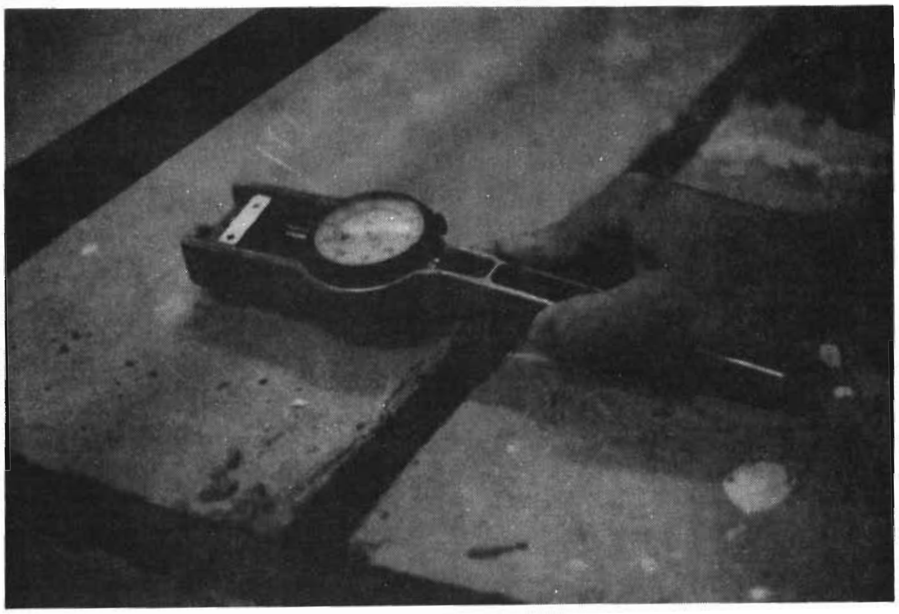


Fig 3.7. Berry strain gauge used to measure crack width at the midspan of each base slab and overlay.

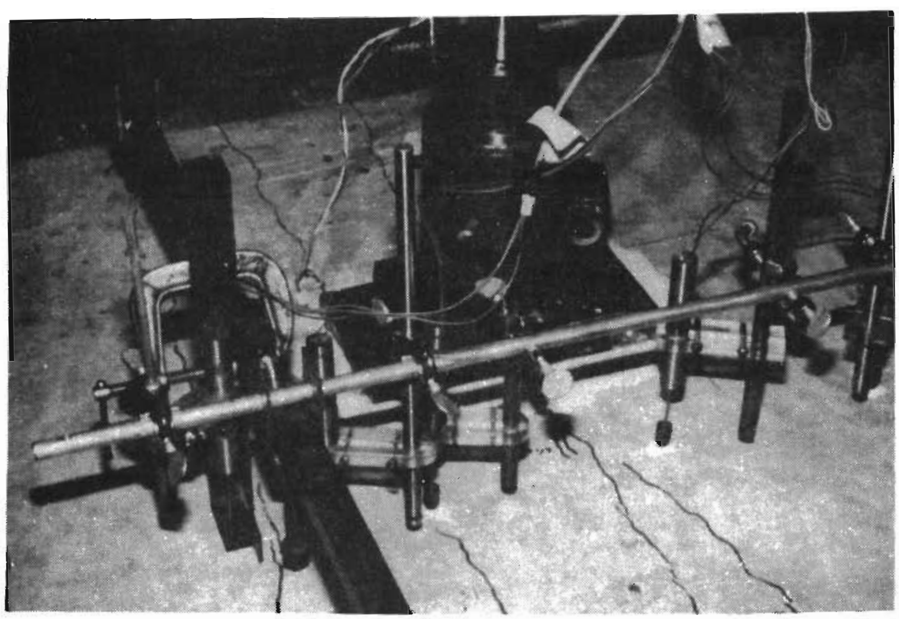


Fig 3.8. DCDTs used to measure vertical displacements for each base slab and overlay.

In addition, a fifth DCDT (Fig 3.9) was placed on the non-moving steel bar that held the other four DCDTs in place. All of the DCDTs were zeroed at the start of loading. The fifth DCDT would thus remain at zero throughout loading--this served as a check to make sure the bar that held the DCDTs in place did not move during loading.

LOADING THE SLAB

Before the slab was loaded, the tie-down beams were placed at the ends of the slab and the loading plate was centered on the slab, behind the crack, and held in place by a mixture of gypsum and water to insure a uniform bearing surface.

The equipment that was used to load the slab and overlay consisted of the following:

(1) MTS System: A Material Testing System (MTS), Model 810 (Fig 3.10), including a master control panel (Model 413), a controller (Model 442), a digital function generator (Model 410), and a counter panel (Model 417) was used to drive the loading actuator.

(2) Loading Actuator: A MTS Model 34G-E1 fatigue-rated loading actuator, with a capacity of 35 kips, was used for loading.

(3) Loading Frame: The loading frame (Fig 3.11) included vertical supports with inner diameters of 3 inches, outer diameters of 4 inches, and upper beams (two W10 x 15) and lower beams (two W12 x 16.5).

The test set-up for loading the slab is similar to the set-up used by Randall (Ref 2). Further details of the set-up can be found in Reference 2.

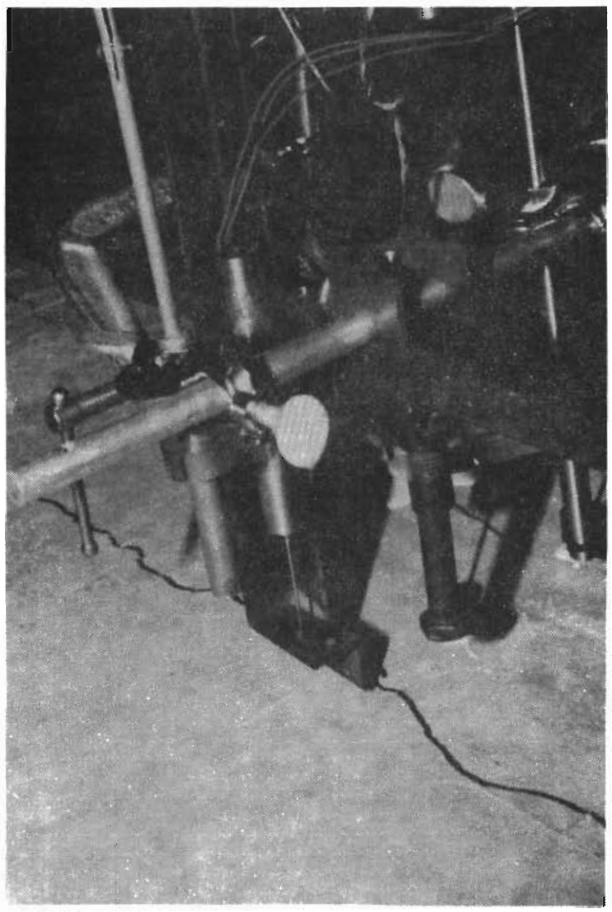


Fig 3.9. DCDT placed on a stationary bar serves as a check for the other DCDTs used to record vertical displacements.

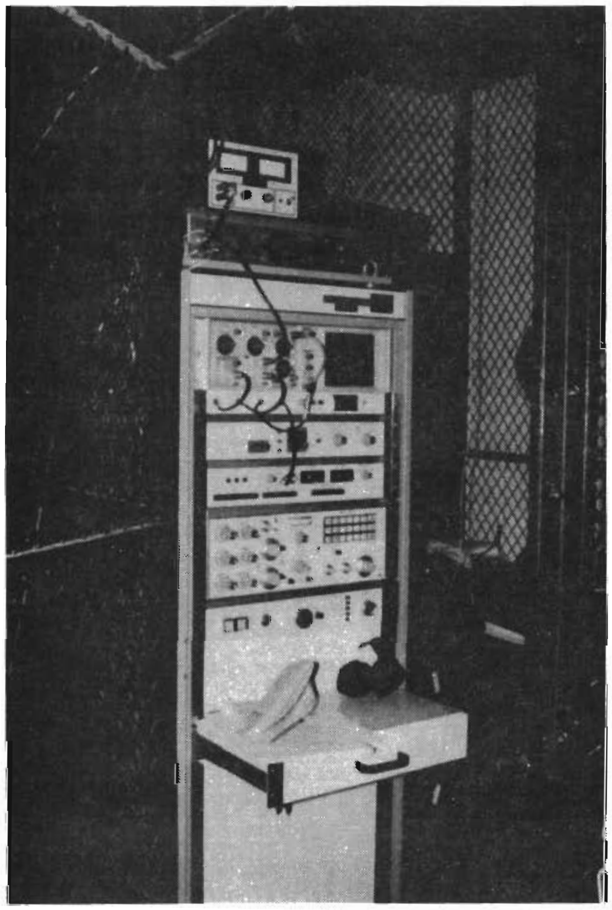


Fig 3.10. MTS System used to drive the loading actuator.

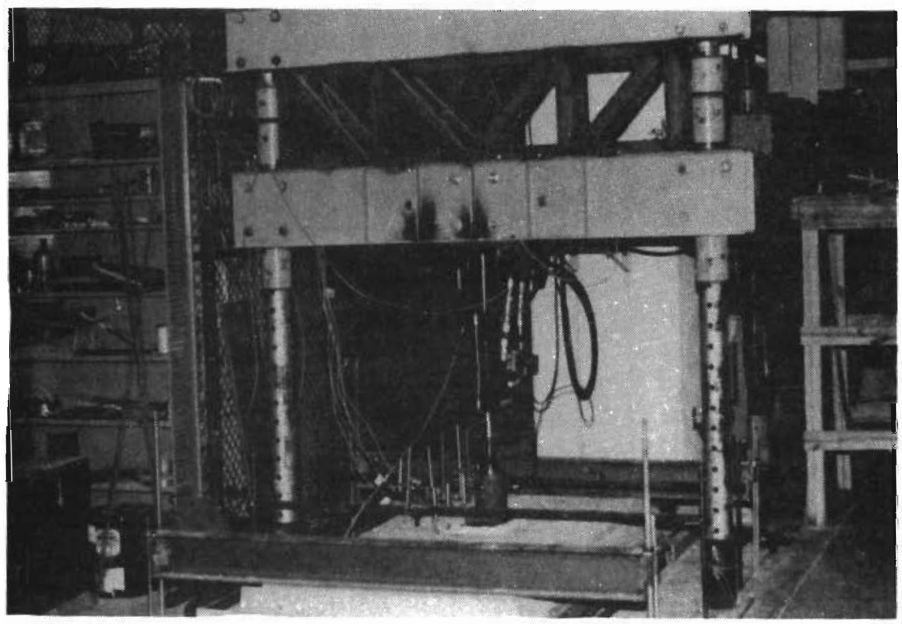


Fig 3.11. MTS actuator, supported on frame, used to load each base slab and overlay.

CHAPTER 4. PRESENTATION OF DATA

This chapter presents the data from the four laboratory test slabs. The loading history of each base slab and overlay and the average deflections are presented first. Load transfer, cracking development, and interface shear test results are then presented.

LOADING HISTORY

At the start of testing, it was decided to load each slab with two million load repetitions at 5 kips to compare the results with previous work (Refs 2 and 3). Thus the first slab was loaded at 5 kips for approximately 2 million cycles (Table 4.1). The overlay was placed and loaded with almost 8 million cycles at 5 kips. Little damage had occurred so the load was increased to 10 kips.

The second base slab was to have a lower remaining life before overlaying than the first slab. After 4 million cycles at 5 kips, the load was increased to 10, 15, and then 20 kips (the capacity of the loading actuator) to produce further damage. The overlay was placed and loaded with 5, 10, and 20, kips when an equipment failure occurred. The equipment had to be replaced and, as a result, testing was shut down for five months. When the loading of the overlay resumed, a load of 5 kips and then 20 kips was again placed.

The third slab, a plain jointed concrete pavement, was brought to a punch-out like failure relatively quickly with approximately 1 million cycles at 5 kips, 2 million at 10 kips, and 2000 at 20 kips. The failure resembled the punch-outs normally associated with CRC pavements as seen in Fig 4.5. The third overlay was loaded with 5 and 10 kips when a punch-out failure again occurred.

It was decided to load the fourth slab to 70 percent of the third slab. Since the third slab had failed (zero remaining life), the fourth slab would have approximately 30 percent remaining life. The fourth overlay was loaded with the same number of 5- kip load repetitions as the third overlay before increasing the load to 10 kips.

TABLE 4.1. LOADING HISTORY OF LABORATORY SLABS

Slab Number and Type	Load (kips)	Number of Load Repetitions at Given Load	Cumulative Number of Load Repetitions
Base Slab No. 1 CRCP	5	2,002,000	2,002,000
Overlay No. 1 CRCP	5	1,252,000	1,252,000
	10	7,951,000	9,203,000
Base Slab No. 2 CRCP	5	4,400,000	4,400,000
	10	800,000	5,200,000
	15	2,400,000	7,600,000
	20	400,000	8,000,000
Overlay No. 2 CRCP	5	836,000	836,000
	10	1,564,000	2,400,000
	20	928,000	3,328,000
	5	2,300,000	5,628,000
	20	3,999,000	9,627,000

(continued)

TABLE 4.1. (CONTINUED)

Slab Number and Type	Load (kips)	Number of Load Repetitions at Given Load	Cumulative Number of Load Repetitions
Base Slab No. 3	5	1,271,000	1,271,000
JCP	10	1,715,000	2,986,000
	20	2,000	2,988,000
Overlay No. 3	5	5,040,000	5,040,000
JCP	10	442,000	5,482,000
Base Slab No. 4	5	950,000	950,000
JCP	10	1,228,000	2,178,000
Overlay No. 4	5	5,163,000	5,163,000
JCP	10	7,683,000	12,846,000

DEFLECTION

In the laboratory, deflections were measured with direct current displacement transducers (DCDTs). DCDTs were placed in four different locations (Fig 4.1). Table 4.2 presents a summary of average deflections at each DCDT for each slab and overlay. It must be noted that the CRCP slabs were placed on 4-inches of neoprene and the JCP slabs were placed on 6-inches of neoprene. Average deflections for each load intensity are presented since deflections stayed fairly constant with time unless the load was increased. Complete plots of deflection as a function of the number of load repetitions can be found in Appendix A.

The summary of deflections shows the increase in deflection with increasing load. In the CRCP, as the load was doubled from 5 to 10 kips (Overlay No. 1) or from 10 to 20 kips (Base Slab No. 2), the deflection increased by over 100 percent . In the JCP, as the load was doubled from 5 to 10 kips (Slabs 3 and 4), deflection increased by an average of 60 percent .

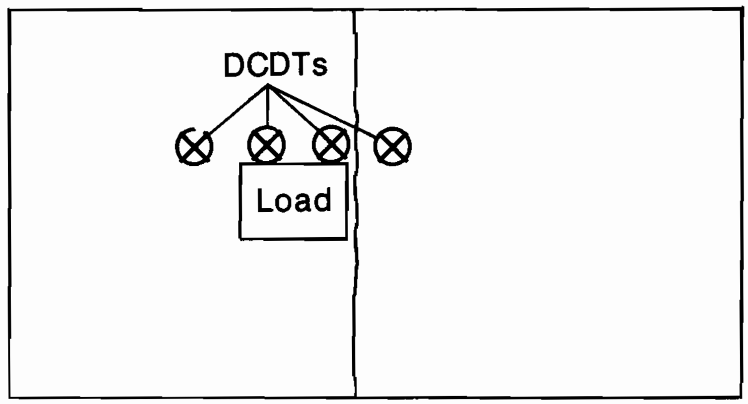
The decrease in deflection when an overlay was placed is also shown. For CRCP, a 60 percent average reduction in deflection was noted after an overlay was placed. A reduction of about 40 percent occurred when an overlay was placed on a JCP.

In general, DCDT #2 measured the greatest deflections (except for Slab 2, where DCDT #3 showed the largest deflections). In the CRCP, DCDT #3 measured larger deflections than DCDT #1, while the opposite was true for the JCP. DCDT #4 measured the smallest deflections for both the CRCP and the JCP slabs.

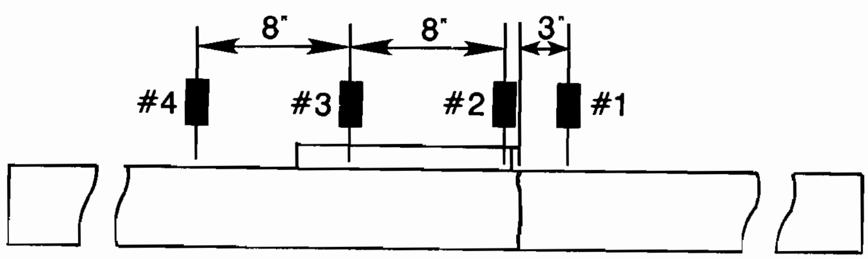
LOAD TRANSFER

For a CRCP, the load must be transferred across transverse cracks. For a JCP, the load is transferred across transverse joints, using dowels as load-transfer devices. A measure of load transfer can be made by comparing deflections on the loaded and unloaded sides. If the deflection on the unloaded side is equal to the deflection on the loaded side, each side is carrying one half of the applied load and the load transfer is 100 percent effective.

In the laboratory, deflection on the unloaded side was measured by DCDT #1, and DCDT #2 measured deflection closest to the crack or joint on the loaded side. Load transfer is defined



(a) Plan view.



(b) Side view.

Fig 4.1. Location of DCDTs.

TABLE 4.2. SUMMARY OF LABORATORY MEASURED DEFLECTIONS

Slab Number and Type	Load (kips)	Average Deflections (Inches) DCDT No. 1	DCDT No. 2	DCDT No. 3	DCDT No. 4
Base Slab No. 1 CRCP	5	0.005	0.026	0.021	0.021
Overlay No. 1	5	0.002	0.009	0.005	0.002
CRCP	10	0.015	0.020	0.017	0.013
	5	*	0.016	0.017	0.014
Base Slab No. 2	10	0.014	0.017	0.019	0.016
CRCP	15	0.019	0.025	0.028	0.021
	20	0.034	0.042	0.049	0.031
Overlay No. 2 CRCP	20	0.016	0.023	0.031	0.014

* Data unavailable

(continued)

TABLE 4.2. (CONTINUED)

Slab Number and Type	Load (kips)	Average Deflections (Inches)			
		DCDT No. 1	DCDT No. 2	DCDT No. 3	DCDT No. 4
Base Slab No. 3	5	0.085	0.095	0.062	0.040
JCP	10	0.123	0.166	0.106	0.050
Overlay No. 3	5	0.040	0.075	0.040	0.035
JCP	10	0.057	0.123	0.053	0.039
Base Slab No. 4	5	0.086	0.087	0.062	0.029
JCP	10	0.116	0.137	0.103	0.041
Overlay No. 4	5	0.037	0.042	0.031	0.023
JCP	10	0.062	0.081	0.056	0.041

* Data unavailable

as the deflection on the unloaded side (measured by DCDT #1) divided by the deflection on the loaded side (measured by DCDT #2). Figures 4.2, 4.3, and 4.4 present the load transfer of slabs 2, 3, and 4, respectively. DCDT #1 of Slab No. 1 was incorrectly calibrated and thus the load transfer results of the first slab are not available.

The load transfer of Base Slab No. 2 (Fig 4.2) starts out high (95 percent) and stays fairly constant with changing load. Before overlaying, the load transfer is 85 percent and the placement of the overlay increases the load transfer slightly. The load transfer of the overlay stays fairly constant for about 8 million load repetitions and then it drops off to about 60 percent .

The load transfer of Base Slab No. 3 (Fig 4.3) starts at 95 percent and decreases rapidly to about 70 percent before failure. A punch-out like failure occurred during the 2000 load repetitions at 20 kips, bringing the load transfer down to zero. Before the overlay was placed, the slab was repaired with a polymer concrete consisting of 4 parts of a 50 percent benzoyl peroxide powder and 1 part of a 12 percent cobalt naphthenate solution added to 100 parts of a commercially available high molecular weight monomer. Figure 4.5(a) and (b) show Slab No. 3 before and after repair. When Overlay No. 3 was placed, the load transfer was increased from zero to 60 percent . The load transfer dropped to about 30 percent before a similar failure (Fig 4.6) occurred during a 10-kip loading, dropping the load transfer again to zero.

The load transfer of Base Slab No. 4 (Fig 4.4) stayed at around 100 percent for the 5-kip loading and then dropped and stayed around 85 percent during the 10-kip loading. After placing the overlay, the load transfer stayed fairly constant for 13 million load repetitions, at around 80 percent .

CRACK DEVELOPMENT

During the AASHO Road Test (Ref 7), cracks that developed on rigid pavements were classified as Class 1, 2, 3, or 4. Class 1 includes fine cracks that are not visible under dry surface conditions from 15 feet away. Class 2 cracks can be seen at 15 feet but have a width of less than 1/4 inch. Class 3 cracks are opened or spalled at the surface to a width of 1/4 inch or more over a distance at least equal to 1/2 of the total crack length. A Class 4 crack is any crack

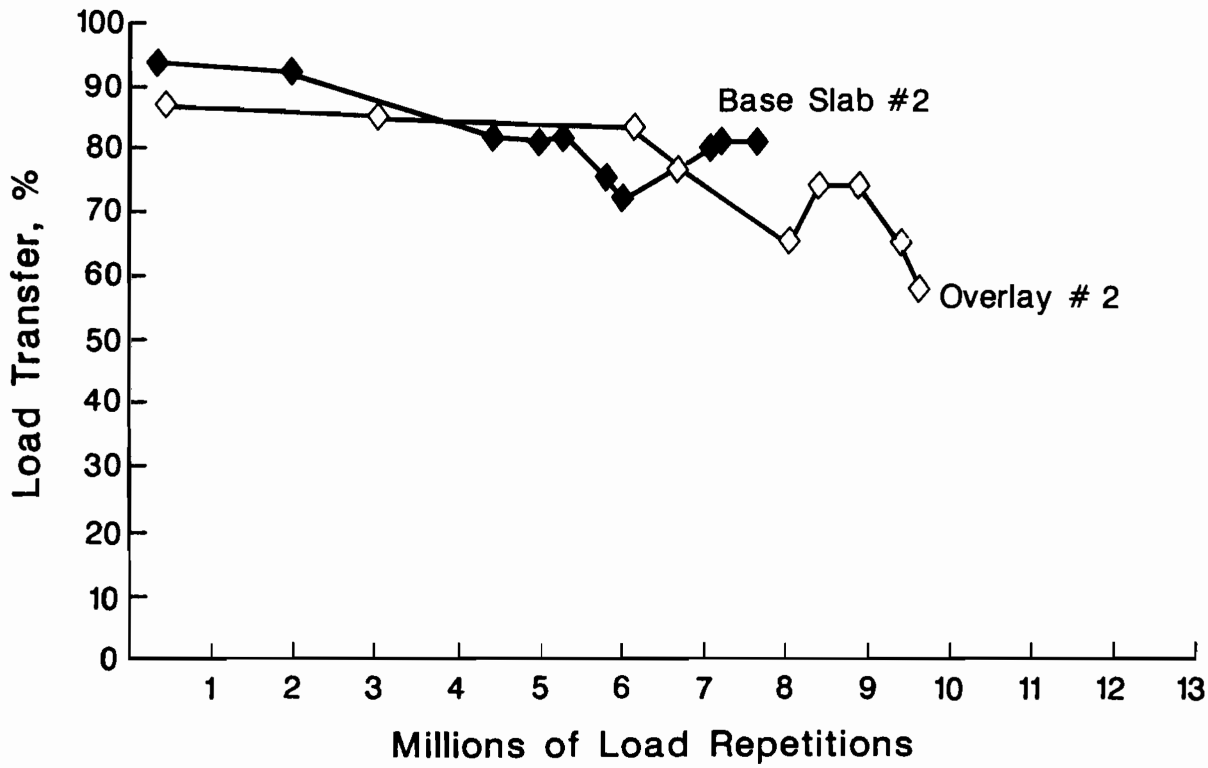


Fig 4.2. Load transfer of Base Slab and Overlay No. 2.

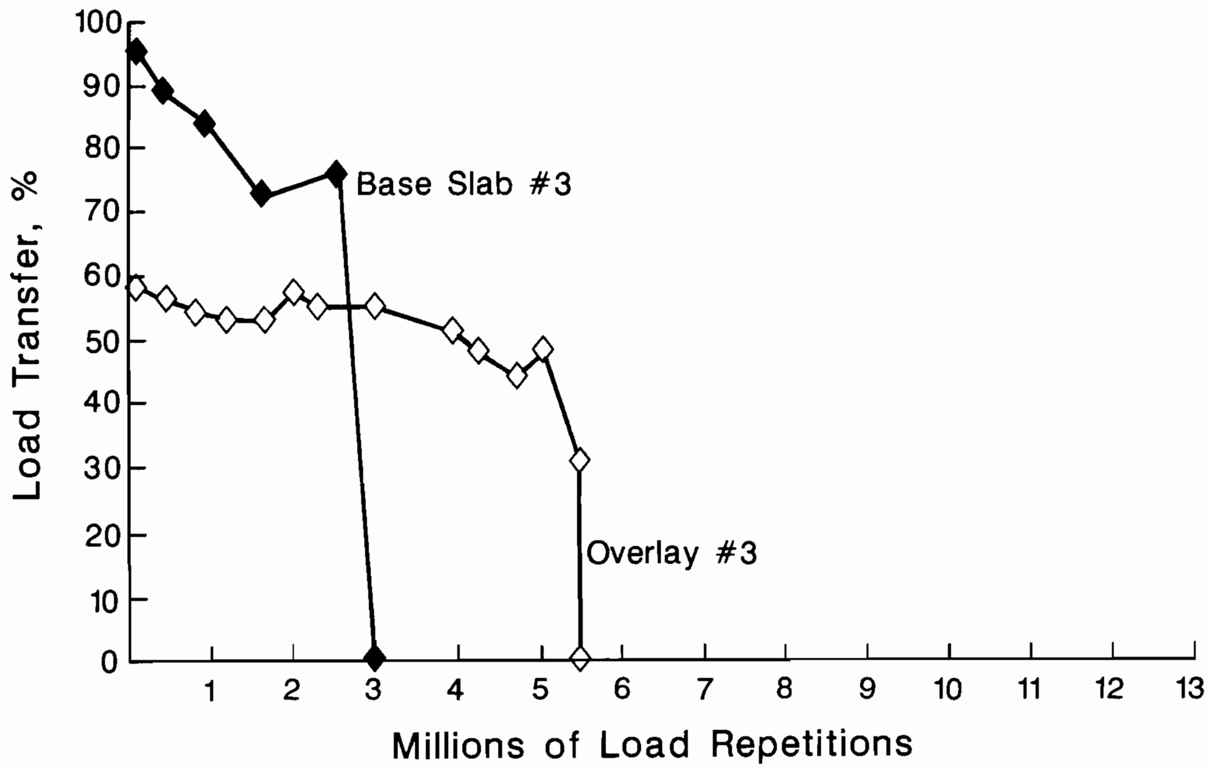


Fig 4.3. Load transfer of Base Slab and Overlay No. 3.

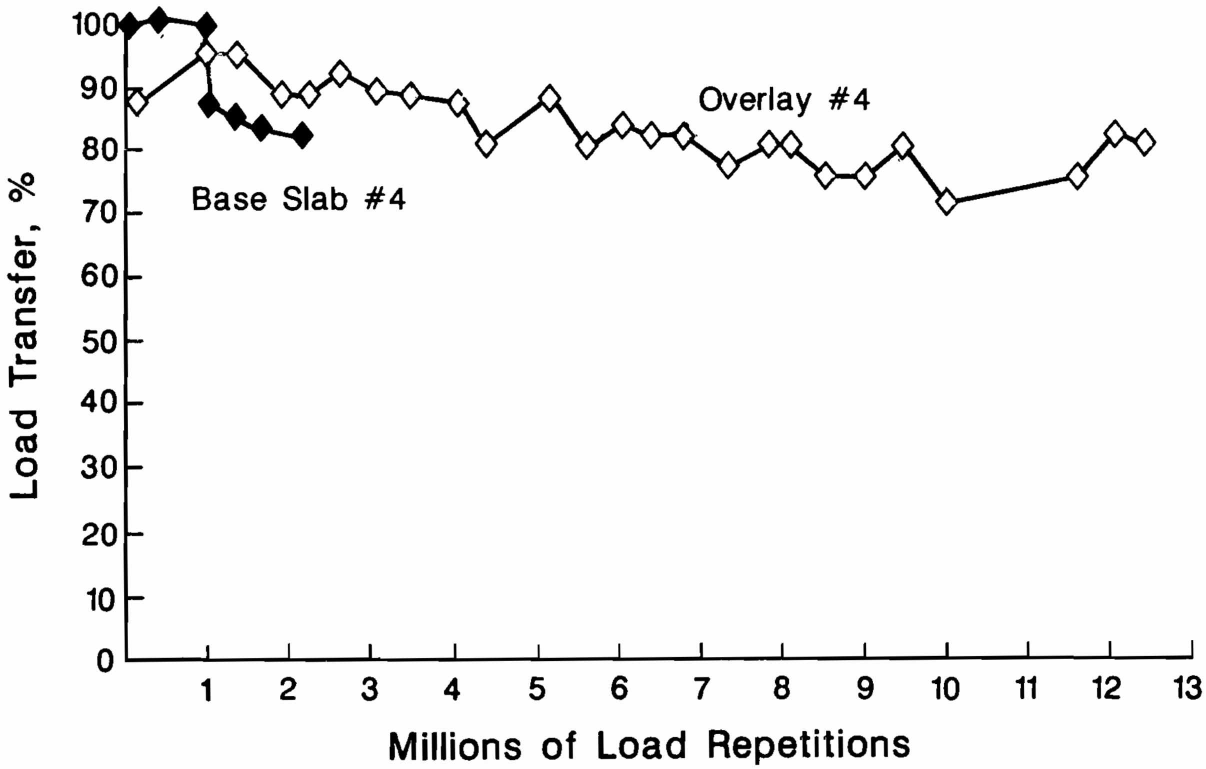
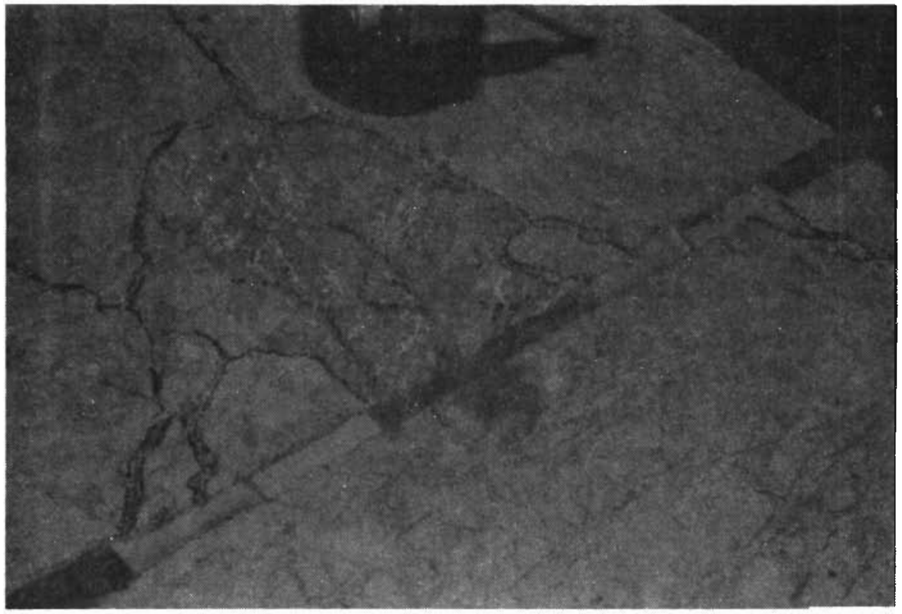
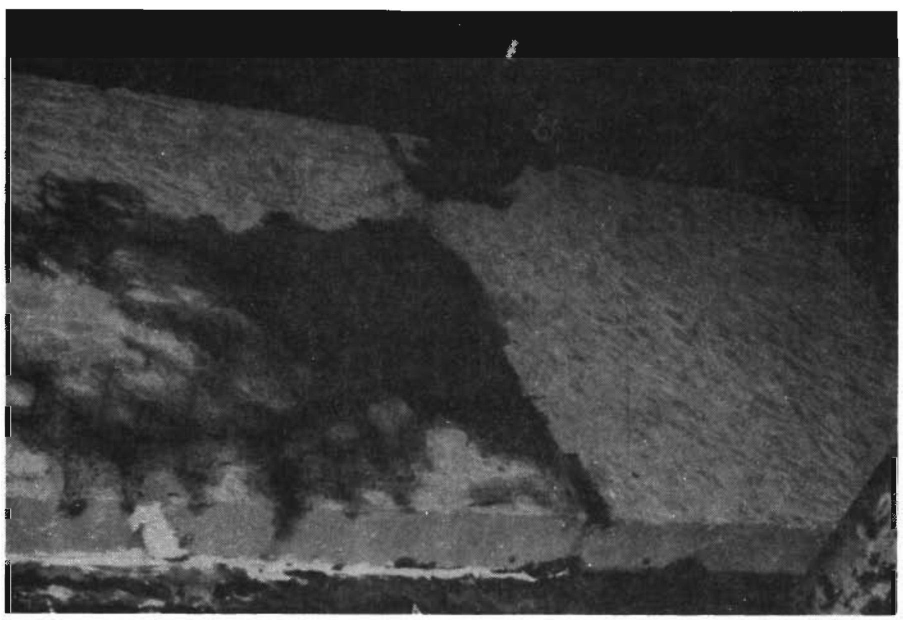


Fig 4.4. Load transfer of Base Slab and Overlay No. 4.



(a) Before repair.



(b) After repair.

Fig 4.5. Punchout failure of Base Slab No. 3.

Fig 4.6. Punchout failure of Overlay No. 3.

that has been sealed. Only Class 3 and Class 4 cracks are used in calculating the present serviceability index.

Figures 4.7, 4.8, and 4.9 show the cracking development of Base Slab and Overlay Nos. 1, 2, and 3, respectively. Cracking is presented as feet of crack length per 1000 square feet of pavement surface. The classification of the cracks is also shown. Each slab and overlay was pulled in tension to force a simulated temperature crack at midspan. The length of this simulated temperature crack is not included in the cracking total. However, during this pulling process, for Overlay No. 1 and Base Slab and Overlay No. 2, other cracks occurred at weak spots in the concrete. This additional cracking which occurred during the pulling process is included and shown as the amount of cracking at zero load repetitions. Both Base Slab and Overlay No. 4 had no cracking throughout the entire loading period; thus no cracking development is presented for the fourth slab. Further details of the cracking development can be found in Appendix B.

The cracking in Base Slab No. 1 (Fig 4.7) started at zero and increased to about 700 feet/1000 square feet in 2 million cycles. When the overlay was placed, there was some initial cracking during the simulation of the temperature crack but there was no additional cracking during the 9 million load repetitions. Figures 4.10 and 4.11 show the crack on Overlay No. 1.

Base Slab No. 2 (Fig 4.8) initially had 800 feet/1000 square feet of cracking and after 8 million cycles the cracking had increased to 1400 feet/1000 square feet (Fig 4.12). After Overlay No. 2 was placed, it initially had 1050 feet/1000 square feet (Fig 4.13) of cracking which increased to 1550 feet/1000 square feet (Figs 4.14, 4.15, 4.16, and 4.17).

Base Slab No. 3 (Fig 4.9) started at zero cracking, increased to about 200 feet/1000 square feet, and then rapidly increased to 700 feet/1000 square feet as failure occurred (Fig 4.18). Overlay No. 3 also started at zero cracking and increased to about 450 feet/1000 square feet over 5 -1/2 million load repetitions before failure (Fig 4.19).

INTERFACE SHEAR STRENGTH

Shear stress was measured at the interface of Slab Nos. 2, 3, and 4 using the direct shear apparatus developed by the Center for Transportation Research (Ref 8). Cores were

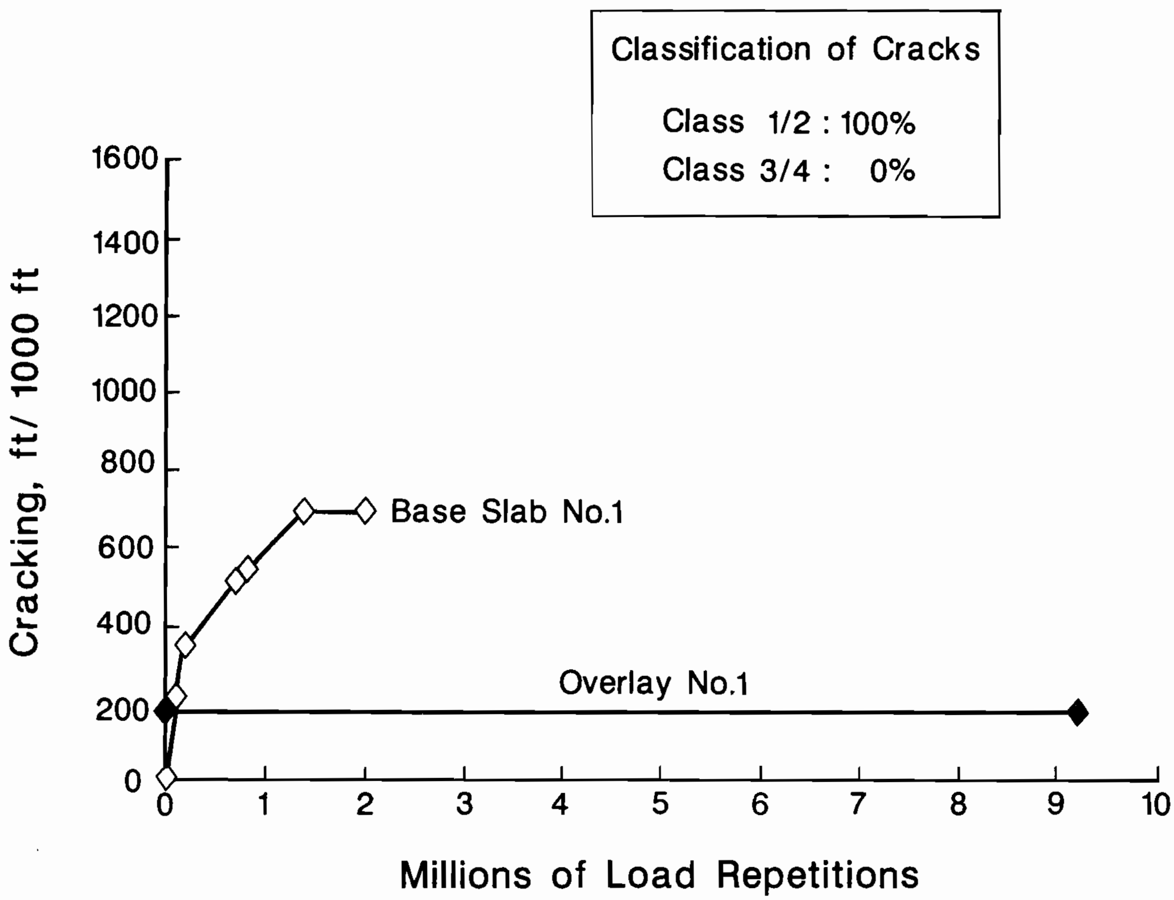


Fig 4.7. Development of cracking for Base Slab and Overlay No. 1.

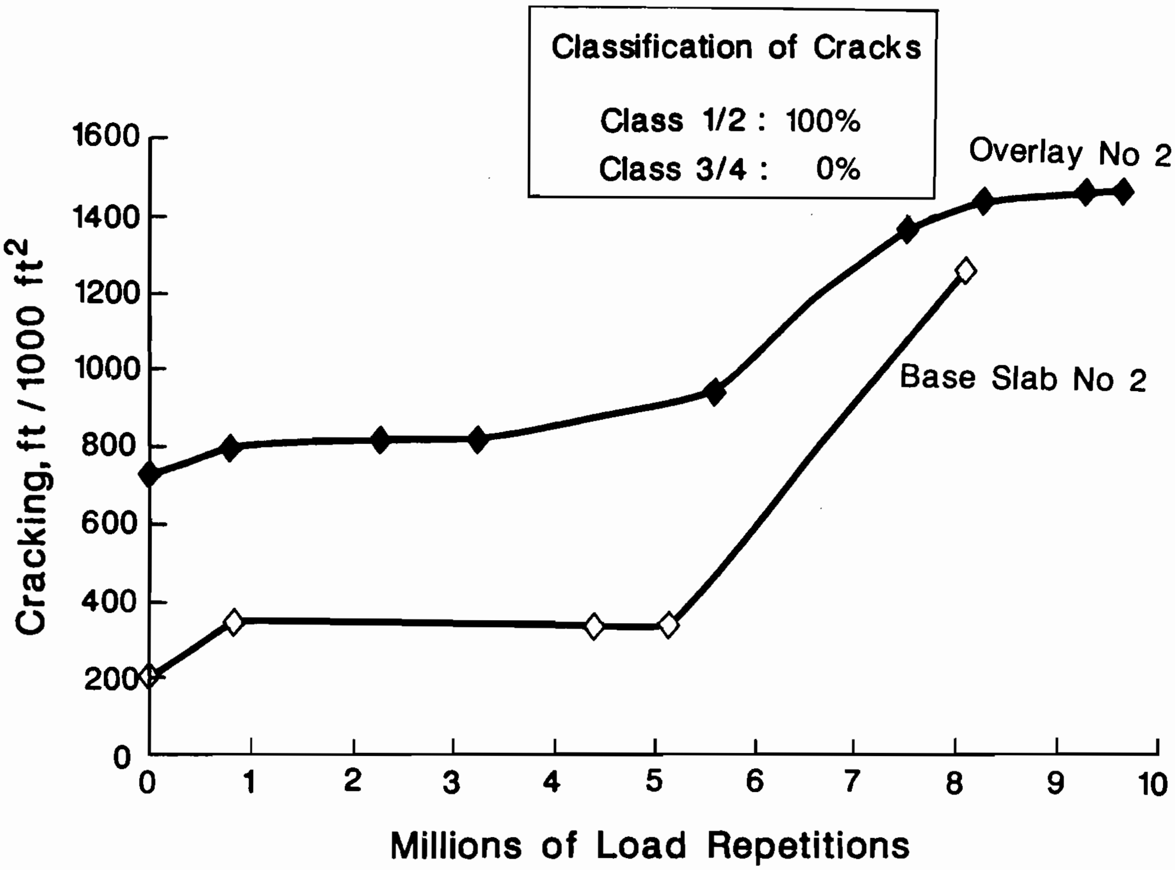


Fig 4.8. Development of cracking for Base Slab and Overlay No. 2.

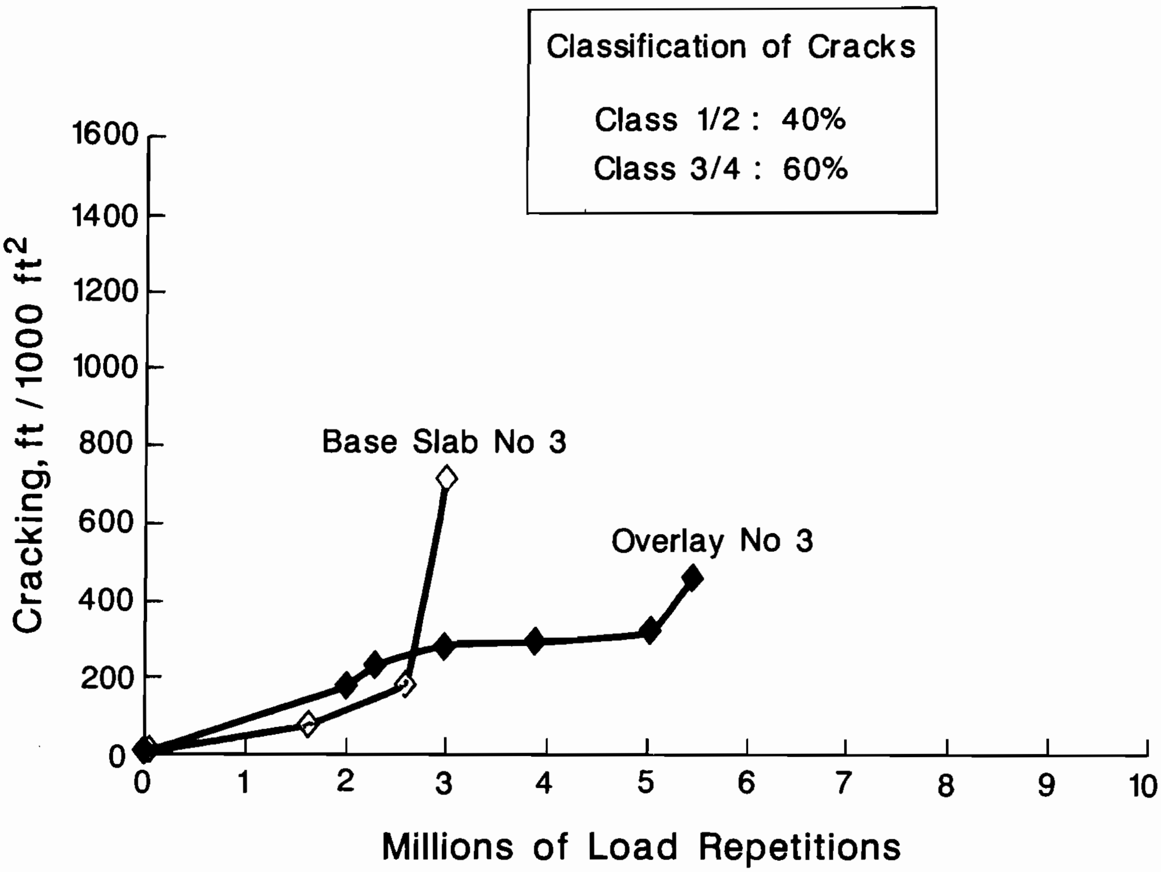


Fig 4.9. Development of cracking for Base Slab and Overlay No. 3.

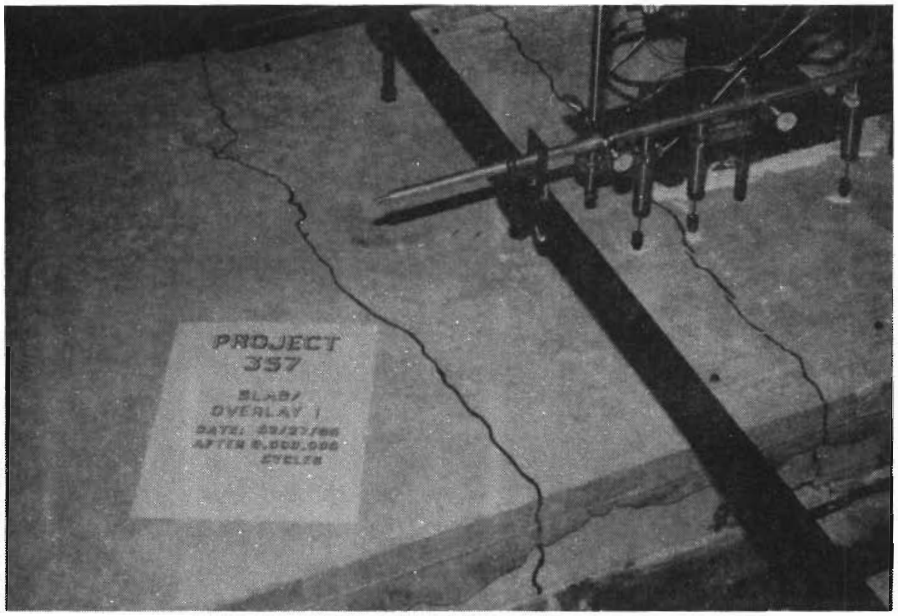


Fig 4.10. Overlay No. 1 after 8 million cycles.

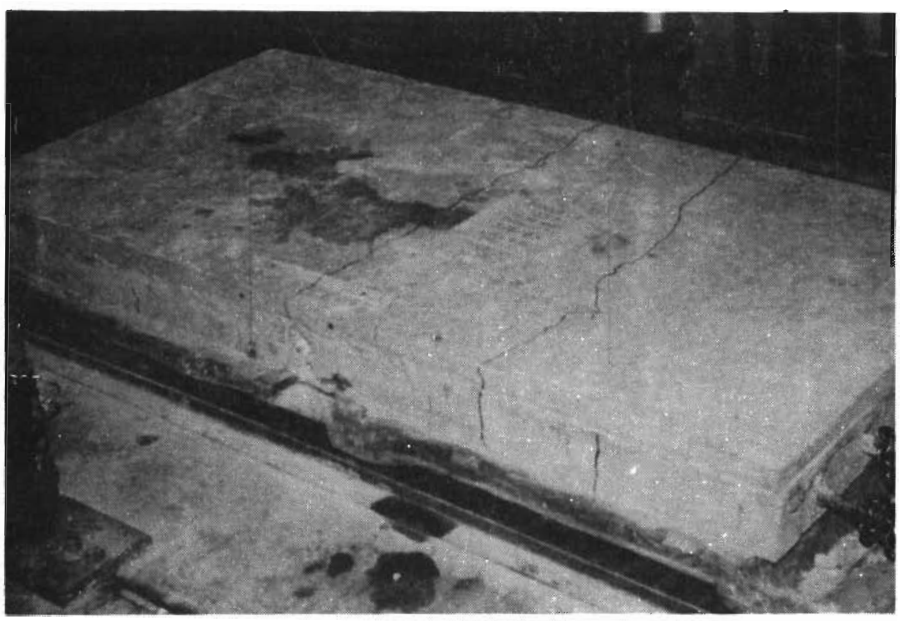


Fig 4.11. Overlay No. 1 after 9 million cycles.

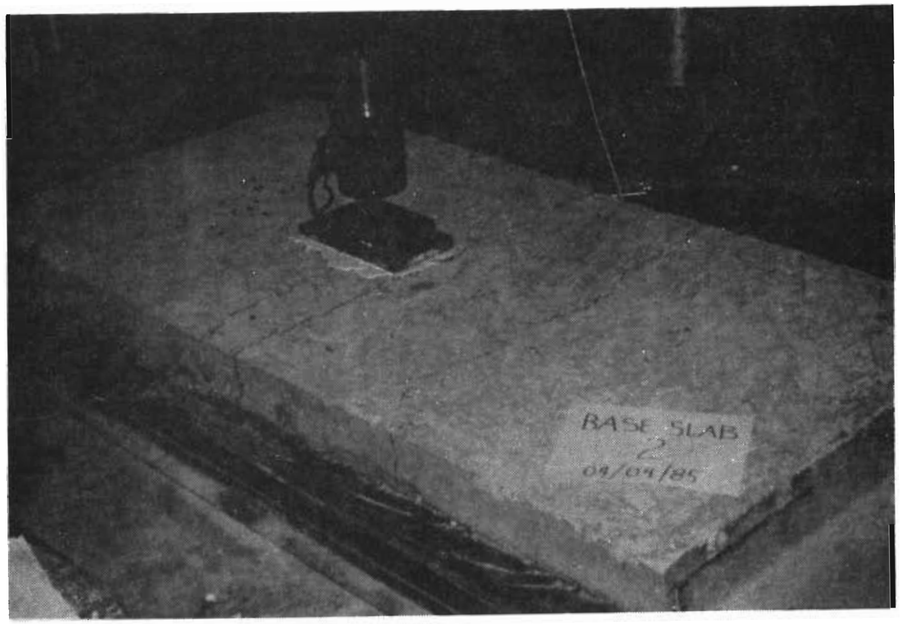


Fig 4.12. Base Slab No. 2 after 8 million cycles.

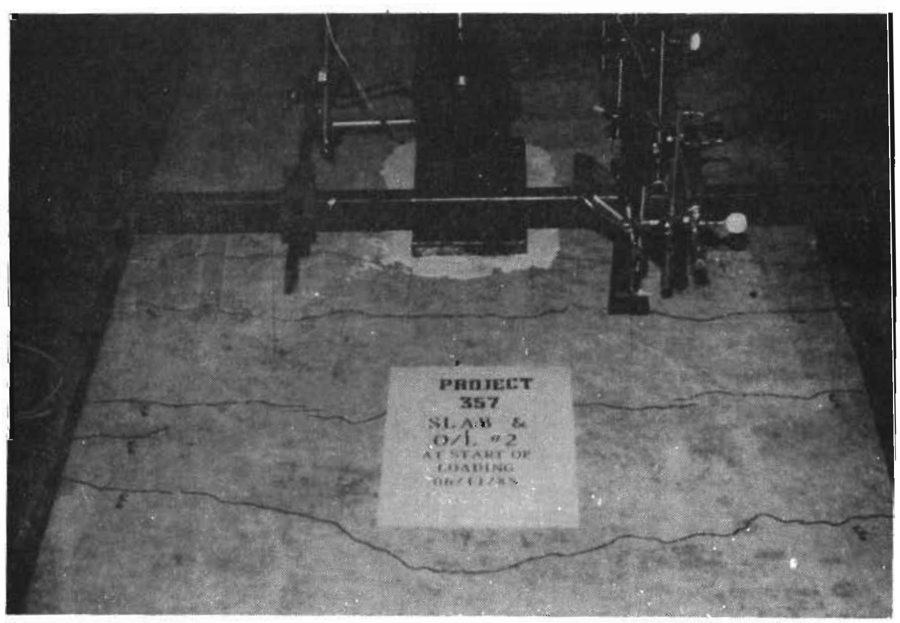


Fig 4.13. Overlay No. 2 at start of loading.

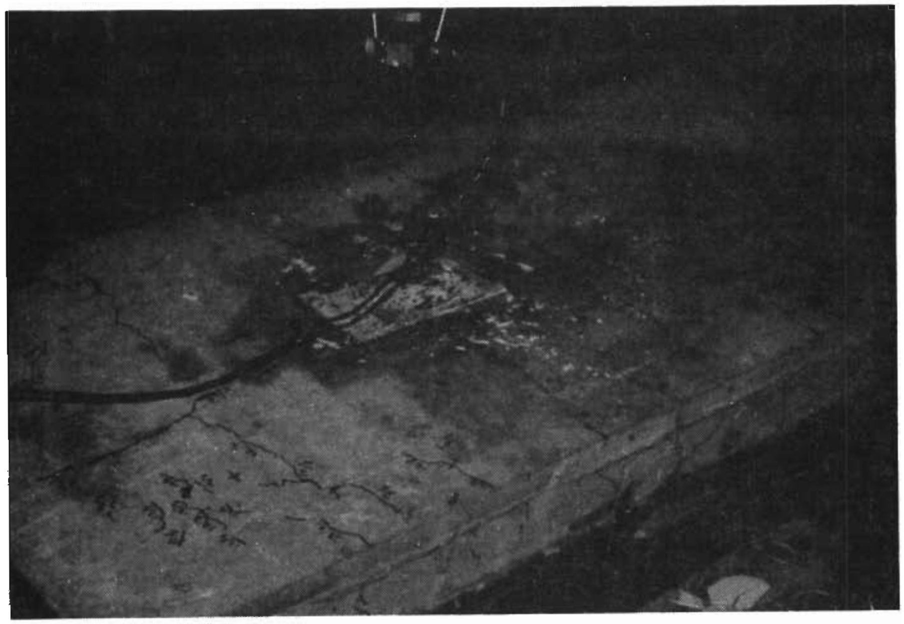


Fig 4.14. Overlay No. 2 after 9 million cycles.

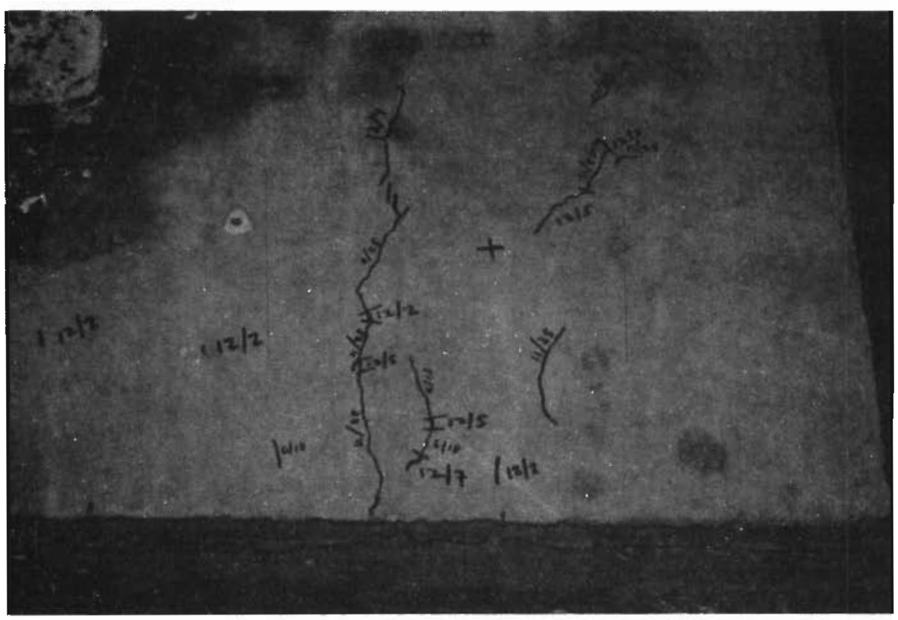


Fig 4.15. Corner of Overlay No. 2 (loaded side) after 9 million cycles.

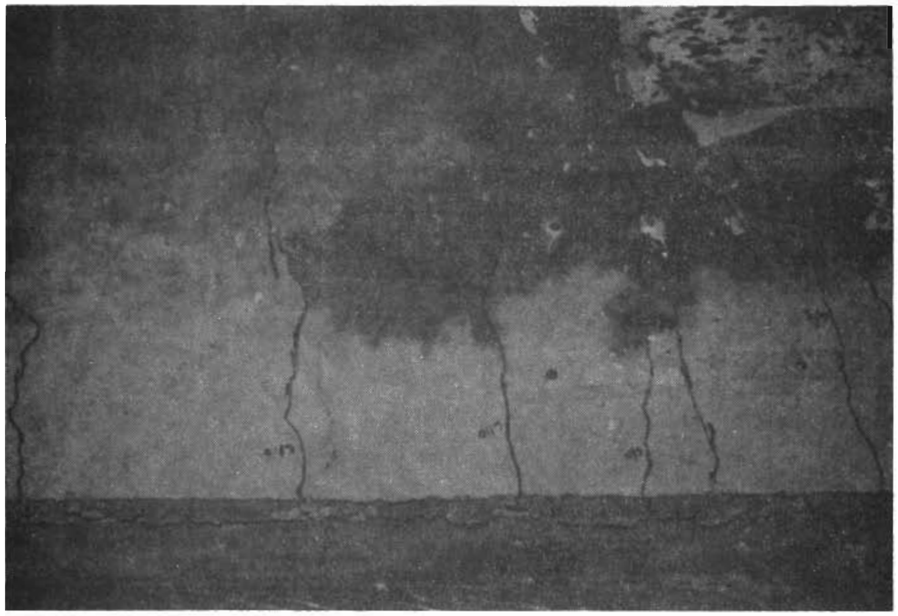


Fig 4.16. Cracks on unloaded side of Overlay No. 2 after 9 million cycles.

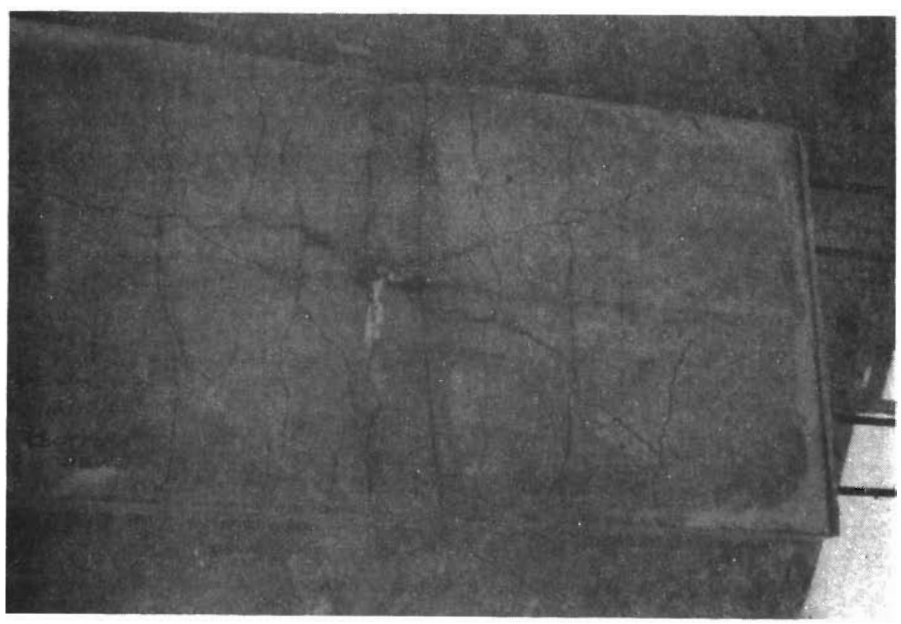


Fig 4.17. Bottom view of Slab No. 2.

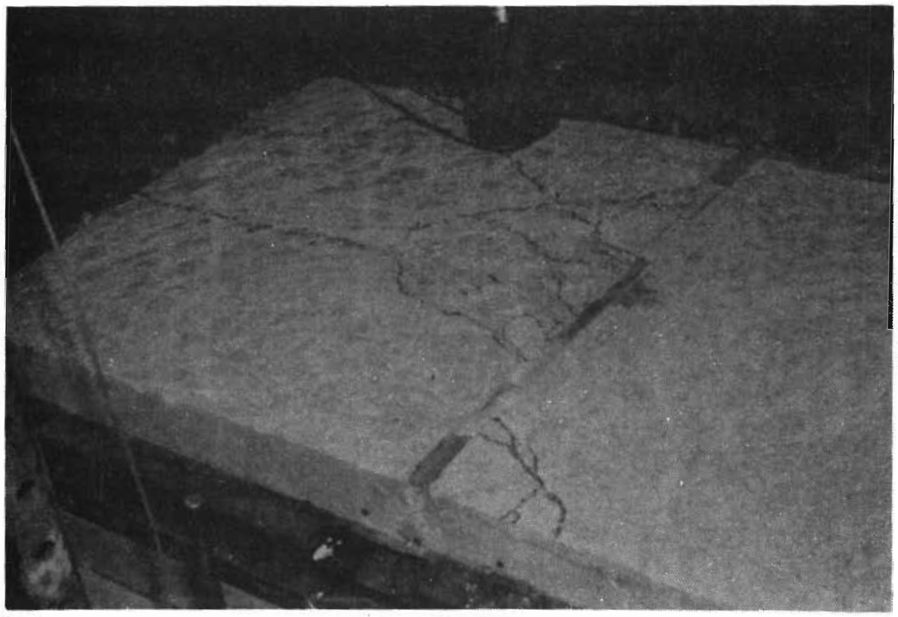


Fig 4.18. Base Slab No. 3 after 3 million cycles.

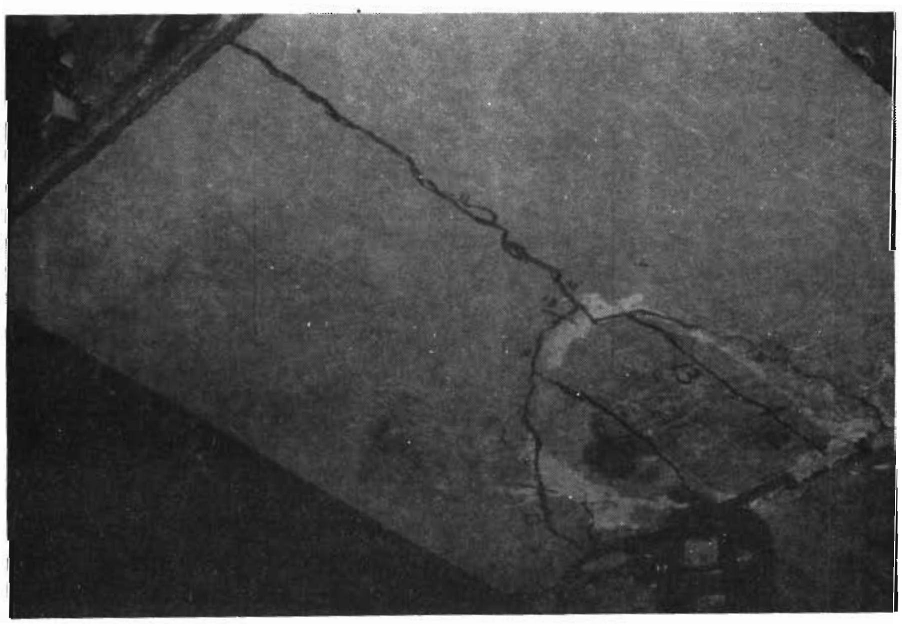


Fig 4.19. Overlay No. 3 after 3 million cycles.

taken from corner and interior locations of the slab after loading was completed. Cores were taken by the Concrete Coring Company, Austin, Texas.

Slab No. 2 (Fig 4.20) had an average shear strength of 253 psi and a standard deviation of 74 psi. Nine cores were taken although one core, taken from directly underneath the loading plate, fell apart during the coring process due to heavy cracking. There were no signs of delamination for Slab No. 2.

Slab No. 3 (Fig 4.21) had an average shear strength of 139 psi and a standard deviation of 102 psi. These numbers include 2 cores out of the 11 taken (Figs 4.22 and 4.23) that had zero shear strength. Delamination in Slab No. 3 had occurred directly beneath the loading plate and at one of the corners of the slab.

Slab No. 4 (Fig 4.24) had an average shear strength of 270 psi and a standard deviation of 62 psi. There were no signs of delamination in Slab No. 4.

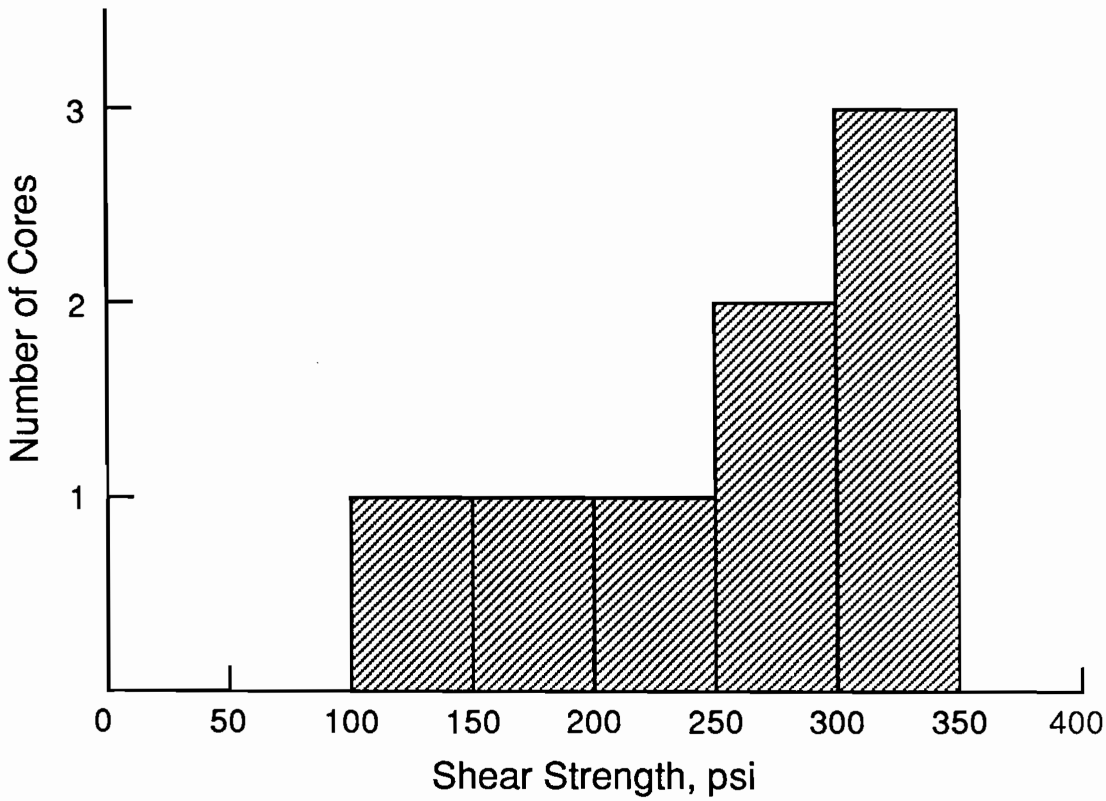


Fig 4.20. Shear strength at interface of Slab No. 2.

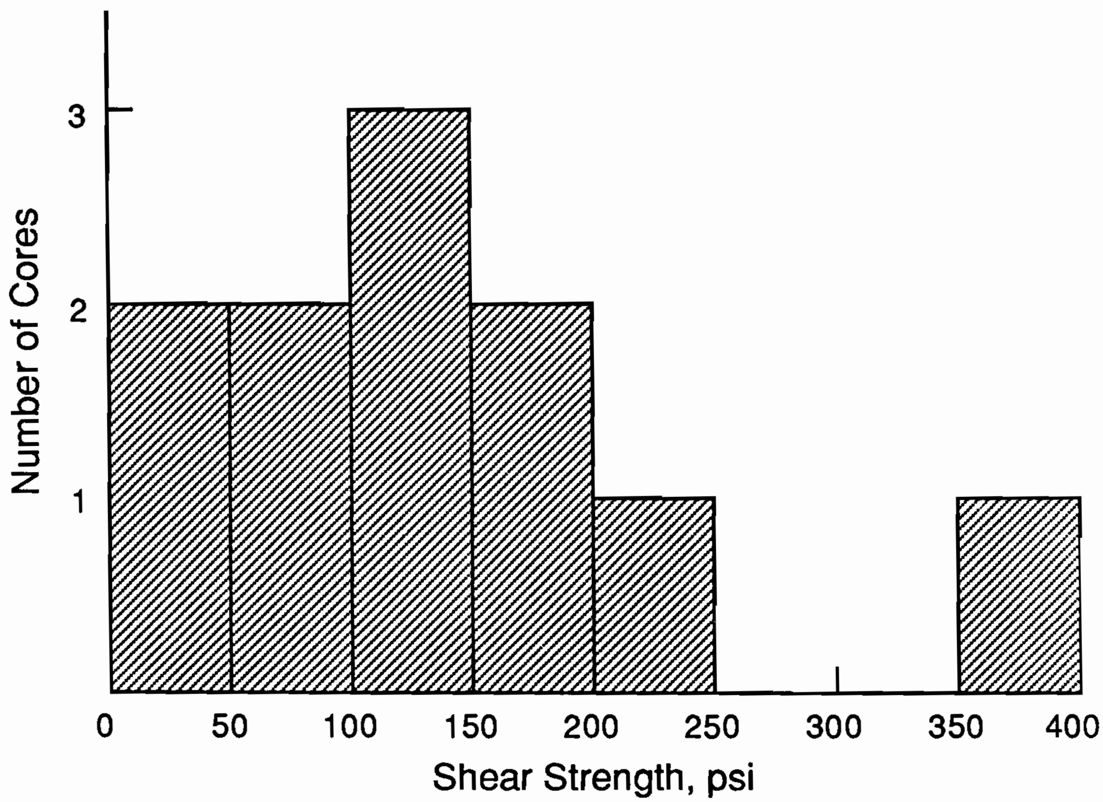


Fig 4.21. Shear strength at interface of Slab No. 3.

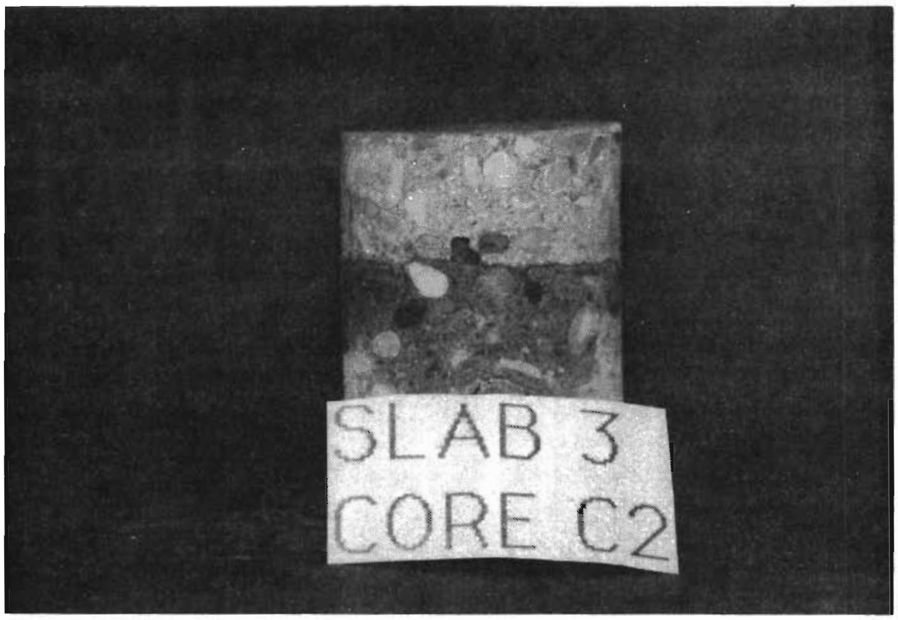


Fig 4.22. Core taken from corner of Slab No. 3.

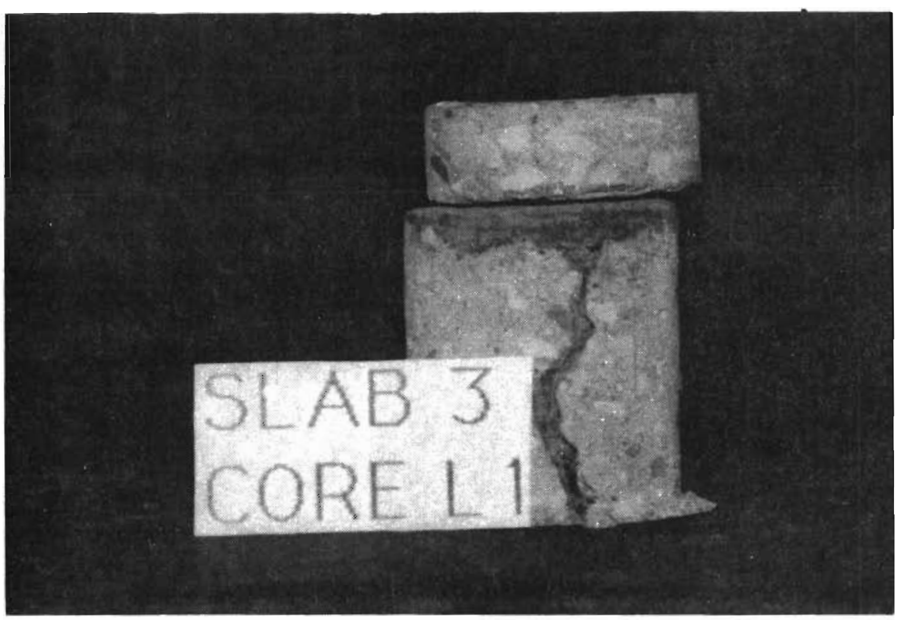


Fig 4.23. Core taken from underneath the loading plate of Slab No. 3.

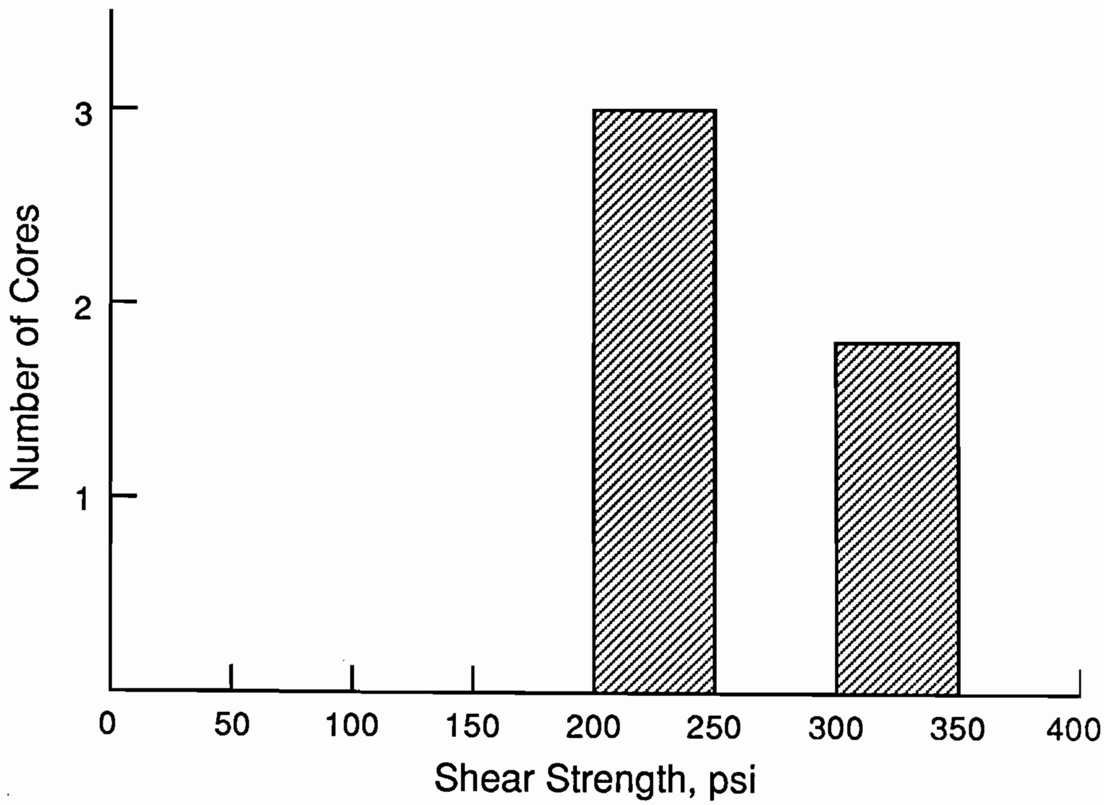


Fig 4.24. Shear strength at interface of Slab No. 4.

CHAPTER 5. ANALYSIS OF DATA

This chapter introduces the concepts of damage, remaining life, and fatigue. The relationship between remaining life and applied load repetitions for a pavement before and after overlaying is explored. This chapter quantifies this relationship using the laboratory data. A summary is also presented.

PAVEMENT DAMAGE

The damage experienced by a pavement due to a cyclic loading at a constant stress may be defined as

$$d = \frac{n}{N} \tag{5.1}$$

where

d	=	damage experienced by the pavement,
n	=	past number of applied load repetitions at the constant stress, and
N	=	total allowable number of load repetitions at that stress.

Failure occurs at d = 1.0, that is, when the number of applied load repetitions is equal to the allowable number. For a variety of stress levels, Miner's Hypothesis (a linear damage hypothesis) states

$$d_T = \left(\frac{n}{N}\right)_1 + \left(\frac{n}{N}\right)_2 + \ldots + \left(\frac{n}{N}\right)_m \tag{5.2}$$

where

d_T	=	total damage experienced by the pavement,
n,N	=	as defined previously, and
1, 2, ..., m	=	m different stress levels.

Again, failure is defined as $d_T = 1.0$

THE CONCEPT OF REMAINING LIFE

Remaining life can be defined as the amount of damage left in a pavement layer after it has been subjected to cyclic loading (Ref 9). If the damage at failure is defined as 1.0, remaining life at some time, t, in the pavement life is

$$R_L = 1.0 - d_t \tag{5.3}$$

where

R_L	=	remaining life at time t, and
d_t	=	damage at time t.

Remaining life is usually expressed as a percentage.

The concept of remaining life is important because remaining life is considered to be highly correlated with data from condition surveys or field observations of the distressed pavement (Ref 10). There is often difficulty in obtaining accurate past traffic information. The development of a relationship between remaining life and field data would help eliminate the need for this precise past traffic information. When pavement rehabilitation is being considered, field data could be relied upon more.

Remaining life is also important in that the deterioration of the bonded overlay is related to the remaining life of the existing pavement at the time of overlay placement. If a pavement has a low remaining life, many cracks will exist and high stress concentrations will occur when a BCO is placed. It follows that the BCO will deteriorate at a faster rate than it would if placed on a pavement with a higher remaining life.

The relationship between remaining life and load repetitions (Fig 5.1) consists of two parts: the remaining life of the pavement (before and after overlaying) and the remaining life of the overlay. At zero load repetitions, the new pavement has a remaining life of 100 percent . The pavement deteriorates at a certain rate until the overlay is placed (Point A). After overlay placement, the original pavement deteriorates at a slower rate because the stresses in the pavement are now lower. The remaining life of the overlay also starts at 100 percent . The rate of deterioration becomes greater at Point B, because, at that number of cycles, the original pavement has reached failure (Point C) and starts to behave as a subbase, and the stresses in the overlay are increased.

FATIGUE IN RIGID PAVEMENTS

Before the life of a pavement can be predicted, the end pavement condition, or failure, must be defined. There are two types of failure: structural failure and functional failure. A structural failure consists of a major breakdown of one or more of the pavement components, resulting in the loss of the load-carrying capacity of the pavement (Ref 11). A functional failure depends primarily on the roughness of the pavement surface. The pavement can no longer carry out its intended function at the same level (measured by the present serviceability index).

A fatigue equation is used to predict the allowable number of load repetitions on a pavement. The fatigue equation usually predicts a structural failure or a terminal condition at which further load repetitions would result in a rapid increase in distress. For rigid pavements, the fatigue equation can take the form of

$$N = A \left(\frac{f}{\sigma} \right)^{B} \tag{5.4}$$

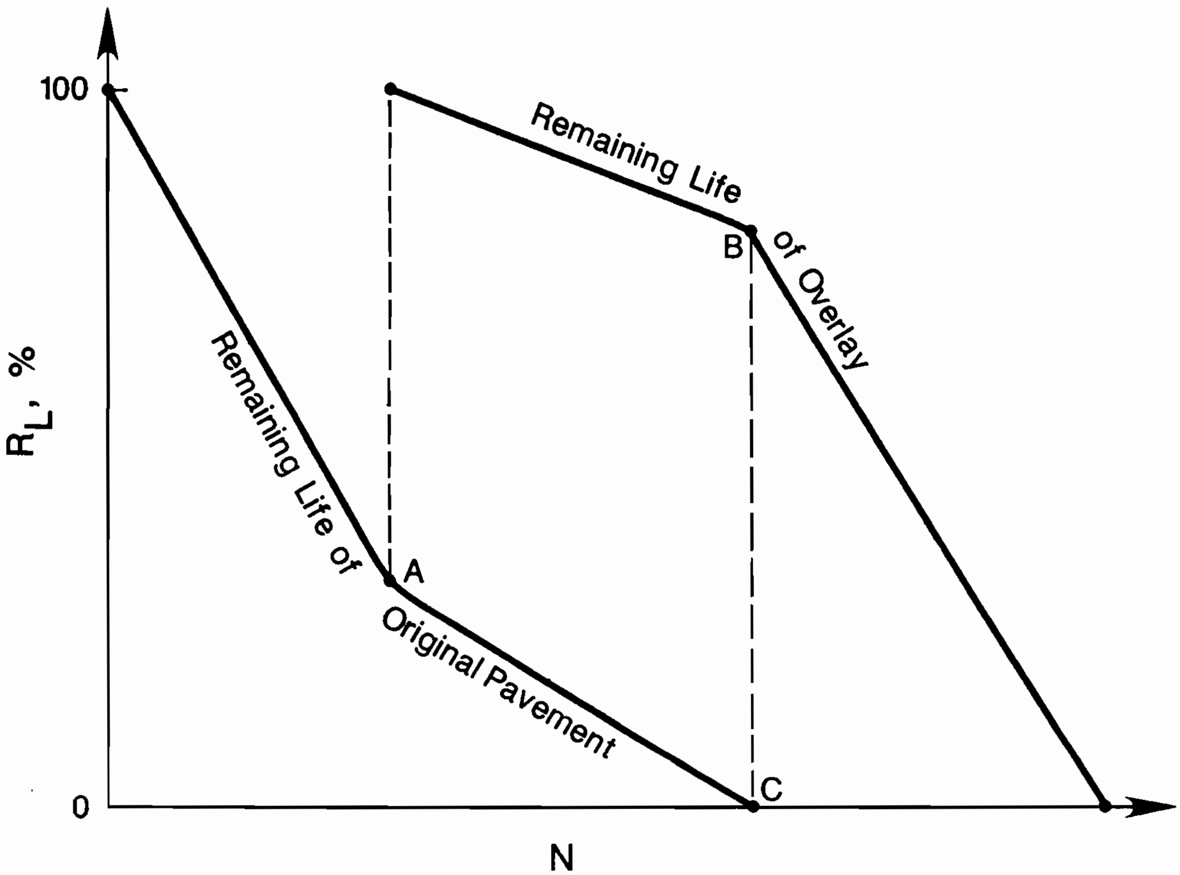


Fig 5.1. Remaining life (R_L) as a function of load repetitions (N).

where

N	=	allowable number of load applications,
f	=	flexural strength of the concrete,
σ	=	critical tensile stress in the concrete under load, and
A,B	=	constants.

Figure 5.2 shows a fatigue equation of this form. It was developed (Ref 10) from field data, using a terminal stress condition of cracking = 50 feet/1000 square feet.

ANALYSIS OF LABORATORY DATA

In the laboratory, two CRCP slabs and two JCP slabs were tested. Different types of distress occurred for the different types of pavements. Thus the CRCP and the JCP slabs were analyzed separately but comparisons were made between the two pavement types. The CRCP slabs (Nos. 1 and 2) is discussed first.

Base Slab No. 2 exhibited heavier cracking than Base Slab No. 1. For the purpose of developing a remaining life analysis, failure is defined as the condition of cracking = 1400 feet/1000 square feet, which occurred at the end of loading of Base Slab No. 2. Because the slabs were loaded at various intensities (5, 10, 15, and 20 kips), equivalency factors must be derived to be able to compare the loadings. As mentioned previously, the general form of a fatigue equation on a rigid pavement is

$$N = A \left(\frac{f}{\sigma} \right)^{B} \tag{5.5}$$

Taute et al (Ref 10) developed a fatigue equation with A = 46,000 and B = 3.0. Assuming B = 3.0 for this study, the ratio of the allowable number of load repetitions with a 5-kip loading to that of a 10-kip loading is

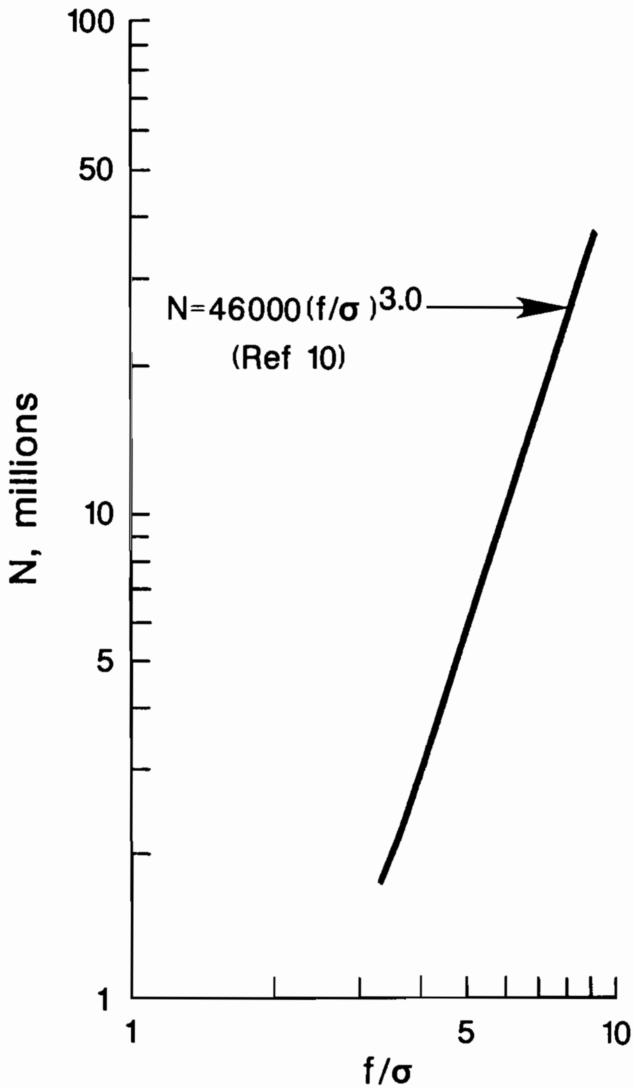


Fig 5.2. Rigid pavement fatigue equation.

$$\frac{N_5}{N_{10}} = \frac{A\left(\frac{f}{\sigma_5}\right)^{3.0}}{A\left(\frac{f}{\sigma_{10}}\right)^{3.0}} \tag{5.6}$$

Since the flexural strength of the concrete was appoximately the same, the ratio reduces to

$$\frac{N_5}{N_{10}} = \left(\frac{\sigma_{10}}{\sigma_5}\right)^{3.0} \quad \text{or} \quad N_5 = \left(\frac{\sigma_{10}}{\sigma_5}\right)^{3.0} N_{10} \tag{5.7}$$

Similar relationships can be derived for 15 and 20-kip loads. Stresses used in calculating the equivalencies (Table 5.1) were found (Appendix C) using an elastic layered computer program (Ref 12).

The loading history (Table 4.1) of Base Slab No. 2 can now be converted to equivalent 5 kip loads:

4,400,000	@	5 kips	x	1.0	=	4,400,000
800,000	@	10 kips	x	8.0	=	6,400,000
2,400,000	@	15 kips	x	27.2	=	65,300,000
400,000	@	20 kips	x	64.4	=	25,700,000
				Σ	=	102,000,000

Thus, a total of 102 x 10^6 equivalent 5-kip load repetitions will produce failure (as defined by cracking = 1400 feet/1000 square feet). Using the same definition of failure, Overlay No. 2 failed (Table 5.2) after 6.7 million cycles. Converting to equivalent loads, Overlay No. 2 had

TABLE 5.1. LABORATORY LOAD EQUIVALENCIES

Load (kips)	Equivalent Number of 5-kip Loads
5	1.0
10	8.0
15	27.2
20	64.4

TABLE 5.2. EQUIVALENT LOAD REPETITIONS AND CRACKING FOR SLABS 1 AND 2.

	Total Number of Load Repetitions (x 10^3)	Load (kips)	Total Number of Equivalent 5-kip Load Repetitions (x 10^3)	Total Cracking ($\frac{ft}{1000\ ft^2}$)
Base Slab No. 1	0	0	0	0
	100	5	100	211
	195	5	195	339
	707	5	707	506
	832	5	832	540
	1,373	5	1,373	693
	2,002	5	2,002	693
Base Slab No. 2	0	0	0	792
	800	5	800	864
	4,400	5	4,400	864
	5,200	10	10,800	864
	7,600	15	76,080	864
	8,000	20	101,840	1429
Overlay No. 1	0	0	0	174
	7,951	5	7,951	174
	9,203	10	18,047	174
Overlay No.2	0	0	0	1049
	836	5	836	1090
	2,400	10	13,348	1100
	3,328	20	73,111	1107
	5,628	5	75,411	1193
	6,700	20	144,448	1401
	7,700	20	208,848	1484
	8,100	20	234,608	1506
	8,900	20	286,128	1549
	9,400	20	318,328	1557
	9,627	20	332,947	1557

failed after 144 million cycles. Although the base slab had failed before the overlay was placed , the overlay still had a life 1-1/2 times longer than the base slab had (Fig 5.3).

Base Slab No. 1 had 2.002 x 10^6 5-kip load repetitions applied. Because failure should occur at 102 x 10^6 5-kip cycles, Base Slab No. 1 had a remaining life of (1.0 - [2.002/102]), or 98 percent . Although Base Slab No. 1 had a fairly high amount of cracking (considering a 98 percent remaining life), the cracking development (refer to Fig 4.7) shows that the cracking stays constant after an initial amount of cracking and could remain at that level for a large number of load repetitions, as was the case for Base Slab No. 2 (Fig 4.8).

Overlay No. 1 had 7.951 x 10^6 cycles at 5 kips and 1.262 x 10^6 at 10 kips for a total of 18 x 10^6 equivalent 5-kip repetitions. Cracking was low (Fig 4.7) and did not increase during the entire loading period. It was apparant that the overlay was not going to fail for quite some time at loads of 5 and 10 kips. Equipment to handle the higher loads, 15 and 20 kips, had to be exchanged for the equipment that was initially being used. It was thus decided to set up the equipment to handle the higher loads and to proceed to the more critical case, Slab No. 2 (low remaining life of base slab before overlay placement).

The remaining lives of Base Slab and Overlay No. 1 are shown with those for Slab No. 2 (Fig 5.4). The slope of the remaining life of Base Slab No. 1 and 2 are the same until Base Slab No. 1 is overlayed at 98 percent remaining life. The remaining life slope of Base Slab No. 1 then becomes flatter because the placement of the overlay reduces the stresses. The remaining life slopes of the overlays can not be the same because the conditions of the base slabs at time of overlay placement were different. The remaining life slope of Overlay No. 1 is expected to be flatter than Overlay No. 2 because of the better condition of Base Slab No. 1 and because of the (lack of) cracking development in Overlay No. 1.

The remaining life of Slab Nos. 1 and 2 can be related to the cracking that occurred in the laboratory (Fig 5.5). Total cracking is plotted as a function of equivalent 5-kip wheel load repetitions on a semi-logarithmic scale. The data of Base Slab Nos. 1 and 2 can be correlated with a straight line having a slope of 500. A few of the data points from Slab No. 2 appear not to fit this lin observed cracking being lower than predicted during load repetitions of 10^7 to 10^8 . Most likely, during this period, cracking was occuring internally and cracks, tightly closed at the surface, were difficult to observe. After additional load repetitions, the cracking is again accurately predicted.

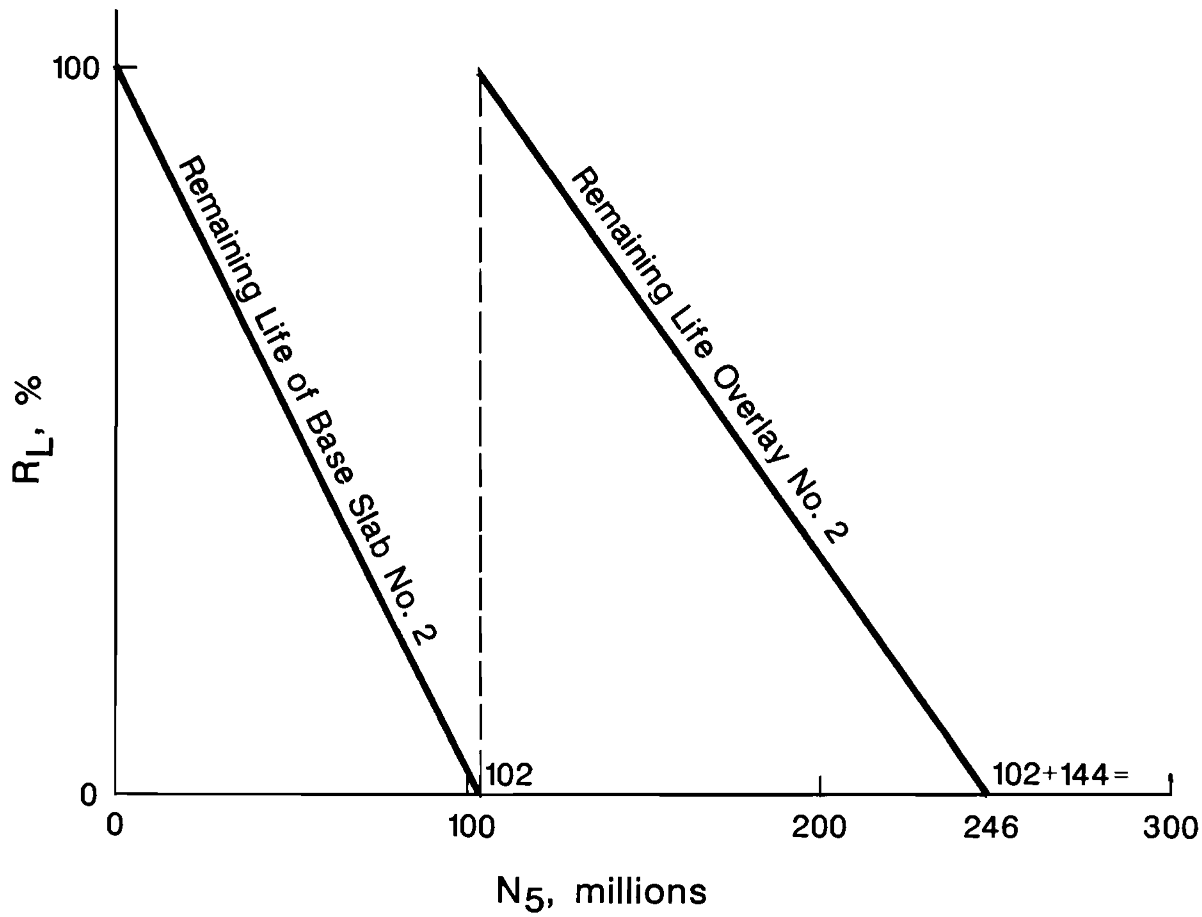


Fig 5.3. Remaining life for Slab No. 2.

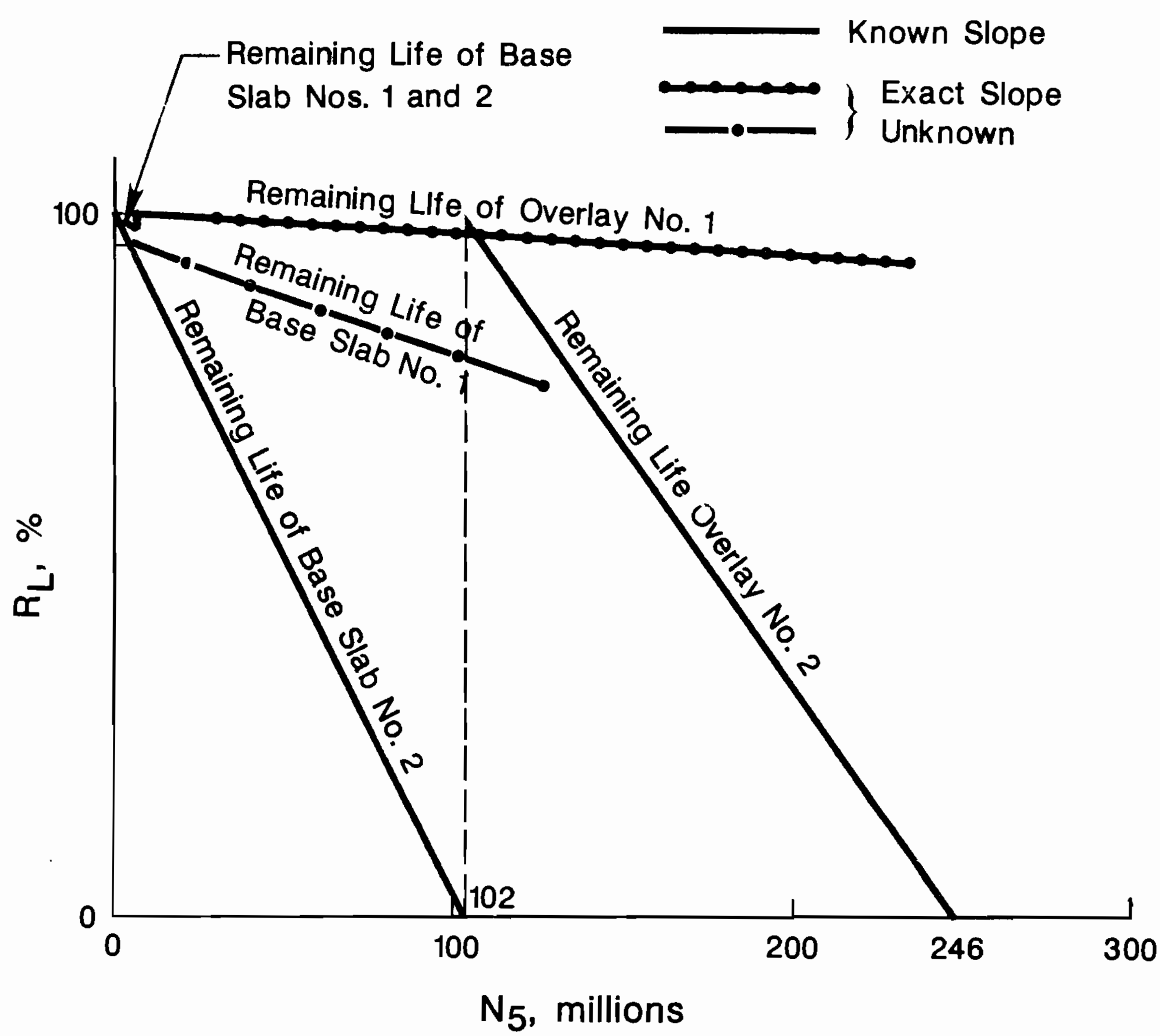


Fig 5.4. Remaining life of Slab Nos. 1 and 2.

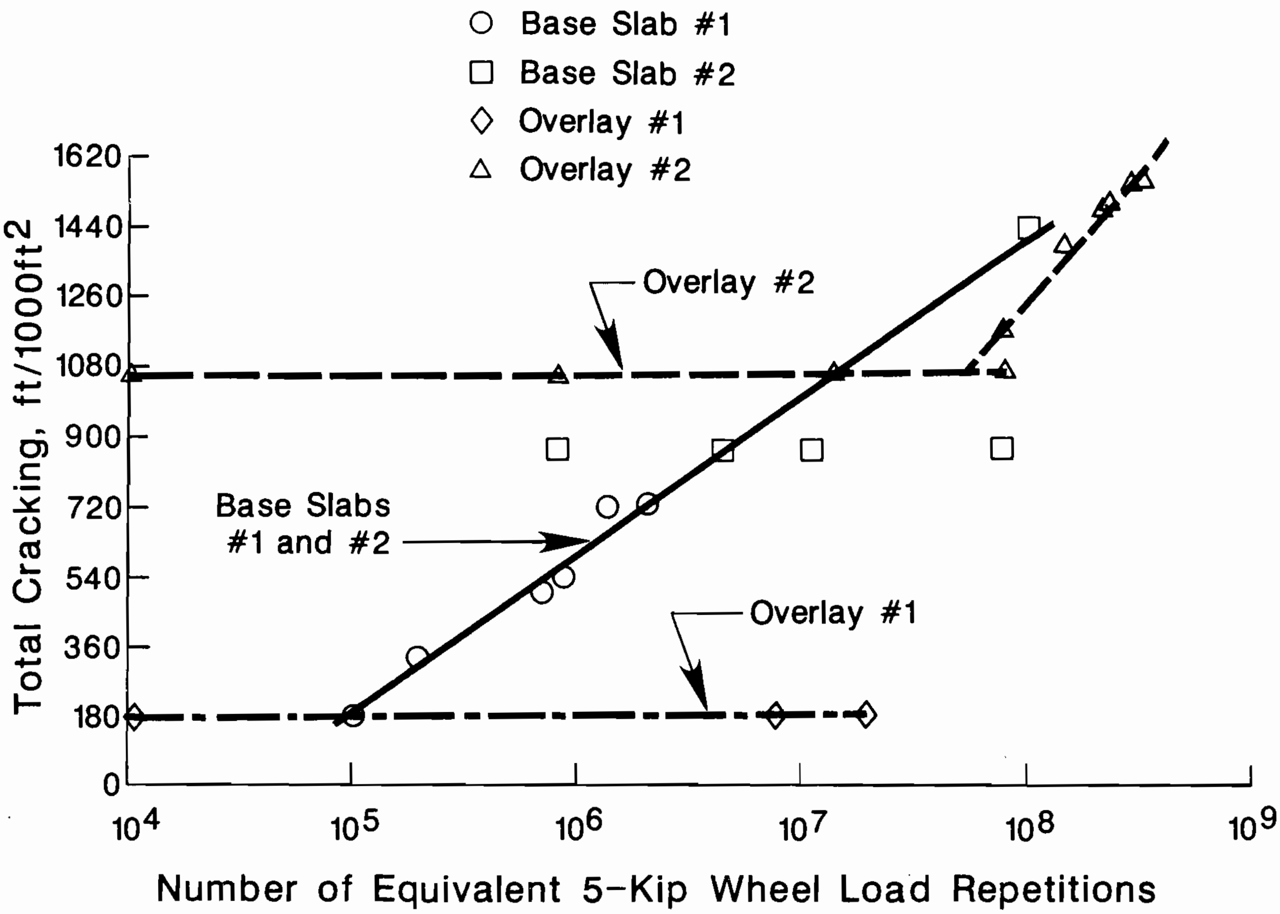


Fig 5.5. Cracking development of Slab Nos. 1 and 2.

The cracking development of the overlays occurs in two distinct phases. In the first stage, cracking is fairly constant over a large number of load repetitions. At a certain point, the cracking increases at a rate more rapid than that of the base slabs. This transition point may be where the base slab has zero remaining life and begins to act as a subbase. Overlay No. 1, placed on a slab with a high remaining life, never reached the second phase of cracking. However, the two phases can be seen in Overlay No. 2. The slope of the line during the second state is approximately 630, greater than the rate of 500 of the base slabs.

For the JCP slabs, failure was defined as a punch-out. Base Slab and Overlay No. 3 both experienced punch-out failures. Base Slab No. 3 had 15 x 10^6 (Table 5.3) equivalent loads before failure occurred and Base Slab No. 4 had 11 x 10^6; thus the remaining life of Base Slab No. 4 is (1.0 - [11/15]) or 27 percent . Overlay No. 3 had 9 x 10^6 equivalent load repetitions before failure while Overlay No. 4 had 67 x 10^6 equivalent loads, with no signs of failure, before the test was stopped.

Although Base Slab No. 3 was taken to failure, it was repaired with a polymer concrete and thus had some life left at the time of overlay placement (Fig 5.6). Due to the nature of the failure it can be assumed that Base Slab and Overlay No. 3 failed at the same time (the base slab failing for the second time) at N_5 = 24 million. Although the remaining life slope of Overlay No. 4 is not known, it can be seen that it is much flatter than the slope of Overlay No. 3 because at N = 78 million, Overlay No. 4 still had a high remaining life (no cracking or any sign of distress had occurred). This flatter slope with Overlay No. 4 deteriorating at a slower rate than Overlay No. 3--is a result of the remaining life that existed in Base Slab No. 4 at the time of overlay placement.

Because the mode of failure for the JCP was a punchout, rather than total cracking, no relationship between cracking and load repetitions can be found, as was with the CRCP. With the JCP, cracking occurred and, with further load repetitions, these cracks became wider. With the CRCP, the cracks did not increase in width.

TABLE 5.3. EQUIVALENT LOAD REPETITIONS FOR SLABS 3 AND 4

Slab Type	Total Number of Load Repetitions ($x 10^3$)	Load (kips)	Total Number of Equivalent 5-kip Load Repetitions ($x 10^3$)
Base Slab No. 3	1,271	5	1,271
	2,986	10	14,991
	2,988	20	15,210
Base Slab No. 4	950	5	950
	2,178	10	10,774
Overlay No. 3	5,040	5	5,040
	5,482	10	8,576
Overlay No. 4	5,163	5	5,163
	12,846	10	66,627

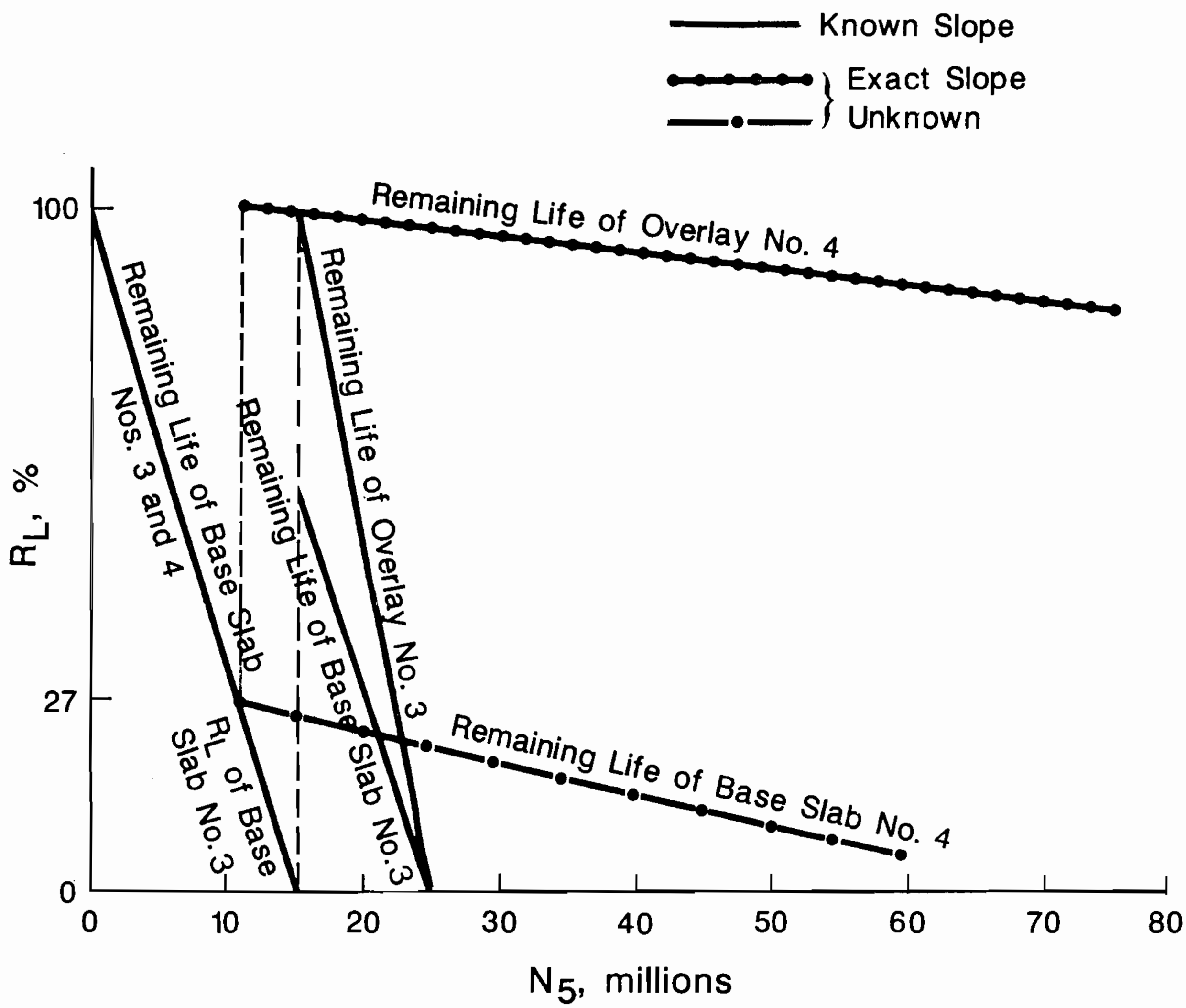


Fig 5.6. Remaining life of Slab Nos. 3 and 4.

SUMMARY

Although Overlay No. 2 was placed on a failed base slab, it still had a fatigue life 45 percent longer than the base slab. Overlay No. 1 was placed on a base slab with a high remaining life. This overlay had a much lower rate of change of distress (cracking) than Overlay No. 2.

The relationship between cracking and load repetitions for CRCP base slabs (Nos. 1 and 2) can be correlated on a semi-logarithmic scale. Cracking for the overlays followed two distinct phases. The first was fairly constant over a large number of load repetitions. Next, the cracking increased at a rate more rapid than that of the base slabs. The transition point between these two stages may be where the base slab fails (zero remaining life) and begins to act as a subbase.

Overlay No. 3, placed on a failed base slab, still had a fatigue life 60 percent greater than the base slab itself. However, the base slab had been repaired with a polymer concrete before overlaying. The rate of change in remaining life of an overlay placed on a base slab with a high remaining life (Base Slab No. 4) was much lower than that of one placed on a failed (but repaired) base slab (Base Slab No. 3). In addition, Overlay No. 4 had a life at least nine times greater than Overlay No. 3. The loading of Overlay No. 4 was stopped before the overlay showed any sign of distress, and thus a life nine times greater is a conservative estimate.

CHAPTER 6. DISCUSSION OF RESULTS

This chapter presents a discussion of the results of the laboratory experiments and of the analysis of laboratory data.

LABORATORY EXPERIMENTS

The discussion of the results of the laboratory experiments is presented in the same manner as the presentation of data in Chapter 4. The loading history, deflection, load transfer, cracking development, and interface shear strength are discussed.

Loading History

Loads of 5, 10, 15, and 20 kips were placed on the laboratory slabs and overlays. In Chapter 4, a loading history was presented. In Chapter 5, load equivalencies based on a fatigue equation were derived. Table 6.1 presents a summary of equivalent loads placed on each slab and overlay. Comments regarding the state of distress at the completion of loading are also included.

Deflection

Deflections on the jointed pavement slabs were 3 to 6 times larger than on the continuously reinforced base slabs (although the JCP slabs were placed on 6 inches of neoprene while the CRCP slabs were on 4 inches). On the JCP overlays, the deflections were approximately 6 to 8 times greater than the deflection on the CRCP overlays.

As a load was doubled (5 to 10 kips or 10 to 20 kips) on the CRCP, deflections also doubled. On the JCP, as the load was doubled from 5 to 10 kips, the deflection increased by an average of 60 percent.

There was a decrease in deflection after overlaying. An average deduction of 60 percent occurred for the CRCP and 40 percent for the JCP.

TABLE 6.1. SUMMARY OF EQUIVALENT LOADS

Slab Number and Type	Total Number of Equivalent 5-kip Load Repetitions	Comments
Base Slab No. 1 CRCP	2×10^6	Moderate Class 1 and 2 Cracking
Overlay No. 1 CRCP	18×10^6	Some Initial Cracking, No Additional Cracking
Base Slab No. 2 CRCP	102×10^6	Severe Cracking (Class 1 and 2)
Overlay No. 2 CRCP	332×10^6	Cracking More Severe Than Base Slab No. 2 (Still Class 1 and 2)
Base Slab No. 3 JCP	15×10^6	Class 1, 2, and 3 Cracking;Failure
Overlay No. 3 JCP	9×10^6	Class 1, 2, and 3 Cracking; Failure
Base Slab No. 4 JCP	11×10^6	No Signs of Distress
Overlay No. 4 JCP	67×10^6	No Signs of Distress

Load Transfer

All of the base slabs started with a high level of load transfer, 95 to 100 percent. Base Slab Nos. 2 and 4, both in relatively good condition at the end of loading, had a load transfer of 80 percent before overlay placement. The load transfer of Base Slab No. 3 dropped to 70 percent before failure (essentially zero load transfer).

Overlay placement increased the load transfer. The placement of the overlay on Base Slab No. 2 increased the load transfer to 90 percent. At the end of loading, the overlay was severely cracked and the load transfer had dropped to 60 percent. After Base Slab No. 3was repaired with a polymer concrete, the overlay increased the load transfer to 60 percent. It then decreased to 30 percent before failure. A large decrease in load transfer may thus indicate imminent failure. After Overlay No. 4 was placed , the load transfer remained fairly constant around 80 percent.

Crack Development

The CRCP slabs had more initial cracking (before loading) than the JCP slabs. The temperature crack that was simulated at the midspan of the slab was to be opened to a width of 0.04 inch. This width was easy to obtain for the jointed slabs, but, for the CRCP, more tension had to be applied and thus more cracking occurred at weak spots throughout the slab.

Because of this initial cracking, the CRCP slabs had more total cracking than the JCP slabs. However, all of the CRCP cracking was Classes 1 and 2 while the majority of the JCP cracking was Class 3.

Overlay No. 1 was placed on a base slab that had a high remaining life. The cracking was less than one-third that of the base slab and had all occurred before the start of loading.

Base Slab No. 2 was severely cracked at the time of overlay placement. Overlay No. 2 obtained an even higher level of cracking in a shorter loading period.

Both Base Slab and Overlay No. 3 experienced punch-out like failures. However, when the overlay failed, it had less cracking than the base slab.

Overlay No. 4 was placed on a base slab which showed no signs of distress. The overlay also showed no signs of distress throughout its loading period.

Interface Shear Strength

Figure 6.1 presents the range of values obtained for the interface shear strength of Slab Nos. 2, 3, and 4. Slab No. 2 had an average shear strength of 253 psi, Slab No. 3, 139 psi, and Slab No. 4, 270 psi. The standard deviations were 74 psi, 102 psi, and 62 psi, respectively.

Slab No. 3 (a JCP) had a punch-out failure in both the slab and the overlay. It had the lowest shear strength average and the highest variation in shear strength and was the only slab with delaminated areas. The mode of failure for the JCP slabs was thus loss of shear strength followed by delamination before punchout occurred. Base Slab No. 4 (also JCP) was in good condition at the time of overlay placement. It had the highest shear strength average and the lowest variation. Slab No. 2 (CRCP) was severely cracked at overlay placement. Its shear strength average was slightly lower than Slab No. 4 and had a slightly higher variation.

ANALYSIS OF LABORATORY DATA

A discussion on Chapter 5 (Analysis of Data) is presented in three parts. First, the CRCP slabs will be discussed, next the JCP slabs, and finally a comparison is made between the CRCP and the JCP slabs.

CRCP

Although Overlay No. 2 was placed on a failed base slab (failure as defined in Chapter 5), it still had a fatigue life 45 percent longer than the base slab had. Overlay No. 1 was placed on a base slab with a high remaining life. This overlay had a much lower rate of change of distress (cracking) due to loading than Overlay No. 2.

The relationship between cracking and load repetitions for CRCP base slabs can be correlated on a semi-logarithmic scale. Cracking for the overlays followed two distinct phases. The first was fairly constant over a large number of load repetitions. Next, the cracking increased at a rate more rapid than those of the base slabs. The transition point between these two stages may be where the base slab fails (zero remaining life) and begins to act as a subbase.

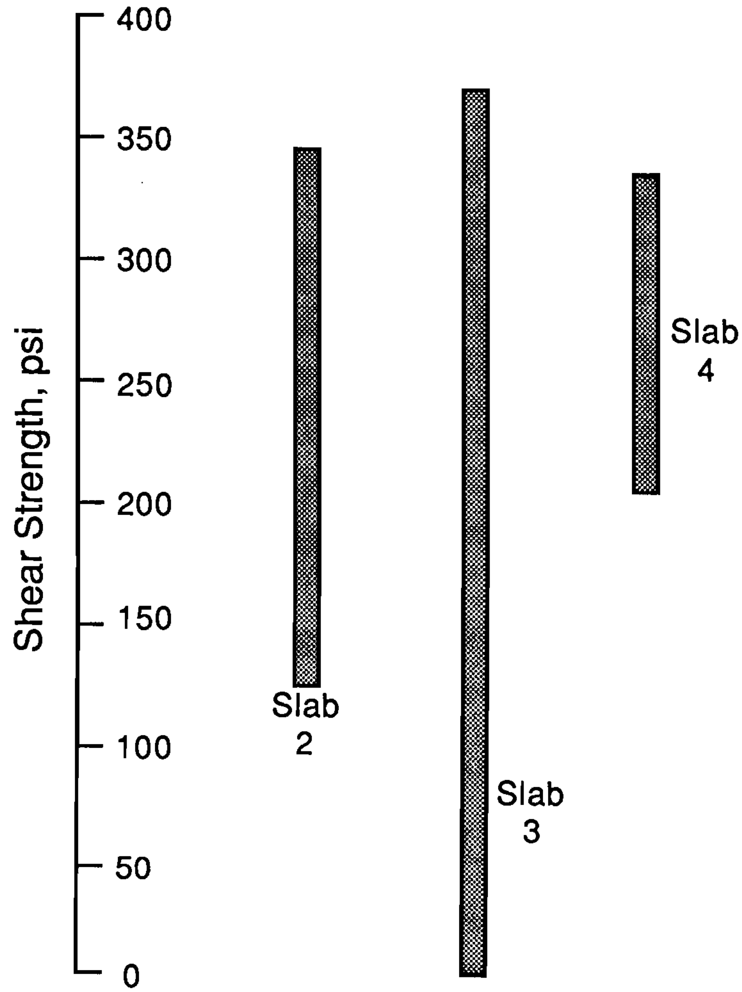


Fig 6.1. Range of interface shear strength of slabs 2, 3, and 4.

JCP

Overlay No. 3, placed on a failed base slab, still had a fatigue life 60 percent greater than the base slab itself. However, the base slab had been repaired with a polymer concrete before overlaying. The rate of change in remaining life of an overlay placed on a base slab with a high remaining life (Base Slab No. 4) was much lower than when placed on a failed (but repaired) base slab (Base Slab No. 3). In addition, Overlay No. 4 had a life at least 9 times greater than Overlay No. 3. The loading of Overlay No. 4 was stopped before the overlay showed any sign of distress, and thus a life nine times greater is a conservative estimate.

Comparison of CRCP and JCP

There were two modes of failure: cracking for CRCP; and punchout, following loss of shear strength and delamination, for JCP. The JCP slabs experienced a more severe type of failure: punchout with Class 1, 2, and 3 cracking and with delamination. The CRCP slabs experienced just Class 1 and 2 cracking with no delamination. The CRCP slabs could still transfer load at failure; the JCP slabs could not. For the case of overlaying on a slab with a high remaining life, both the CRCP and JCP slabs had little, if any, distress during the entire loading period.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Conclusions from the laboratory experiments and the remaining life analysis are presented in this chapter. It must be emphasized that these conclusions are based on results of a laboratory study and may not necessarily be applicable under other conditions. Recommendations are presented following the conclusions.

CONCLUSIONS

(1) Placement of an overlay on a base slab with a high or low remaining life increases the load transfer of a slab.

(2) The interface shear strength of a slab is much higher if the base slab is overlaid before it has failed. In addition, less variation in the shear strength will occur.

(3) CRCP slabs and bonded overlays have a longer fatigue life than JCP slabs and overlays.

(4) If an overlay is placed on a failed base slab, it still has a fatigue life greater than the base slab itself.

(5) An overlay placed on a base slab with some remaining life yields a much longer fatigue life than one placed on a more severely distressed base slab.

(6) Continuously reinforced and plain jointed concrete slabs may fail in different manners. In this study, CRCP slabs failed by cracking with no other signs of distress while the JCP slabs failed by punchout like cracking.

RECOMMENDATIONS

The recommendations are presented in two parts; field implementation and future studies. Recommendations for field implementation include:

(1) Laboratory studies on surface preparation types should be done prior to field experiments because failure can occur at the interface.

(2) It is important to overlay before the pavement deteriorates; a relationship between remaining life of the existing pavement and the resulting overlay condition has been shown.

(3) Pavement failures should be repaired prior to the placing of a BCO as the repairs add life to the pavement structure.

(4) Cracks with low load transfer, based on field deflection measurements, should be repaired before a BCO is placed. Because load transfer influences life, this crack repair will add pavement life.

Bonded concrete overlaying is still a new method of rehabilitation. Recommendations for further studies include:

(1) Surface Preparation. If determining which method (scarifying, shotblasting, or other) is most effective (in terms of strength and fatigue life) as well as most cost-effective in the laboratory, surface textures obtained in the field must be accurately simulated.

(2) Materials. Repairs made with polymer concrete before overlaying need to be studied more thoroughly. High strength concrete and polymer concrete are possible bonded overlay types.

(3) Reinforcement. More studies using steel fiber reinforced bonded concrete overlays are needed.

(4) Shear Strength. Tests for interface shear strength should be done at various times within the fatigue life to see how shear strength varies with time.

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APPENDIX A

DEFLECTIONS OF BASE SLABS AND OVERLAYS

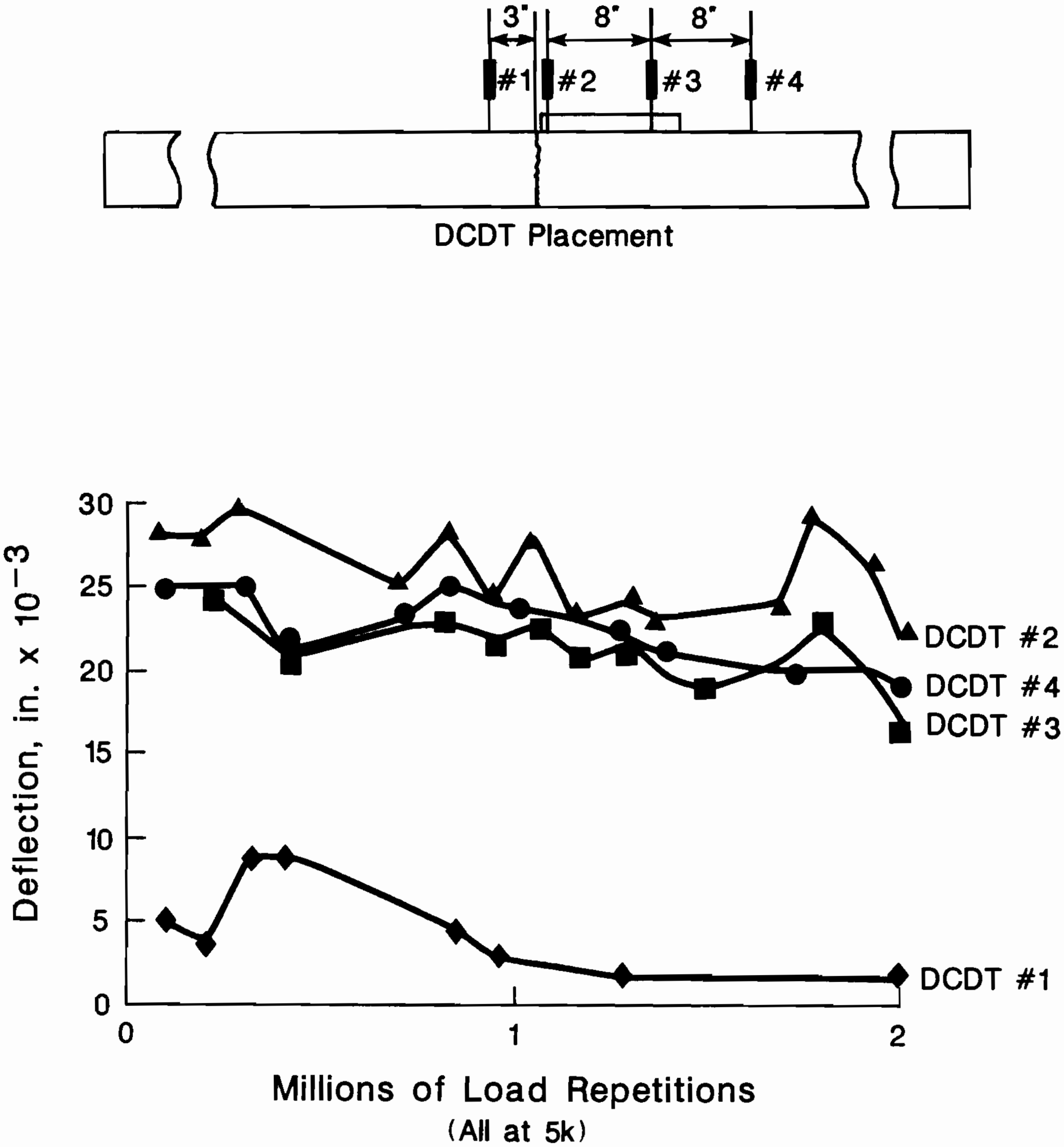
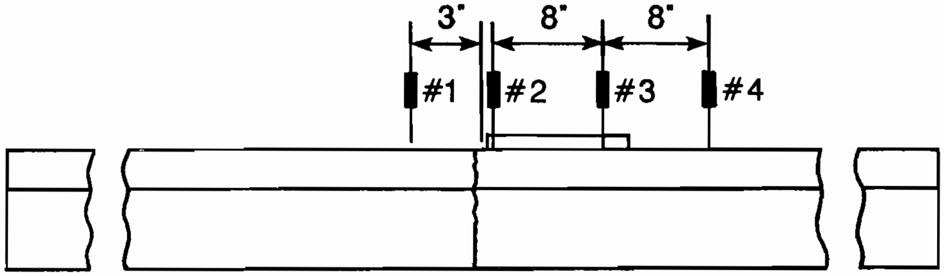


Fig A.1. Deflections of Base Slab No. 1.



DCDT Placement

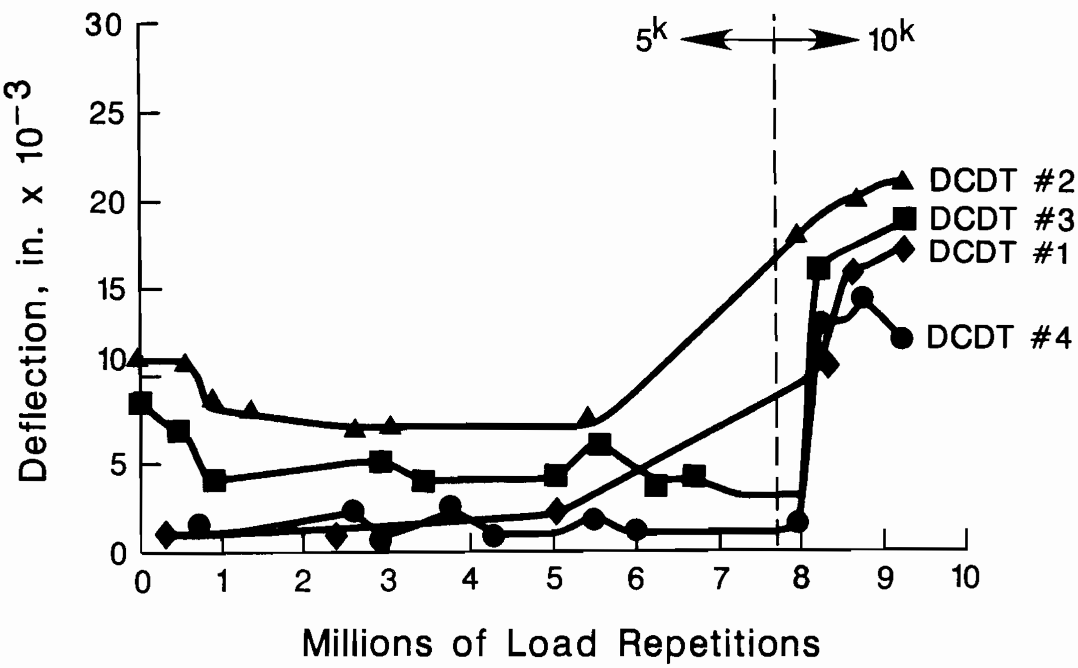
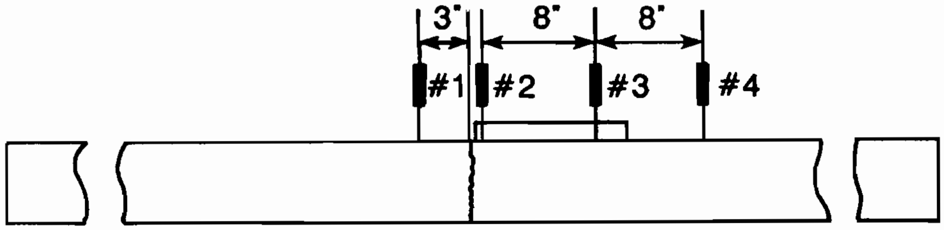


Fig A.2. Deflections of Overlay No. 1.



DCDT Placement

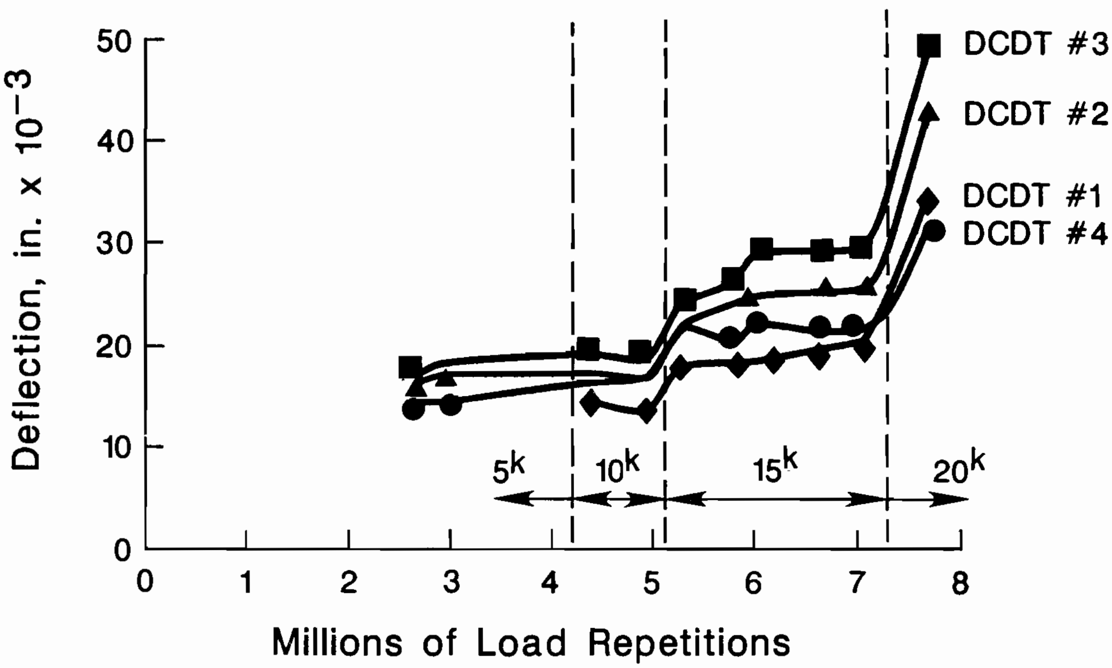
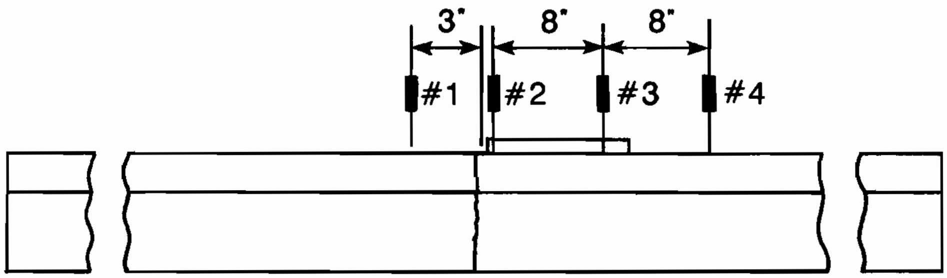


Fig A.3. Deflections of Base Slab No. 2.



DCDT Placement

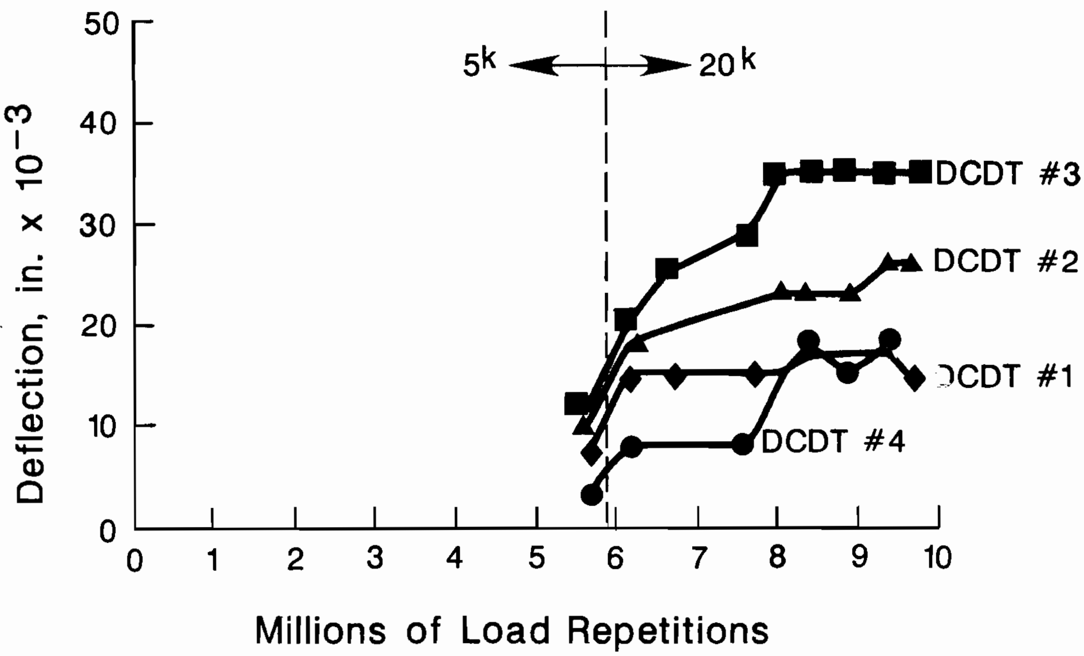


Fig A.4. Deflections of Overlay No. 2.

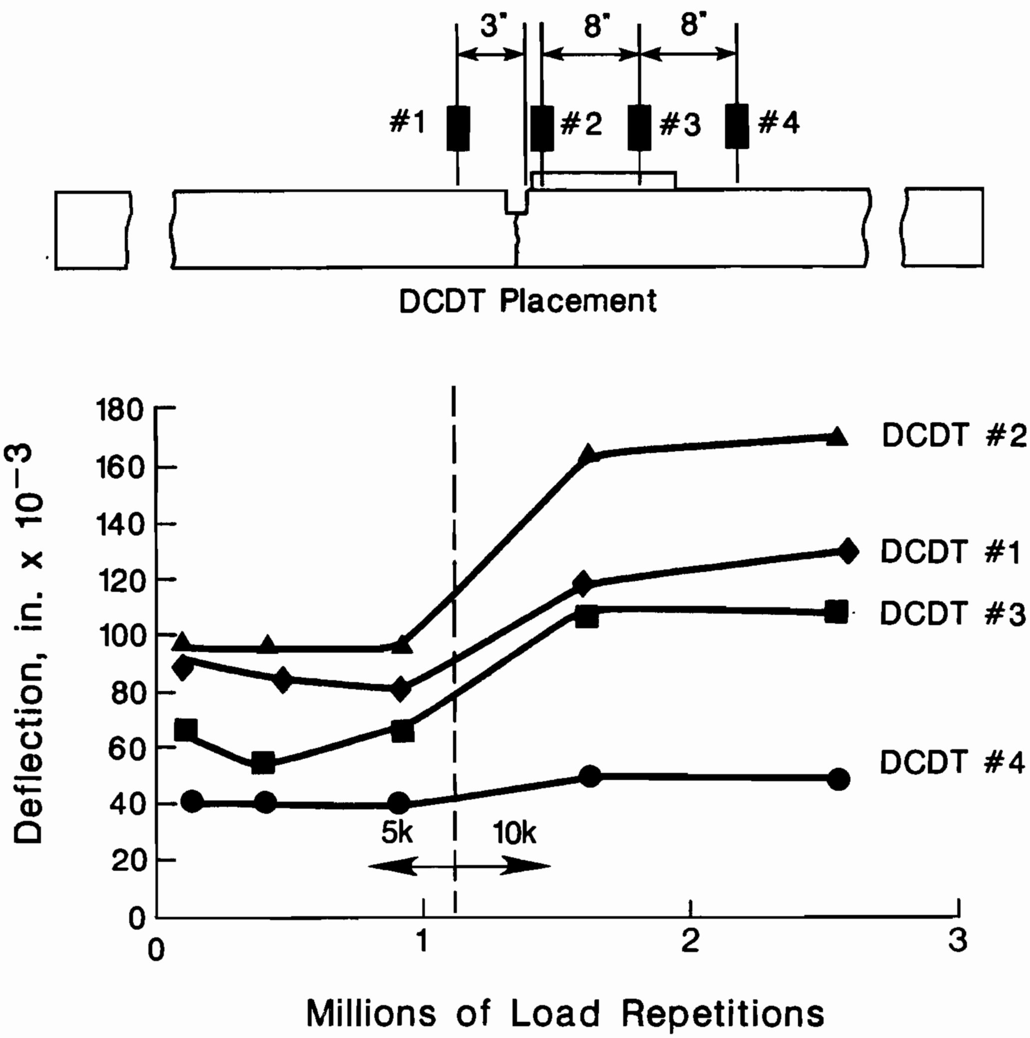
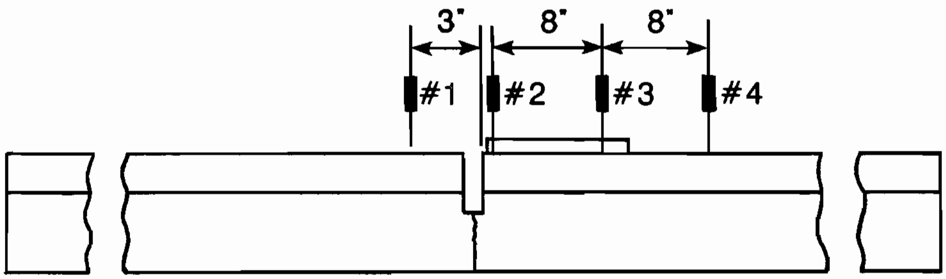


Fig A.5. Deflections of Base Slab No. 3.



DCDT Placement

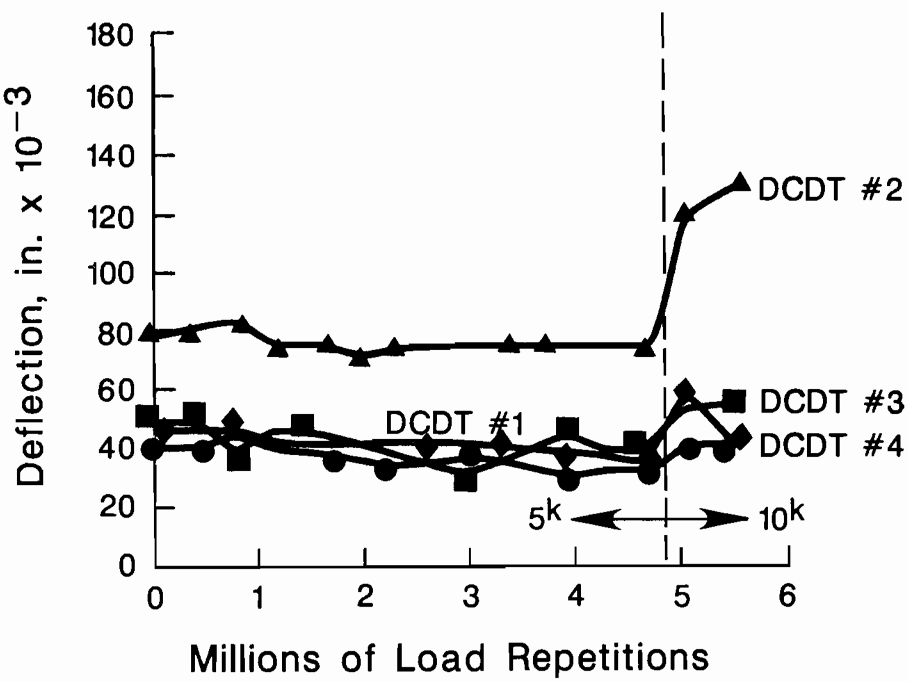
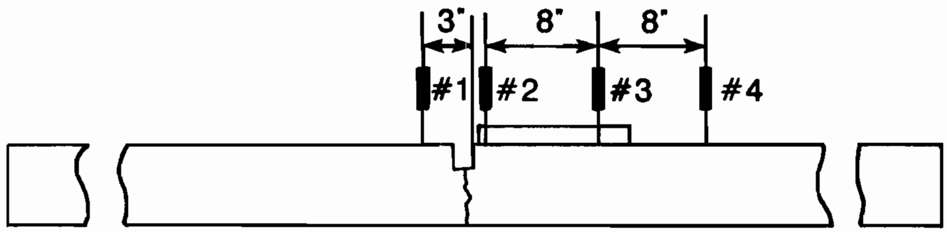


Fig A.6. Deflections of Overlay No. 3.



DCDT Placement

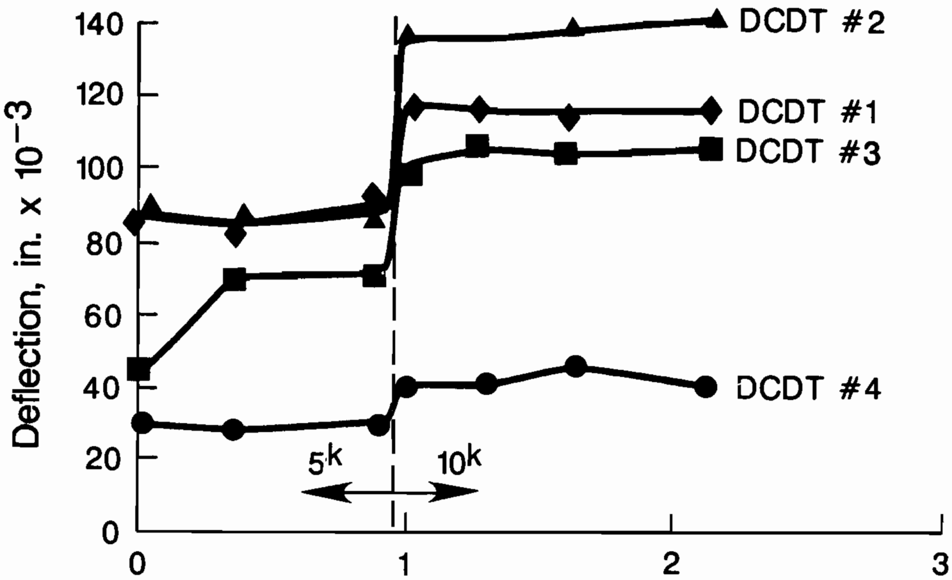
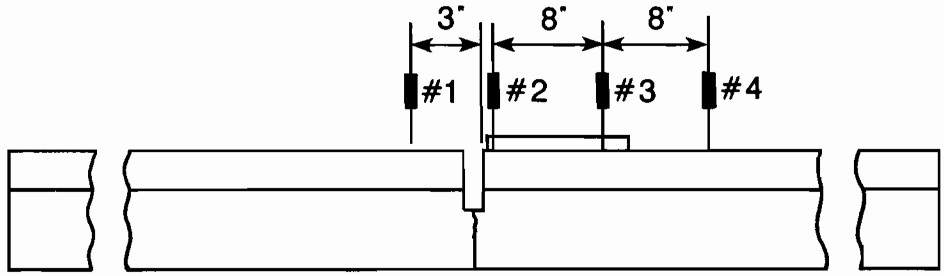


Fig A.7. Deflections of Base Slab No. 4.



DCDT Placement

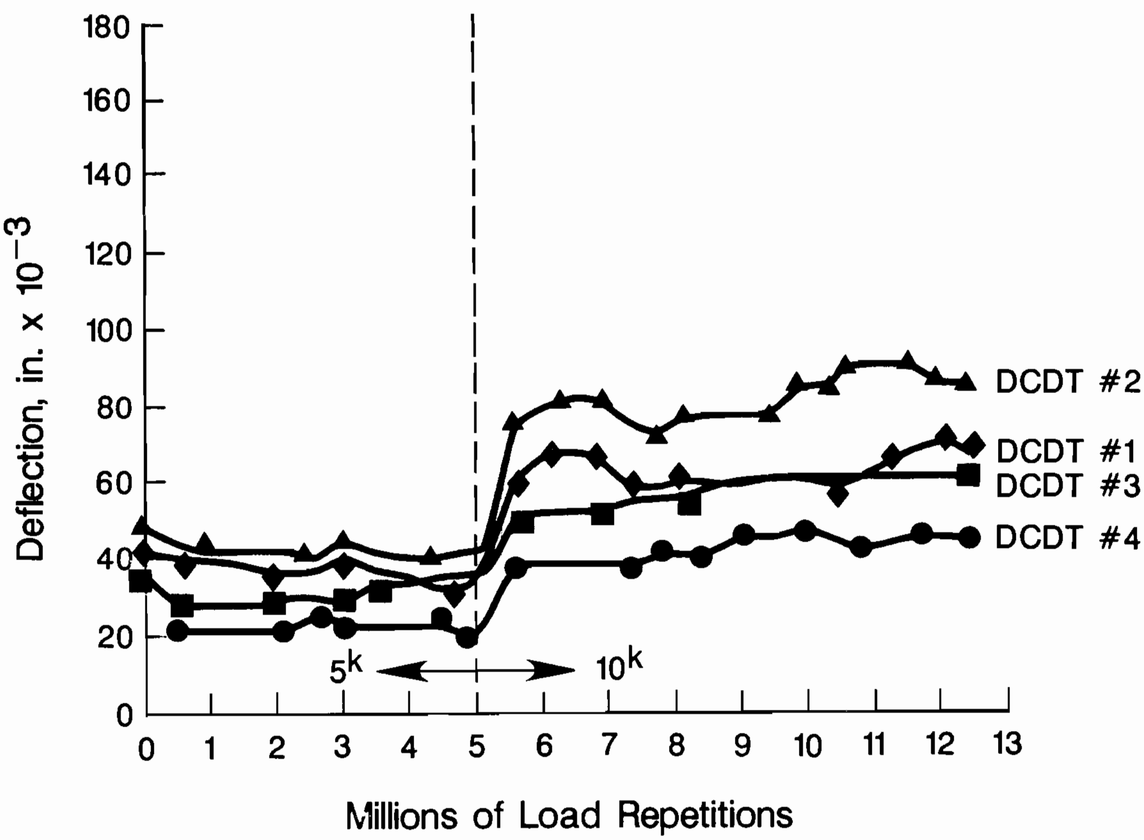


Fig A.8. Deflections of Overlay No. 4.

APPENDIX B

DEVELOPMENT OF CRACKING FOR BASE SLABS AND OVERLAYS

SUMMARY OF CRACKING DATA OF BASE SLAB AND OVERLAY NO. 1

Base Slab No. 1

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
100,000	5	46	46
195,000	5	28	74
707,000	5	36	110
832,000	5	7	117
1,373,000	5	33	150
2,002,000	5	0	150

Overlay No. 1

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
0	0	38**	38
7,951,000	5	0	38
9,213,000	10	0	38

* This number does not include the length of the simulated temperature crack at midspan

** This cracking occurred during the pulling process of simulating the temperature crack

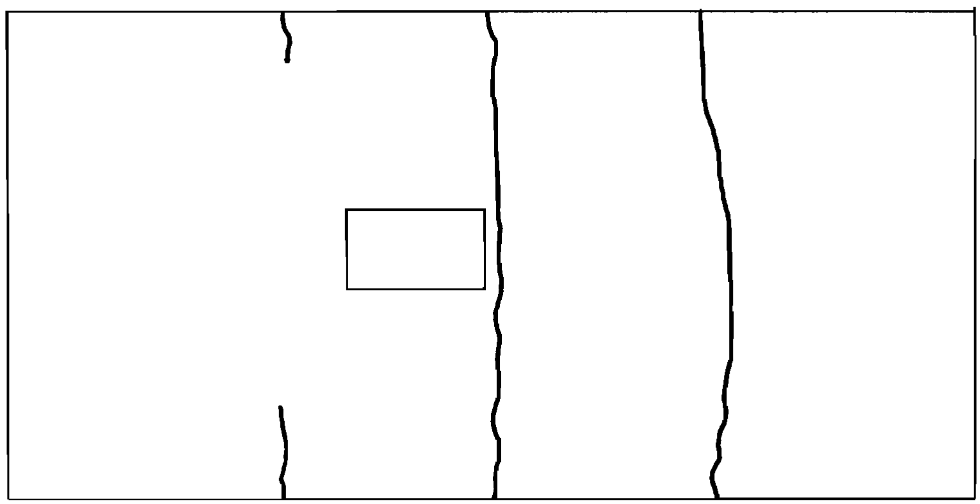


Fig B.1. Base Slab No. 1 after 100,000 load repetitions.

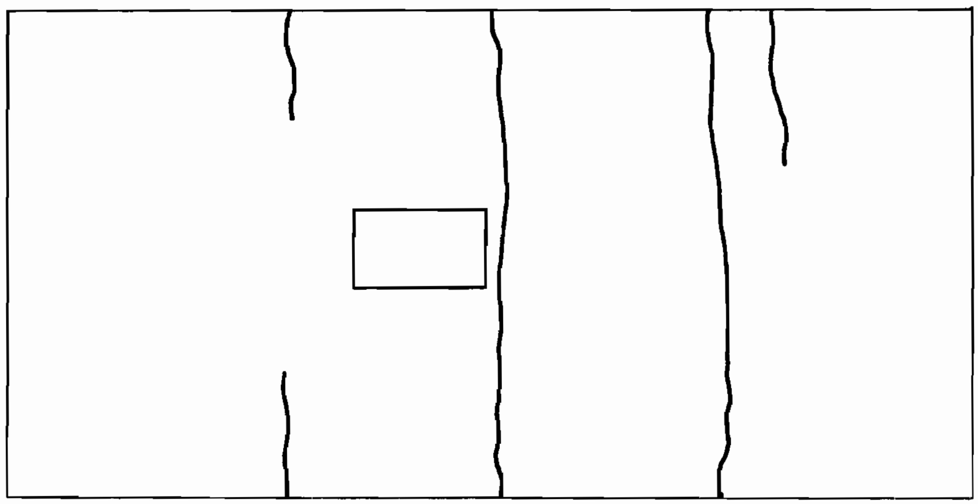


Fig B.2. Base Slab No. 1 after 195,000 load repetitions.

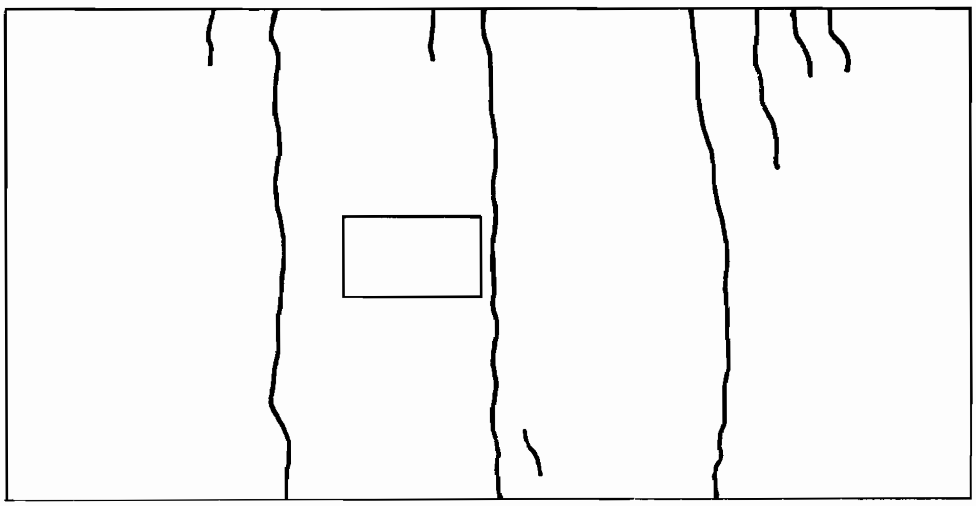


Fig B.3. Base Slab No. 1 after 707,000 load repetitions.

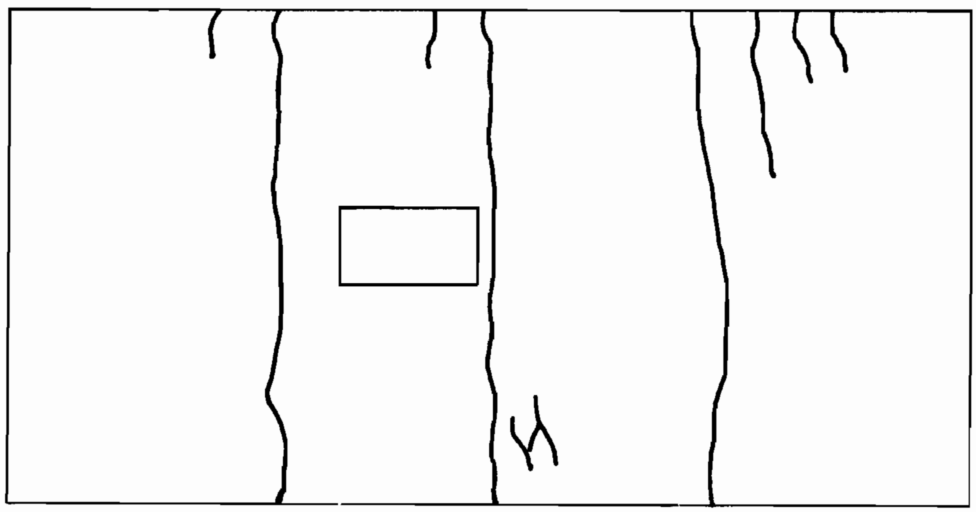


Fig B.4. Base Slab No. 1 after 832,000 load repetitions.

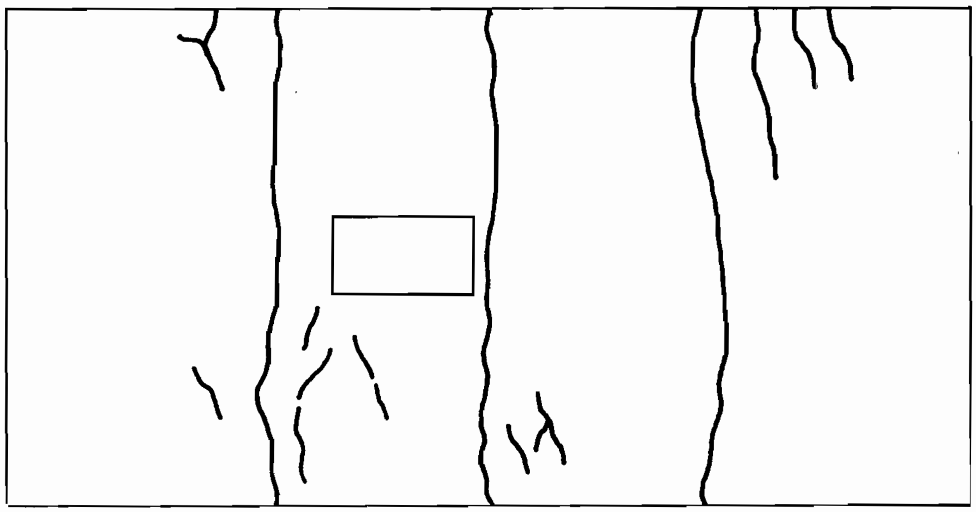


Fig B.5. Base Slab No. 1 after 1,373,000 load repetitions.

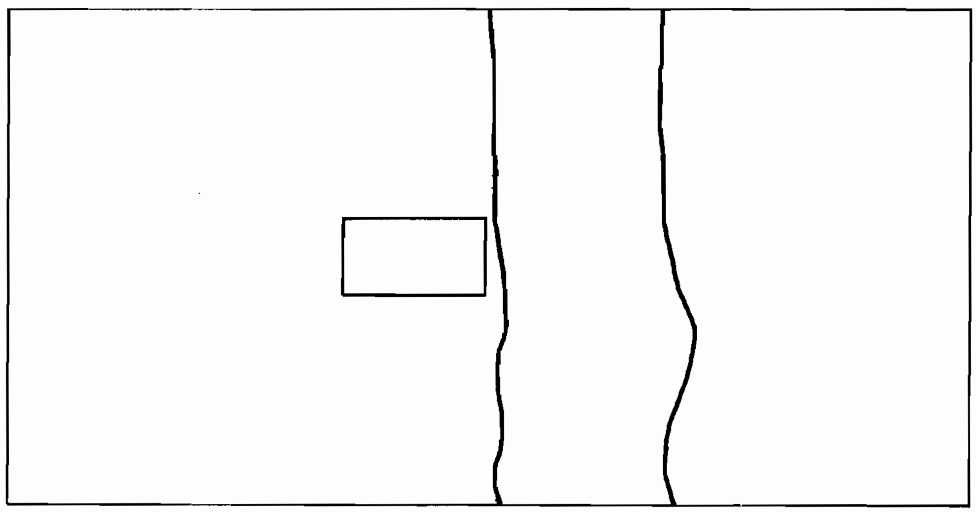


Fig B.6. Overlay No. 1 at start of loading and after 9,213,000 load repetitions.

SUMMARY OF CRACKING DATA OF BASE SLAB AND OVERLAY NO. 2

Base Slab No. 2

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
0	0	171**	171
800,000	5	16	187
4,400,000	5	0	187
5,200,000	10	0	187
7,600,000	15	0	187
8,000,000	20	122	190

Overlay No. 2

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
0	0	226**	226
836,000	5	9	235
2,400,000	10	2	237
3,328,000	20	2	239
5,628,000	5	19	258
6,700,000	20	45	303
7,700,000	20	18	321
8,100,000	20	4	325
8,900,000	20	9	334
9,400,000	20	2	336
9,627,000	20	0	336

* This number does not include the length of the simulated temperature crack at midspan

** This cracking occurred during the pulling process of simulating the temperature crack

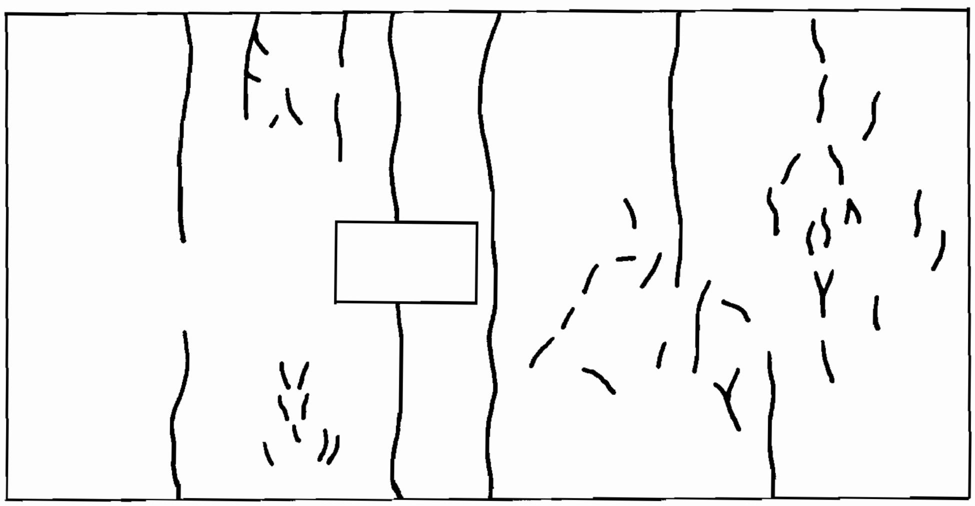


Fig B.7. Base Slab No. 2 at start of loading.

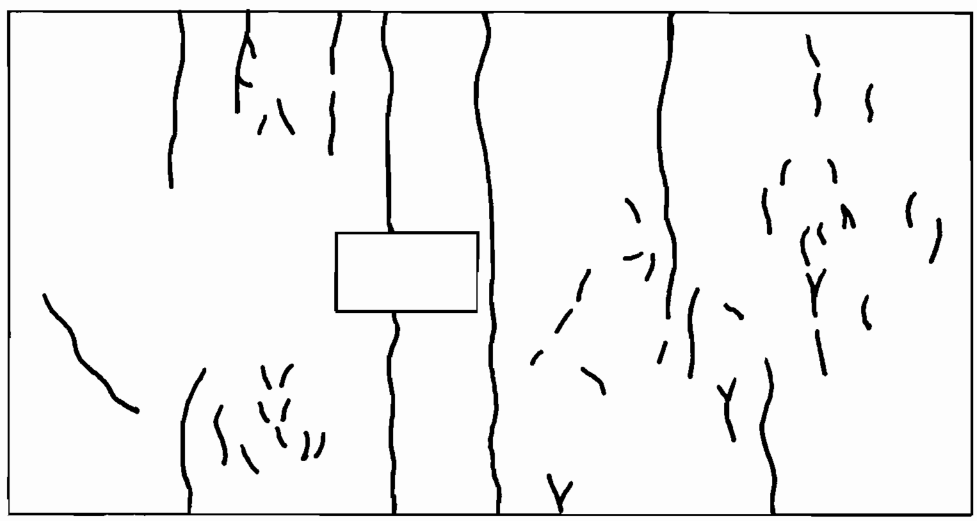


Fig B.8. Base Slab No. 2 after 800,000 load repetitions.

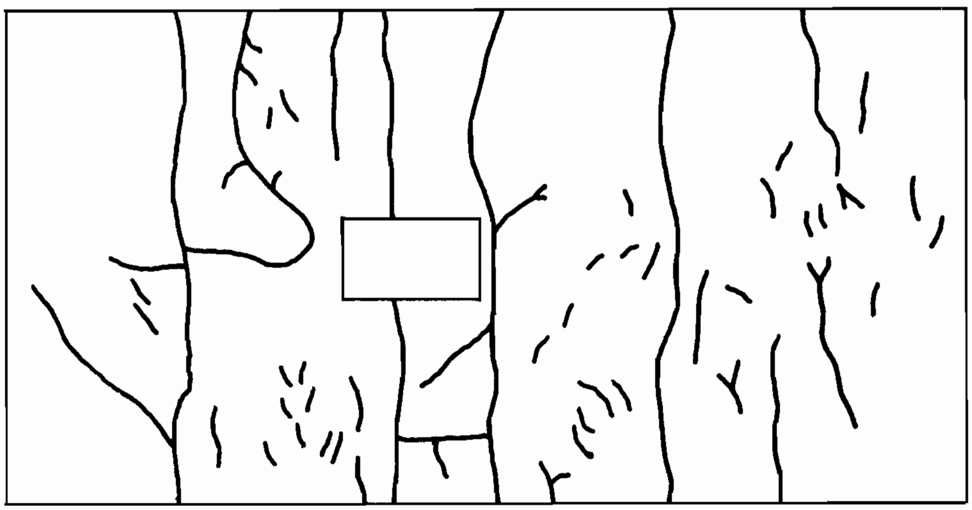


Fig B. 9. Base Slab No. 2 after 8,000,000 load repetitions.

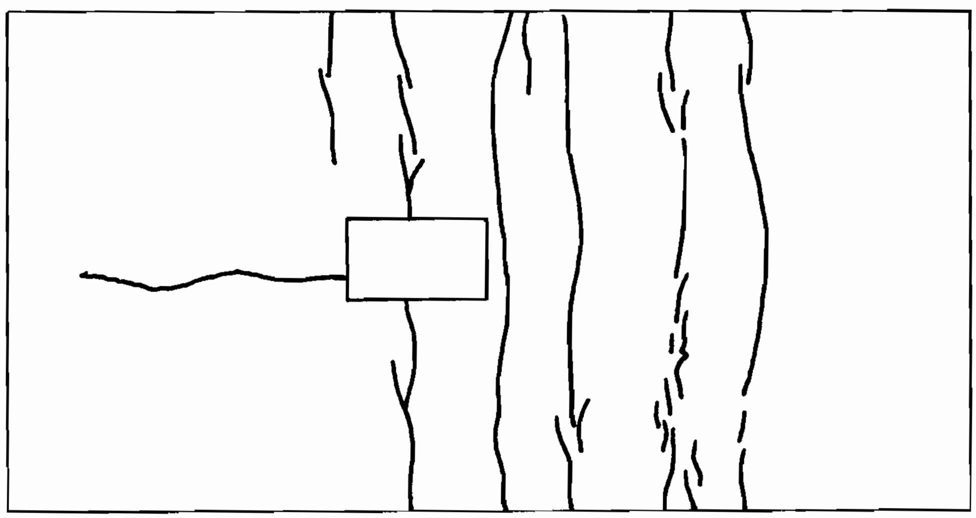


Fig B.10. Overlay No. 2 at start of loading.

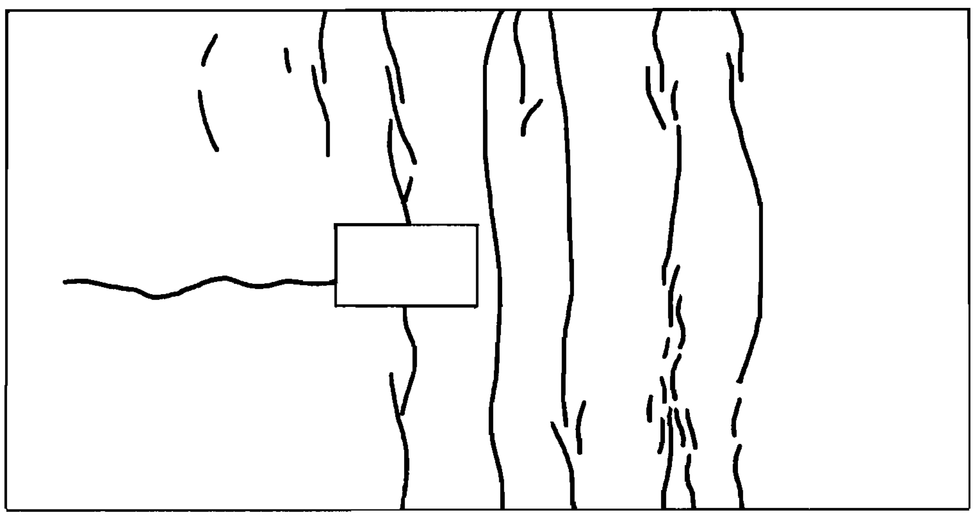


Fig B.11. Overlay No. 2 after 3,328,000 load repetitions.

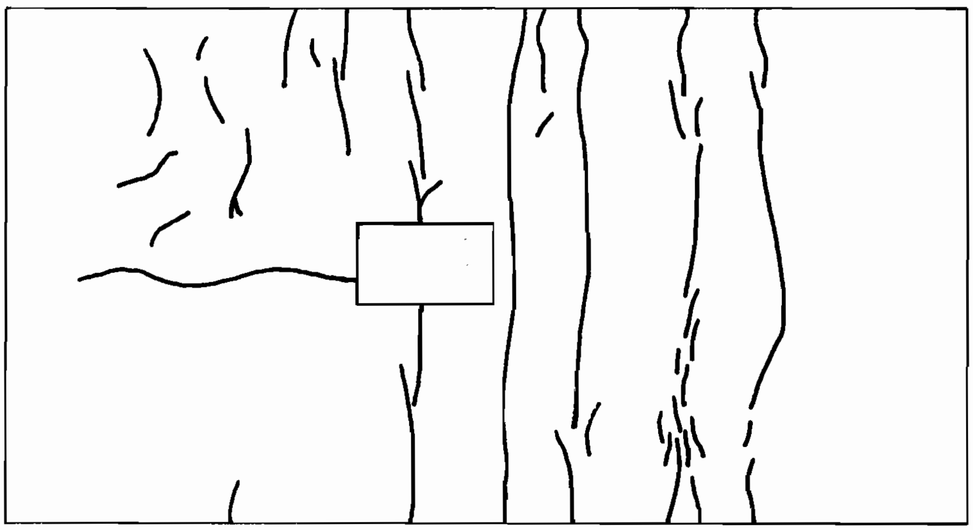


Fig B.12. Overlay No. 2 after 5,628,000 load repetitions.

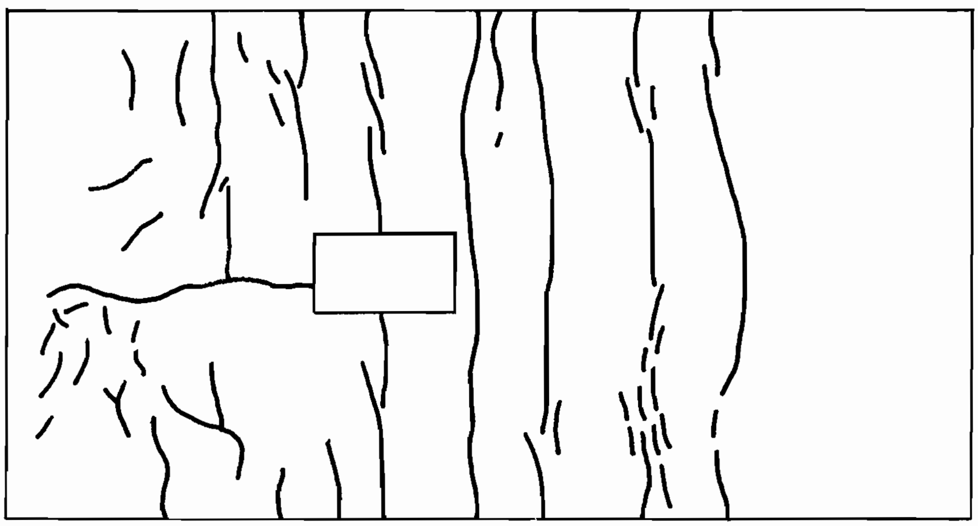


Fig B.13. Overlay No. 2 after 6,700,000 load repetitions.

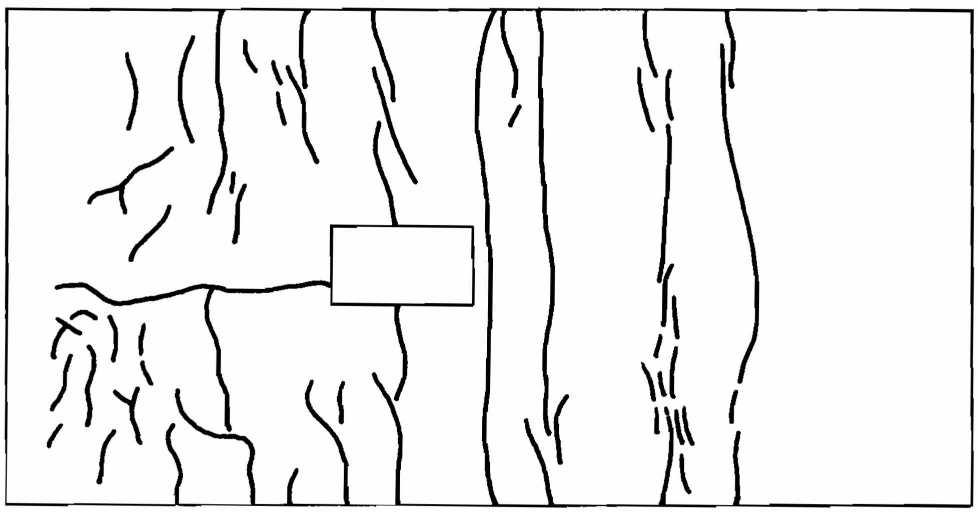


Fig B. 14. Overlay No. 2 after 9,400,000 load repetitions.

BASE SLAB NO. 3

Base Slab No. 3

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
100,000	5	5	5
1,271,000	5	0	5
1,600,.000	10	11	16
2,600,000	10	22	38
2,986,000	10	0	38
2,988,000	20	117	155

Overlay No. 3

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
2,000,000	5	38	38
2,300,000	5	12	50
3,000,000	5	11	61
3,900,000	5	2	63
5,040,000	5	0	63
5,042,000	10	5	68
5,482,000	10	29	97

* This number does not include the length of the simulated temperature crack at midspan

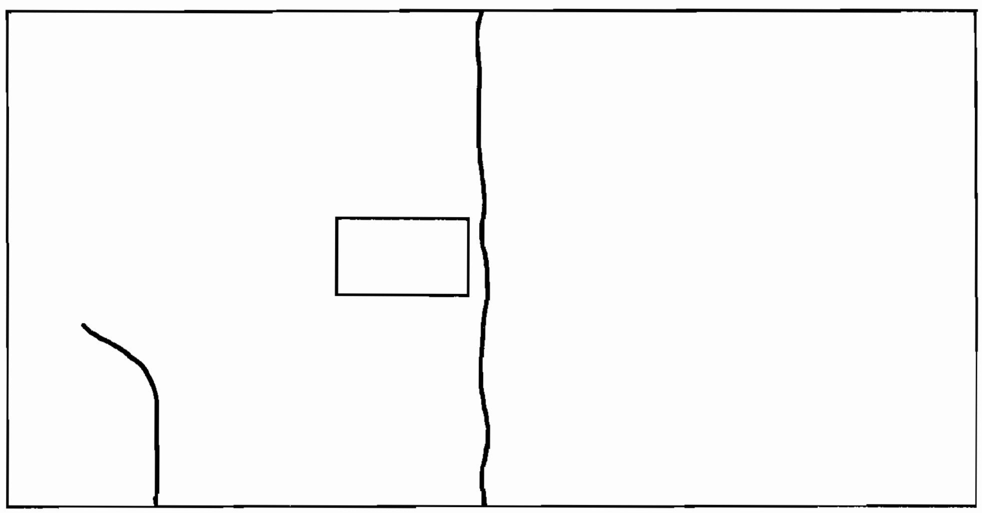


Fig B.15. Base Slab No. 3 after 1,600,000 load repetitions.

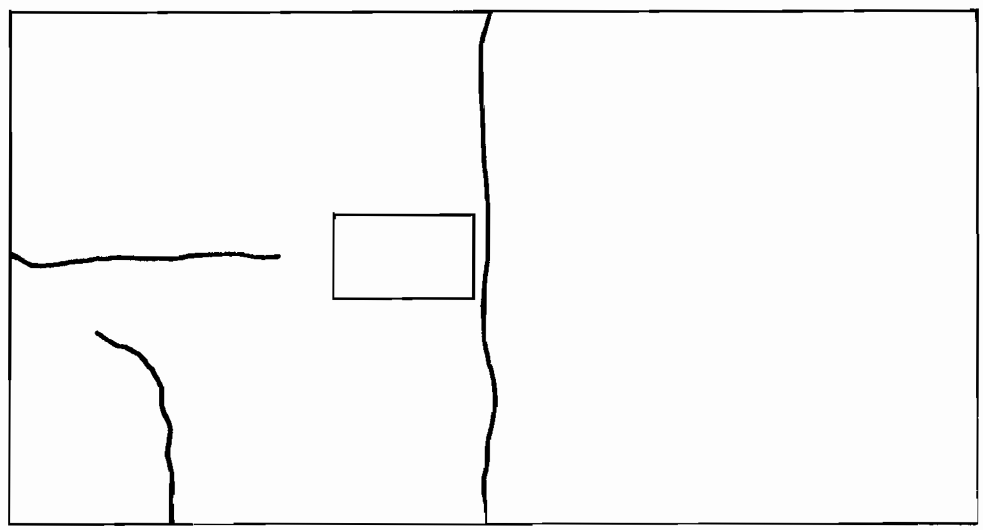


Fig B.16. Base Slab No. 3 after 2,600,000 load repetitions.

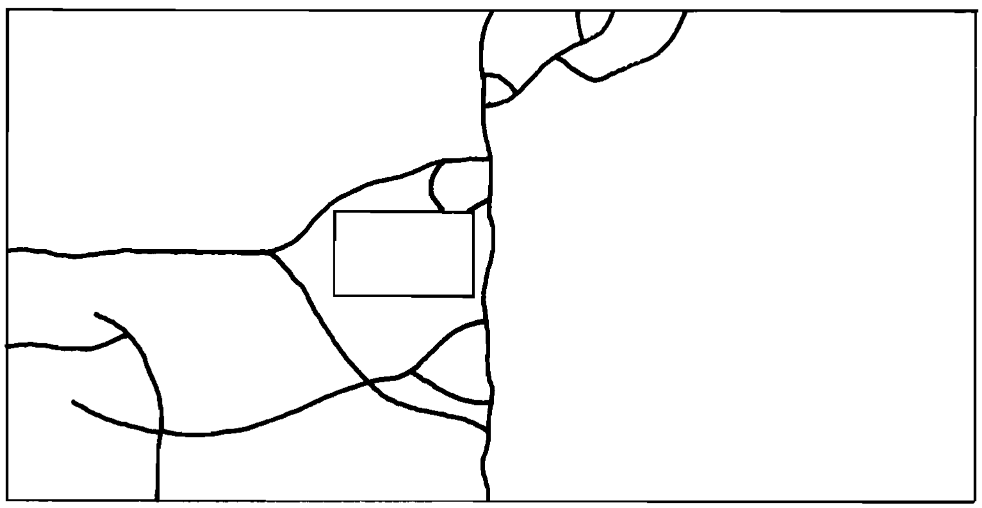


Fig B.17. Base Slab No. 3 after 2,988,000 load repetitions.

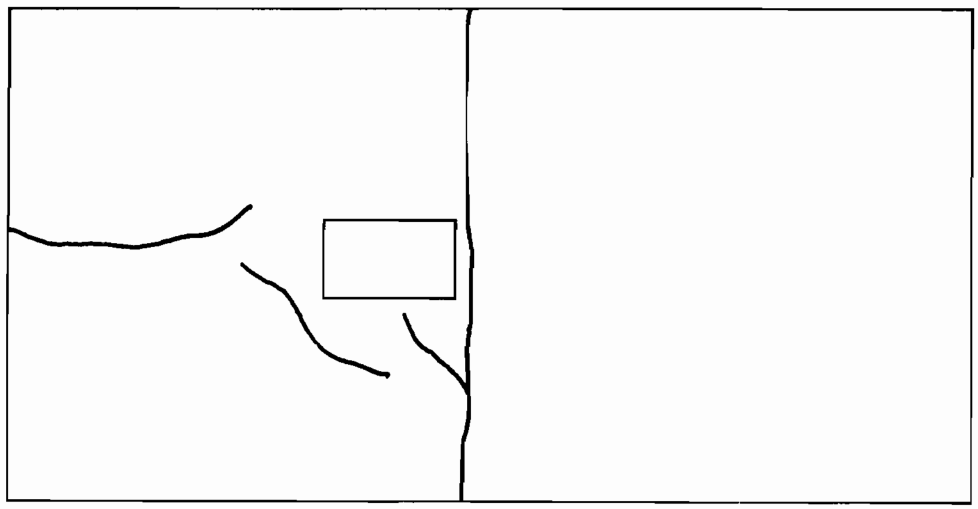


Fig B.18. Overlay No. 3 after 2,000,000 load repetitions.

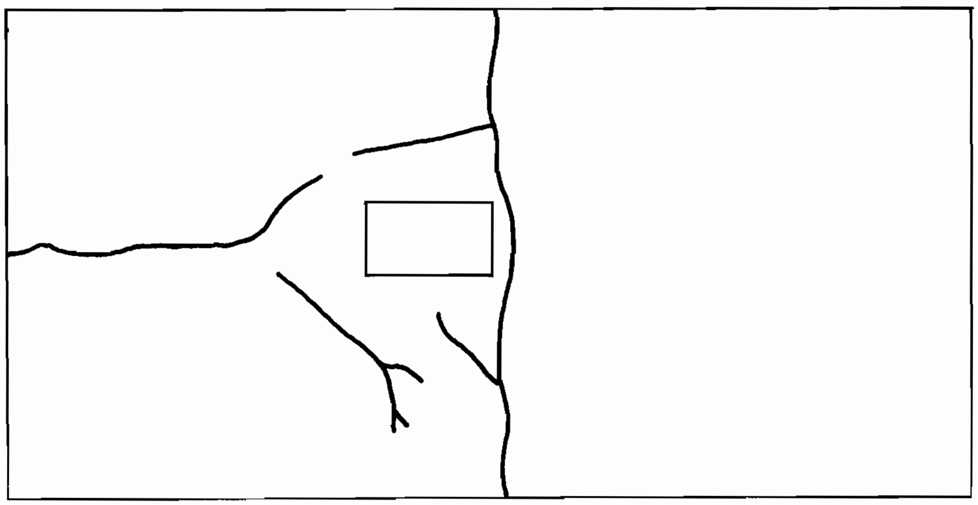


Fig B.19. Overlay No. 3 after 2,300,000 load repetitions.

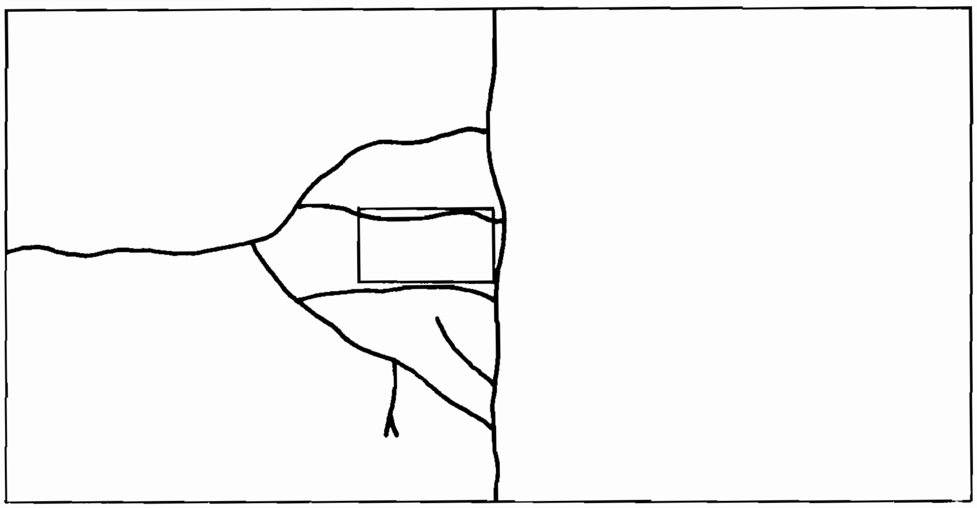


Fig B.20. Overlay No. 3 after 5,481,000 load repetitions.

SUMMARY OF CRACKING DATA OF BASE SLAB AND OVERLAY NO. 4

Base Slab No. 4

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
950,000	5	0	0
2,178,000	10	0	0

Overlay No. 4

Total Number of Load Repetitions	Load Intensity (kips)	Length of Cracking* (inches)	Cumulative Length of Cracking (inches)
5,163,000	5	0	0
12,846,000	10	0	0

* This number does not include the length of the simulated temperature crack at the joint at midspan.

APPENDIX C

ELSYM5 COMPUTER OUTPUT

```
ELSYM5  3/72 - 3,  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  I -      LAB MODEL 4-INCH BASE SLAB  5,000#

           ELASTIC    POISSONS
LAYER      MODULUS    RATIO        THICKNESS
  1       2740000.     .150          4.000 IN
  2          7000.     .150          4.000 IN
  3       3000000.     .150          8.000 IN
  4         20000.     .450       SEMI-INFINITE

  ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD.....     5000.00 LBS
LOAD STRESS....       75.87 PSI
LOAD RADIUS....        4.58 IN

       LOCATED AT
LOAD    X         Y
  1        0         0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z=    4.00
X-Y POINT(S)
X=       0
Y=       0
```

```
ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -       LAB MODEL 4-INCH BASE SLAB  5,000#

  Z=   4.00 LAYER NO,  1

  X=          0
  Y=          0

NORMAL STRESSES
SXX    .2405E+03
SYY    .2405E+03
SZZ   -.6749E+01

SHEAR STRESSES
SXY        0
SXZ        0
SYZ        0

PRINCIPAL STRESSES
PS 1   .2405E+03
PS 2   .2405E+03
PS 3  -.6749E+01

PRINCIPAL SHEAR STRESSES
PSS 1  .1237E+03
PSS 2      0
PSS 3  .1237E+03

DISPLACEMENTS
UX         0
UY         0
UZ     .6194E-02

NORMAL STRAINS
EXX    .7500E-04
EYY    .7500E-04
EZZ   -.2880E-04

SHEAR STRAINS
EXY        0
EXZ        0
EYZ        0

PRINCIPAL STRAINS
PE 1   .7500E-04
PE 2   .7500E-04
PE 3  -.2880E-04

PRINCIPAL SHEAR STRAINS
PSE 1  .1038E-03
PSE 2      0
PSE 3  .1038E-03
```

```
ELSYM5  3/72 - 3,  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -      LAB MODEL 4-INCH BASE SLAB  10,000#

          ELASTIC    POISSONS
LAYER     MODULUS    RATIO        THICKNESS
  1       2749000.     .150          4.000 IN
  2          7000.     .150          4.000 IN
  3       3003000.     .150          8.000 IN
  4         20000.     .450       SEMI-INFINITE

  ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD.....   10000.00 LBS
LOAD STRESS....     151.75 PSI
LOAD RADIUS....       4.58 IN

       LOCATED AT
LOAD    X         Y
  1        0         0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z=   4.00
X-Y POINT(S)
X=      0
Y=      0
```

```
ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -      LAB MODEL 4-INCH BASE SLAB  10,000#

  Z=   4.00 LAYER NO,  1

  X=          0
  Y=          0

NORMAL STRESSES
SXX    .4812E+03
SYY    .4812E+03
SZZ   -.1350E+02

SHEAR STRESSES
SXY        0
SXZ        0
SYZ        0

PRINCIPAL STRESSES
PS 1   .4812E+03
PS 2   .4812E+03
PS 3  -.1350E+02

PRINCIPAL SHEAR STRESSES
PSS 1  .2473E+03
PSS 2      0
PSS 3  .2473E+03

DISPLACEMENTS
UX         0
UY         0
UZ     .1239E-01

NORMAL STRAINS
EXX    .1500E-03
EYY    .1500E-03
EZZ   -.5761E-04

SHEAR STRAINS
EXY        0
EXZ        0
EYZ        0

PRINCIPAL STRAINS
PE 1   .1500E-03
PE 2   .1500E-03
PE 3  -.5761E-04

PRINCIPAL SHEAR STRAINS
PSE 1  .2076E-03
PSE 2      0
PSE 3  .2076E-03
```

```
ELSYM5  3/72 - 3,  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -      LAB MODEL 4-INCH BASE SLAB  15,000#

           ELASTIC    POISSONS
LAYER      MODULUS    RATIO        THICKNESS
  1       2740000.     .150           4.000 IN
  2          7000.     .150           4.000 IN
  3       3000000.     .150           8.000 IN
  4         23000.     .450        SEMI-INFINITE

  ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD.....    15000.00 LBS
LOAD STRESS....      227.62 PSI
LOAD RADIUS....        4.58 IN

       LOCATED AT
LOAD     X          Y
  1          0          0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z=    4.00
X-Y POINT(S)
X=        0
Y=        0
```

```
ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -       LAB MODEL 4-INCH BASE SLAB  15,000#

  Z=    4.00 LAYER NO,  1

  X=           0
  Y=           0

NORMAL STRESSES
SXX     .7218E+03
SYY     .7218E+03
SZZ    -.2025E+02

SHEAR STRESSES
SXY          0
SXZ          0
SYZ          0

PRINCIPAL STRESSES
PS 1    .7218E+03
PS 2    .7218E+03
PS 3   -.2025E+02

PRINCIPAL SHEAR STRESSES
PSS 1   .3710E+03
PSS 2        0
PSS 3   .3710E+03

DISPLACEMENTS
UX           0
UY           0
UZ      .1858E-01

NORMAL STRAINS
EXX     .2250E-03
EYY     .2250E-03
EZZ    -.8641E-04

SHEAR STRAINS
EXY          0
EXZ          0
EYZ          0

PRINCIPAL STRAINS
PE 1    .2250E-03
PE 2    .2250E-03
PE 3   -.8641E-04

PRINCIPAL SHEAR STRAINS
PSE 1   .3114E-03
PSE 2        0
PSE 3   .3114E-03
```

```
ELSYM5  3/72 - 3,  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -      LAB MODEL 4-INCH BASE SLAB  20,000#

          ELASTIC    POISSONS
LAYER     MODULUS    RATIO       THICKNESS
  1      2740000.     .150         4.000 IN
  2         7000.     .150         4.000 IN
  3      3000000.     .150         8.000 IN
  4        20000.     .450      SEMI-INFINITE

  ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD.....    20000.00 LBS
LOAD STRESS....      303.49 PSI
LOAD RADIUS....        4.58 IN

       LOCATED AT
LOAD     X         Y
  1         0         0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z=    4.00
X-Y POINT(S)
X=       0
Y=       0
```

```
ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -      LAB MODEL 4-INCH BASE SLAB  20,000#

  Z=   4.00 LAYER NO,  1

  X=           0
  Y=           0

NORMAL STRESSES
SXX    .9623E+03
SYY    .9623E+03
SZZ   -.2700E+02

SHEAR STRESSES
SXY        0
SXZ        0
SYZ        0

PRINCIPAL STRESSES
PS 1   .9623E+03
PS 2   .9623E+03
PS 3  -.2700E+02

PRINCIPAL SHEAR STRESSES
PSS 1  .4947E+03
PSS 2      0
PSS 3  .4947E+03

DISPLACEMENTS
UX         0
UY         0
UZ     .2478E-01

NORMAL STRAINS
EXX    .3000E-03
EYY    .3000E-03
EZZ   -.1152E-03

SHEAR STRAINS
EXY        0
EXZ        0
EYZ        0

PRINCIPAL STRAINS
PE 1   .3000E-03
PE 2   .3000E-03
PE 3  -.1152E-03

PRINCIPAL SHEAR STRAINS
PSE 1  .4152E-03
PSE 2      0
PSE 3  .4152E-03
```

ELSYM5 3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM 1 - LAB MODEL 4-INCH BASE SLAB WITH 1-1/2-INCH O/L 5,00

LAYER	ELASTIC MODULUS	POISSONS RATIO	THICKNESS
1	3600000.	.150	1.500 IN
2	2740000.	.150	4.000 IN
3	7000.	.150	4.000 IN
4	3000000.	.150	6.000 IN
5	20000.	.450	SEMI-INFINITE

ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD..... 5000.00 LBS
LOAD STRESS.... 75.87 PSI
LOAD RADIUS.... 4.58 IN

LOAD	LOCATED AT X	Y
1	0	0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z= 5.50
X-Y POINT(S)
X= 0
Y= 0

```
ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -    LAB MODEL  4-INCH BASE SLAB WITH 1-1/2-INCH O/L  5,00

  Z=    5.50 LAYER NO,  2

  X=           0
  Y=           0

NORMAL STRESSES
SXX     .1466E+03
SYY     .1466E+03
SZZ    -.3961E+01

SHEAR STRESSES
SXY          0
SXZ          0
SYZ          0

PRINCIPAL STRESSES
PS 1    .1466E+03
PS 2    .1466E+03
PS 3   -.3961E+01

PRINCIPAL SHEAR STRESSES
PSS 1   .7528E+02
PSS 2        0
PSS 3   .7528E+02

DISPLACEMENTS
UX           0
UY           0
UZ      .4529E-02

NORMAL STRAINS
EXX     .4570E-04
EYY     .4570E-04
EZZ    -.1750E-04

SHEAR STRAINS
EXY          0
EXZ          0
EYZ          0

PRINCIPAL STRAINS
PE 1    .4570E-04
PE 2    .4570E-04
PE 3   -.1750E-04

PRINCIPAL SHEAR STRAINS
PSE 1   .6320E-04
PSE 2        0
PSE 3   .6320E-04
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ELSYM5 3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM 1 - LAB MODEL 4-INCH BASE SLAB WITH 1-1/2-INCH O/L 10,0

LAYER	ELASTIC MODULUS	POISSONS RATIO	THICKNESS
1	3600000.	.150	1.500 IN
2	2740000.	.150	4.000 IN
3	7000.	.150	4.000 IN
4	3000000.	.150	8.000 IN
5	20000.	.450	SEMI-INFINITE

ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD..... 10000.00 LBS
LOAD STRESS.... 151.75 PSI
LOAD RADIUS.... 4.58 IN

LOAD	LOCATED AT X	Y
1	0	0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z= 5.50
X-Y POINT(S)
X= 0
Y= 0

```
ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -     LAB MODEL  4-INCH BASE SLAB WITH 1-1/2-INCH O/L  10.0

  Z=   5.50 LAYER NO,  2

  X=          0
  Y=          0

NORMAL STRESSES
SXX    .2932E+03
SYY    .2932E+03
SZZ   -.7923E+01

SHEAR STRESSES
SXY         0
SXZ         0
SYZ         0

PRINCIPAL STRESSES
PS 1   .2932E+03
PS 2   .2932E+03
PS 3  -.7923E+01

PRINCIPAL SHEAR STRESSES
PSS 1  .1506E+03
PSS 2       0
PSS 3  .1505E+03

DISPLACEMENTS
UX          0
UY          0
UZ     .9058E-02

NORMAL STRAINS
EXX    .9139E-04
EYY    .9139E-04
EZZ   -.3500E-04

SHEAR STRAINS
EXY         0
EXZ         0
EYZ         0

PRINCIPAL STRAINS
PE 1   .9139E-04
PE 2   .9139E-04
PE 3  -.3500E-04

PRINCIPAL SHEAR STRAINS
PSE 1  .1264E-03
PSE 2       0
PSE 3  .1264E-03
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ELSYM5  3/72 - 3,  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -    LAB MODEL  4-INCH BASE SLAB WITH 1-1/2-INCH O/L  15,0

           ELASTIC    POISSONS
LAYER      MODULUS    RATIO       THICKNESS
  1       3600000.     .150         1.500 IN
  2       2740000.     .150         4.000 IN
  3          7000.     .150         4.000 IN
  4       3000000.     .150         8.000 IN
  5         20000.     .450       SEMI-INFINITE

  ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD.....    15000.00 LBS
LOAD STRESS....      227.62 PSI
LOAD RADIUS....        4.58 IN

       LOCATED AT
LOAD    X         Y
  1        0         0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z=   5.50
X-Y POINT(S)
X=       0
Y=       0
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ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -    LAB MODEL  4-INCH BASE SLAB WITH 1-1/2-INCH O/L  15,0

  Z=   5.50 LAYER NO,  2

  X=          0
  Y=          0

NORMAL STRESSES
SXX     .4398E+03
SYY     .4398E+03
SZZ    -.1188E+02

SHEAR STRESSES
SXY         0
SXZ         0
SYZ         0

PRINCIPAL STRESSES
PS 1    .4398E+03
PS 2    .4398E+03
PS 3   -.1188E+02

PRINCIPAL SHEAR STRESSES
PSS 1   .2259E+03
PSS 2       0
PSS 3   .2259E+03

DISPLACEMENTS
UX          0
UY          0
UZ      .1359E-01

NORMAL STRAINS
EXX     .1371E-03
EYY     .1371E-03
EZZ    -.5249E-04

SHEAR STRAINS
EXY         0
EXZ         0
EYZ         0

PRINCIPAL STRAINS
PE 1    .1371E-03
PE 2    .1371E-03
PE 3   -.5249E-04

PRINCIPAL SHEAR STRAINS
PSE 1   .1895E-03
PSE 2       0
PSE 3   .1895E-03
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ELSY45  3/72 - 3,  ELASTIC LAYERED SYSTEM WITH ONE TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -    LAB MODEL  4-INCH BASE SLAB WITH 1-1/2-INCH O/L  20,0

          ELASTIC   POISSONS
LAYER     MODULUS   RATIO        THICKNESS
  1      3600000.     .150          1.500 IN
  2      2740000.     .150          4.000 IN
  3         7000.     .150          4.000 IN
  4      3000000.     .150          8.000 IN
  5        20000.     .450       SEMI-INFINITE

  ONE LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD.....    20000.00 LBS
LOAD STRESS....      303.49 PSI
LOAD RADIUS....        4.58 IN

       LOCATED AT
LOAD    X         Y
  1        0         0

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

DEPTH(S)
Z=   5.50
X-Y POINT(S)
X=      0
Y=      0
```

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ELSYM5  3/72 - 3, ELASTIC LAYERED SYSTEM WITH ONE  TO TEN NORMAL IDENTICAL CIRCULAR UNIFORM LOAD(S)

ELASTIC SYSTEM  1 -    LAB MODEL  4-INCH BASE SLAB WITH 1-1/2-INCH O/L  20,0

  Z=   5.50 LAYER NO,  2

  X=          0
  Y=          0

NORMAL STRESSES
SXX    .5864E+03
SYY    .5864E+03
SZZ   -.1585E+02

SHEAR STRESSES
SXY        0
SXZ        0
SYZ        0

PRINCIPAL STRESSES
PS 1   .5864E+03
PS 2   .5864E+03
PS 3  -.1585E+02

PRINCIPAL SHEAR STRESSES
PSS 1  .3011E+03
PSS 2      0
PSS 3  .3011E+03

DISPLACEMENTS
UX         0
UY         0
UZ     .1812E-01

NORMAL STRAINS
EXX    .1828E-03
EYY    .1828E-03
EZZ   -.6999E-04

SHEAR STRAINS
EXY        0
EXZ        0
EYZ        0

PRINCIPAL STRAINS
PE 1   .1828E-03
PE 2   .1828E-03
PE 3  -.6999E-04

PRINCIPAL SHEAR STRAINS
PSE 1  .2528E-03
PSE 2      0
PSE 3  .2528E-03
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