PERFORMANCE OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS IN THE LTPP PROGRAM

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ABSTRACT

Since the 1960's, thousands of miles of continuously reinforced concrete pavements (CRCP) have been built in the U.S. These pavements have typically provided 20 or more years of service life without requiring major rehabilitation. Design procedures of CRCP have evolved over time. The thickness design is typically based on the design procedures for jointed concrete pavements, with many agencies using slightly lower thickness than those determined for comparable jointed concrete pavements. The design for the continuous longitudinal steel is based on meeting the requirements of three criteria related to crack spacing, crack width and concrete strength.

Over the last 10 years the performance of eighty-five CRCP sections throughout the US has been monitored as part of the GPS-5 experiment of the Long-Term Pavement Performance (LTPP) program. The age of these sections range from about 5 to about 34 years and the thickness of the sections are primarily 203 to 254 mm. Most of the sections incorporate about 0.60% of steel. This paper provides the results of a study conducted to evaluate the performance of these sections. Key features of the sections are detailed and the performance trends, in terms of observed distresses, ride, and structural testing, are discussed. Finally, the results of the analysis of well performing CRCP sections are presented.

Study results indicate that most of the CRCP sections of the GPS-5 experiment in the LTPP program are performing very well. These sections do not exhibit significant amount of distresses

even after more than 20 years of service. The ride quality of these sections does not appear to deteriorate with time/traffic loading. Sections constructed smooth remain smooth.

INTRODUCTION

Continuous reinforced concrete (CRC) pavement is a portland cement concrete (PCC) pavement with continuous longitudinal steel reinforcement with no intermediate expansion or contraction joints. The continuous joint-free length of CRC pavements can extend to several kilometers with breaks provided only at structures. CRC pavements are designed to develop naturally a transverse cracking pattern, with cracks generally spaced at about 0.6 to 1.8 m. The cracking pattern is governed by the environmental conditions at the time of construction, the amount of steel reinforcement, and concrete strength. The steel reinforcement restrains the opening of the cracks and provides high load transfer across the cracks. Because of this high load transfer characteristic, CRC pavements, when properly designed and constructed, maintain a relatively low state of stress under load and consequently can provide excellent performances. Most of the cracks develop shortly after concrete placement; however, additional cracking may develop over several years as a result of drying shrinkage of concrete, temperature variations, and traffic loading.

Major forms of CRC pavement distress include punchout, spalling along transverse cracks, faulting across transverse cracks, wide transverse cracks due to steel rupture, and steel corrosion. Punchout distress is a major concern for CRC pavements and is defined as the area enclosed by two closely spaced (usually less than 0.6 m) transverse cracks, a short longitudinal crack, and the edge of the pavement or a longitudinal joint. The punchout distress is related to crack spacing, pavement thickness, poor foundation support, and heavy truck loading. The repair of punchout distress typically consists of full-depth concrete patches.

Transverse cracks in a properly designed and constructed CRC pavement are held tight by the continuous reinforcement to ensure the integrity of the aggregate interlock and load transfer across the cracks. The riding quality of CRC pavements is typically very good and will remain good as long as the structural continuity of the transverse cracks remains good.

Over the years, many studies have been conducted to investigate the behavior and performance of CRC pavements. Many of these studies have focused on the mechanism of transverse crack development and punchout development. The availability of the General Pavement Study –5 (GPS-5) CRC pavement sections in the Federal Highway Administration's (FHWA) Long-Term Pavement Performance (LTPP) program provides an opportunity for comprehensive analysis of CRC pavement performance. This paper provides a detailed assessment of the performance of GPS-5 CRC pavement sections.

BACKGROUND

Initiated in 1987, the LTPP study is a 20-year program to collect pavement performance and other related data to establish a database of information to support pavement research. The primary objective of the program is to increase pavement life by investigating the results of different designs, loads, environmental factors, and maintenance practices on pavement

performance. As part of the program, existing design methods are being evaluated, improvements in design and rehabilitation methods are being developed, and factors affecting pavement distress and performance are being investigated.

Pavements studied in the GPS-5 experiment are continuously reinforced portland cement concrete slabs placed over different types of base layer. Sampling design factors for this study are environment, subgrade type, traffic rate, percent reinforcement, and PCC slab thickness. There are 85 CRC pavement sections in the GPS-5 experiment. Data types collected under the LTPP program are classified as (a) inventory, (b) materials testing, (c) climatic, (d) monitoring, (e) traffic, and (f) seasonal. In addition, maintenance, rehabilitation, and construction data are also collected as appropriate.

A preliminary evaluation of GPS-5 data was performed to identify factors that influence long-term crack spacing in CRC pavements and to determine the effects of crack spacing on pavement performance.[1] No definitive conclusions were derived from this study. But, it was observed that there were many well-performing sections in the LTPP GPS-5 experiment. In a study conducted to identify common characteristics of good and poorly performing LTPP PCC pavement sections, it was observed that most CRC pavements in GPS-5 fell in the good performance category.[2] The authors stated that, because of the lack of poorly-performing CRC sections in the GPS-5 database, it was difficult to find clear trends relating various CRC pavement parameters to their performance.

In another study investigating the development of pavement roughness, it was observed from the GPS-5 data that the ride (as indicated by the IRI) of CRC pavements remained relatively constant over the years. This observation indicated that the CRC pavements appeared to generally maintain their initial IRI over a longer period of time.[3]

GPS-5 DATA CHARACTERISTICS

The LTPP GPS-5 data used in the study reported here were obtained from DataPave version 2.0,[4] released September 1999. The 85 150-m long GPS-5 sections are located in four climatic regions and 29 different states. Texas has the largest number of sections (19 or about 22 percent of the total sections). A list of the 85 sections is presented in Table 1, with each section identified by a reference number (from 1 to 85). These reference numbers are used to identify the sections in subsequent sections of this paper. Also shown in this table is the current status of these sections. As of September 1999, 13 sections had been overlaid and were removed from the GPS-5 study. For the overlaid sections, only data for the period prior to overlay was used in this study.

The LTPP database for the GPS-5 sections consists of the following data types: inventory, environmental, materials testing, monitoring, and traffic. Each data type are collected and stored at different times for different sections. The monitoring data (performance data) used in the analysis are from the latest measurements available for each section, except that the profile data measured at different times are used in the time-series analysis.

Table 1. List of GPS-5 sections.

Reference No.	Section Number	State	Overlay Date	Climatic Region	Open-to-Traffic Date
1	013998	AL	08/01/1991	WNF	03/01/1974
2	015008	AL		WNF	12/01/1977
3	047079	AZ		DNF	08/01/1989
4	055803	AR		WNF	07/01/1973
5	055805	AR		WNF	08/01/1975
6	067455	CA		DNF	12/01/1971
7	095001	CT	08/25/1996	WF	11/01/1981
8	105004	DE		WF	06/01/1977
9	105005	DE	06/07/1995	WF	06/01/1971
10	135023	GA		WNF	06/01/1974
11	165025	ID		DNF	09/01/1972
12	175020	IL		WF	10/01/1986
13	175151	IL	10/02/1990	WF	10/01/1966
14	175843	IL		WF	09/01/1982
15	175849	IL		WF	11/01/1971
16	175854	IL		WF	10/01/1982
17	175869	IL		WF	12/01/1979
18	175908	IL		WF	04/01/1971
19	179267	IL		WF	10/01/1966
20	185022	IN	05/16/1993	WF	01/01/1972
21	185043	IN		WF	01/01/1969
22	185518	IN	11/15/1993	WF	12/01/1970
23	195042	IA		WF	12/01/1975
24	195046	IA		WF	11/01/1975
25	199116	IA	09/15/1989	WF	08/01/1972
26	245807	MD		WF	06/01/1990
27	265363	MI		WF	12/01/1976
28	275076	MN	08/15/1990	WF	10/01/1970
29	283099	MS	01/18/1994	WNF	11/01/1970
30	285006	MS		WNF	04/01/1979
31	285025	MS		WNF	07/01/1978
32	285803	MS		WNF	09/01/1979
33	285805	MS		WNF	06/01/1975
34	295047	MO		WF	02/01/1972
35	315052	NE		WF	12/01/1969
36	375037	NC		WF	10/01/1972
37	375826	NC	11/30/1995	WNF	06/01/1977
38	375827	NC		WNF	03/01/1973
39	385002	ND		WF	11/01/1973
40	395003	OH		WF	08/01/1988
41	395010	OH	06/01/1990	WF	07/01/1975
42	404158	OK		WF	06/01/1989
43	404166	OK		WNF	06/01/1990
44	405021	OK		WF	10/01/1987
45	415005	OR		WNF	10/01/1985
46	415006	OR		DF	06/01/1973

Table 1. List of GPS-5 sections (continued).

Reference No.	Section Number	State	Overlay Date	Climatic Region	Open-to-Traffic Date
47	415008	OR		DF	06/01/1972
48	415021	OR		WNF	07/01/1986
49	415022	OR		WNF	10/01/1984
50	417081	OR		DF	09/01/1988
51	421598	PA		WF	01/01/1975
52	421617	PA	08/13/1990	WF	06/01/1972
53	425020	PA		WF	05/01/1980
54	455017	SC		WNF	03/01/1979
55	455034	SC		WNF	06/01/1975
56	455035	SC		WNF	11/01/1975
57	465020	SD		WF	08/01/1972
58	465025	SD		DF	11/01/1974
59	465040	SD		WF	07/01/1963
60	483719	TX		WNF	01/01/1965
61	483779	TX		DNF	06/01/1978
62	485024	TX		WNF	01/01/1982
63	485026	TX		WNF	06/01/1988
64	485035	TX		WNF	09/01/1979
65	485154	TX		WNF	08/01/1971
66	485274	TX		WNF	03/01/1973
67	485278	TX		DNF	06/01/1975
68	485283	TX		WNF	04/01/1988
69	485284	TX		WNF	03/01/1988
70	485287	TX		WNF	08/01/1973
71	485301	TX		WNF	02/01/1982
72	485310	TX		WNF	07/01/1987
73	485317	TX		WNF	04/01/1982
74	485323	TX		WF	10/01/1980
75	485328	TX		WNF	09/01/1975
76	485334	TX		WF	04/01/1970
77	485335	TX		WF	10/01/1980
78	485336	TX		WF	12/01/1986
79	512564	VA		WNF	02/01/1969
80	515008	VA		WNF	08/01/1977
81	515009	VA		WNF	06/01/1980
82	515010	VA		WNF	10/01/1988
83	545007	WV	06/29/1992	WF	06/01/1977
84	555037	WI		WF	11/01/1973
85	555040	WI		WF	11/01/1980

* WF = Wet-Freeze Region, WNF = Wet-Nonfreeze Region,
DF = Dry-Freeze Region, DNF = Dry-Nonfreeze Region

Note: Data as of September 1999.

GPS-5 Test Section Inventory Data

Age

The age for the GPS-5 sections was determined as of either December 2000, or for the overlaid sections, the date when the sections were overlaid. As of that date, the age of the sections were from 11 to 38 years, with 55 sections over 20 years of age, as shown in Figure 1.

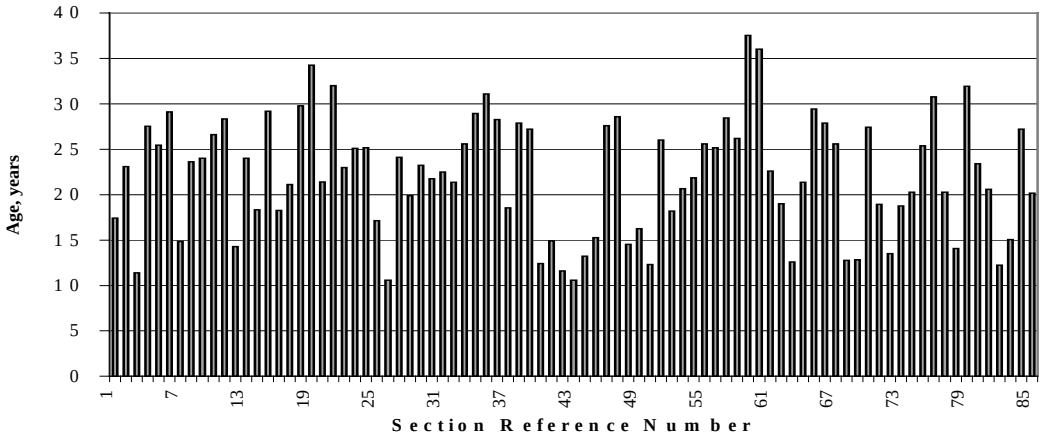
Slab Design Data

The slab design data include mean slab thickness, design percent longitudinal steel, and spacing of longitudinal and transverse reinforcing bars. The following observations are made:

1. As shown in Figure 2, the slab thickness of the sections is not uniformly distributed. Out of the 85 sections, 46 had 203-mm thick slabs and 18 had 229-mm-thick slabs. Only five sections had slab thickness greater than 270 mm.
2. As shown in Figure 3, most sections contain 0.62% or less longitudinal steel (61 sections). Only nine sections had steel content equal to or greater than 0.7 percent, and 13 sections had steel content equal to or less than 0.51 percent.
3. Design depth to longitudinal reinforcement was between 75 and 127 mm.
4. Design spacing of longitudinal steel reinforcement was between 147 and 229 mm.
5. Where used, design spacing of transverse bars was between 610 and 1,524 mm.

Base and Subgrade Data

Base material for the sections was characterized by material type. The material type code used and the distribution of base type are presented in Table 4. As can be observed from this table, the dense-graded asphalt, cement-aggregate mixture, and gravel represent over three-quarters of the base material types in the GPS-5 sections.



(For overlaid sections, actual age at time of overlay is shown)

Figure 1. Age distribution of GPS-5 sections as of December 31, 2000.

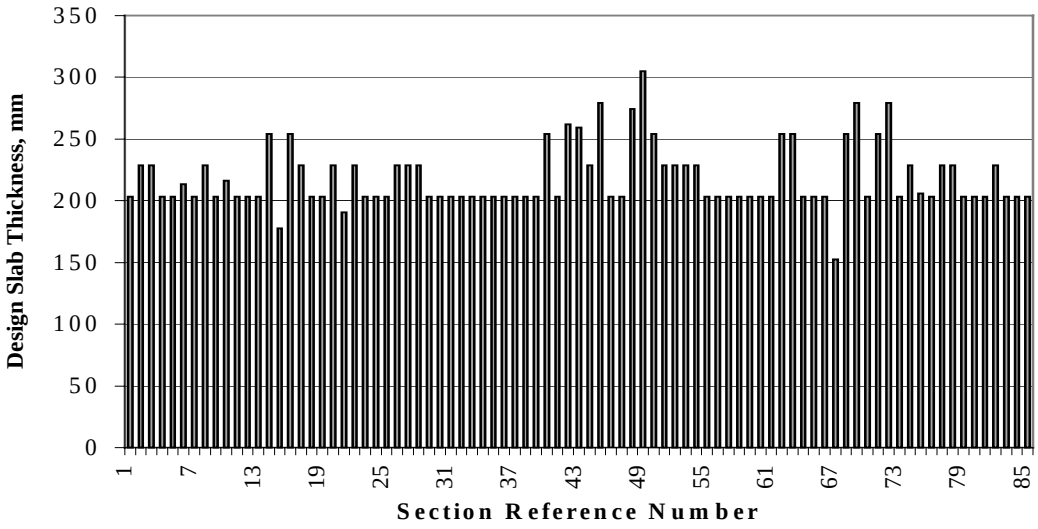


Figure 2. Design slab thickness.

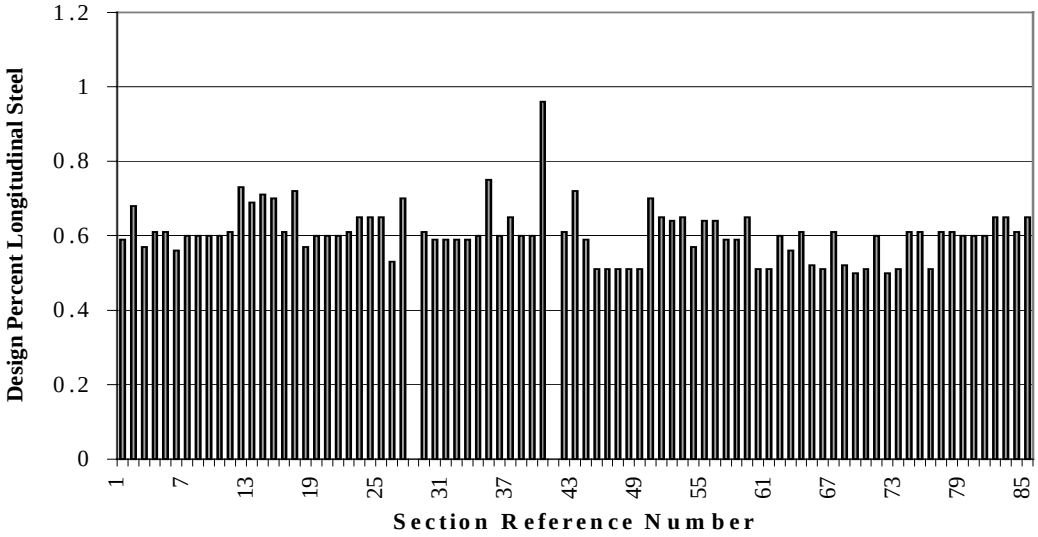


Figure 3. Design percent longitudinal steel.

Table 4. Distribution of base material types.

Material Type	No. of Sections	Percent Distribution
Cement-Aggregate Mixture	19	22
Cement Treated Subgrade Soil	2	2
Dense Graded Asphalt Cement	33	39
Gravel	17	20
Lean Concrete	2	2
Lime Treated Subgrade Soil	1	1
Open Graded Asphalt Cement	3	4
Soil Cement	8	10

The American Association of State Highway and Transportation Officials (AASHTO) soil classification system was used in this study to describe the subgrade types for the GPS-5 CRCP sections. The distribution of subgrade soil type according the AASHTO classification is given in Table 5.

Table 5. Distribution of subgrade types by AASHTO classification.

AASHTO Classification	No. of Sections	Percent Distribution
A-1-a	1	1
A-1-b	2	2
A-2-4	14	16
A-2-5	2	2
A-2-6	3	4
A-2-7	3	4
A-3	5	6
A-4	14	16
A-5	6	7
A-6	12	14
A-7-5	4	5
A-7-6	4	5
Not Documented	15	18

Shoulder Type

Forty percent of the GPS-5 sections have concrete shoulders and sixty percent of the sections have AC shoulders. A majority of the concrete shoulders are jointed plain concrete with a few jointed reinforced concrete shoulders.

GPS-5 Test Section Climatic Data

Climatic data for GPS-5 sections include climatic region, average annual freezing index (FI), average annual precipitation, and average mean annual temperature. The GPS-5 sections are

distributed throughout the US and are subjected to a range of environmental conditions, as shown in Table 1. A majority of projects are in the wet regions (annual precipitation greater than 500 mm).

Traffic Data

The cumulative 80-kN equivalent single-axle load (ESAL) was used to characterize traffic loading. The cumulative 80-kN ESALs were determined by summing the estimated annual 80-kN ESALs over the years the sections were in service to the date of the latest distress survey. In the case where some ESAL values were missing for a few years, regression analysis was performed to estimate the annual total ESALs for these years. A summary of the cumulative ESAL data is given in Figure 4. Because of the potential for the estimated traffic data to be somewhat unreliable, the estimated traffic data presented should be used with care. The LTPP program is currently developing more reliable traffic data for each test section using site specific weigh-in-motion and automatic vehicle classification data. There were twelve sections for which traffic data were not available.

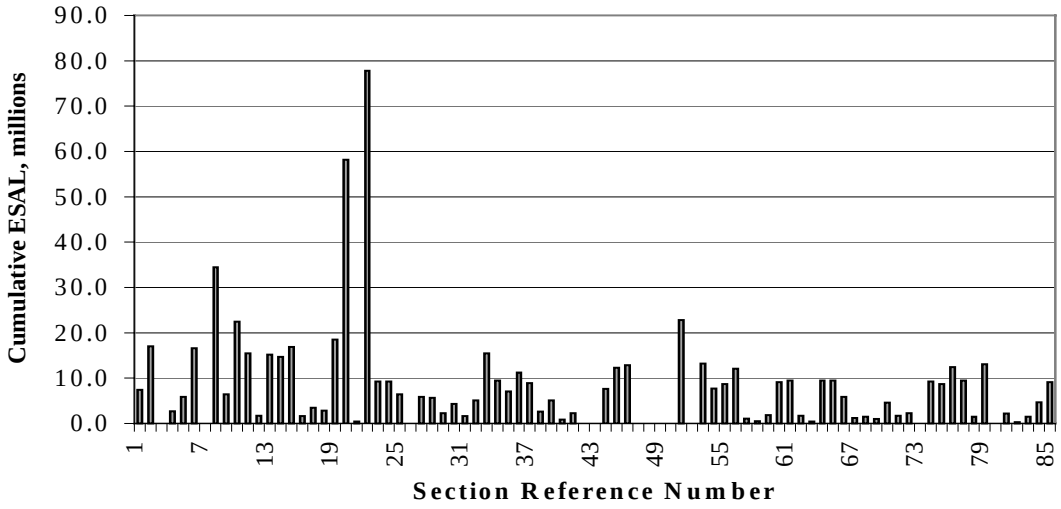


Figure 4. Cumulative ESAL summary.

Monitoring (Performance) Data

The GPS-5 pavement performance data available include high-severity transverse cracking, average crack spacing, total punchouts and patches, and IRI. Two types of distress surveys were performed in the LTPP program, the manual survey and the photographic survey using PADIAS system. In the analysis presented here, the following guidelines were used:

- If data from several survey dates were available, the information from the latest survey was used.

- If the manual and PADIAS surveys indicated different numbers of cracks and local failures for the same section, data obtained from manual surveys were used since majority of the manual surveys were the latest surveys conducted for the sections.

Out of the 85 sections, there were six sections with both manual survey and PADIAS survey data missing (Sections 013998, 175151, 275076, 421617, 465040, and 545007). These sections were excluded from further distress data analysis. Similarly, Section 199116, without IRI data, was not included in the IRI data analysis.

High Severity Transverse Cracking

Both manual and PADIAS surveys indicate a very small percentage of high severity transverse cracking. Based on total number of transverse cracks, the percentages of high-severity cracking are 0.33 and 0.20 for the manual and PADIAS surveys, respectively.

Transverse Crack Spacing

Average transverse crack spacing was calculated by dividing the length of the section (152 m) by the total number of cracks. Generally, PADIAS surveys gave larger crack spacing compared to the manual surveys, as shown in Figure 5. This finding is consistent with that observed from earlier studies that indicate that the photographic procedures could not adequately identify all low-severity transverse cracking, resulting in larger estimated crack spacing. Based on the manual survey data, the average crack spacing for the GPS-5 sections ranged from 0.33 m to 2.06 m, with an average value of 1.13 m.

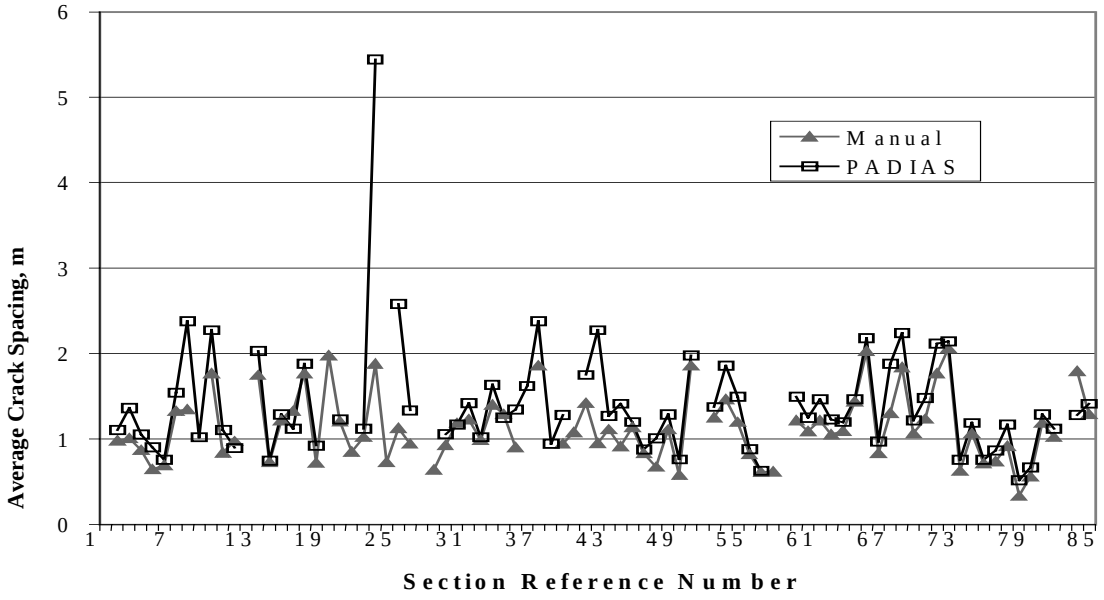


Figure 5. Average crack spacing

Punchout and Patching

The total number of localized failures was determined by adding the total number of punchouts and rigid and flexible patches, across all severity levels. In general, the localized failures have not been a serious problem to date for the GPS-5 sections. Based on the manual survey data, only four sections exhibited localized failures. The number of localized failures for these four sections were 16, 18, 22, and 39. It is believed that these high number of failures are due to problems with interpretation of the distress data. For example, 39 localized failures over a length of 152.4 m would equate to a rate of about 256 localized failures per kilometer. Apparently the presence of longitudinal cracking resulted in those segments being classified as having punchouts. It is highly unlikely that any highway agency would permit such a high amount of localized failures to remain on a public highway. Also, the interpretation of the localized failure data from the manual survey and the PADIAS survey was not consistent showing large discrepancies for some sections.

Overall, it appears that the GPS-5 CRC pavements have performed very well.

Profile Data

The IRI is one of the indices used in the LTPP program for characterization of pavement ride. IRI data determined from testing at different times over the years are available in the database. The IRI values for GPS-5 sections ranged from about 0.7 to 2.8 m/km, with almost 80% of the sections having IRI of less than 2.0 m/km. Considering the ages of the sections in the GPS-5 experiment, the CRC pavements are exhibiting good ride quality. The summary of the IRI data for the GPS-5 sections is shown in Figure 6.

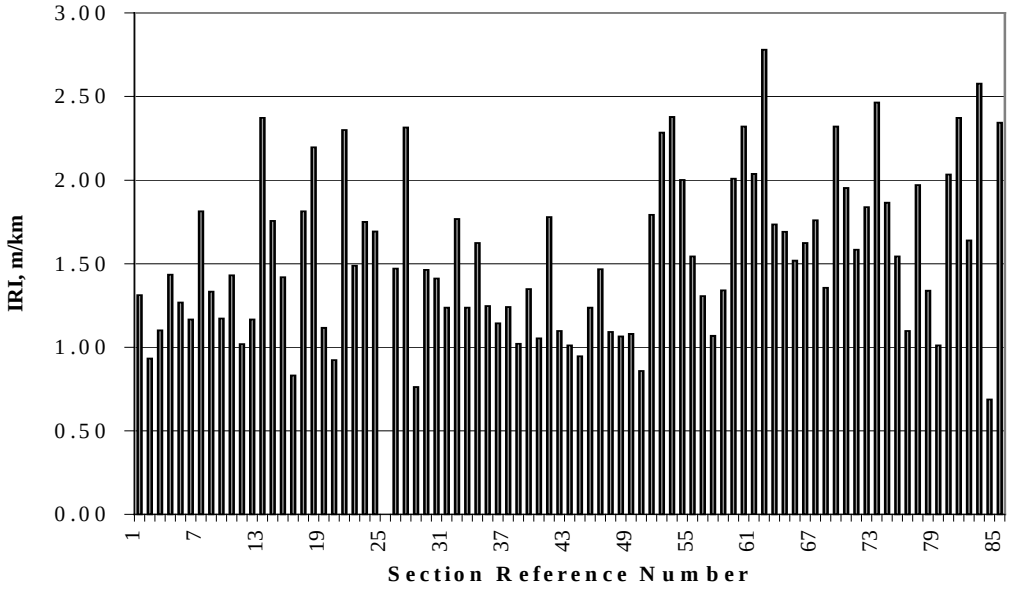


Figure 6. IRI data summary.

Time series analyses were performed for CRC sections located in four different states – Illinois, Mississippi, Oregon, and Texas, each which had five or more CRCP sections. The time series analyses are presented in Figure 7. It is clear from these time series plots that, although some variability exists, the IRI remained relatively constant over time for most sections. Sections of different ages showed the same IRI pattern. It is therefore reasonable to conclude that the CRC pavements appear to generally maintain their initial IRI over a long period of time.

Deflection Test Data

Deflection testing using a falling weight deflectometer (FWD) is performed regularly at LTPP test sections. For the GPS-5 sections, deflection testing is performed at interior locations and at cracks. The deflection data at cracks were analyzed to determine load transfer efficiency (LTE) at cracks. Testing at GPS-5 sections is typically conducted at about 20 crack locations at both approach and leave sides of the cracks. The statistics for the LTE data are given in Table 6 and the distribution of the LTE values is given in Figure 8.

Table 6. Average LTE and CV for CRC test sections.

	Load Applied at						Combined Data		
	Approach Side (C4)			Leave Side (C5)					
	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
Average LTE, %	91	100	77	92	101	78	91	100	77
CV, %	3	12	1	3	13	1	3	13	1

It is seen from Table 6 and Figure 11 that the CRC pavement test sections exhibit very good LTE with most of the cracks tested exhibiting 90% or greater LTE, irrespective of temperature/time of testing. Also, within each section the variation in LTE is very small indicating very consistent LTE distribution with a section, irrespective of the crack spacing pattern.

There also did not appear to be any effect of base type or shoulder type on LTE development. The coefficient of variation tended to be lower for sections exhibiting higher LTEs. The LTE values remain high even as pavements get older and are subjected to increasing traffic loadings.

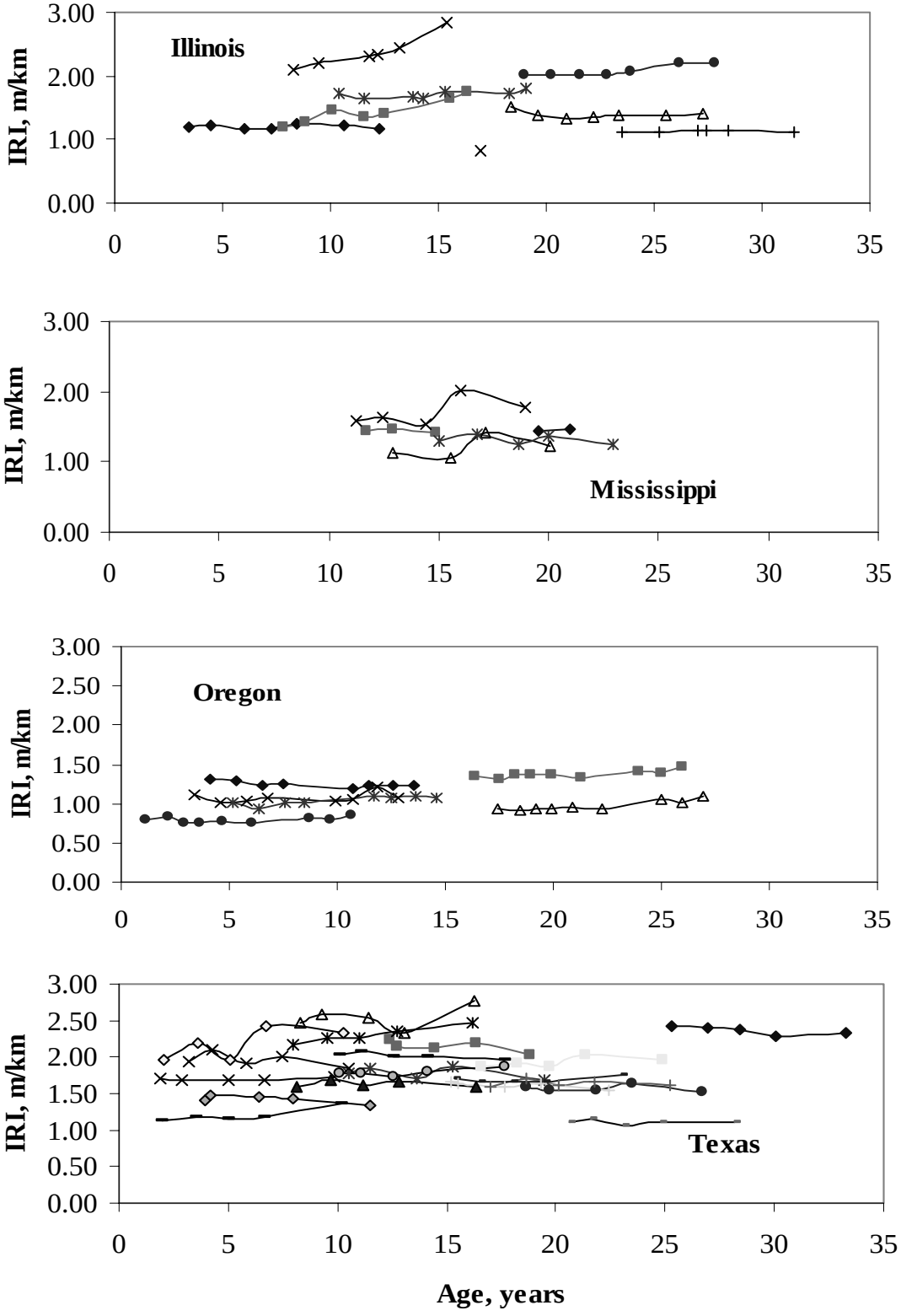


Figure 7. IRI vs. time.

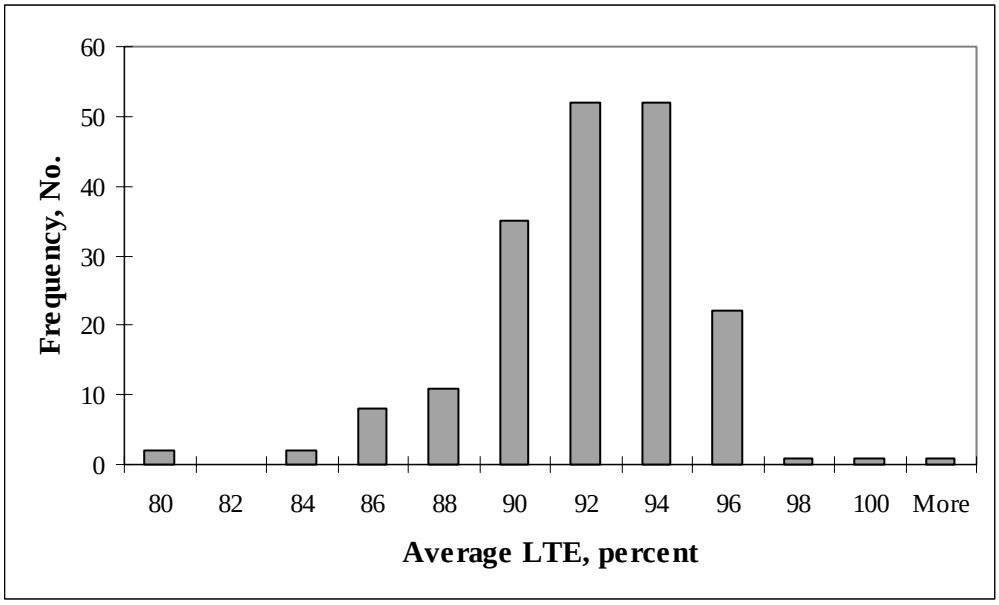


Figure 8. Distribution of average LTE for CRC pavements in LTPP database.

CHARACTERISTICS OF EXCEPTIONALLY WELL-PERFORMING GPS-5 CRC SECTIONS

As discussed in previous sections of the report, the GPS-5 CRC sections have, generally, performed well over long periods of time. This section focuses on sections that have shown exceptional performance. Detailed information related to the design, climatic conditions, traffic data, and performance data of these well-performing sections are presented. For the purpose of this analysis, the following criteria were used to identify exceptionally well performing sections:

- Years in service 20 or more
- IRI, m/km <1.5
- High-severity cracking None
- Punchouts & Patches None

Using these criteria, thirteen out of the 85 GPS-5 sections were identified as exceptionally well performing sections. These thirteen sections are 015008, 055803, 055805, 067455, 175849, 179267, 315052, 375037, 415006, 415008, 455035, 465020, and 512564. Detailed information related to pavement geographic locations, design parameters, climatic conditions, traffic data, and performance data for these thirteen sections is given in Reference 5.

Summary of Characteristics of the Exceptionally Well-Performing Sections

The summary statistics of the characteristics for the exceptionally well performing GPS-5 sections are presented in Table 7. Included in this table are the minimum, maximum, average, and the 75-percentile point for several design parameters, material properties, climatic conditions, and performance data.

Table 7. Summary of characteristics of the well-performing GPS-5 sections.

Characteristics	Minimum	Maximum	Average
Concrete Compressive Strength, MPa	39.5	60.6	50.2
Concrete Elastic Modulus, GPa	21.4	42.9	29.2
Base Thickness, mm	51	122	122
Design Longitudinal Steel, %	0.51	0.75	0.61
Depth to Steel, mm	64	114	91
Average Annual FI, ˚C-day	0	585	214
Annual Precipitation, mm	351	1,368	917
Total 80-kN ESAL, *1000	1,051	18,591	11,266
Average Crack Spacing, m	0.33	1.29	0.81
Average IRI, m/km	0.93	1.47	1.21
Average LTE, %	77	100	92

The following general observations are made:

- All sections had concrete with high strength, with compressive strength well above 27.6 MPa, which is a commonly specified 28-day concrete strength for pavements.
- Most of the sections (12 out of 13) used treated base layer.
- Three quarters of the sections had design longitudinal steel percentage of 0.59 percent or higher.
- Average crack spacing ranged from 0.33 to 1.29 m, with 75% less than 0.90 m. The generally recommended crack spacing is between 0.6 and 1.8 m.
- Average IRI for the sections ranged from 0.93 to 1.47 m/km, with 75% less than 1.31 m/km.

In addition, the time series analysis of the IRI for these thirteen well-performing sections was also conducted. The IRI remained relatively constant over long periods of time.

SUMMARY

The data obtained from the LTPP GPS-5 sections were analyzed to evaluate the performance of the CRC sections and to identify exceptionally well performing CRC pavements. It was observed that most of the CRC pavement sections have performed well, as evidenced by the low IRI number and the lack of localized failures and high-severity transverse cracking even after more than 20 years of service for many sections. The low IRI values indicate that CRC pavements generally provide a good ride even after many years of services. Also, the time series analysis showed that the IRI remained relatively stable over time for most sections. Sections of different ages showed the same IRI pattern. It is therefore reasonable to conclude that the CRC pavements appear to generally maintain their initial IRI over a long period of time. Finally, as of September 1999, 44 of the 85 sections were in service for more than 20 years, and these sections

have not been subjected to major rehabilitation. It can be concluded that properly designed and constructed CRC pavements can be expected to provide low maintenance long term service, exhibiting good ride characteristics and maintaining desirable structural capacity.

Thirteen GPS-5 sections were identified as exceptionally well performing CRC pavements based on the criteria established in a previous section of the report. By examining the exceptionally well performing sections, they appear to have the following characteristics:

- Higher concrete strength.
- Higher concrete modulus of elasticity.
- Stiffer base layer (treated base).
- Smaller crack spacing.
- Design percent longitudinal steel greater than 0.59%.
- 90% or greater LTE at crack locations.

Because reliable traffic data were not yet available at the time of this study for GPS-5 sections, it was not possible to perform in-depth analysis of the effect of various design features on CRC pavement performance. It is expected that such analysis will be possible in the near future when good quality traffic data are available.

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