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16. Abstract

Two small sections of the north and south frontage roads of Interstate Loop 610 around Houston were built in 1964 as experimental CRCP sections to study the effects of differences in percent steel, preformed crack spacing, and type of aggregate. The performance of these sections was monitored by performing several surveys during the year after construction. Then data were collected in 1974 and again in 1984. In addition, a small amount of data was collected in 1988. This report includes an empirical study made to address questions on the effect of the design variables on the long-term performance of CRCP. An attempt is also made to compare observed performance indicators with theoretical expectations, with a view to gaining insights that will be helpful in refining the theoretical model.

This study indicated that the pavement sections built using lightweight aggregate concrete have relatively less surface distress than the standard-aggregate sections.

17. Key Words
concrete pavements, continuous reinforcement, crack spacing, lightweight-aggregate, preformed cracks

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A TWENTY-FOUR YEAR PERFORMANCE REVIEW OF CONCRETE PAVEMENT SECTIONS MADE WITH SILICEOUS AND LIGHTWEIGHT COARSE AGGREGATES

by

Mooncheol Won
Kenneth Hankins
B. Frank McCullough

Research Report Number 472-3

Research Project 3-8-86-472
Rigid Pavement Data Base

conducted for

Texas State Department of Highways and Public Transportation

in cooperation with the

**U.S. Department of Transportation
Federal Highway Administration**

by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

April 1989

PREFACE

This report presents the results of empirical analysis of deflection and distress data on Houston Loop 610 experimental CRCP sections and makes conclusions of significance to CRCP designers. This report also presents the results of comparing the observed condition and performance of these sections in 1964, 1974, 1984, and 1988 with theoretical predictions obtained with the CRCP-3 computer program.

Thanks go to Eduardo Ricci and Jim Long for getting field measurements, Ahlam Barakat and Michele Mason Sewell for their help in drafting, and Lyn Gabbert for word processing. Thanks go also to Mooncheol Won for contributing the chapter on comparison of theoretical predictions and observed behavior of the pavement sections.

Mooncheol Won
Kenneth Hankins
B. Frank McCullough

LIST OF REPORTS

Report No. 472-1, "Evaluation of Proposed Texas SDHPT Design Standards for CRCP," by Mooncheol Won, B. Frank McCullough, and W. R. Hudson, presents the results of an evaluation of a proposed CRCP Design Standard for various coarse aggregates used, describes the theoretical models used in the study, and discusses several important design parameters of CRCP. April 1988.

Report No. 472-2, "Development of a Long-Term Monitoring System for Texas CRC Pavement Network," by Chia-pei J. Chou, B. Frank McCullough, W. R. Hudson, and C. L. Saraf, presents the application of an experimental design method for developing a long-term monitoring system in Texas. Development of a distress index and a decision criteria index for determining the present and terminal conditions of pavements is also discussed.

Research Report 472-3, "A Twenty-Four Year Performance Review of Concrete Pavement Sections Made With Siliceous and Lightweight Coarse Aggregates," by Mooncheol Won, Kenneth Hankins, and B. Frank McCullough, presents the results of statistical analyses over a twenty-four year performance period of continuously reinforced concrete pavements made with lightweight and conventional/standard-aggregates. The performance variables include pavement deflections, and visual condition survey data. Recommendations and directions for future research emanating from the study are also presented for consideration by CRCP designers.

ABSTRACT

Two small sections of the north and south frontage roads of Interstate Loop 610 around Houston were built in 1964 as experimental CRCP sections to study the effects of differences in percent steel, preformed crack spacing, and type of aggregate. The performance of these sections was monitored by performing several surveys during the year after construction. Then data were collected in 1974 and again in 1984. In addition, a small amount of data were collected in 1988. This report includes an empirical study made to address questions on the effect of the design variables on the long-term performance of CRCP. An attempt is also made to compare observed performance indicators with theoretical expectations, with a view to gaining insights that will be helpful in refining the theoretical mode. This study indicated that the pavement sections built using lightweight aggregate concrete have relatively less surface distress than the standard-aggregate sections.

KEY WORDS: concrete pavements, continuous reinforcement, crack spacing, lightweight-aggregate, preformed cracks

SUMMARY

Two small sections of the north and south frontage streets of Interstate Loop 610 around Houston were built in 1964 as experimental CRCP sections to study the effects of difference in percent steel, preformed crack spacing, and type of aggregate. Condition surveys were made at periodic intervals during the year after construction. Also, data were collected in 1974, in 1984, and in 1988. This report includes an empirical study made to address questions on the effect of the design variables on the long-term performance of CRCP. An attempt is also made to compare observed performance indicators with theoretical expectations, with a view toward gaining insights that will be helpful in refining the theoretical model.

This study indicates that the pavement sections built using lightweight-aggregate concrete have less surface distress than the standard/conventional aggregate sections. An analysis based on the data collected in 1964 through 1988 shows that the use of lightweight-aggregates in CRCP construction results in fewer cracks in both the short term and the long term. Also, the lightweight-aggregate sections had no failures and required no repair, whereas the standard-aggregate sections required the full depth pavement repair and showed considerable spalling. These are other findings of significance:

(1) In general, 5-foot preformed crack spacing seems better than 8-foot for standard-aggregate sections, while 8-foot seems more natural than the 20-foot preformed crack spacing tried for lightweight-aggregate sections.

(2) The performance of both standard and lightweight-aggregate sections is affected by the amount of longitudinal steel in the pavement. Results for the conventional aggregate sections show the sections with the 0.5 percent steel had superior performance and two of the three sections with 0.3 percent steel experienced shearing of the longitudinal bars. The sections with both 0.3 percent and 0.4 percent steel using lightweight-aggregate performed well in the 24-year observation period.

IMPLEMENTATION STATEMENT

This report presents some very useful design implications for continuously reinforced pavements made with different aggregate types, longitudinal steel, and preformed crack spacing. The study has also identified certain limitations of the current state-of-the-art technology to theoretically predict crack spacings.

It is recommended that the optimal combination of preformed crack spacing and longitudinal steel percent identified in this study be adopted as a recommended practice for design and construction of standard-aggregate CRC pavements. however, considering the fact that the conclusions are based on limited data, it is recommended that the task of further refining computer program CRCP-3 be undertaken.

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CHAPTER 1. INTRODUCTION

Two short lengths of CRCP were constructed on the Interstate Highway 610 (South) frontage roads in 1963-1964. Each length contained several experimental sections where the experiment included variations in the type of coarse aggregate, the steel percentage, and a performed crack spacing. At the present time the test sections are still in service even though the siliceous gravel section shows considerable wear (Figs 1.1 to 1.4). The test sections have been monitored at periodic intervals since construction, and performance data have been collected and analyzed. This report gives an account of the study and findings of the analysis.

Fig 1.1. Standard aggregate section.

LOCATION AND LAYOUT

The two test areas are located in Houston, Texas, and are the frontage roads to Interstate Highway 610 (South) (Fig 1.5). One test area, located on the north frontage street, consists of continuously reinforced concrete pavement made with siliceous gravel coarse aggregate. The second test area is located on the south frontage street, and consists of continuously reinforced concrete pavement made with lightweight coarse aggregate.

Figure 1.6 depicts the general layout of the test sections, with transition sections where the percentage of steel was changed. The siliceous gravel or "conventional concrete" and the lightweight-aggregate concrete were placed near enough to one another to reduce differences in environmental conditions to a minimum. In general, the terrain consists of a flat plain with black clayey soil. Each test slab has two lanes, and the traffic in each is in the same direction.

The test slabs consist of 6-inch-thick concrete on a subbase of 6 inches of cement-stabilized oyster shell. The slabs were placed monolithically and are either 22 or 24 feet wide.

SIGNIFICANCE OF THIS STUDY

The experimental sections were constructed to evaluate the possibility of reducing the amount of steel used in CRC pavements by introducing preformed cracks at regular intervals. The condition survey information for these sections are available for 1964, 1974, and 1984 . The condition surveys collected in 1988, 24 years after the sections were opened to traffic, have been combined with previous observations to develop a performance history for the CRC pavements.

Fig 1.2. Standard aggregate section – close-up.

Probably no other pavement in Texas has been observed with this diligence for this period of time. With limited financial resources, there is increasing need for and emphasis on maintenance and rehabilitation of existing highway pavements. The subject study will add to the much-needed information on long-term performance as affected by materials, design, traffic, and environment.

Fig 1.3. Lightweight-aggregate section.

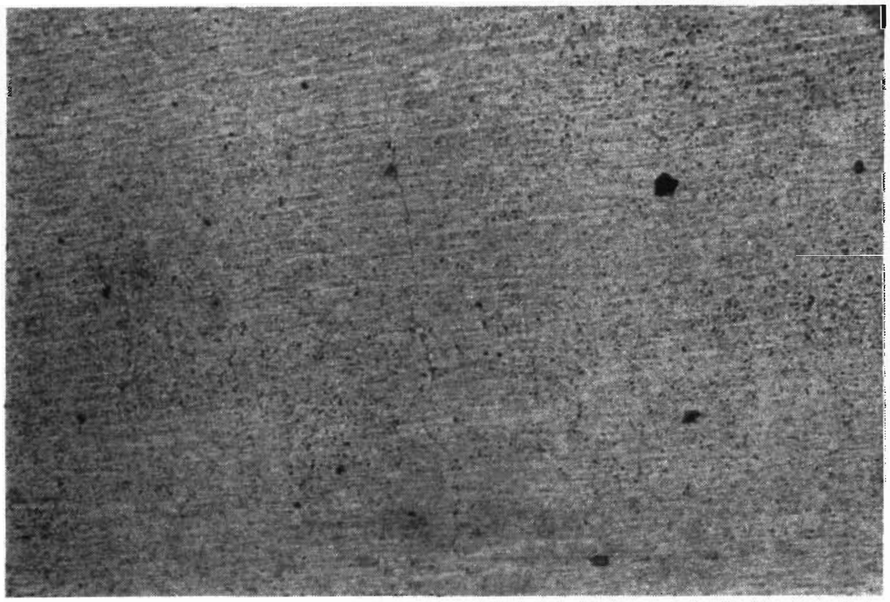


Fig 1.4. Lightweight-aggregate section – close-up.

OBJECTIVES OF THE STUDY

The subject study was undertaken to document information useful in expanding or updating the understanding of pavement performance and hence pavement modelling systems. Toward this end, the following objectives were defined:

(1) Evaluate the effect of preformed crack spacing, percent steel, and coarse aggregate type on the long-term performance of this experimental CRCP project in the Houston.
(2) Compare the present conditions of standard-aggregate CRCP and lightweight-aggregate CRCP to those predicted for one year after construction.
(3) Compare actual (observed) performance data with mechanistic model predictions made using the CRCP computer program.

STUDY APPROACH

This study included obtaining performance data for 1988 similar to those collected in 1964, 1974, and 1984. The previous data consisted of deflection measurements, spacing between transverse cracks, and, in 1984, spalling and other distress determined by visual surveys of pavement condition. The 1988 data were transverse crack spacing, crack widths, and pavement conditions based on a visual survey.

The new data were analyzed by developing graphs and tables similar to those in Research Report 46-3 (Ref 1). Theoretical predictions of crack spacing were determined using appropriate computer programs, and actual measured values were compared with the theoretical predictions.

SCOPE OF STUDY

This study is based on data available for the two short stretches of Houston Loop frontage roads shown in Fig 1.5. The condition survey information, available since 1964, allows us to study the effects of time. The frontage sections were used as the main lanes for about five years after their construction and there is a significant difference between the sections in terms of volume and type of traffic. However, the effects of traffic on the performance of these types of pavements can also be studied. The performance of the pavement sections is evaluated in terms of crack spacing, deflection, and surface conditions. The sections are compared in order to evaluate the effects of each of the experimental variables on pavement performance.

Program CRCP-3, developed by CTR, is useful in predicting crack spacing, crack width, and stresses in steel and concrete of a CRC pavement. These sections were analyzed using this program and the values predicted are compared with the observed values.

SCOPE OF THIS REPORT

This report describes the study approach, data collected, and findings of pavement performance as affected by design and construction materials. Chapter 2 describes the setup of the experiment and summarizes previous findings. Chapter 3 gives a brief account of the measurements in 1963-64 (soon after the sections were completed and opened for traffic), in 1973-74, in 1984-85, and in 1988. Chapter 4 gives a performance analysis of each section over the past 24 years, done to compare the effects on deflection of reinforcement (percent steel), preformed crack spacing, and type of aggregate. Chapter 5 attempts to compare the observed results with predictions made using mechanistic models. Chapter 6 discusses the results of the previous chapters. Chapter 7 summarizes findings of significance to designers, identifies questions raised by this study, and recommends further studies needed.

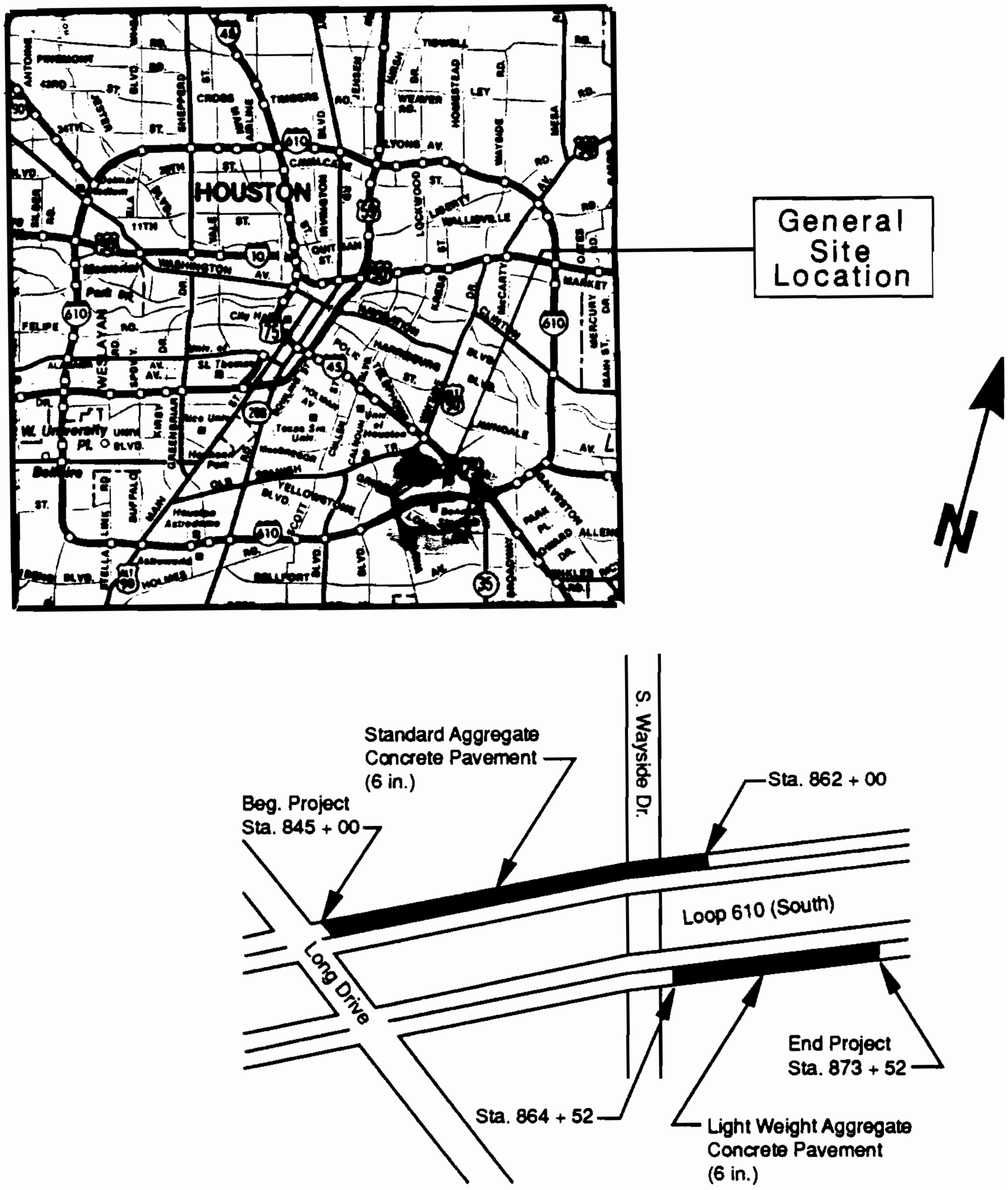
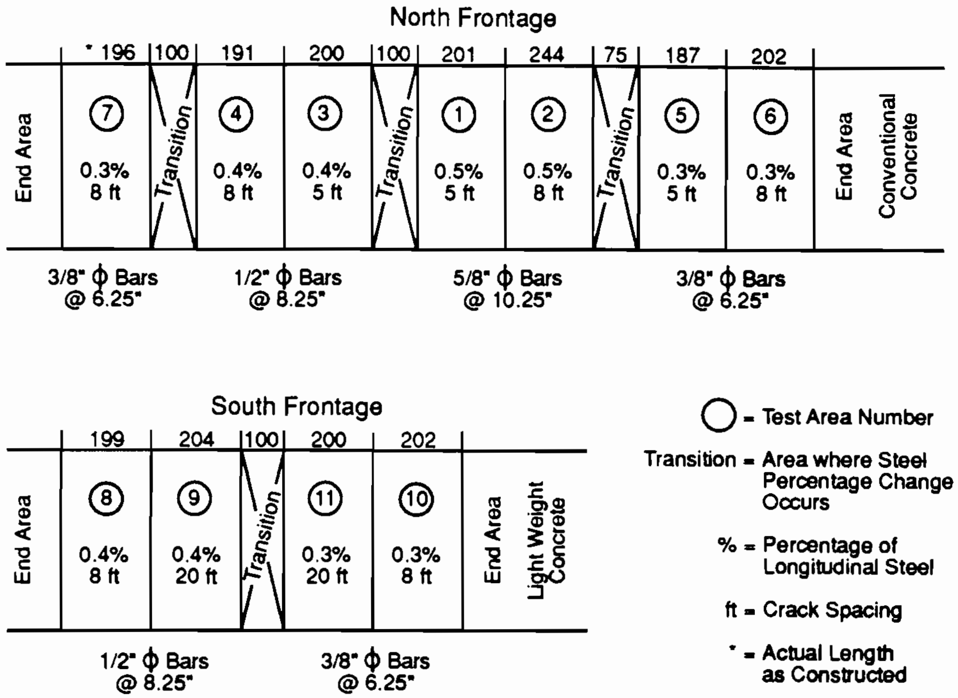


Fig 1.5. Location and layout of the project.



Note: All text sections are 6 inches thick and are placed over 6 inches of ement-stabilized oyster shell.

Fig 1.6. General layout of the test sections.

CHAPTER 2. DESCRIPTION OF THE EXPERIMENT AND PREVIOUS FINDINGS

This chapter presents the background information in terms of the layout of the factorial experiment and a summary of major findings from the previous study (Ref 2). More detailed information is available in Research Report 46-3 (Ref 1).

SUMMARY ACCOUNT OF THE DESIGN OF THE EXPERIMENT

Steel Design

The two test areas in this project had 0.3 percent (ratio of the cross-sectional area of the steel to the concrete area), 0.4 percent, and 0.5 percent longitudinal reinforcing steel in the standard CRCP and 0.3 percent and 0.4 percent steel in the lightweight CRCP. The larger percent steel was not used in the lightweight CRCP since analytical and field studies indicated the lower range was adequate. Complete randomization of test sections was not used due to construction problems and the length of the project. Table 2.1 shows the layout of the experiment.

The longitudinal steel for the 0.5 percent design consisted of 5/8-inch bars at 10-1/4 inch centers, the 0.4 percent design consisted of 1/2-inch bars at 8-1/2 inch centers, and the 0.3 percent design consisted of 3/8-inch bars at 6-1/4-inch centers. While the designs are referred to as 0.5, 0.4, and 0.3 percent, the actual percentages are 0.504, 0.404, and 0.293, respectively. On both designs, lightweight and standard, the transverse steel consisted of 1/2-inch bars at 32-inch centers. The bond area to volume of concrete ratios for the 0.5, 0.4, and 0.3 designs were 55.7, 55.5, and 55.3 inch^2/feet^3, respectively. Previous studies show the bond area/concrete volume ratio was an important factor and therefore the strategy on this project was to make this variable constant (Ref 3).

TABLE 2.1. EXPERIMENTAL SECTIONS IDENTIFIED BY COARSE AGGREGATE TYPE, PERCENT STEEL, AND PREFORMED CRACK SPACING

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5	5	3	1	*	*
8	6,7	4	2	10	8
20	*	*	*	11	9

*Not considered.

Note: Numbers in cells are section numbers.

Concrete Design

The standard CRCP was designed in accordance with Item 366 of the Standard Specifications, which requires a minimum flexural strength (mid-point loading) of 575 psi (Ref 4). The specifications for lightweight concrete call for a flexural strength and modulus of rupture of not less than 500 pounds per square inch at the age of seven days. The specifications for the lightweight concrete are shown in Table 2.2.

TABLE 2.2. SPECIFICATIONS FOR LIGHTWEIGHT-AGGREGATE CONCRETE (REF 4)

Cement Ratio	Air Content, % by volume	Slump, in.	Lightweight Aggregate	Unit Weight	Fine Aggregate
5-1/2 sacks per cu yd	6-9	2.3	ASTM C330	No more than 55 lb per cu ft	Natural Sand

The lightweight coarse aggregate used in the concrete was a synthetic lightweight aggregate, prepared by heating shale at high temperatures. The maximum size of the lightweight aggregate was approximately 3/4-inch. The conventional aggregate was a siliceous river gravel with a maximum size of approximately 1-1/2 inches. The concrete composed of the two types of aggregate had the following properties at 28 days:

Property	Lightweight Aggregate	Conventional Aggregate
Compressive Strength, psi	3828	4313
Tensile Strength, psi	312	488
Modulus of Elasticity, psi	3.05×10^6	7.8×10^6
Flexural Strength, psi	607	643

In both the standard CRCP and the lightweight CRCP, the design was considered to provide optimum crack spacing. To obtain different crack spacings, the design called for preformed cracks. These preformed cracks were provided by placing corrugated sheet metal strips 2 inches high across the width of the pavement at predetermined distances. These sheet metal strips were fabricated from thin gage galvanized sheet metal.

Terminal Treatment

In addition to the normal expansion joint on the west end of the north frontage road, the pavement end was anchored by means of two transverse lugs to limit end movement (Refs 3 and 4).

Construction

In order to minimize the effect of weather conditions, the specifications require that all the test sections in each slab be placed in one working day. All the test sections with standard CRCP were placed in one day, and those with lightweight CRCP were placed ten days later. Section 6 and its replicate, Section 7, were placed at opposite ends of the conventional slab to evaluate any possible effects of curing temperatures.

Environmental and Traffic Aspects

For about five years after the frontage roads were constructed, the frontage roads carried all the IH-610 traffic. At the end of this period the main freeway lanes were constructed. Thus, the frontage road sections were subjected to much heavier traffic during the early five years of their lives. A traffic history has been included in the following information.

CHAPTER 3. SUMMARY OF MEASUREMENTS

An account of all the field measurements made is given in this chapter. First, the measurements made during the year after the section was opened for traffic are summarized. These measurements are as reported in Reference 1. Next the measurements of deflection and crack pattern made in 1973-74 are summarized. Then, deflection and cracking measurements taken in 1984-85 are given. Finally, the data collected in 1988 is presented.

TABLE 3.1. CONVENTIONAL CONCRETE AVERAGE CRACK SPACING (FEET) FOR 1964

Section Number	7	4	3	1	2	5	6
Preformed Crack Spacing	8	8	5	5	8	5	8
Steel Percentage	0.3	0.4	0.4	0.5	0.5	0.3	0.3
Age of Concrete in Days							
4	8.69	8.00	5.00	5.00	8.00	14.28	8.33
16	8.33	8.00	5.00	5.00	8.00	7.69	8.33
18	8.33	8.00	5.00	5.00	8.00	6.25	8.33
27	8.33	8.00	5.00	5.00	8.00	6.25	8.33
53	8.33	8.00	5.00	5.00	8.00	6.25	8.33
201	8.00	5.40	4.16	5.00	5.40	5.00	8.00
378	6.06	5.00	3.77	4.17	5.00	5.00	8.00

SUMMARY OF 1964 MEASUREMENTS

Soon after construction, the concrete movement, steel stress, and temperature data were recorded every two hours during the first five days for all sections. Later these measurements were recorded at varying periods (whenever temperature and strain readings changed drastically). Crack propagation was monitored by visually examining and recording the distance between cracks at periodic intervals of time for 378 days (368 days for lightweight-aggregate sections). Tables 3.1 and 3.2 show these measurements.

The 1964 deflection measurements were collected using a Benkleman Beam and a loaded truck. The values are available for each section from graphs found in Ref 1. Table 3.3 shows a summary of the 1964 deflection measurements.

TABLE 3.2. LIGHTWEIGHT CONCRETE AVERAGE CRACK SPACING (FEET) FOR 1964

Section Number	10	11	9	8
Preformed Crack Spacing	8'	20'	20'	8'
Steel Percentage	0.3	0.3	0.4	0.4
Age of Concrete in Days				
5	25.00	100.00	200.10	200.00
6	18.18	22.22	200.00	200.00
8	13.33	22.22	200.00	200.00
16	10.00	20.00	100.00	15.38
43	9.52	15.38	15.38	13.33
80	9.09	11.11	12.50	13.33
191	8.69	8.33	9.09	8.00
368	8.00	8.33	9.09	8.00

SUMMARY OF 1974 MEASUREMENTS

The transverse crack spacing information collected in 1974 was obtained in a manner similar to that used in 1964. The average transverse crack spacing was calculated and the information for each section is shown in Table 3.4. Deflection measurements in 1974 used a Dynaflect. A summary of deflection measurements is shown in Table 3.5. Note that the deflection measurements made using the Benkelman Beam in 1964 should not be used for a direct comparison with the deflection measurements in 1974 or in 1984 since the 1974 and 1984 measurements were obtained with a Dynaflect.

SUMMARY OF 1984 MEASUREMENTS

In November 1984, the experimental sections were visually surveyed to note their condition in terms of spalling and cracks. Again the distance between each transverse crack in each section was measured and recorded together with the number of transverse cracks. Dynaflect deflections were also recorded at cracks and between cracks. Table 3.6 contains the deflection information. Tables 3.7 and 3.8 show the spalling data in terms of minor and severe spalling. The transverse crack information is included in Table 3.9.

SUMMARY OF 1988 MEASUREMENTS

The 1988 measurements were obtained because it was desired to collect and document the latest condition information. When the main lanes were constructed in 1969 the plans included an off ramp for the westbound lanes, which deposited a large amount of traffic over the north frontage road

TABLE 3.3. DEFLECTION (MILS) ATCRACKS AND MIDSPAN FO18,000-POUNDLOAD FOR 1964

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5 Midspan	21	15	14		
Crack	19	15	-		
Average	20	15	14		
8 Midspan	18	14	12	6	9
Crack	21	16	14	7	9
Average	19.5	15	13	6.5	9
20 Midspan				8	8
Crack				8	7
Average				8	7.5

TABLE 3.4. AVERAGE CRACK SPACING (FEET) AS MEASURED FOR 1974

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5 1/73	5	2.9	3.0		
8 1/73	8.0/3.4	3.2	3.1	6.3	8.0
20 1/73				8.2	8.9

(See Table 2.1 for Section Numbers)

TABLE 3.5. DEFLECTION (MILS) AT THE CRACKS AND MIDSPAN FOR 1974

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5 Midspan	0.75	0.65	0.87		
Crack	0.84	0.73	0.83		
Average	0.80	0.69	0.85		
8 Midspan	0.81/0.89	0.90	0.74	0.92	0.63
Crack	0.93/0.93	0.87	0.78	1.04	0.95
Average	0.88/0.91	0.88	0.76	0.98	0.79
20 Midspan				0.66	0.77
Crack				0.66	0.76
Average				0.66	0.77

(See Table 2.1 for Section Numbers)

TABLE 3.6. DEFLECTION (MILS) AT THE CRACKS AND MIDSPAN FOR 1984

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5 Midspan	0.72	0.72	0.97		
Crack	0.75	0.91	0.90		
Average	0.78	0.81	0.93		
8 Midspan	0.82/0.81	1.08	*	0.92	1.16
Crack	0.92/0.82	1.00		1.04	0.78
Average	0.80/0.81	1.04		0.98	0.97
20 Midspan				0.66	0.63
Crack				0.66	0.71
Average				0.66	0.67

*Not measured.

(See Table 2.1 for Section Numbers)

TABLE 3.7. NUMBER OF SPALLED LOCATIONS WITH MINOR SPALLING ON EXPERIMENTAL SECTIONS FOR 1984

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5	5	3	0		
8	4/9	2	1	0	0
20				0	0

(See Table 2.1 for Section Numbers; for example, Section 6 has 4 spalled locations and Section 7 and 9 spalled locations)

TABLE 3.8. NUMBERS OF LOCATIONS WITH SEVERE SPALLING ON EXPERIMENTAL SECTIONS, 1984-85

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5	5	6	1		
8	22/13	2	9	0	0
20				0	0

(See Table 2.1 for Section Numbers)

TABLE 3.9. AVERAGE CRACK SPACING (FEET) AS MEASURED FOR 1984

	Percent Steel				
	Conventional Aggregate			Lightweight Aggregate	
Preformed Cracks, ft	0.3	0.4	0.5	0.3	0.4
5	5.1	2.60	2.8		
8	5.8/2.7	2.3	2.6	6.3	8.0
20				8.0	8.5

(See Table 2.1 for Section Numbers)

sections containing the siliceous gravel (sections 1 through 7). The traffic over the sections containing the lightweight-aggregate was considerably less, so a visit was made to establish the traffic patterns and obtain estimates of movements at the intersection. Because the traffic movement observations were made on site, it was decided to also collect condition survey information and to obtain a measure of the crack width. When compared to the 1984 values, the small increase in crack spacing is probably due to operator error and the differences encountered when collecting data from the edge of the roadway as compared to observations while walking in the roadway.

Table 3.10 shows the average crack spacing values obtained in 1988. Table 3.11 reveals the minor spalling and Table 3.12 indicates the severe spalling on each section as obtained in 1988. Table 3.13 contains pavement distress information collected in terms of failures (punchouts) and patches. In addition, it should be noted that visual observations of Section 6 (0.3 percent steel and an 8-foot preformed spacing) indicate two locations where the longitudinal steel has sheared completely across the two (outside) lanes. This section is at the off ramp and receives the brunt of the cornering and braking action of a heavy volume of existing traffic. The transverse cracks where the steel has sheared are very wide (around 1/4-inch) and the downstream portion of the slab is lower in elevation (faulted) as compared to the upstream portion of the slab. Table 3.14 shows the crack width information. It should be noted that the crack width information is very questionable. The measurements were obtained while the roadway was under traffic. The measurement location was at the edge of the pavement at arbitrarily selected spots along the roadway. A comparison card was used to estimate the crack widths. The card is clear plastic and has several black lines of varying widths. The card is placed near the crack and the line on the card is selected which most closely represents the crack width. The associated line width is then recorded. Most of the cracks contain spalling from minute widths to very large widths. The crack widths were difficult to estimate because of this spalling. Even though this measurement technique was less than desirable (for this type of pavement) it was believed that large differences in the average values could provide information of the trends. The crack width measurements on the lightweight-aggregate sections were obtained in a manner dissimilar to that for the conventional aggregate sections. Because of this the values are not shown. However, the crack widths associated with the lightweight sections are relatively small and are significantly less than those of the conventional aggregate. In addition the transverse cracks in the lightweight sections are straight with little meandering and with few exceptions are evenly spaced, with little variation from the average 1988 crack spacing. Appendix A contains the crack spacing measurements.

SUMMARY OF DATA COLLECTED IN THE 24-YEAR PERIOD

Table 3.15 is a listing of the types of data, the dates, and the availability of the data collected within the 24-year period. General summaries which list the average crack spacing for each measurement period may be found in Tables 3.16 and 3.17 for the conventional aggregate and the lightweight-aggregate sections respectively. Table 3.18 contains a summary of the average deflection information collected during the 24-year period. Table 3.19 is a summary of the spall information collected in 1984 and 1988. Table 3.13 shows the pavement condition information and Table 3.14 shows the crack width information.

Table 3.20 lists the traffic information for three periods for which condition survey information was collected. The traffic volume information is given in terms of average daily traffic (ADT) and the traffic load information is presented in terms of 18-kip equivalent single axle loads (18-KSAL). This information was furnished by the Texas SDHPT Transportation Planning Division and is available in their permanent records.

PROBLEMS ENCOUNTERED

A preliminary study of crack information showed discrepancies between the measured lengths of some sections. Therefore, during the February 1985 collection period the section lengths were again established, based on brass markers which were installed during the original construction. Table 3.21 shows the measured lengths of each of the eleven experimental sections together with the lengths as originally planned.

TABLE 3.10. AVERAGE CRACK SPACING (FEET) FOR 1988

Preformed Cracks, ft	Percent Steel Conventional Aggregate 0.3	0.4	0.5	Lightweight Aggregate 0.3	0.4
5	5.11	2.52	2.97		
8	2.87/6.13	2.34	2.9	7.53	7.72
20				10.14	10.08

(See Table 2.1 for Section Numbers)

TABLE 3.11. NUMBER AND TOTAL LENGTH OF MINOR SPALLING ON THE EXPERIMENTAL SECTIONS FOR 1988

Preformed Cracks, ft	Percent Steel Conventional Aggregate 0.3	0.4	0.5	Lightweight Aggregate 0.3	0.4
5	6	4	2		
8	12/3	3	2	0	0
20				0	0

(See Table 2.1 for Section Numbers)

TABLE 3.12. NUMBER OF SEVERE SPALLS ON THE EXPERIMENTAL SECTIONS

Preformed Cracks, ft	Percent Steel Conventional Aggregate 0.3	0.4	0.5	Lightweight Aggregate 0.3	0.4
5	5	2	1		
8	12/0	0	2	0	0
20				0	0

(See Table 2.1 for Section Numbers)

TABLE 3.13. PAVEMENT CONDITION INFORMATION FOR 1988

Preformed Cracks, ft	Type of Distress	Percent Steel Conventional Aggregate 0.3	0.4	0.5	Lightweight Aggregate 0.3	0.4
5	Severe PO	0	3	0		
	Minor PO	9	71	38		
	AC Patches	5	1	0		
	PCC Patches	0	0	0		
8	Severe PO	21/5	0	0	0	0
	Minor PO	6/32	62	51	0	0
	AC Patches	14/13	1	8	0	0
	PCC Patches	0/0	0	16	0	0
20	Severe PO				0	0
	Minor PO				0	0
	AC Patches				0	0
	PCC Patches				0	0

TABLE 3.14. CRACK WIDTH INFORMATION FOR 1988

	Sections						
Readings	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	0.013	0.020	0.010	0.010	0.016	0.016	0.050
2	0.015	0.013	0.020	0.013	0.020	0.040	0.030
3	0.010	0.016	0.025	0.016	0.030	0.030	0.020
4	0.013	0.013	0.010	0.016	0.040	0.060	0.016
5	0.013	0.016	0.010	0.010	0.050	0.050	0.030
Average	0.013	0.016	0.015	0.013	0.031	0.039	0.029

TABLE 3.15. SUMMARY OF TYPES OF MEASUREMENTS

Type	Date	Remarks
1. Deflection		
Benkelman Beam		Raw Data Not Available; Sectionwise Summary from Graphs in Research Report 46-3
Basin Beam		
18,000 lb Load	8-20-64	
24,000 lb Load	11-25-64	Raw Data Available;
Dynaflect	3-14-74 11-7-84	
2. Number of Transverse Cracks	1963-1964 January 1973 May 1988	Periodically up to 378 Days after Construction
Space between Cracks	November 1984 February 1984	Redone to check November 1984 Measurements
3. Condition Survey	May 1988	
Minor Spalling	November 1984 and	
Severe Spalling	May 1988	
Minor P.O.	May 1988	
Severe P.O.		
ACP and PCC Patches	May 1988	
Crack Widths	May 1988	

TABLE 3.16. SUMMARY OF CRACK SPACING (FEET) FOR CONVENTIONAL AGGREGATE SECTIONS

Section Number	7	4	3	1	2	5	6	
Preformed Crack Spacing	8	8	5	5	8	5	8	
Steel Percentage	0.3	0.4	0.4	0.5	0.5	0.3	0.3	18 KSAL
Age of Concrete in Days								
4	8.69	8.00	5.00	5.00	8.00	14.28	8.33	5,000
16	8.33	8.00	5.00	5.00	8.00	7.69	8.33	19,000
18	8.33	8.00	5.00	5.00	8.00	6.25	8.33	22,000
27	8.33	8.00	5.00	5.00	8.00	6.25	8.33	33,000
53	8.33	8.00	5.00	5.00	8.00	6.25	8.33	65,000
201	8.00	5.40	4.16	5.00	5.40	5.00	8.00	245,000
378	6.06	5.00	3.77	4.17	5.00	5.00	8.00	460,000
Jan. '73	3.38	3.18	2.86	3.00	3.10	5.00	8.00	3,268,000
Feb. '85	2.72	2.33	2.60	2.75	2.60	5.10	5.77	6,098,000
May '88	2.87	2.34	2.52	2.97	2.90	5.11	6.13	6,811,000

TABLE 3.17. SUMMARY OF CRACK SPACING (FEET) FOR LIGHTWEIGHT-AGGREGATE SECTIONS

Section Number	10	11	9	8	
Preformed Crack Spacing	8'	20'	20'	8'	
Steel Percentage	0.3	0.3	0.4	0.4	18 KSAL
Age of Concrete in Days					
5	25.00	100.00	200.10	200.00	6,000
6	18.18	22.22	200.00	200.00	7,500
8	13.33	22.22	200.00	200.00	10,000
16	10.00	20.00	100.00	15.38	20,000
43	9.52	15.38	15.38	13.33	54,000
80	9.09	11.11	12.50	13.33	100,000
191	8.69	8.33	9.09	8.00	239,000
368	8.00	8.33	9.09	8.00	460,000
Jan. '73	6.31	8.16	8.87	7.96	3,096,000
Feb. '85	6.31	8.00	8.50	7.96	4,488,000
May '88	7.53	10.14	10.08	7.72	4,923,000

TABLE 3.18. SUMMARY OF THE DEFLECTION (MILS) BY COARSE AGGREGATE TYPE, PERCENT STEEL, AND PREFORMED CRACK SPACING FOR THE THREE TEST PERIODS

Preformed Cracks, ft		Percent Steel				
		Conventional Aggregate			Lightweight Aggregate	
		0.3	0.4	0.5	0.3	0.4
5	1984	0.78	0.81	0.93		
	1974	0.80	0.69	0.85		
	1964	2.22	1.56	1.56		
8	1984	0.80/0.81	1.04	n/a	0.908	0.97
	1974	0.88/0.91	0.88	0.90	0.77	0.79
	1964	2.11	1.56	1.22	0.72	1.06
20	1984				0.66	0.67
	1974				0.70	0.77
	1964				0.94	0.94

(See Table 2.1 for Section Numbers)

TABLE 3.19. SPALLING ON THE EXPERIMENTAL SECTIONS (NUMBER OF SPALLED LOCATIONS)

Preformed Cracks, ft			Percent Steel				
			Conventional Aggregate			Lightweight Aggregate	
			0.3	0.4	0.5	0.3	0.4
5	1984	Severe	5	3	0		
		Minimum	5	6	1		
	1988	Severe	6	4	2		
		Minimum	5	2	1		
8	1984	Severe	4	2	1	0	0
		Minimum	22/13	2	9	0	0
	1988	Severe	12/3	3	2	0	0
		Minimum	13/0	0	0	0	0
20	1984	Severe				0	0
		Minimum				0	0
	1988	Severe				0	0
		Minimum				0	0

(See Table 2.1 for Section Numbers)

TABLE 3.20. TWENTY-FOUR-YEAR TRAFFIC INFORMATION FOR IH-610 FRONTAGE ROADS

	Conventional Aggregate		Lightweight Aggregate	
Year	ADT	Cumulative 18-KSAL	ADT	Cumulative 18-KSAL
1964	2,500	460,000	2,500	460,000
1974	6,119	3,268,000	1,530	3,096,000
1984	11,100	6,098,000	3,030	4,488,000
1988	13,500	6,811,000	3,600	4,923,000

TABLE 3.21. PLANNED AND MEASURED TEST SECTION LENGTHS

Section	Measured Length, ft February 1985	Length as Planned, ft
1	201.3	200
2	243.7	200
3	199.9	200
4	190.9	200
5	187.2	200
6	202.0	200
7	195.8	200
8	199.3	200
9	204.0	200
10	201.5	200
11	200.3	200
Total		2,200

CHAPTER 4. PERFORMANCE ANALYSIS 1965 TO 1988

This chapter presents an analysis of the performance of the experimental sections during the 24-years since their construction. The analysis was done to determine the effect on pavement performance of the two design variables (percent steel and preformed crack spacing) and the coarse aggregate material used. As conventional coarse aggregate material was used exclusively in the west-bound frontage section, and lightweight-aggregate was used in the east-bound frontage section, it is not totally possible to separate the traffic effect from the effect of the type of aggregate. However, the Transportation Planning Division of the Texas SDHPT used historical traffic records to develop the traffic volume and traffic load information for the IH-610 frontage road sections. This information was developed for both frontage roads (see Table 3.20). The traffic and load information permitted an analysis which included the effects of traffic as well as age. The performance was analyzed in terms of transverse crack spacing and deflection. Also, a comparative study of the pavement condition of various sections is presented, based on the condition surveys of November 1984 and May 1988.

PERFORMANCE ANALYSIS IN TERMS OF DEFLECTION

In Research Report 46-3 (Ref 1) deflection data were analyzed and several conclusions were drawn regarding the effects of percent longitudinal steel, preformed crack spacing, and type of aggregate on pavement deflection. In the following, similar analyses are done using the deflection data collected in 1974 and 1984. Each of the conclusions of Research Report 46-3 is considered, and parallel analyses are made with 1974 and 1984 data.

(1) In Reference 1, it was noted that the deflection varied inversely with percent longitudinal steel. The data, as seen in Table 3.5, Figs 4.1, and 4.3, indicate that this was largely true in 1974. The deflections at cracks as well as deflections at midspan varied inversely with percent steel for all conventional-aggregate sections with one exception. (Section 1, with 0.5 percent steel, 5-foot preformed crack spacing, and conventional-aggregate concrete, was reported to have consistently differed from other section measurements. This difference was possibly because of a drainage ditch which existed in the area [Ref 1]). In 1984, the deflection trends are generally the reverse of the trends established with the two previous measurement periods, as seen in Table 3.6, Figs 4.2, and 4.4. A study of deflection versus steel percent for lightweight-aggregate sections, as seen in Figs 4.5 to 4.8, does not lead to any conclusion. In 5 out of 8 plots, deflection increases with steel percent while in the remaining 3 cases the converse is true. It is worth noting here that Research Report 46-3 also found the results inconclusive.

(2) In Research Report 46-3 it was concluded that the optimum longitudinal steel was 0.5 percent for conventional-aggregate pavement and 0.3 percent for lightweight-aggregate pavement. This conclusion was made because, in general, deflections at cracks as well as midspans of conventional-aggregate sections decreased with increase in percent steel while the effectiveness of the steel in reducing deflection became less with increasing percent steel. Similar analyses of lightweight-aggregate sections did not lead to any conclusion at that time. The 1974 data for conventional-aggregate sections reaffirmed the 1964 conclusion, as can be seen in Figs 4.1 and 4.2. However, in 1984, the trends are reversed and there seems to be an increase in deflection with increase in percent steel, the two exceptions being (1) the deflection at the crack position of lightweight-aggregate sections with 8-foot preformed crack spacing and (2) the midspan deflection of lightweight-aggregate sections with 20-foot preformed crack spacing. It is as if the heavily reinforced sections remained stiffer than lightly reinforced ones up to a point and then started losing stiffness at a faster rate.

(3) Research Report 46-3 noted that lightweight-aggregate (low E concrete) pavement sections deflected considerably less than conventional-aggregate, contrary to theoretical expectations. This observation was based on comparison of Sections 4 and 8, which differed only in the type of aggregate. The data for 1974 show this is true except

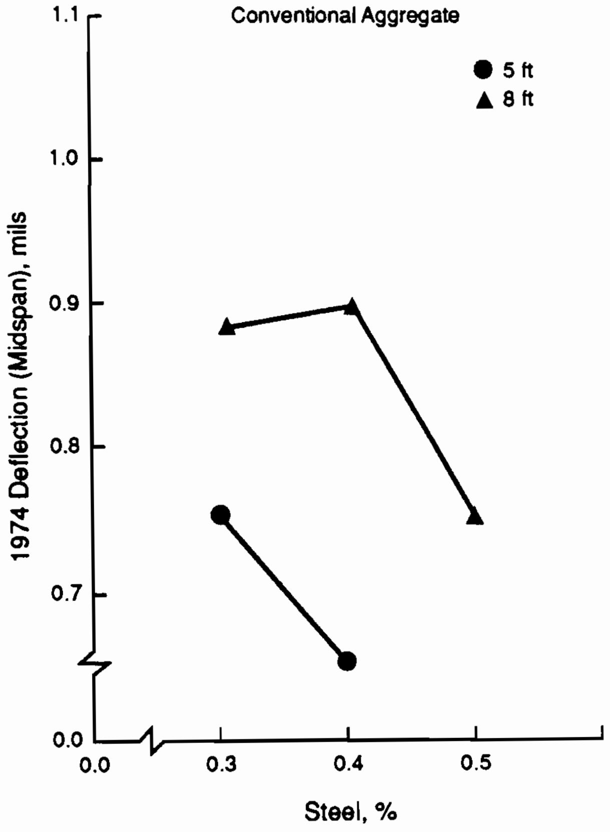


Fig 4.1. Deflection versus steel, midspan, for 1974.

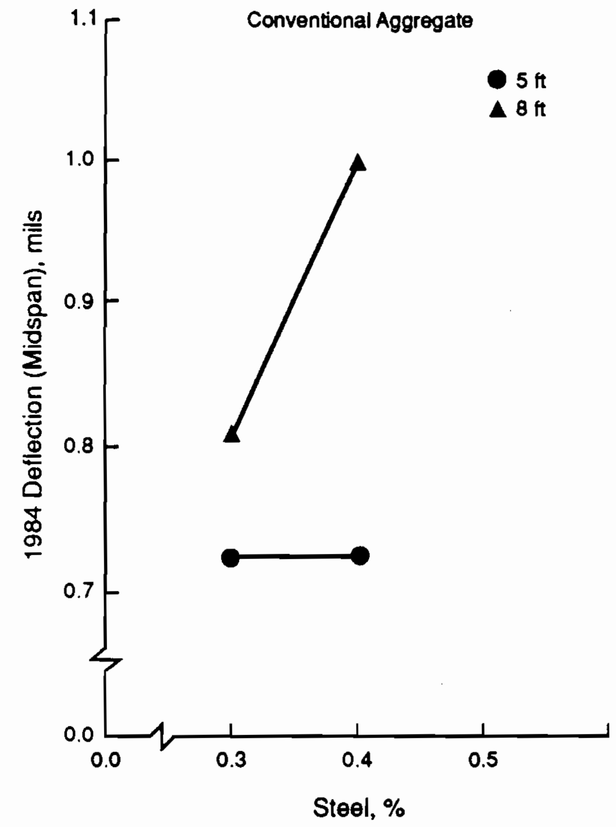


Fig 4.2. Deflection versus steel, midspan, for 1984.

for deflections at the cracks for the pavement with 0.4 percent steel, in which case the lightweight-aggregate pavement section (Section 8) deflected 9.2 percent more than the corresponding conventional-aggregate section (Section 4). The 1984 deflection data, however, indicate that, in all cases except for the crack position deflections of the 0.4 percent steel sections, the lightweight-aggregate section deflected more.

(4) Research Report 46-3 concluded that, for conventional concrete pavement, 5 feet was an optimum preformed crack spacing. This conclusion was based on the fact that, overall, 8-foot sections deflected 4 percent and 23 percent more than 5-foot sections for single wheel loads of 18,000 and 24,000 pounds, respectively. In 1974, deflections at cracks for 8-foot sections with conventional-aggregate were 7.5 percent greater than for 5-foot sections. At midspan the 8-foot sections deflected about 11 percent more than the 5-foot sections. The corresponding figures for 1984 are 12.5 percent and 12.1 percent for crack and midspan, respectively. Sections with the 8-foot preformed crack spacing always deflected more. It should be noted that the actual average crack spacing widths have been reduced to relatively short widths during the 1974 and 1984 test periods. Nevertheless, the deflection information tends to reaffirm the earlier conclusion that 5-foot preformed spacing is optimal for conventional-aggregate pavements. Similar analysis using the deflection information for lightweight-aggregate sections seems to indicate that, in general, 20-foot preformed crack spacing is better than the 8-foot preformed crack spacing. However, the 20-foot preformed crack spacing sections as well as the 8-foot preformed crack spacing sections seem to have stabilized at an 8-foot mean crack spacing. Thus, it appears that, for lightweight-aggregate sections, an 8-foot preformed crack spacing is optimal.

Summary of Deflection Analysis

(1) Heavily reinforced sections seem to be stiffer than lightly reinforced sections up to a certain age, after which the data are more random.

(2) Overall, lightweight-aggregate sections (sections with low modulus of elasticity concrete) continued to show less deflection up to 1974. Between 1974 and 1984, lightweight-aggregate sections indicate a greater decline in stiffness than conventional-aggregate sections. However, the visual inspection of the lightweight-aggregate sections does not reflect this loss of stiffness.

(3) It is possible that the conventional-aggregate sections reached the end of their design life at some period between 10 and 20 years of age. Some of the deflection measurements would be on or near distressed areas causing unusual values and disrupting previous trends. It should be noted that the only deflection information available was the deflection at the load, probably since

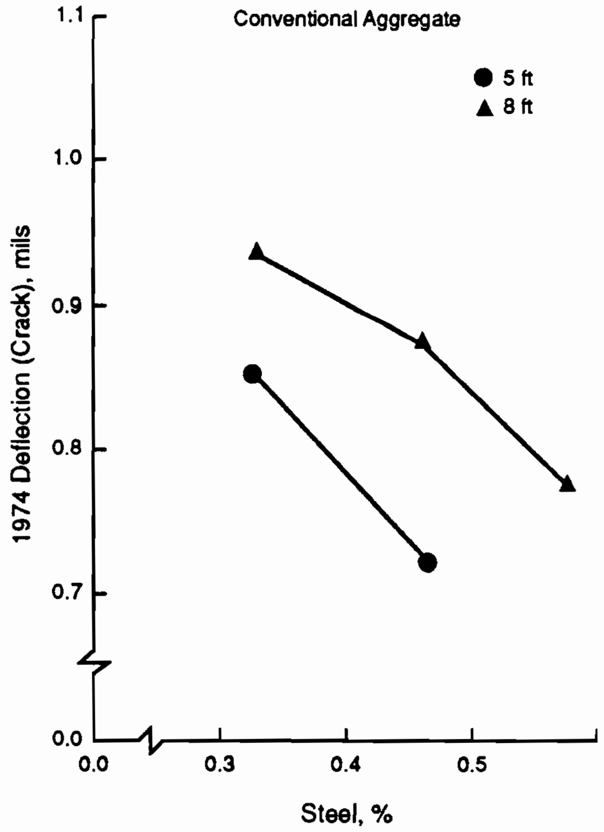


Fig 4.3. Deflection versus steel, at crack, for 1974.

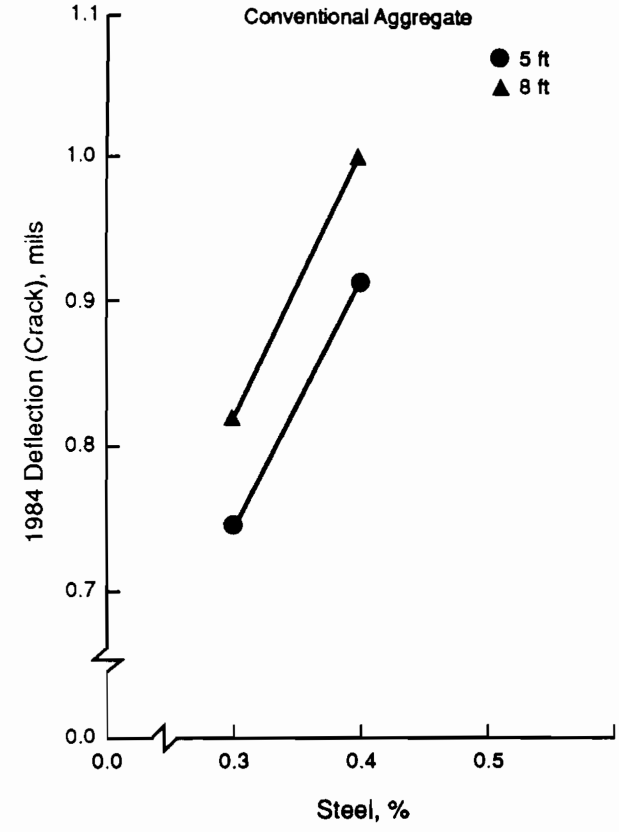


Fig 4.4. Deflection versus steel, at crack, for 1984.

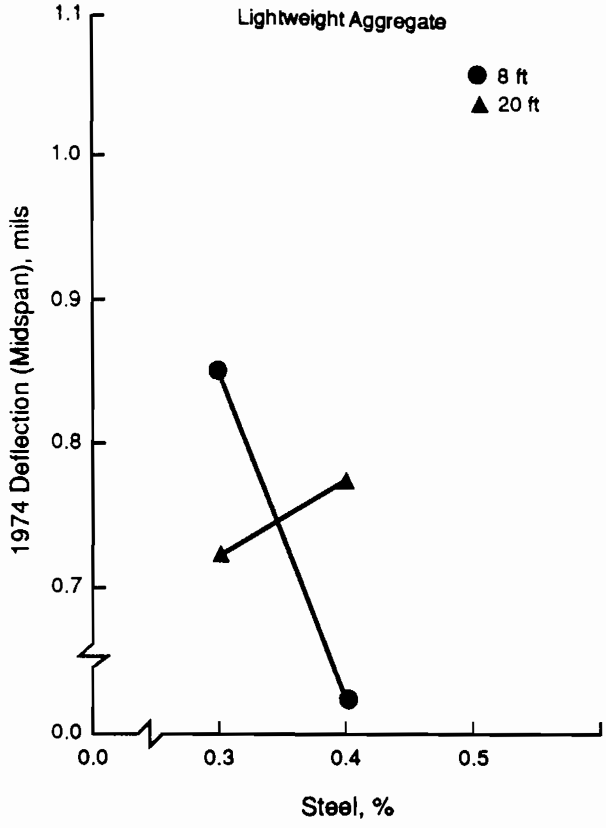


Fig 4.6. Deflection versus steel, midspan for 1984.

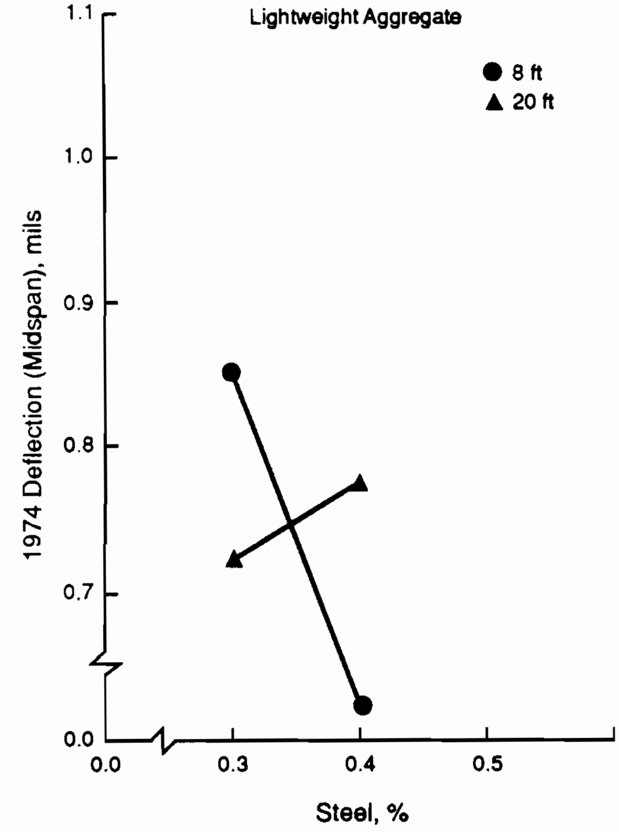


Fig 4.5. Deflection versus steel, midspan for 1974.

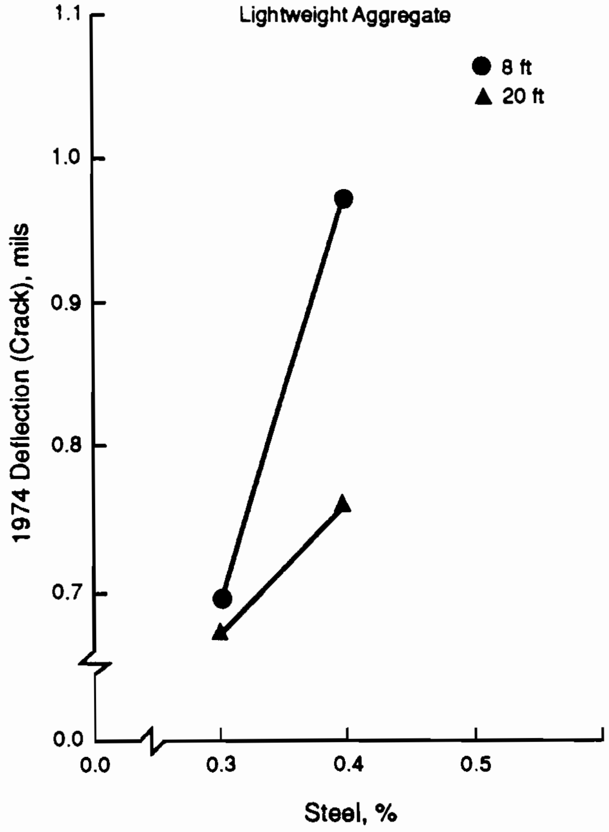


Fig 4.7. Deflection versus steel at crack for 1974.

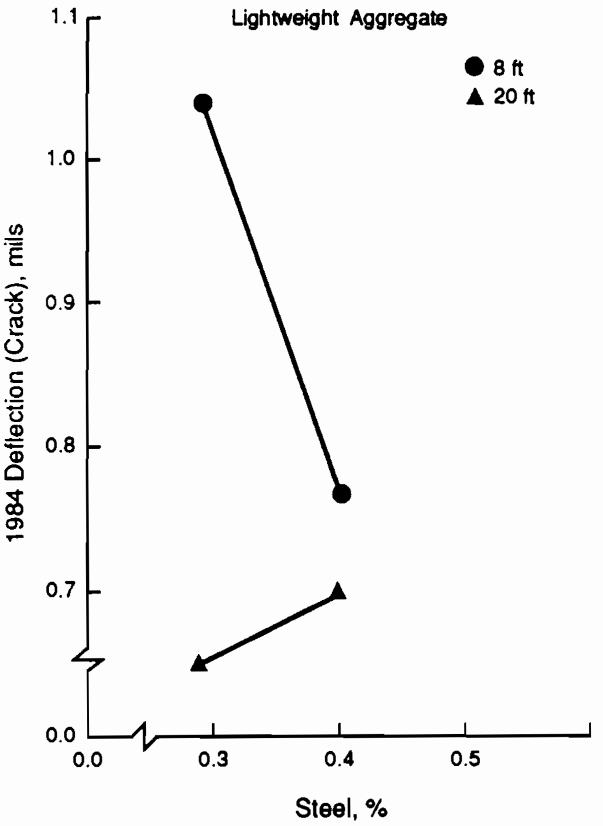


Fig 4.8. Deflection versus steelat crack for 1984.

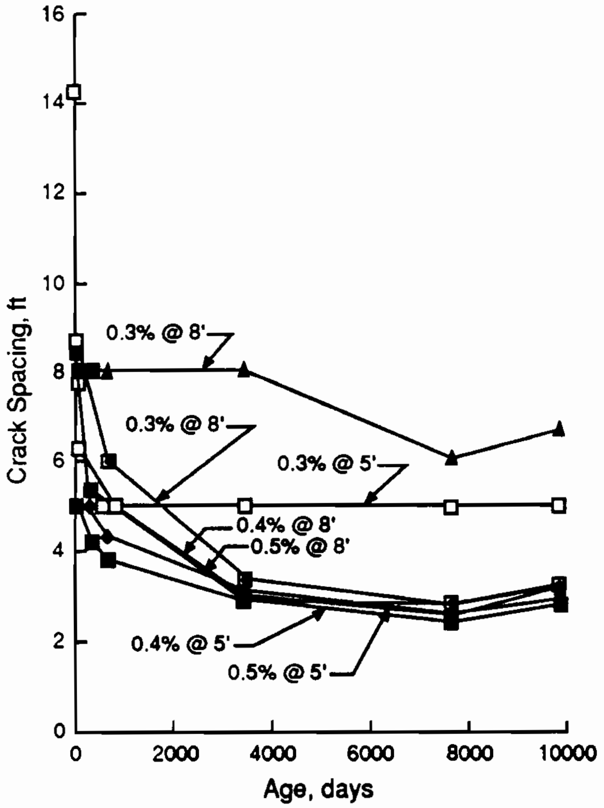


Fig 4.9. Average crack spacing of conventional-aggregate concrete by age.

the initial deflection values were obtained with a Benkelman Beam at the wheel load. A more detailed analysis would have been possible in 1974 and 1984 by using the Deflection Basin information available from the Dynaflect's five geophones. The data were not available at the time this report was prepared. Thus, it is suggested that the reader weigh the results of the visual performance and the early deflection values more heavily than the later ones.

PERFORMANCE ANALYSIS IN TERMS OF TRANSVERSE CRACKS

This section presents an analysis of the performance in terms of transverse cracks of various sections. The analysis was done by plotting mean crack spacing against both time and traffic loads. The percent steel, preformed crack spacing, and coarse aggregate type are shown in each plot.

Standard Aggregate Concrete Sections

Figure 4.9 shows the mean crack spacing of conventional-aggregate concrete sections by age. A study of this graph reveals the following:

(1) Section 5, 0.3 percent steel and 5-foot preformed spacing, and Section 6 which has 0.3 percent steel and 8-foot preformed crack spacing, have maintained a relatively large average crack spacing as compared to the remainder of the sections. However, as reported in Chapter 3 and in the performance information following, the longitudinal steel in these sections apparently sheared at some time in the past. It is possible that when the longitudinal steel parted, a thermal stress/traffic load relationship was established, much like the ends of a CRC pavement without terminal anchorage. That is, the ends are free to move over the subbase and transverse cracking is minimal for a relatively long length until sufficient subgrade drag develops to restrain the concrete slab movement. In this case the average crack spacing would be large and should not be compared with the remainder of the sections. Sections 5 and 6 are directly in line with traffic exiting the main lanes and as such receive high speed traffic which is applying tire/pavement friction from both cornering and braking.

Section 7 is a replicate of Section 6 and the history of the crack spacing for Section 7 seems to be the more representative. The plots in Fig 4.9 indicate that the longitudinal steel in Sections 5 and 6 may have parted at an early age, possibly around 200 to 400 days.

(2) The larger preformed spacings tend to provide larger average crack spacings for longer time periods. This seems reasonable since the preformed cracks tend to relieve the thermal strains on the concrete. Then, as the larger thermal/traffic stresses are applied, the concrete continues to form additional transverse cracks. The average crack spacing seems to level off at around 2 to 3 feet; however, it should be noted that several failures and repairs have and are being made at this spacing at

some time between 10 to 20 years of age.

(3) The effect of percent longitudinal steel on crack spacing is difficult to detect. However, the percent steel does not appear to have a large effect on crack spacing except that 0.3 percent is probably inadequate for the conditions found at the test sites. The dominating factor appears to be the bond area/concrete volume ratio, which was constant.

Lightweight-Aggregate Sections

Figure 4.10 shows the mean crack spacing by age for sections constructed with lightweight-aggregate concrete. The following observations are evident from these graphs:

(1) Again the larger preformed spacing tended to provide larger average crack spacings for longer time periods. Crack spacing is slightly more on 20-foot sections than on 8-foot sections at all levels of steel percent and at all ages; however, the mean crack spacing on 20-foot sections has been close to 8 feet since the beginning. Thus, we may conclude that 8 feet is a more natural spacing.

(2) Longitudinal steel of 0.4 percent seems marginally better than 0.3 percent from the point of view of transverse cracks.

(3) An interaction between steel percent and preformed crack spacing seems to exist.

Crack Spacing and Cumulative Traffic Loads

Figure 4.11 shows a plot of crack spacing and traffic loads where the cumulative 18-kip equivalent single axle loads (18-KSAL) have been developed for each measurement period. The plot includes all sections and the lightweight-aggregate sections have purposely been included with the siliceous river gravel sections. Note the lightweight sections have received only about two-thirds of the cumulative loads received by the conventional-aggregate sections. However, at comparable cumulative loads of around four to five million 18-KSAL the lightweight-aggregate sections have considerably larger average crack spacings. As may be noted, the conventional-aggregate sections have experienced several failures, much spalling, and several repairs at some time when the load equivalencies were between three and six million 18-KSAL. At present, after about five million 18-KSAL, the lightweight-aggregate sections are showing almost no distress.

Summary of Transverse Crack Analysis

(1) The analysis of the transverse cracks for the conventional or siliceous river gravel aggregate sections tends to indicate 0.3 percent steel is not sufficient since it appears the longitudinal steel on the 0.3 percent sections has been sheared. The sections with the 0.4 percent and the 0.5 percent steel have average crack spacings of 2 to 3 feet after 24 years of service. The average crack spacing for the lightweight-aggregate sections reveals little difference between the steel percentages, with both 0.3 percent and 0.4 percent steel sections having an average crack spacing around 8 feet.

(2) The analysis of the preformed crack technique indicates transverse cracks occur at the preformed locations. All the preformed locations developed transverse cracks after a period of about one year, or after about 500,000 18-KSALs. Transverse cracking continues to develop between the preformed locations and the average transverse crack spacing tends to level off at about 8 feet for the lightweight-aggregate and 2 to 3 feet for the conventional-aggregate sections.

(3) There are characteristics of transverse cracks other than the average crack spacing that should be considered. Others could be the variation of the crack spacings, the smallest or largest spacing, and how straight or random the crack is as it crosses the pavement. Preforming the cracks seems to have reduced if not eliminated the pronged or Y cracks in the sections observed. Also, it is interesting to observe the transverse cracks in the lightweight sections. Even the cracks occurring between the preformed cracks at the 20-foot spacing seem more uniformly spaced and the cracks are straight with little meandering.

(4) The larger preformed spacings tend to provide larger average crack spacings for a longer time. These larger spacings tended to last as much as ten years or around three million 18-KSALs.

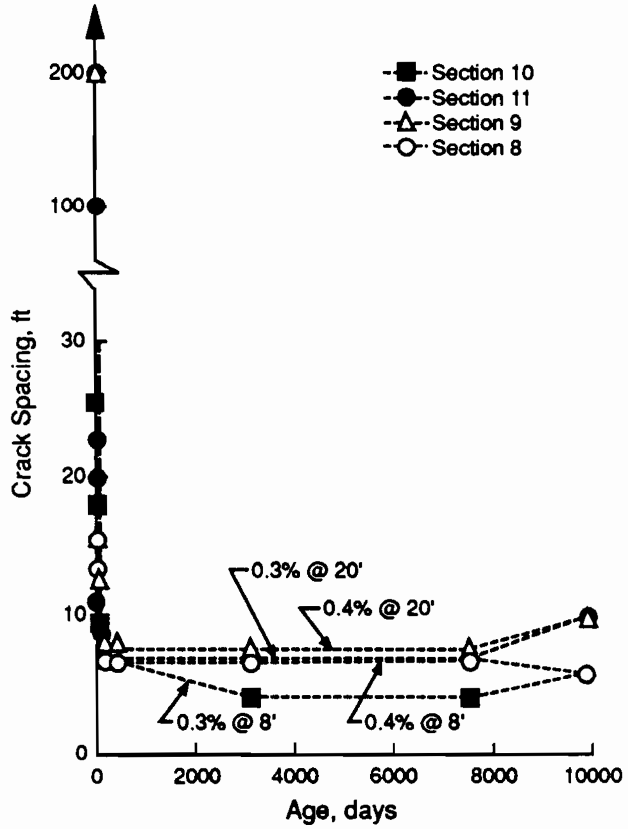


Fig 4.10. Average crack spacing of lightweight-aggregate concrete by age.

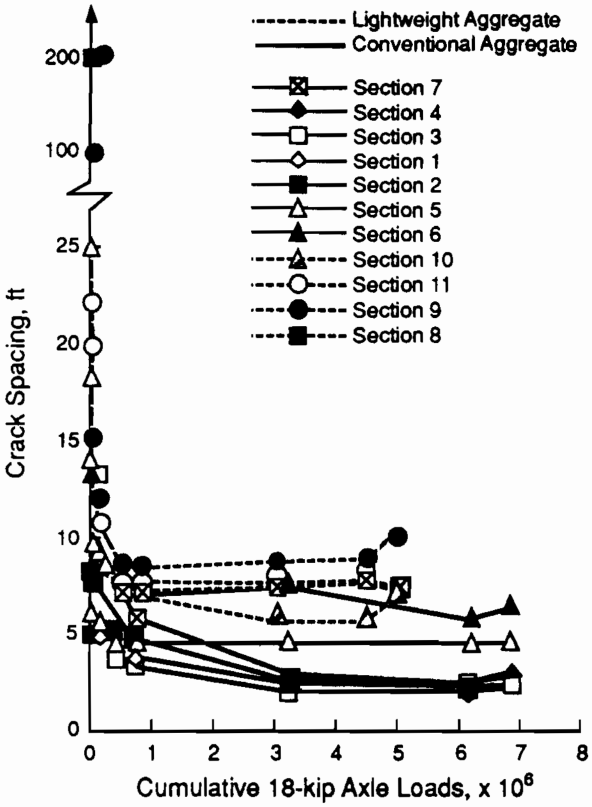


Fig 4.11. Average crack spacing by traffic loads.

PERFORMANCE ANALYSIS IN TERMS OF CONDITION SURVEYS

This section presents the condition survey information collected in 1984 and in 1988. The analysis was performed by developing bar charts showing the number and various types of failures which occurred in each section. The reader should refer to Fig 4.11 for cumulative traffic load information and note that the failures were first recorded in 1984, after about six million 18-KSAL for the conventional-aggregate sections.

Spalls

Figure 4.12 shows the number of spalls which were found in each test section. The spalls were normally found along the transverse cracks even though several were noted along longitudinal cracks. The spalls varied but the depth was generally around one to 3 inches. The spalls were normally about as wide as they were deep. The data are given for 1984, 1988, and as an average of the two measurement periods. There is some discrepancy between the values for the two periods, with the 1988 values being less than the 1984 values for several sections. It is believed that observer variance in counting the number of spalls was large. Also, the length between two spalls along the same crack could spall out, reducing the count from two to one in certain conditions. Effort will be made in the future to measure spall length as well as the number of spalls; however, the average of the two periods will be used for this study. The following may be concluded from this analysis:

(1) The conventional-aggregate or siliceous-river-gravel sections had more spalling as compared to the lightweight-aggregate sections where no spalling was noted.

(2) The conventional sections having 0.3 percent steel had more spalling as compared to the remaining sections. Of these, Section 6 had more spalls than the replicate Section 7. Again it should be noted that Sections 5 and 6 received traffic from an off ramp from the main lanes. There may be an interaction between percent steel and the preformed crack spacing; however, 0.5 percent steel sections may have had slightly less damage than the 0.4 percent steel.

(3) It is doubtful that the preformed crack spacing contributed greatly to the spalling since the conventional sections had cracked to much smaller crack spacings before a large amount of spalling was reported. Also, the spalls occurred at both the preformed cracks and the cracks between the preformed spaces.

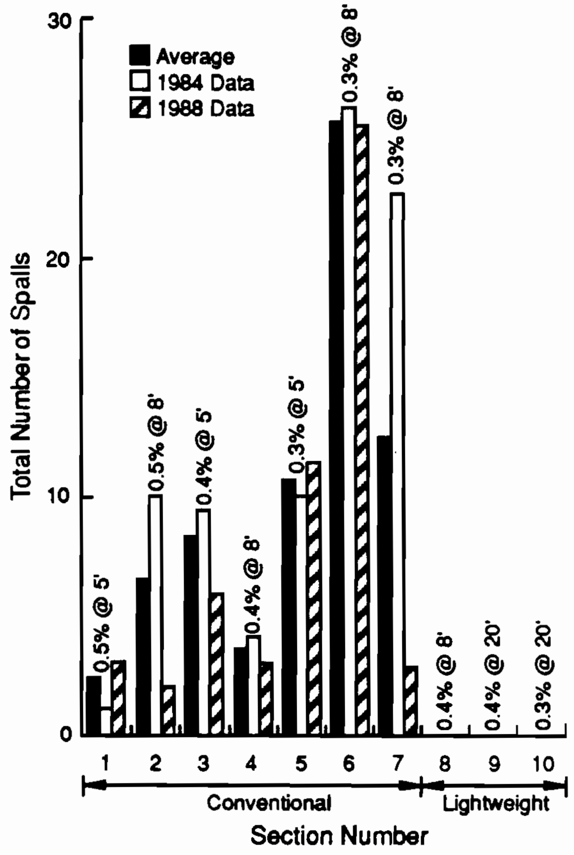


Fig 4.12. Number of spalls for each test section.

Severe Punchouts

Severe rather than minor punchouts were used in this analysis because of the inability to accurately classify minor punchouts. The punchout has been defined by others and used for many years to denote a type of failure. Normally a punchout is found when a longitudinal crack occurs between two transverse cracks. If the crack widths are small, there is little or no spalling, and there is no apparent movement of the block formed, the punchout is termed minor. When the cracks around the punchout are relatively large, there is spalling, or there is movement of the block formed, the punchout is said to be severe. When the subject paving was placed, a longitudinal joint was not formed or sawed. Because of this a random longitudinal crack has developed, which at times meanders several feet from the center or lane line. At times two longitudinal cracks have developed. The observer has difficulty in determining if a punchout has occurred or if a normal longitudinal crack has developed. Again, because of this fact, minor punchouts were not considered in this analysis.

Figure 4.13 shows the number of severe punchouts occurring in each section. The following information was developed from this figure:

(1) No severe punchouts were found in the lightweight sections.

(2) The conventional-aggregate sections having 0.3 percent steel and an 8-foot preformed crack spacing were found to have severe punchouts. Also Section 3, having 0.4 percent steel and a 5-foot preformed crack spacing, was found to have severe punchouts. Even though vague, there may be a trend for more punchouts with the smaller steel percentages.

Patches

Figure 4.14 shows the area of each section which has been patched. Because of the variation in section length and to provide a familiar dimension, the patched area is presented as square feet of patched area per 100 feet (or an engineering station) along the pavement, which is 24 feet wide. The patched areas are basically punchouts which have been repaired. Both asphaltic concrete and PC concrete patches are shown, along with the total area patched.

It should be noted that Section 2 is in the intersection with South Wayside Drive. As such it receives traffic from both South Wayside Drive and the IH610 frontage road, whereas the other sections receive only the frontage road traffic. Most of the patches shown in Section 2 are in the intersection area. The following was developed from the figure:

(1) The sections containing the lightweight-aggregate in the concrete have not required patches.

(2) Discounting Section 2 for the reasons described previously, the area patched increases as the percent steel decreases. Section 6 and the replicate Section 7 have required essentially the same area to be patched.

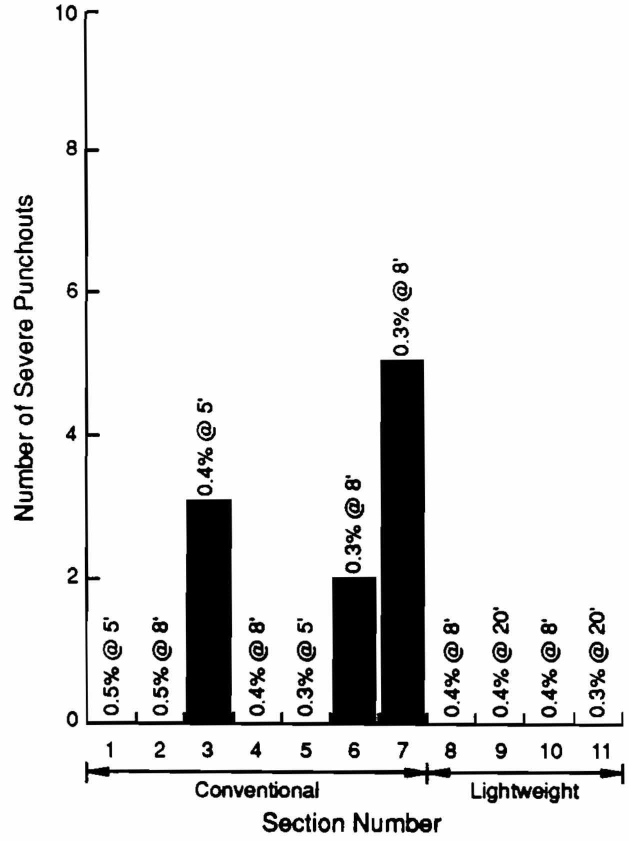


Fig 4.13. Number of severe punchouts for each test section.

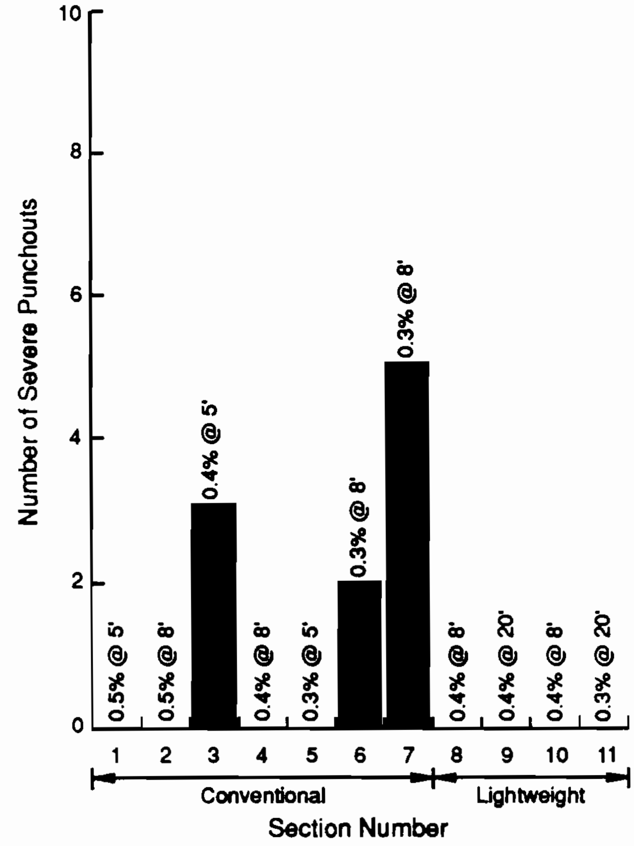


Fig 4.14. Area patched for each test section.

(3) The preformed crack spacing seems to have little effect on the area patched with the possible exception of the sections having 0.3 percent steel. Section 5 with a 5-foot preformed spacing has less patched area than Sections 6 and 7, which have an 8-foot preformed spacing.

Summary of Condition Surveys

(1) No spalling was found on the lightweight-aggregate sections. The sections containing the conventional-aggregate have experienced considerable spalling. The spalling was first recorded in 1984, after 20 years of service and about six million 18-KSALs. The amount of spalling appears to increase as the percent of steel decreases, with the largest amount of spalling occurring on the sections with 0.3 percent longitudinal steel.

(2) Severe punchouts were not noted on the lightweight-aggregate sections. Several severe punchouts were noted on the conventional-aggregate sections having 0.3 percent steel and an 8-foot crack spacing. Severe punchouts were also found on the conventional-aggregate sections having 0.4 percent steel and a 5-foot crack spacing.

(3) Patches were not found on the lightweight-aggregate sections. The sections having the conventional-aggregate have required several patches and the patches were first recorded in 1984, after 20 years of service and about six million equivalent 18-KSALs. The area patched increases as the percent of steel decreases.

(4) Even considering the smaller amount of loads, the sections containing the lightweight-aggregate appear to have performed in a superior manner as compared to the siliceous river gravel sections. Current work in other research projects suggest the moduli or the strengths of PC concrete used in CRCP deserve additional consideration. The thermal properties of the lower modulus concretes are also significantly different from those of the higher modulus material.

CHAPTER 5. COMPARISON OF OBSERVED RESULTS AND PREDICTIONS BY MECHANISTIC MODELS

This chapter presents a comparison of the observed crack spacing on each of the test sections with theoretical predictions from mechanistic models. Mechanistic analyses of pavement systems are gaining more popularity with the development of mechanistic theories and with improved methods to identify material properties. Computer program CRCP was developed at the Center for Highway Research of the University of Texas at Austin under NCHRP Project 1-15. The program provides detailed information on the structural responses of continuously reinforced concrete pavements for environmental conditions and wheel loads as a function of time. Based on that information, a rational design can be developed for CRC pavements. The objectives of this chapter are to gain insights into the working parts of the theoretical model, to identify variations between predicted and actual values, and to hypothesize the causes for these variations.

The three structural variables to be considered in CRC pavements design are crack spacing, crack width, and steel stress. They interact with each other, and the change of value in one variable immediately changes the values of other variables. Mechanistically, if a value of one variable is known, it is possible to determine the value of the other two variables. Among those three variables, crack width and steel stress are not easy to measure, whereas crack spacing can be easily and accurately measured. In the experimental sections, crack width and steel stress were measured only in the first year of construction, whereas crack spacing was measured in 1964, 1974, 1984, and 1988. Therefore, a comparison was made of crack spacings between actual values and theoretical predictions.

INPUT INFORMATION

The input parameters for the computer program CRCP consist of (1) material properties, (2) steel and thickness design, (3) environmental conditions, and (4) traffic loading conditions. Material properties include those of steel, concrete, roadbed soil, and subbase friction. Concrete properties, such as drying shrinkage, tensile strength, and thermal expansion of concrete, were measured at the test site during construction, and detailed information is available from the two related reports (Refs 1 and 2). These properties are shown in Table 5.1 for conventional-concrete and Table 5.2 for lightweight-concrete. Figures 5.1 and 5.2 present age-tensile strength relationships interpolated from actual values for conventional and lightweight-aggregate concrete. However, subgrade modulus of reaction and subbase characteristics were not measured during construction. Many researchers have found that concrete stress due to external wheel loading is not significantly influenced by subgrade modulus of reaction; therefore a subgrade modulus of reaction of 200 psi/in was assumed. Other information which was assumed is shown in Table 5.3. For subbase material, cement-stabilized oyster shell was used. In an extensive study conducted at the Center for Transportation Research, detailed information on subbase friction characteristics of various subbase materials was obtained (Ref 5). Friction information from the above project was used in this study, as shown in Fig 5.3.

Steel reinforcement and other design details are also available from Refs 1 and 2. Three steel reinforcement levels, 0.3, 0.4, and 0.5 percent, were used for conventional aggregate sections, and two levels, 0.3 and 0.4 percent, were used for lightweight-aggregate sections. However, bar size was selected in such a way that the ratio of bond surface area to concrete volume was almost constant (about 55 $\text{inch}^2/\text{inch}^3$) for all sections. A 6-inch pavement slab was placed over 6 inches of cement-stabilized oyster shell subbase. These data are summarized in Tables 5.1 for conventional and 5.2 for lightweight-aggregate concrete.

Information on curing conditions is available from Refs 1 and 2, and the information on environmental conditions after construction was obtained from the Weather Bureau at Houston Intercontinental Airport, which is about 25 miles from the experimental site. The concrete strengths at the early time periods are is shown in Table 5.4. The environmental information is presented in Table 5.5.

Traffic loading conditions were obtained from SDHPT files and are shown in Table 3.20.

DISCUSSION OF RESULTS

With these input values, computer program CRCP was run for each of the 11 test sections. Though the program provides predictions for crack width and for stresses in concrete and steel, in addition to mean crack spacing, the discussion here is concerned with crack spacing only. Mean crack spacings were measured at several time intervals but those measured in 1984 were compared with the computer predictions, because the cracks that occurred before 1984 were believed to be caused by environmental conditions and wheel load stress but not by fatigue. Cracking due to fatigue is not considered in the computer program. The actual mean crack spacing as observed during the observation periods and the values predicted by the program are presented in Table 5.6. The mean crack spacing observed in 1984 and the computer predicted values are plotted for each section, as shown in Fig 5.4 for conventional and Fig 5.5 for lightweight-aggregate sections.

For the conventional aggregate sections, there is general agreement between actual values and the predictions for Sections 1, 2, 3, and 4, whereas there are discrepancies for Sections 5, 6, and 7. For Sections 3 and 4, the differences

TABLE 5.1. ACTUAL INPUT VALUES FOR CONVENTIONAL-CONCRETE SECTIONS

Input Variables		Section Numbers						
		1	2	3	4	5	6	7
Steel Properties	Yield Strength of Steel[a]	–	–	–	–	–	–	–
	Steel Reinforcement, percent	0.5	0.05	0.4	0.4	0.3	0.3	0.3
	Bar Diameter, in.	5/8	5/8	1/2	1/2	3/8	3/8	3/8
	Modulus of Elasticity of Steel, psi x10^{6}	30.2	30.2	30.2	30.2	30.2	30.2	30.2
	Thermal Coefficient of Steel[a]	–	–	–	–	–	–	–
Concrete Properties	Slab Thickness, in.	6	6	6	6	6	6	6
	Thermal Coefficient of Concrete, x10^{6} in./in./°F	6.04	6.04	6.04	6.04	6.04	6.04	6.04
	Drying Shrinkage Strain, in./in. x10^{-5}	12.7	12.7	12.7	12.7	12.7	12.7	12.7
	Unit Weight of Concrete, pcf	150	150	150	150	150	150	150
	Age Tensile-Strength Relationship[b]	–	–	–	–	–	–	–
Environmental Inputs	Curing Temperature, °F	83	82	80	80	86	91	77
	Number of Days before Concrete Gains Full Strength	28	28	28	28	28	28	28
	Number of Days before Minimum Temperature	254	254	254	254	254	254	254
	Minimum Temperature after Concrete Gains Full Strength, °F	23	23	23	23	23	23	23
	Minimum Temperature within 28 Days[c]	–	–	–	–	–	–	–
External Load	Number of Days before Wheel Load Is Applied	4	4	4	4	4	4	4
	Wheel Load, lb	9,000	9,000	9,000	9,000	9,000	9,000	9,000
	Wheel Base Radius[a]	–	–	–	–	–	–	–
	Modulus of Subgrade Reaction	–	–	–	–	–	–	–
Slab Base-Friction[a]								

[a] Assumed Variable, See Table 5.3

[b] See Table 5.4

[c] See Table 5.5

TABLE 5.2. ACTUAL INPUT VALUES FOR LIGHTWEIGHT-CONCRETE SECTIONS

Input Variables		Section Numbers			
		8	9	10	11
Steel Properties	Yield Strength of Steel[a]	–	–	–	–
	Steel Reinforcement, percent	0.4	0.4	0.3	0.3
	Bar Diameter, in.	1/2	1/2	3/8	3/8
	Modulus of Elasticity of Steel, psi $\times 10^6$	30.2	30.2	30.2	30.2
	Thermal Coefficient of Steel[a]	–	–	–	–
Concrete Properties	Slab Thickness, in.	6	6	6	6
	Thermal Coefficient of Concrete, $\times 10^6$ in./in./°F	5.03	5.03	5.03	5.03
	Drying Shrinkage Strain, in./in., $\times 10^{-5}$	20.38	20.38	20.38	20.38
	Unit Weight of Concrete, pcf	100	100	100	100
	Age Tensile-Strength Relationship[b]	–	–	–	–
Environmental Inputs	Curing Temperature, °F	91	87	84	84
	Number of Days before Concrete Gains Full Strength	28	28	28	28
	Number of Days before Minimum Temperature	244	244	244	244
	Minimum Temperature after Concrete Gains Full Strength, °F	23	23	23	23
	Minimum Temperature within 28 Days[c]	–	–	–	–
External Load	Number of Days before Wheel Load Is Applied	4	4	4	4
	Wheel Load, lb	9,000	9,000	9,000	9,000
	Wheel Base Radius[a]	–	–	–	–
	Modulus of Subgrade Reaction	–	–	–	–
Slab Base-Friction[a]					

[a] Assumed Variable, See Table 5.3

[b] See Table 5.4

[c] See Table 5.5

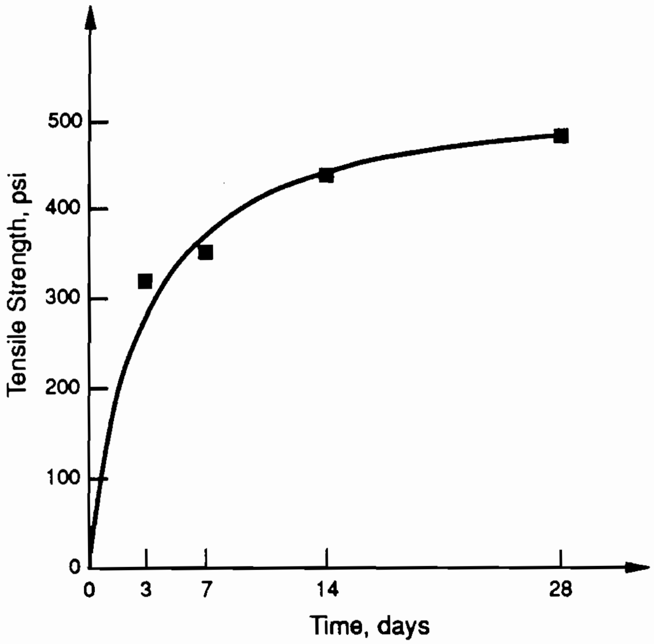


Fig 5.1. Interpolation of age/tensile strength for conventional concrete.

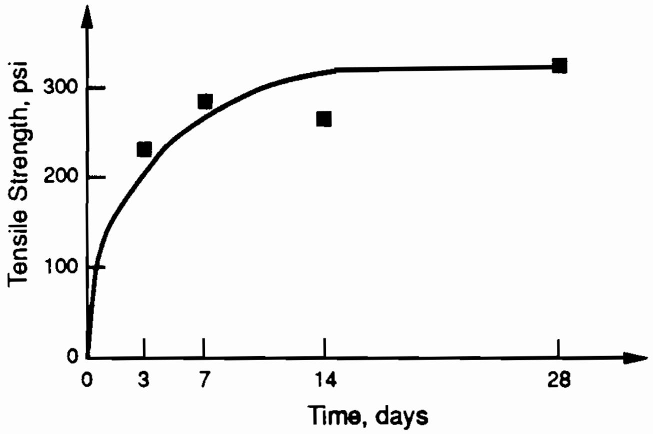


Fig 5.2. Interpolation of age/tensile strength for lightweight concrete.

TABLE 5.3. ASSUMED VALUES FOR INPUT VARIABLES

Variable	Assumed Value
Yield Stress of Steel, psi	60,000
Thermal Coefficient of Steel, in./in./°F	6.5×10^{-6}
Wheel Base Radius, in.	6
Subgrade Modulus of Reaction, pci	200
Slab Base-Friction Relationship	See Fig 5.3

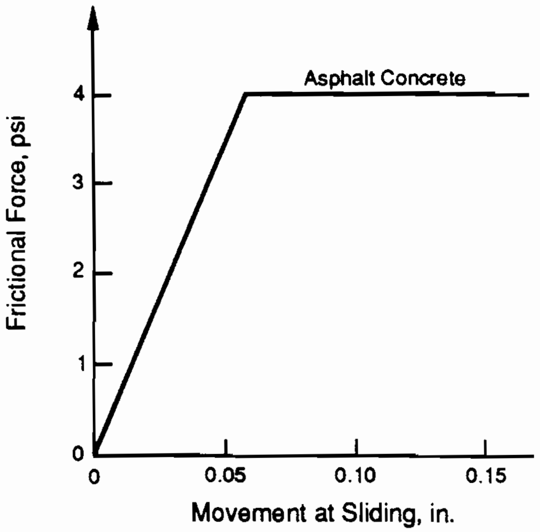


Fig 5.3. Slab-movement base-friction relationship.

TABLE 5.4. AGE TENSILE-STRENGTH RELATIONSHIP

Conventional Concrete		Lightweight Concrete	
Age, days	Tensile Strength, psi	Age, days	Tensile Strength, psi
0	0	0	0
1	147	1	165
3	272	3	223
5	332	5	248
7	370	7	266
14	442	14	302
21	480	21	310
28	488	28	312

between the actual values and predictions are less than one standard deviation in the actual crack spacing distributions. The one-sample t-test shows they are statistically the same at the 0.05 level of significance. For Section 6, it was noted that the longitudinal steel was sheared near the exit ramp from the main lanes. For Section 6, crack spacing distribution in the area near where the steel failed was different from that in other areas within Section 6. In the 1988 condition survey, the mean crack spacing within 50 feet on both sides from where the steel failed was 8.2 feet; however, in the other 100-feet, the mean crack spacing was 4.9 feet. The reason for the difference in the mean crack spacing within the same section is that, where the longitudinal steel failed, the concrete slab behaved like a free-end without terminal

TABLE 5.5. MINIMUM TEMPERATURE DURING FIRST 28 DAYS

Sections 1-7		Sections 8-11	
Days	Minimum Temperature, °F	Days	Minimum Temperature, °F
1	74	1	69
2	74	2	70
3	76	3	72
4	74	4	73
5	67	5	74
6	62	6	76
7	68	7	73
8	70	8	74
9	65	9	74
10	69	10	75
11	69	11	75
12	70	12	68
13	72	13	66
14	73	14	59
15	74	15	59
16	76	16	59
17	73	17	64
18	74	18	62
19	74	19	67
20	75	20	70
21	75	21	71
22	68	22	78
23	66	23	76
24	59	24	74
25	59	25	72
26	59	26	72
27	64	27	74
28	62	28	70

anchorage, and, thus, concrete stress due to restraint on concrete volume changes was not significant. However, where sufficient friction had accumulated, a normal crack pattern developed. The difference in mean crack spacing within the same section indicates that cracking in CRCP is due to a combined effect of wheel loads and environmental conditions. Near where the steel failed, cracks had developed at only the preformed locations, implying that when the concrete stress due to environmental conditions is small, wheel loads are not significant in cracking development. However, this finding does not seem compatible with the finding at the AASHO Road Test. In the AASHO Road Test, the cracking in jointed concrete pavements on the traffic loops was not attributed to environmental changes since no cracks were observed in the non-traffic loop: in jointed reinforced concrete pavements with relatively short joint spacings, most stress due to volume change restraint is caused by subbase friction and not by steel reinforcement, because steel and concrete have very similar values for thermal coefficient of expansion.

In continuously reinforced concrete pavements, due to the continuity in longitudinal reinforcement, the subbase friction along with the steel reinforcement causes concrete stresses to be developed by concrete volume restraint. Section 7 is a replicate of Section 6. The only difference in the two sections are the curing temperature (14 degrees higher in Section 6) and a slight difference in traffic applications; however, there is a significant difference in mean crack spacing. As described above, the longitudinal steel failed in Section 6, and the crack distribution in Section 7 is probably more representative. In determining slab thickness, the 1986 AASHTO Guide (Ref 6) uses the same equation for jointed and continuously reinforced concrete pavements, with the only difference being the load transfer coefficient. The procedure presented in the guide is based on data developed by the AASHO Road Test, supplemented and modified by theoretical analysis. However, continuously reinforced concrete pavement was not included in the road test. The Guide recommends a load transfer coefficient of 3.2 for jointed concrete pavements with some type of load transfer device at the joint, and 2.9 to 3.2 for continuously reinforced concrete pavement without a tied shoulder. The use of this procedure gives a little larger slab thickness for continuously reinforced concrete pavements. It is felt that a more comprehensive project is needed to study the effect of the relationship of concrete volume change stress and wheel load stress on the behavior and performance of continuously reinforced concrete pavements.

In lightweight-aggregate sections, generally, there is a large discrepancy between predictions and actual values except for Section 10. Low thermal expansion and low modulus values of lightweight-concrete reduce the curling stresses. Higher values in long-term creep of lightweight-concrete are believed to reduce the concrete volume change stress. The above factors probably contribute to the large mean crack spacings in lightweight-concrete sections and explain the large discrepancy between actual mean crack spacing and predicted values. The computer program does not consider the effect of creep. More detailed study seems necessary to take advantage of desirable properties of lightweight-aggregate in concrete pavements.

TABLE 5.6. COMPARISON OF PREDICTED AND OBSERVED CRACK SPACING

Test Section	Steel Reinforcement, percent	Curing Temperature, °F	Preformed Crack Spacing	Actual Observation Data						CRCP-3 Output
				53	201	378[a]	1974	1984[b]	1988	
1	0.504	83	5	5	5	4.17	3.00	2.75	2.97	3.12
2	0.504	82	8	8	5.40	5.00	3.10	2.60	2.90	3.09
3	0.404	80	5	5	4.16	3.77	2.86	2.60	2.52	3.97
4	0.404	80	8	8	5.40	5.00	3.18	2.33	2.34	3.97
5	0.293	86	5	6.25	5.00	5.00	5.00	5.05	5.11	5.07
6	0.293	91	8	8.33	8.00	8.00	8.00	5.77	6.13	4.88
7	0.293	77	8	8.33	8.00	6.06	3.38	2.72	2.87	5.35
8	0.404	91	8	13.33	8.00	8.00	8.00	8.00	7.72	3.55
9	0.404	87	20	12.50	9.09	9.09	8.87	8.50	10.08	4.02
10	0.293	84	8	9.09	8.69	8.00	6.32	6.31	7.53	6.23
11	0.023	84	20	11.11	8.33	8.33	8.16	8.00	10.14	6.23

[a] Days after the Curing of Concrete

[b] Year of Observation

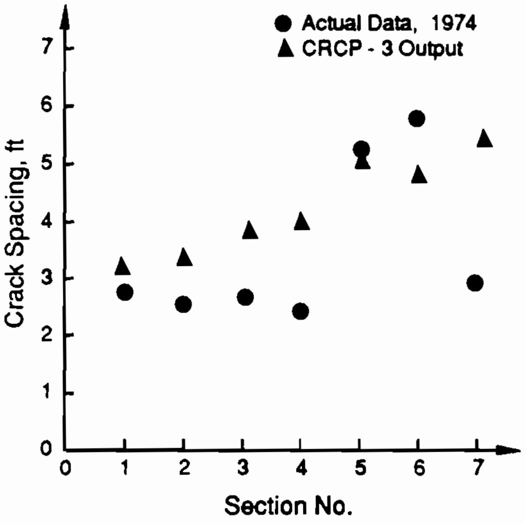


Fig 5.4. Comparison of final crack spacing for conventional-concrete sections.

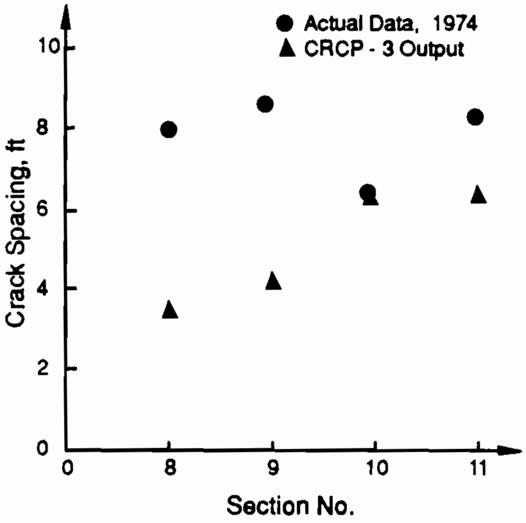


Fig 5.5. Comparison of final crack spacing for lightweight-concrete sections.

CHAPTER 6. DISCUSSION OF RESULTS

It is rare that observations are available for a 24-year period, as is the case for the subject pavement. Often the performance used for design or construction decisions is based on an observation period of about two to three years, or the length of a research project. Therefore, this study is important since it has offered the opportunity to study a continuously reinforced concrete pavement throughout an entire life cycle.

The original design for the CRCP experimental sections had anticipated some 1.5 million 18-KSAL in a 20 year design period. Table 3.20 shows that the original estimate of traffic loads was exceeded rapidly. In fact, over twice the expected loads had accumulated in the first ten years. At present, the pavement sections have exceeded the design loadings by a factor of about four.

Analyses based on deflection, crack spacing, and condition survey data for each experimental section were presented in Chapter 4. Chapter 5 presented a comparison of observed conditions with theoretical predictions by mechanistic models. This chapter is a discussion of the results of these analyses.

EFFECT OF AGGREGATE TYPE

The lightweight-aggregate sections have performed remarkably well throughout the observation period. After 24-years these sections have no failures, relatively large crack spacings, and a good appearance. The conventional sections contrast markedly with the lightweight-aggregate sections in that these sections have experienced failures in terms of spalling, punchouts, and repairs. The conventional-aggregate sections are probably in need of rehabilitation; however, with minor repairs these sections continue to serve well without danger to the public or damage to vehicles.

VALUE OF PREFORMED CRACK SPACING

The value of a preformed crack spacing becomes confused in the later years of a pavement's life cycle since the average crack spacing becomes shorter than the preformed crack spacing. After the average crack spacing becomes shorter, performance observations along with interactions and comparisons with other experimental variables should be weighted by other crack spacing information, rather than the preformed crack spacing. However, when the effects of the preformed crack spacing were observed, several unique performance features occurred which can potentially lengthen pavement life. For example, the transverse cracks were noted at the preformed locations first, after about one year of service, or about one half million 18-KSALs. Other transverse cracks formed later but these tend to be midway between the preformed locations. The N or Y cracking seems to be eliminated, or at least reduced, and there is less longitudinal meandering of the transverse crack. The longer preformed spacings tend to provide larger average crack spacings for longer time periods or periods up to around ten years (about three million 18-KSALs).

It may be postulated that the preforming technique provides a straighter crack, which will reduce early spalling and punchouts.

Preforming tends to reduce the number of very small crack spacings since intermediate cracking is delayed and tends to be centered between the preformed locations. Further, when the transverse crack occurs at the preformed locations, the stress in the steel as well as in the concrete is distributed more uniformly. This stress distribution would tend to increase the time before other transverse cracks occur and reduce the steel strain of the large transverse crack spacing locations. The preforming strips have a cost, and labor and equipment are involved, but the 24-year performance of the subject pavement sections suggests preforming transverse cracks may be cost effective.

The preforming technique needs further study. Preforming the transverse crack from the surface by sawing has been used on jointed reinforced concrete paving for many years and surface sawing of transverse joints in plain concrete is being used effectively by other states. However, using the preforming strips prior to placing the concrete would eliminate the doubt that a random crack could occur before the surface would be sawed.

It should be noted that this study indicates the preformed crack spacing length should vary depending on the concrete material properties. The material property emphasized in this study was the coarse aggregate type. The conventional-aggregate, or siliceous river gravel, sections tend to crack to smaller spacings as compared to the lightweight-aggregate sections. This reinforces the fact that the thermal and shrinkage properties of the portland cement concrete play a very important role in pavement performance. For example, the thermal coefficient of concrete composed of limestone is about two-thirds that of concrete with siliceous river gravel. It is possible that a procedure of insuring cracks by preforming will be beneficial regardless of the type of concrete used with the CRCP, but the preformed spacing will probably depend on the properties of the concrete used in the paving. An additional study about preformed cracks is needed, including a variety of pavement materials and depths.

EFFECT OF REINFORCING STEEL PERCENTAGE

As with the preformed crack spacing, there is an interaction of the steel percentage and the type of aggregate used in the concrete. Because, in two of the three sections having siliceous gravel and 0.3 percent steel, the steel has separated at a transverse crack, it is believed that 0.3 percent steel is insufficient for CRCP using this aggregate type. The majority of the crack spacing and condition survey data show performance of the river gravel sections increases as the steel percentage increases. Earlier studies encouraged the Texas SDHPT to use 0.6 percent steel in CRCP (Ref 2). This study tends to enforce that decision; however, this study also indicates the concrete properties should be considered when selecting the steel percentage. For example the lightweight-aggregate sections having 0.3 percent steel are still performing well. This again shows the thermal and shrinkage properties of concrete must be considered along with the strength. Currently, SDHPT Research Project 422, "Evaluation of Pavement Concrete Using Texas Coarse Aggregates," along with the subject project, is studying the effects of the concrete properties, and revised design standards are being considered.

Another interesting finding is that the mean crack spacing may be better explained by the ratio of bond area to concrete volume than by the percent of steel reinforcement. In this experiment, the percent steel reinforcement and bar size were selected in such a way that the ratio of bond area to concrete volume was nearly constant. Examination of the mean crack spacings after 1974 in the conventional-aggregate sections illustrated that, even though the percent steel reinforcing and the preformed crack spacings were varied, the mean crack spacings for each section were almost the same, at around 3 feet, except for Sections 6 and 7 (see Fig 4.9). A similar trend was found in the lightweight-aggregate sections, where the mean crack spacing was around 8 feet (see Fig 4.10).

Volume can be interpreted as the bond area per unit concrete force, in other words, the inverse of bond stress. Since the concrete stress in CRCP largely depends on the bond stress between steel and concrete, similar crack spacing will result from environmental loadings.

VERIFICATION OF MECHANISTIC MODELS

Study of the mean crack spacing predictions made with computer program CRCP-3 should be tempered by the design features of the experimental sections and the resultant performance. CRCP-3 was developed from studies of non-experimental sections of CRCP using conventional-aggregate which was generally composed of concrete using river gravel or crushed limestone. The subject study contained experimental sections of CRC paving in which the first cracks were forced at preformed locations. Also, the steel percentage was varied and was so small in some sections that the steel completely parted along a transverse crack. Given this information CRCP-3 was found to do a reasonable job in predicting the mean crack spacing for conventional-aggregate. However, additional work is needed for the lower modulus concrete.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This study was based on data collected in 1964, 1974, 1984, and 1988. Analyses of the performance of experimental CRCP sections has resulted in several conclusions of significance to highway pavement designers. This study has also opened up some questions for further investigation.

RECOMMENDATIONS OF SIGNIFICANCE TO DESIGNERS

(1) Over a span of 24 years, lightweight-aggregate concrete pavement sections have maintained an excellent performance record. It is recommended that lightweight-aggregate be considered as a concrete paving material on a competitive basis.

(2) Preformed crack spacing appears to be beneficial in providing a longer crack spacing for a longer time period. Also it is postulated that preforming provides several other benefits that prolong the pavement life cycle, such as the uniformity of the crack across the pavement, the reduction in the pronged or "Y" cracks, and the improvement in crack spacing variation. It is recommended that preforming be considered in pavement design, using the values established by the CRCP-3 computer program, which considers the load and environment.

(3) There is a strong interaction between the concrete materials properties and the percent steel. Thus, the percent steel should be determined for the aggregate type to be used in construction.

(4) The bond area/concrete volume ratio is an important factor in design, since, for a given coarse aggregate type, the crack spacings were generally equal regardless of percent steel. Since in this study, the bond area/concrete volume ratio was fixed at a constant level for the various steel percentages, these facts demonstrate the significance of the variable.

(5) The crack spacings were established early (within the first year) and then started to decrease as load-fatigue cracking occurred. Thus, a design analysis package must consider both the environmental and the wheel load stresses simultaneously.

(6) CRCP is an excellent capital investment. If the initial estimate of 1.5 million 18-KSAL and a pavement thickness of 6 inches is compared with the present 6 million 18-KSAL after 24 years of service, the pavement has provided exceptional service.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study was helpful in developing information of interest to CRC pavement designers. However, there are still some questions that are unanswered and point to areas for further research. The following are recommended for future study:

(1) This study considered CRCP made with two aggregate types. The performance of other conventional or low modulus concrete pavements were not considered. In the past CRC pavements have been constructed using a variety of concrete materials. This study suggests additional performance studies should be undertaken by observing those pavements periodically.

(2) This study considered CRCP sections with one depth, 6 inches, which is minimal compared with the majority of pavements which have been constructed or are being constructed. Information similar to that developed in this study is needed for pavements with a variety of depths to verify the results of this study.

(3) This work has revealed the need for additional study of concrete materials properties in relation to pavement performance. The interaction of thermal, shrinkage, and strength properties during the early life of the pavement provide input to the pavement that influence later performance. Of equal importance are the traditional thermal and strength properties that resist seasonal environmental changes and traffic loads. The study would be directed at the coarse aggregate and the mix design. The benefits could be the reduction in steel quantities as well as improved performance.

(4) This study considered longitudinal steel needs as being the cross sectional area of the steel as a percent of the cross-sectional area of the concrete. Even though the percent steel is needed in design, this study indicates continued work is needed to develop the correct ratio of steel bond area to concrete volume.

(5) This study indicates CRCP-3 does a reasonable job in predicting the mean crack spacing for siliceous gravel aggregate. However, the CRCP program needs additional work to develop the effects of long-term creep, particularly in low modulus concrete paving.

(6) Observations of the CRCP-3 data indicate a comprehensive project is needed to study the effect of the relationship of concrete volume change stress and wheel load stress on the behavior and performance of continuously reinforced concrete pavements.

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APPENDIX. 1988 CRACK SPACING MEASUREMENTS

EXPLANATION OF HEADINGS USED

Section 1 (SRG, 0.5% reinforcement, # 5 bar, and 5 feet preformed crack spacing)

Section 2 (SRG, 0.5% reinforcement, # 5 bar, and 8 feet preformed crack spacing)

Section 3 (SRG, 0.4% reinforcement, # 4 bar, and 5 feet preformed crack spacing)

Section 4 (SRG, 0.4% reinforcement, # 4 bar, and 8 feet preformed crack spacing)

Section 5 (SRG, 0.3% reinforcement, # 3 bar, and 5 feet preformed crack spacing)

Section 6 (SRG, 0.3% reinforcement, # 3 bar, and 8 feet preformed crack spacing)

Section 7 (SRG, 0.3% reinforcement, # 3 bar, and 8 feet preformed crack spacing)

Section 8 (LW, 0.4% reinforcement, # 4 bar, and 8 feet preformed crack spacing)

Section 9 (LW, 0.4% reinforcement, # 4 bar, and 20 feet preformed crack spacing)

Section 10 (LW, 0.3% reinforcement, # 3 bar, and 8 feet preformed crack spacing)

Section 11 (LW, 0.3% reinforcement, # 3 bar, and 20 feet preformed crack spacing)

Section 1		Section 2		Section 3	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
0.40		4.40		0.30	
3.70	3.30	6.40	2.00	4.30	4.00
5.40	1.70	9.90	3.50	5.70	1.40
10.50	5.10	11.20	1.30	9.20	3.50
15.60	5.10	13.60	2.40	14.30	5.10
18.30	2.70	15.10	1.50	15.40	1.10
20.70	2.40	18.50	3.40	17.90	2.50
23.20	2.50	20.00	1.50	19.30	1.40
24.20	1.00	23.50	3.50	22.90	3.60
26.00	1.80	25.10	1.60	24.50	1.60
27.90	1.90	30.30	5.20	28.70	4.20
29.60	1.70	33.50	3.20	29.70	1.00
30.20	0.60	35.40	1.90	30.50	0.80
31.00	0.80	38.40	3.00	32.90	2.40
31.80	0.80	41.10	2.70	34.60	1.70
33.10	1.30	43.50	2.40	37.90	3.30
36.10	3.00	46.90	3.40	39.80	1.90
41.30	5.20	49.40	2.50	42.80	3.00
46.40	5.10	51.50	2.10	44.80	2.00
50.20	3.80	54.70	3.20	49.90	5.10
51.40	1.20	60.10	5.40	55.00	5.10
56.60	5.20	62.50	2.40	60.10	5.10
58.00	1.40	65.00	2.50	62.10	2.00
61.70	3.70	67.50	2.50	65.10	3.00
64.20	2.50	70.20	2.70	67.10	2.00
66.60	2.40	72.80	2.60	68.90	1.80
71.90	5.30	76.40	3.60	70.10	1.20
77.10	5.20	78.30	1.90	72.00	1.90
82.40	5.30	80.70	2.40	74.30	2.30
87.80	5.40	84.40	3.70	75.30	1.00
92.90	5.10	86.00	1.60	76.80	1.50
94.00	1.10	88.50	2.50	77.60	0.80
98.10	4.10	92.60	4.10	80.40	2.80

Section 1		Section 2		Section 3	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
99.80	1.70	94.70	2.10	85.30	4.90
101.60	1.80	96.20	1.50	89.10	3.80
103.30	1.70	98.20	2.00	90.40	1.30
105.00	1.70	100.90	2.70	95.40	5.00
107.60	2.60	103.10	2.20	100.50	5.10
108.30	0.70	104.70	1.60	101.60	1.10
113.70	5.40	107.00	2.30	103.90	2.30
115.00	1.30	109.10	2.10	105.60	1.70
118.90	3.90	114.00	4.90	106.60	1.00
120.20	1.30	116.40	2.40	107.50	0.90
124.10	3.90	117.30	0.90	108.80	1.30
127.70	3.60	121.80	4.50	110.60	1.80
129.30	1.60	125.60	3.80	112.20	1.60
132.50	3.20	129.60	4.00	115.50	3.30
134.20	1.70	133.30	3.70	120.90	5.40
139.20	5.00	146.20	12.90	123.50	2.60
141.80	2.60	149.30	3.10	126.00	2.50
144.30	2.50	154.50	5.20	128.70	2.70
147.20	2.90	157.10	2.60	131.00	2.30
149.40	2.20	159.30	2.20	133.70	2.70
152.20	2.80	161.10	1.80	136.00	2.30
154.40	2.20	162.20	1.10	138.30	2.30
159.60	5.20	162.50	0.30	141.10	2.80
164.60	5.00	169.10	6.60	143.20	2.10
169.80	5.20	170.00	0.90	144.80	1.60
		173.90	3.90	146.20	1.40
	MEAN=2.97	182.20	8.30	147.80	1.60
	SD=2.43	186.70	4.50	151.40	3.60
	CV= 82%	189.90	3.20	154.00	2.60

Section 1		Section 2		Section 3	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
		194.40	4.50	156.50	2.50
		198.10	3.70	161.40	4.90
		199.60	1.50	163.20	1.80
		200.90	1.30	166.50	3.30
		202.50	1.60	169.30	2.80
		203.70	1.20	171.60	2.30
		206.50	2.80	176.60	5.00
		210.30	3.80	178.00	1.40
		214.70	4.40	180.10	2.10
		219.60	4.90	181.80	1.70
		222.80	3.20	182.60	0.80
		229.90	7.10	185.30	2.70
		230.90	1.00	186.80	1.50
		232.60	1.70	190.00	3.20
		234.20	1.60	192.00	2.00
		235.50	1.30	195.10	3.10
		238.60	3.10	197.00	1.90
		240.90	2.30	200.00	3.00
		242.00	1.10	202.10	2.10
		243.30	1.30	205.00	2.90
		244.40	1.10	207.20	2.20
		247.10	2.70	209.90	2.70
		248.90	1.80	211.90	2.00
		250.80	1.90		
		254.10	3.30		MEAN=2.52
					SD=1.47
			MEAN=2.90		CV=58%
			SD=3.22		
			CV=111%		

Section 4		Section 5		Section 6	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
1.30		5.90		7.60	
4.10	2.80	10.90	5.00	15.60	8.00
5.60	1.50	16.20	5.30	17.00	1.40
7.10	1.50	21.20	5.00	22.40	5.40
8.00	0.90	26.40	5.20	24.10	1.70
9.50	1.50	31.60	5.20	30.30	6.20
10.70	1.20	36.70	5.10	31.90	1.60
122.20	111.50	41.70	5.00	33.30	1.40
13.60	-108.60	47.00	5.30	40.00	6.70
17.60	4.00	52.80	5.80	48.30	8.30
21.50	3.90	57.10	4.30	56.30	8.00
28.40	6.90	62.20	5.10	59.40	3.10
30.50	2.10	67.20	5.00	64.30	4.90
35.60	5.10	72.20	5.00	69.80	5.50
36.60	1.00	77.40	5.20	72.40	2.60
38.60	2.00	82.40	5.00	79.70	7.30
41.30	2.70	87.50	5.10	81.10	1.40
43.80	2.50	92.70	5.20	88.90	7.80
44.60	0.80	97.70	5.00	97.50	8.60
46.10	1.50	102.90	5.20	98.60	1.10
48.10	2.00	108.10	5.20	105.50	6.90
49.30	1.20	113.20	5.10	115.70	10.20
51.10	1.80	118.30	5.10	122.00	6.30
52.70	1.60	123.50	5.20	130.00	8.00
54.70	2.00	128.40	4.90	138.20	8.20
57.40	2.70	133.40	5.00	146.20	8.00
59.30	1.90	138.60	5.20	154.10	7.90
60.10	0.80	143.70	5.10	162.50	8.40
61.00	0.90	148.60	4.90	170.70	8.20
62.70	1.70	153.80	5.20	178.90	8.20
65.20	2.50	159.10	5.30	187.30	8.40
69.10	3.90	164.00	4.90	195.40	8.10
73.20	4.10	169.40	5.40	203.70	8.30

Section 4		Section 5		Section 6	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
75.80	2.60	174.40	5.00		
77.10	1.30	179.50	5.10		MEAN=6.13
78.40	1.30	184.60	5.10		SD=7.44
81.20	2.80	189.70	5.10		CV=121%
84.00	2.80				
85.20	1.20		MEAN=5.11		
87.00	1.80		SD=0.05		
89.10	2.10		CV=1%		
93.20	4.10				
94.80	1.60				
96.40	1.60				
98.50	2.10				
99.60	1.10				
101.40	1.80				
102.50	1.10				
103.50	1.00				
104.60	1.10				
105.50	0.90				
106.50	1.00				
108.70	2.20				
109.50	0.80				
110.90	1.40				
112.60	1.70				
115.60	3.00				
117.70	2.10				
123.60	5.90				
125.80	2.20				
132.80	7.00				
133.90	1.10				

Section 4		Section 5		Section 6	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
136.00	2.10				
141.80	5.80				
143.20	1.40				
147.90	4.70				
149.90	2.00				
158.10	8.20				
160.50	2.40				
166.30	5.80				
168.40	2.10				
169.70	1.30				
174.50	4.80				
176.70	2.20				
179.70	3.00				
182.00	2.30				
183.10	1.10				
184.70	1.60				
186.30	1.60				
188.70	2.40				
189.50	0.80				
191.50	2.00				
193.00	1.50				
195.40	2.40				

MEAN=2.34

SD=2.37

CV= 101%

Section 7		Section 8		Section 9	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
18.00		0.50		0.40	
21.20	3.20	8.30	7.80	10.90	10.50
26.10	4.90	16.60	8.30	20.90	10.00
29.00	2.90	24.90	8.30	27.40	6.50
34.20	5.20	33.00	8.10	41.20	13.80
37.00	2.80	41.20	8.20	52.50	11.30
39.50	2.50	49.00	7.80	61.20	8.70
42.40	2.90	57.20	8.20	68.70	7.50
48.20	5.80	65.30	8.10	73.00	4.30
50.50	2.30	73.00	7.70	81.20	8.20
52.90	2.40	81.50	8.50	101.40	20.20
55.50	2.60	89.30	7.80	121.40	20.00
57.40	1.90	97.30	8.00	131.50	10.10
58.60	1.20	105.60	8.30	141.60	10.10
63.20	4.60	107.60	2.00	144.20	2.60
66.70	3.50	113.70	6.10	149.00	4.80
74.80	8.10	121.60	7.90	161.70	12.70
82.90	8.10	129.80	8.20	173.50	11.80
91.00	8.10	137.80	8.00	182.00	8.50
96.80	5.80	145.80	8.00	190.90	8.90
97.70	0.90	153.80	8.00	202.00	11.10
99.10	1.40	161.80	8.00		
100.70	1.60	169.40	7.60		MEAN=10.08
101.70	1.00	177.10	7.70		SD=18.66
103.00	1.30	185.40	8.30		CV=185%
104.80	1.80	193.40	8.00		
107.30	2.50	201.10	7.70		
108.60	1.30				
113.80	5.20		MEAN=7.72		
115.40	1.60		SD=1.49		
116.40	1.00		CV=19%		
123.70	7.30				
124.80	1.10				

Section 7		Section 8		Section 9	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
130.00	5.20				
131.90	1.90				
140.00	8.10				
141.50	1.50				
143.00	1.50				
145.70	2.70				
148.20	2.50				
149.30	1.10				
153.80	4.50				
155.30	1.50				
156.40	1.10				
157.40	1.00				
159.00	1.60				
160.80	1.80				
161.60	0.80				
162.80	1.20				
164.40	1.60				
165.30	0.90				
172.70	7.40				
175.30	2.60				
177.50	2.20				
180.70	3.20				
185.70	5.00				
188.30	2.60				
189.10	0.80				
190.10	1.00				
191.00	0.90				
193.00	2.00				
196.00	3.00				

Section 7		Section 8		Section 9	
Distance	Crack Spacing	Distance	Crack Spacing	Distance	Crack Spacing
197.40	1.40				
198.80	1.40				
	MEAN=2.87				
	SD=4.23				
	CV=147%				

Section 10		Section 11	
Distance	Crack Spacing	Distance	Crack Spacing
4.00		2.80	
11.90	7.90	16.10	13.30
17.90	6.00	23.30	7.20
20.00	2.10	30.80	7.50
28.20	8.20	44.40	13.60
36.40	8.20	53.20	8.80
44.50	8.10	64.70	11.50
52.40	7.90	74.70	10.00
60.00	7.60	85.00	10.30
61.40	1.40	95.60	10.60
70.00	8.60	105.40	9.80
78.20	8.20	114.50	9.10
86.60	8.40	125.60	11.10
94.70	8.10	132.30	6.70
102.70	8.00	145.90	13.60
110.70	8.00	155.40	9.50
118.70	8.00	166.00	10.60
127.00	8.30	178.40	12.40
135.00	8.00	186.30	7.90
143.10	8.10	194.90	8.60
151.20	8.10	205.70	10.80
159.40	8.20		
167.60	8.20		MEAN=10.14
175.90	8.30		SD=4.05
183.40	7.50		CV=40%
191.70	8.30		
199.70	8.00		
	MEAN=7.53		
	SD=3.00		
	CV=40%		