This is to certify that the
thesis entitled

QUANTIFYING THE RELATIVE EFFECTS OF DESIGN AND SITE FACTORS ON THE PERFORMANCE OF RIGID PAVEMENTS USING SPS-2 LTPP DATA

presented by

ASWANI SASAANKA PULIPAKA

has been accepted towards fulfillment
of the requirements for the

M. S. degree in Civil Engineering

Major Professor's Signature

8/9/05

Date

QUANTIFYING THE RELATIVE EFFECTS OF DESIGN AND SITE FACTORS ON THE PERFORMANCE OF RIGID PAVEMENTS USING SPS-2 LTPP DATA

By

Aswani Sasaanka Pulipaka

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Civil and Environmental Engineering

2005

ABSTRACT

QUANTIFYING THE RELATIVE EFFECTS OF DESIGN AND SITE FACTORS ON THE PERFORMANCE OF RIGID PAVEMENTS USING SPS-2 LTPP DATA

By

Aswani Sasaanka Pulipaka

The results of a study conducted to evaluate the relative effects of various design and site factors on the performance of jointed plain concrete (JPC) pavements are presented here. Data related to the Specific Pavement Study-2 (SPS-2) experiment of the Long Term Pavement Performance (LTPP) program were used in the study. The experiment was designed to investigate the effects of concrete slab thickness, base type, drainage, concrete flexural strength and slab width on the performance of JPC pavements. Based on an assessment of performance using published standards, a majority of the SPS-2 sections are exhibiting "good" performance. Data were analyzed by employing appropriate frequency- and magnitude-based statistical methods. On the whole, base type was found to be the most critical design factor affecting performance, in terms of cracking and roughness (IRI). Pavement sections with permeable asphalt-treated base and in-pavement drainage performed better than those with a dense-graded aggregate base or a lean concrete base. PCC slab thickness also played an important role in determining the cracking performance. PCC flexural strength and slab width only have marginal effects on performance, at this point in time.

To my parents, Syamala and Satyanarayana,

to my brother Anirudh,

and to my other kith and kin.

ACKNOWLEDGEMENTS

I would first like to thank my academic advisor Dr. Neeraj Buch for his support and guidance throughout my graduate program. I would also like to thank the National Cooperative Highway Research Program (NCHRP) for sponsoring this research.

I would like to express thanks to Dr. Karim Chatti and Dr. Gilbert Baladi for being a part of the thesis committee. The guidance provided by Dr. Denis Gilliland and Dr. Richard Lyles has played an important role in the completion of this research study.

Heartfelt appreciation is due to my friend Dr. Syed W. Haider (former graduate research assistant) for his invaluable guidance during this research. Mr. Praveen Desaraju's (former graduate assistant) help in getting me acquainted with the research is appreciated. I also appreciate Mr. Phani R. Mullapudi's help during final formatting of my thesis.

Finally, I would like to express my gratitude to my alma mater Michigan State University for everything it has given to me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND

Pavement design and construction have a major influence on pavement performance, which in turn has a significant impact on the management of highway infrastructure. Each design feature affects the performance of a pavement in different ways, depending on site conditions. Highway agencies currently use a wide variety of alternative design features that have evolved over time based on experience and/or research studies. However, for most of the highway agencies, the design features are often a part of the agency "standards" that remain unchanged over years (Gharaibeh and Darter, 2001).

The Long-Term Pavement Performance (LTPP) program was initiated in 1987 as a part of the Strategic Highway Research Program (SHRP) to address the needs of the highway agencies by means of studying in-service pavements. This program comprises of many full-scale field experiments that address a variety of issues aimed at improving the design and management of highways. The objective of LTPP program is to "Increase pavement life by investigation of the long-term performance of various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soils, and maintenance practices" (SHRP 1986). From this broad objective, six specific objectives were established for the LTPP program (Elkins et al. 2003):

- Evaluate existing design methods.
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements.
- Develop improved design equations for new and reconstructed pavements.

- Determine the effects of loading, environment, material properties and variability, construction quality, and maintenance level on pavement distress and performance.
- Determine the effects of specific design features on pavement performance.
- Establish a national long-term pavement database to support SHRP objectives and needs.

In order to meet these objectives, the program has two complementary sets of studies—General Pavement Studies (GPS) and Specific Pavement Studies (SPS). The GPS use existing pavements while the SPS usually use newly constructed pavements. The SPS-2 experiment is aimed at the fifth of the above said objectives of the LTPP program.

1.2 RESEARCH GOAL AND OBJECTIVES

For specific site conditions, the performance of pavements will depend not only on thickness of each pavement layer and material properties, but also on other design features such as slab width, base type, and in-pavement drainage. The performance of a pavement system also depends on the interaction effects between these features.

This research focuses on the effects of design features on the performance of rigid pavements, based on an evaluation of the test sections from the ongoing Specific Pavement Study-2 (SPS-2) experiment of the LTPP. The SPS-2 experiment, titled as "Strategic Study of Structural Factors for Rigid Pavements", provides an opportunity for the study of the effects of PCC slab thickness, in-pavement drainage, base type, slab width and PCC flexural strength, in various site conditions (soil-climate combinations). In addition to this, rigid pavement sections of the SPS-8 experiment were used to investigate the effects of environment and traffic on rigid pavement performance. The SPS-8 experiment is aimed at studying the effects of environment, in the absence of heavy loads, on pavement performance.

1.3 SCOPE OF THE STUDY

The findings presented in this thesis are based on the assessment of test sections included in the SPS-2 and SPS-8 experiments of the LTPP. The analysis is limited to the use of relevant LTPP data (i.e. DataPave) available from Release 17 of National Information Management System (NIMS) database.

1.4 LAYOUT OF THE THESIS

The thesis is divided into 9 chapters including this introductory chapter. A description of the experiment design and the current status of the SPS-2 experiment are presented in Chapter 2. A summary of findings from a review of relevant literature is presented in Chapter 3. A summary of data availability and findings from a review of the experiment are presented in Chapter 4. Chapter 5 contains results of an evaluation of performance trends of the SPS-2 sections. Based on the extent and occurrence of distresses, different methods of analysis were employed. A brief description of these methods is presented in Chapter 6. The results from statistical analyses conducted on performance of the SPS-2 test sections are presented in Chapter 7. An evaluation of the performance of rigid pavement sections in SPS-8 experiment is presented in Chapter 8. Chapter 9 contains the conclusions and recommendations for future research.

CHAPTER 2 - AN OVERVIEW OF THE SPS-2 EXPERIMENT

2.1 INTRODUCTION

This chapter presents an overview of the SPS-2 experiment in terms of its goals, experiment design, and associated experimental factors. The chapter also contains a brief description of the current status of the experiment.

2.2 STRATEGIC STUDY OF STRUCTURAL FACTORS FOR RIGID PAVEMENTS — SPS-2 EXPERIMENT

2.2.1 Objective

The Specific Pavement Study-2 (SPS-2) experiment, entitled *Strategic Study of Structural Factors for Rigid Pavements*, was designed as a controlled field experiment to study the relative influence and long-term effectiveness of design features, in different site conditions, on the performance of doweled jointed plain concrete pavements (JPCP) with uniform transverse joint (perpendicular) spacing (Hanna et al. 1994; SHRP 1986; SHRP 1990). As the test sections in the experiment are monitored since inception, the experiment provides an opportunity to infer, more precisely, the influence of the experimental factors on pavement performance.

2.2.2 Experiment Design

The experimental design plan for the SPS-2 experiment was developed by SHRP in cooperation with state highway agencies. Table 2-1 presents the experimental design for the SPS-2 experiment. The experimental factors can be grouped into structural factors that relate to the base and concrete slab, and site factors that relate to climate and subgrade soil type.

Table 2- 1 SPS-2 Experiment Design Matrix

Pavement Structure					Climate, Subgrade soil type															
Drainage	Base Type	PCC		Slab Width (m)	Wet								Dry							
		Thickness (mm)	14-day Flexural Strength (MPa)		Freeze				No-Freeze				Freeze				No-Freeze			
					Fine		Coarse		Fine		Coarse		Fine		Coarse		Fine		Coarse	
No	DGAB	203	3.8	3.7	201		201		201		201		201		201		201		201	
				4.3		213		213		213		213		213		213		213		213
			6.2	3.7		214		214		214		214		214		214		214		214
				4.3	202		202		202		202		202		202		202		202	
		279	3.8	3.7		215		215		215		215		215		215		215		215
				4.3	203		203		203		203		203		203		203		203	
			6.2	3.7	204		204		204		204		204		204		204		204	
				4.3		216		216		216		216		216		216		216		216
No	LCB	203	3.8	3.7	205		205		205		205		205		205		205		205	
				4.3		217		217		217		217		217		217		217		217
			6.2	3.7		218		218		218		218		218		218		218		218
				4.3	206		206		206		206		206		206		206		206	
		279	3.8	3.7		219		219		219		219		219		219		219		219
				4.3	207		207		207		207		207		207		207		207	
			6.2	3.7	208		208		208		208		208		208		208		208	
				4.3		220		220		220		220		220		220		220		220
Yes	PATB	203	3.8	3.7	209		209		209		209		209		209		209		209	
				4.3		221		221		221		221		221		221		221		221
			6.2	3.7		222		222		222		222		222		222		222		222
				4.3	210		210		210		210		210		210		210		210	
		279	3.8	3.7		223		223		223		223		223		223		223		223
				4.3	211		211		211		211		211		211		211		211	
			6.2	3.7	212		212		212		212		212		212		212		212	
				4.3		224		224		224		224		224		224		224		224

The structural (design) factors included in the experiment are:

- drainage –presence or lack of in-pavement drainage,
- base type –dense-graded aggregate base (DGAB), lean concrete base (LCB), and permeable asphalt-treated base (PATB),
- PCC slab thickness – 203 mm (8 in) and 279 mm (11 in),
- PCC flexural strength– 3.8 MPa (550 psi) and 6.2 MPa (900 psi), at 14-day, and
- lane (slab) width– 3.66 m (12 ft) and 4.27 m (14 ft).

The site factors included in the experiment are:

- subgrade soil type (fine-grained and coarse-grained),
- climate (wet freeze, wet no-freeze, dry freeze and dry no-freeze), and
- traffic (considered as a covariate).

At each site, 6 sections have a target PCC slab thickness of 203 mm (8 in) and the remaining 6 have a target PCC slab thickness of 279 mm (11 in). The 76 mm (3-in) difference in thickness was planned to "demonstrate the effect of surface thickness and its interaction with other factors on performance" (SHRP 1990). The other factors with two levels (PCC flexural strength and slab width) have 6 test sections corresponding to each level. Also 4 test sections have dense-graded aggregate base (DGAB) of 153 mm (6 in), 4 sections have lean concrete base (LCB) of 153 mm (6 in), and the other 4 sections have permeable asphalt treated base (PATB) of 102 mm (4 in) placed over a DGAB of 102 mm (4 in). In-pavement drainage is provided only in sections with PATB.

Certain design features are controlled in the experiment and are common to all SPS-2 sections. These features include (SHRP 1986):

- The monitored part of a test section is 152.4 m (500 ft) long excluding transition zones of at least 15.2 m (50 ft) each on both sides of the monitoring length, for material sampling and other destructive testing.
- A uniform perpendicular joint spacing of 4.6 m (15 ft).
- All the sections with 203 mm (8 in) as the target PCC slab thickness are built with dowel bars of 32 mm (1.25 in) diameter. The sections with the target PCC slab thickness of 279 mm (11 in) are built with dowel bars of 38 mm (1.5 in) diameter. Also, all the dowels are 457 mm (18 in) long and placed at slab mid-depth with a center-to-center spacing of 305 mm (1 ft).
- The HMA or PCC shoulders are not tied to the mainline pavement of the test sections.
- Longitudinal joints are tied using 762 mm (30 in) long, No. 5 epoxy-coated deformed steel bars of grade 40 steel and spaced 762 mm (30 in) center-to-center.
- All structural repairs are performed on the test sections before opening to traffic. In addition, all joint sealing is completed prior to opening to traffic.

A SPS-2 test site must have a minimum estimated traffic loading of 200,000 rigid ESAL per year in the design lane. Traffic will thus vary from site to site and will therefore be treated as a covariant in the study.

Based on the average annual precipitation and the average annual Freezing Index, the sites in the experiment have been categorized into different climatic zones using the thresholds defined in LTPP. While 508 mm (20 in) is the precipitation threshold for wet and dry climates, 83.3 ^{o}C-day (150 ^{o}F-day) of freezing index is the threshold for freeze and no-freeze climates.

In the experiment, the 12 sections at a given site are represented by either XX-0201 through XX-0212, or XX-0213 through XX-0224, where XX denotes the site code (abbreviation). The number 02 indicates the SPS experiment number and the last two digits represent the sequential numbering of the sections.

The SPS-2 experiment requires construction of multiple test sections with similar details and/ or materials at several sites. Construction uniformity was thus considered important for the success of the experiment, and guidelines were developed to help participating highway agencies. Adherence to the criteria ensures that any difference in performance between test sections constructed with similar experimental parameters at different locations is mainly due to the site conditions and their interactions with design factors. Details of the guidelines are presented elsewhere (Hanna et al. 1994).

With respect to monitoring of the test sections for collection of various data (e.g. inventory, materials and testing, traffic, distress, profile, deflection, climate, maintenance, etc.), guidelines were developed for the experiment and details are available elsewhere.

2.2.3 Current Status of the Experiment

A total of 14 sites with 167 (NV site has 11 sections) test sections are included in the experiment according to the data (Release 17 of DataPave). The geographical distribution of the sites within the SPS-2 experiment is presented in Figure 2-1.

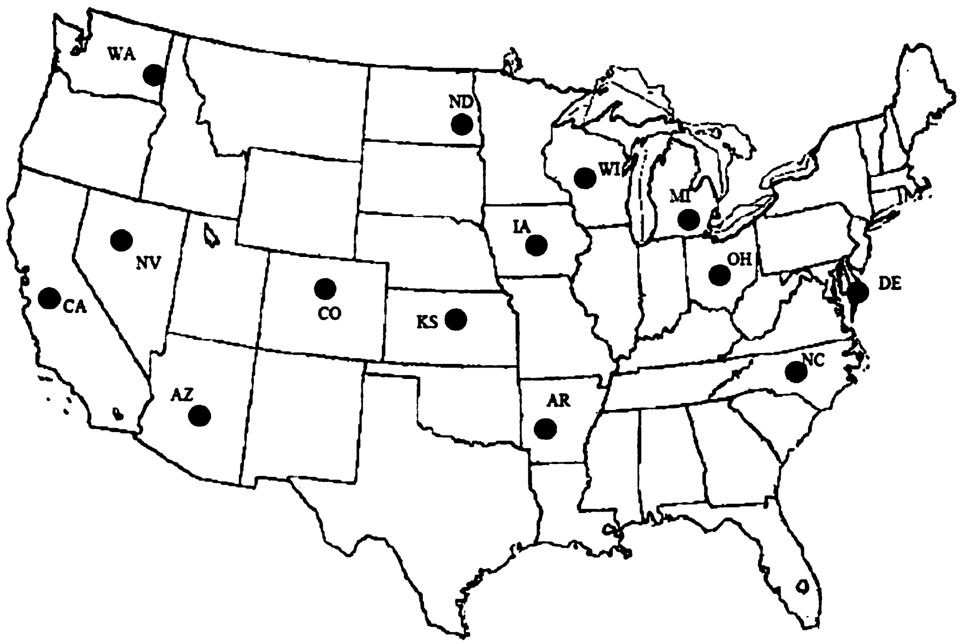


Figure 2- 1 Geographical distribution of the SPS-2 sites

For the seven factors in the experiment if a full-factorial design were implemented, the experiment will have 384 sections, i.e. 48 designs in each of the 8 soil-climate combinations. However, in the existing fractional-factorial design (see Table 2-1) there are 192 factor-level combinations comprising of 8 site-related (subgrade soil type and climate) combinations and 24 pavement structure combinations (design factors). The experiment was developed such that 12 sections are built, with only half of the possible combinations of design factors, at each of the sites.

Originally, it was planned that "48 test sections representing all structural factor and subgrade type combinations in the basic experiment are to be constructed in each of the four climatic zones, with 24 test sections to be constructed on fine-grained subgrade and 24 test sections to be constructed on coarse-grained subgrade" (SHRP 1990). Moreover, for each climatic zone and soil type combination, 12 sections are to be constructed at one site and the other 12 sections at the other site. The experiment thus permits the construction of 12 test sections (0201 through 0212 or 0213 through 0224) at one site with the complementary 12 test sections to be constructed at another site within the same climatic region and on a similar subgrade soil type.

The current status of the design factorial is shown in Table 2-2. There are six cells within the table that are missing from the original factorial. Though the experiment was designed to have 4 sites in each climatic zone, there are only 2 sites each in Wet No-Freeze and Dry No-Freeze climatic zones, and 3 sites in the Dry Freeze climatic zone. A majority of sites (7 of 14) were constructed in the Wet Freeze zone.

Table 2- 2 Status of the SPS-2 design factorial

Subgrade Type	Designs	Wet		Dry		Total
		Freeze	Non Freeze	Freeze	Non Freeze	
Fine-grained	0201-0212	KS (20) OH (39)	NC (37)	WA (53) NV (32)*		9
	0213-0224	MI (26) IA (19) ND (38)		CO (8)*		
Coarse-grained	0201-0212	DE (10)			CA (6)	5
	0213-0224	WI (55)	AR (5)*		AZ (4)	
Total		7	2	3	2	14

Note: * Two sections in NV and five sections in CO are coarse-grained while two sections in AR are fine-grained.

The experiment design also called for half of the sites to be constructed on coarse-grained soil and the other half to be constructed on fine-grained soil. In addition to this, it was required that all the sections within a site be constructed on the same type of soil (coarse or fine). Of the 14 sites, 5 sites were constructed on coarse-grained subgrade soil (see Table 2-2). In 3 of the 4 climatic zones the number of sites constructed on fine-grained and coarse-grained soils is not the same.

2.2.4 Monitoring Requirements

A summary of data collection guidelines is presented in Table 2-3 (Chatti et al, 2005). Monitoring of sections is to be continued until the LTPP program concludes, application of rehabilitation construction event, or test section goes out-of-study.

Table 2- 3 Monitoring Requirements

Data type	Post construction monitoring	Long-term Monitoring Frequency	
		In effect before 10/1/99	In effect after 10/1/99
Longitudinal profile	<6 months is permitted	Biennially, but may be postponed up to one year	Annually
Deflection	<6 months is permitted	Biennially and responsive	Biennially and responsive
Manual distress	<3 months	Biennially, but may be postponed up to one year	Annually

CHAPTER 3- LITERATURE REVIEW

This chapter summarizes the existing understanding of the effects of design features on pavement performance, based on a literature review that focused on publications (reports and papers) that documented research relevant to the objectives of the SPS-2 experiment.

3.1 SIGNIFICANCE OF DESIGN FACTORS

The process of designing pavements is more than just the determination of thickness. Design factors such as base type, drainability, joint spacing, and edge support conditions play an important role in long-term performance (Smith et al. 1989). A "complete JPCP design" consists of the following main design features (Gharaibeh and Darter 2001):

- Portland cement concrete (PCC) slab,
- Transverse joints,
- Longitudinal joints,
- Base course,
- Subbase course (if any),
- Subdrainage (edge drains, permeable layer),
- Shoulders and curb and gutters, and
- Subgrade treatment.

The performance of a pavement system depends on the interactions between these features. Each of these design features is defined by several characteristics that also affect pavement performance. Though each design feature affects the pavement performance (and in turn costs) in a different manner, the design features are "often part of the agency "standards", which remain unchanged over years" (Gharaibeh and Darter 2001). Many forms of functional and structural distress in pavements are direct consequences of problems in design (Armaghani 1993).

A comprehensive understanding of the effects (main and interaction) of design and site factors can help engineers design the most cost-effective combination of the features for given site conditions. The impact of drainage alone can extend the service life of pavements by 10 years (50 percent) and save about 41% of the costs, not including user and maintenance costs, according to a study by Forsyth et al (Forsyth et al. 1987). Provision of doweled joints can increase the life by 55% (reduced joint faulting, spalling, cracking) according to another study by Smith et al (Smith et al. 1990). As the magnitude of the effects vary depending on the site conditions (traffic, subgrade soil type and climate), a thorough project-level life cycle cost analysis will give a better estimate of the effects.

3.2 FINDINGS FROM PREVIOUS STUDIES ON SPS-2

Important findings from previous studies on the SPS-2 experiment that are relevant to this study are presented here.

Desaraju studied the influence of design and construction features on the response and performance of the SPS-2 test sections (Desaraju 2003). It was found that pavements with undrained, DGAB or LCB performed poorly than those with PATB and drainage. Sections with thinner PCC slabs and standard slab width showed higher transverse cracking and pumping. It was considered "too early" to comment on the occurrence of faulting because of "insignificant magnitudes of faulting in the test sections".

Jiang and Darter conducted a "first comprehensive review and evaluation" of the SPS-2 experiment and identified early trends in the performance of the test sections; the details of the study are presented elsewhere (Jiang and Darter 2001). Based on the study, positive effects of slab thickness on cracking (transverse and longitudinal) were observed. Thinner widened slabs were found to have highest levels of cracking. Sections with PATB showed lowest levels of cracking, faulting and roughness, while sections with LCB exhibited the highest levels of cracking and sections with DGAB show evidence of higher faulting. Widened slabs showed a positive effect on faulting. It was also found that sections constructed on coarse-grained soil were smoother than those built on fine-grained soil.

Perera and Kohn studied the effects of factors affecting pavement smoothness based on LTPP data from various experiments including SPS-2 (Perera and Kohn 2001). The findings related to the SPS-2 experiments are presented here. While the effect of PCC slab thickness was found to be insignificant, base type was found to have an effect on early-age roughness. Highest early-age roughness was observed on sections with LCB. The design with thin slab, normal strength concrete and DGAB was found to be more susceptible to changes in curvature than the other designs.

The effects of subsurface drainage on pavement performance were studied using data from SPS-2, by Hall and Correa (Hall and Correa 2003). It was found that un-drained pavement sections built on DGAB or on LCB may develop roughness, transverse and longitudinal cracking more rapidly than drained sections built on PATB. The quality of drainage in the test sections was evaluated by the researchers as a part of the project; however, the effect of quality of drainage was found only on cracking.

Selezneva et al evaluated the faulting data in LTPP and developed "indices and related statistical parameters" (Selezneva et al. 2000). A significant positive effect of widened slabs was found. Also use of drainage was found to improve faulting performance.

Pavements with stabilized bases were observed to have significantly lower levels of faulting compared to those with untreated bases. However, the effect of dowels was found to overshadow the effects of design features on faulting.

Vongchusiri et al performed a site-level evaluation of the Michigan SPS-2 test sections (Vongchusiri et al. 2003), while Suthahar et al performed a site-level evaluation of Colorado SPS-2 test sections (Suthahar et al. 2000). Based on the analysis of Michigan test sections, it was found that the undrained sections have higher roughness compared to those with drainage. Early age cracking in some Michigan sections with LCB was related to shrinkage cracking in LCB. At the time of analysis, the Colorado test sections showed comparable performance, however based on analysis of the deflection data, use of a widened slab was "highly recommended".

3.3 EFFECTS OF EXPERIMENTAL FACTORS ON RIGID PAVEMENT PERFORMANCE

Findings from studies that dealt with SPS-2 data were presented above. Based on a review of the literature that is relevant to the objectives of the SPS-2 experiment, the understanding of the effects of these factors was studied and is presented below.

3.3.1 Effect of structural factors

In a study that was based on analysis of LTPP data from concrete pavement sections (JPCP), it was found that key design and construction features significantly affect JPCP performance (Khazanovich et al, 1998). The "general order of impact on performance" of the design factors (included in SPS-2) is as follows:

1. Subdrainage,
2. Base type and modulus,
3. Slab widening,

4. Slab thickness, and

5. Slab modulus/strength.

The effects of each of these factors, based on the literature review, are summarized below:

Effect of drainage: It is common practice in many states to incorporate positive subsurface drainage into new pavements (Forsyth et al. 1987; NCHRP 2002). In order to estimate the cost-benefit aspects of the provision of drainage, an understanding of the precise effects of drainage on long-term pavement performance is required.

In the SPS-2 experiment, drainage is provided to sections with PATB. In comparison to sections with PATB are the sections with DGAB, to study the effect of drainage. The type of drainage system planned for SPS-2 is considered the most positive drainage system (Forsyth et al. 1987; Hagen and Cochran 1996) with a minimum laboratory permeability value typically around 300 m/day (Mallela et al. 2000). It can also be cost-effective in addition to being beneficial to pavement performance according to research conducted under the project NCHRP 1-34 (NCHRP 2002).

Drainage is considered as one of the important factors that can reduce wide variability in the overall performance of concrete pavements (Ring III 1977). In undrained pavements, all the layers will be subjected to flooding for a minimum of a few weeks in arid areas and many months in wet climates. Water trapped in a pavement is a major contributor to poor performance as the action of loads on an inadequately drained pavement can reduce subgrade support causing pumping, and also redistribute the subgrade and subbase materials causing faulting (Cedergren 1988; Ring III 1977). In well-drained designs all layers above the drainage layer will be moist, not fully saturated, most of the time thereby decreasing the chances of rapid deterioration due to traffic (Cedergren 1988). It was found through field experiments that about 40% of rainfall gets into the concrete pavement and also that spring thaw flows are roughly equivalent to a major rain event (Hagen and Cochran 1996). The action of in-pavement drainage can reduce the saturation time under the concrete by a factor of 10 to 100 (Ray 1981b).

It is believed that in many cases one of the best ways to improve performance at a relatively low additional cost is to provide a drainage system (Cedergren 1988; Fleckenstein and Allen 1996; Mallela et al. 2000; Ray 1981b). Reduction in pumping, faulting, cracking, and D-cracking was observed as an effect of drainage in various studies (Fleckenstein and Allen 1996; Forsyth et al. 1987; Harvey et al. 2000; NCHRP 2002; Peshkin et al. 1989; Smith et al. 1997; Tart Jr. 2000). In addition to having lesser distress, pavements with edge drains have significantly lesser growth in roughness (Khazanovich et al. 1998) and higher subgrade strength (Fleckenstein and Allen 1996). Though drainage systems are known to be beneficial to concrete pavements, drainage is not a substitute for poor pavement design and for a drainage system to be effective other design features that help minimize moisture intrusion should be present (Mallela et al. 2000).

<u>Effect of base type</u>: Slabs on different types of bases will have different mechanistic response under same load (Wu and Qian 1997). The slab-base interface friction, erodibility, stiffness, and drainability of a base are the main characteristics that influence the performance of concrete pavements (Smith et al. 1989). While the erodibility of a base course determines the amount of support available to the slab during wet conditions, stiffness of the base layer influences stresses and deflections of the slab. Drainability of a

pavement determines the amount of time for which water is present at the slab-base interface and thus a highly drainable base would result in better performance compared to an undrained one. In light of the wide variation in the types of bases, base type is known to be an important factor in determining concrete pavement performance (Khazanovich et al. 1998; Smith et al. 1997; Wade et al. 1995; Wu 1992), especially in terms of cracking, faulting and spalling (Smith et al. 1989).

In the SPS-2 experiment, three types of base types are included— DGAB, LCB and PATB. Table 3-1 is a summary of relative advantages and disadvantages of these base types, along with design considerations. In comparison with stabilized bases, DGAB is known to be more erodible and to have lesser stiffness. It is undesirable according to some experts to design untreated bases, unless it is of high quality and is equipped with drainage, for pavements with heavy traffic, especially in severe climate. In view of less erodibility and greater stiffness of stabilized bases, they have been in use for pavements with heavy traffic (Ray 1981a; Ray 1981b; Wade et al. 1995). When a good drainage system is provided, the stabilized bases are more beneficial. However, stabilized bases can cause uncontrolled early cracking because of higher slab-base friction and bonding at the interface (Voigt 2000). Uncontrolled cracking during early age is often the cause for poor performance of concrete pavements (Forster 2000). LCB is known to have early occurrence of cracks owing to shrinkage and some analytical designs have thus suggested a two stage approach for its design— the first to deal with "primary cracking" and the second to tackle "secondary cracking" (Brown 1979).

As a result of a major national field study it was found that permeable bases are "very good", DGAB is "good" and LCB is a "poor" base (Smith et al. 1989). While LCB was associated with "considerable" pumping, faulting and cracking, PATB sections had virtually no faulting, cracking or spalling. DGAB was found to be "generally fair to very good" with open-graded ones performing better than others. Poor drainage of LCB was considered to be the reason for its poor performance. Similar results were obtained in a study on LTPP pavements (Khazanovich et al. 1998).

Large curling and warping stresses are also associated with slabs constructed on LCB, owing to the high slab-base friction offered by LCB. In the US, reflection cracking that may result from friction between slab and LCB is prevented by breaking the bond (Smith et al. 1997). However, in Germany the two layers are allowed to remain bonded, and the LCB layer is notched to coincide with joints in the slab (Springenschmid and Fleischer 2001). This allows the transverse joints to open up uniformly while allowing for monolithic action of the slab-base system.

In contrast to LCB, DGAB was found to contribute the least to curling and warping in slabs. Bases with stiffness between 800 and 1100 psi, such as LCB and econocrete, can significantly increase stresses in slabs during early ages (Armaghani 1993; Harvey et al. 2000). Separation of the slab from the LCB was also observed from a study, which could be because the LCB does not conform to the shape of the deformed slab (Hansen et al. 2001; Wu and Qian 1997). This action results in loss of support for the slab and affects the slab's response to loading.

Contrary to the findings mentioned above, some studies have indicated that PATB may not be cost-effective while LCB can be cost-effective when doweled joints and shorter joint spacing are designed (Gharaibeh and Darter 2001).

Effect of PCC slab thickness: The effect of PCC slab thickness is perhaps the best understood among the main design features of the SPS-2 experiment. In the experiment, two levels of PCC slab thickness are present— 203 mm (8-in) and 279 mm (11-in). As mentioned before, the 76 mm (3-in) difference was planned to allow for interaction of this factor with other factors in the experiment.

Field studies have shown that regardless of the site conditions, slab thickness plays a significant role in pavement performance with thicker slabs showing less distress, especially cracking (Smith et al. 1989). The effect of increasing slab thickness, from the same study, was found to be more noticeable for thinner pavements than for thicker pavements. However, based on a study of LTPP concrete pavements, it was found that slab thickness did not show "much significance" in the general data analysis (Khazanovich et al. 1998).

Though thicker slabs have more fatigue life than thinner slabs for a given traffic loading, it is to be noted that usually pavements seldom fail in fatigue (Armaghani 1993). Most failures are direct consequences of design and construction issues.

Table 3-1 Summary of PCC Pavement Base Types (Smith et al. 1997)

Base Type	Advantages	Disadvantages	Key Design Considerations	Recommended Traffic Levels
Permeable Base (*stabilized and nonstabilized*)	• Removes water from pavement • Low susceptibility to erosion • Decrease in moisture-related distresses (faulting, D-cracking, etc.)	• Difficult to construct (*particularly nonstabilized*) • Granular separator layer required • May have to limit construction traffic • High cost (from 14 to 24 percent greater than conventional aggregate base)	• Design of separator layer • Collect/outlet pipe design • Adequate stabilizer contents (*generally 200-250 lb/yd*^{3} *of cement or 2-3% of asphalt*) • Compaction/curing	Medium to High
Lean Concrete	• Easy to construct • Strong stable platform • Strong resistance to erosion • Improves pavement rideability • Reduces slab stresses (*if bonded*)	• High cost (about 22 percent greater than conventional aggregate base) • Increased friction with slab • Increases slab curling/warping • Granular subbase required to prevent pumping	• Shorter JPCP joint spacing • Curing of base • Bonding of base • Notching of joints in base if bonded • Match longitudinal joints	Medium to High (*with granular subbase*)
Dense-Graded Aggregate	• Easy to construct • Low cost • Low friction with slab	• Susceptible to erosion • May retain moisture for long periods	• Compaction (*to 95% of AASHTO T180*) • Controls on liquid limit, plastic limit, and percentage of fines	Low to Medium

Effect of PCC flexural strength: In the SPS-2 experiment, PCC flexural strength has two levels— 3.8 MPa (550 psi) and 6.2 MPa (900 psi), at 14 days. Through the experiment, the effect of this factor on long-term pavement performance is being studied. Though the experiment includes flexural strength as the only PCC material property, it is to be noted that other PCC properties such as transport properties, elastic modulus, coefficient of thermal expansion, drying shrinkage, and entrained air void system significantly affect pavement performance (Hansen et al. 2001). However, PCC fatigue is typically related to flexural strength.

In concrete applications other than in pavements, the use of high strength concrete is on the rise (Hansen et al. 1998). There is lack of sufficient information on the effects of high strength concrete on pavement performance and pavement engineers are usually reluctant to consider using higher than normal (28 MPa) concrete for typical pavement applications. In case of good design and construction practices normal strength concrete can produce excellent pavement performance, however, higher strength concrete may be advantageous to control cracking due to loss of support (Hansen et al. 2001; Harvey et al. 2000).

Presently, for pavement applications, concrete mixes are designed to develop 17 to 20 MPa (2500 to 3000 psi) of compressive strength at early age (1 to 3 days), for reducing user costs by opening pavements early to traffic (Armaghani 1993; Harvey et al. 2000). Design compressive strength for high strength concrete is usually 55 to 75 MPa (8000 to 10900 psi, approximately). Higher strength concrete is known to have the benefits of higher resistance to physical and chemical deterioration as the permeability of high strength concrete is lower than normal concrete (Hansen et al. 2001). From a study on LTPP concrete pavements, it was found that the main distress affected by concrete strength is transverse cracking i.e. concrete with lower strength has more cracks in comparison to concrete with higher strength (Khazanovich et al. 1998).

This high strength is obtained by increasing the cement content in the concrete mixture. Higher the cement content higher is the heat development in the mixture during hydration. Field surveys have shown "strong evidence" of its negative effects, major problem being early age (within one year) mid-slab transverse shrinkage cracking (Armaghani 1993). Temperature control during hydration is thus an important issue for high strength concrete to control drying shrinkage and in turn cracking. Current specifications, however, neglect many of the early age environmental effects on performance of PCC pavements (Grater et al. 1999).

<u>Effect of slab width</u>: Displacement and deformations in the slab play a major role in creating critical conditions for occurrence of distress (Armaghani 1993). Widened slabs are usually used in truck lanes to significantly reduce the edge stresses and corner deflections caused by heavy loads (Ray, 1981), and increase the fatigue life of the pavement (Harvey et al. 2000). The design is also cost-effective compared to standard slab width designs according a study (NCHRP Research Results Digest, 2002). This design has been in use in Europe since early 1970s (Ray 1981b). In the SPS-2 experiment, slab width, sometimes referred to as lane width, has two levels— 3.7 m (12-ft) and 4.3 m (14-ft).

Widened slab pavements have shown lesser distress (pumping and corner cracking) and better ride quality compared to pavements with standard slab width (Armaghani 1993). Widened slab also reduces both faulting and cracking, irrespective of site conditions, and increases JPCP life by 5 to 13 years (Gharaibeh and Darter 2001). However, from an early analysis of LTPP data from SPS-2 experiment, it was found that longitudinal cracking is more prevalent in widened slab sections in comparison with those with conventional width, among sections with thinner slabs [203 mm (8-in)] (Gharaibeh and Darter 2001). In contrast to this finding, based on analysis of LTPP SPS-2 experiment in Colorado, widened lane sections are "highly recommended" for increasing the load carrying capacity of the pavements (Suthahar et al. 2000).

Widened slab may also have an important role in reducing faulting and pumping. In a research concerned with pumping hydrodynamics, it was found that the water ejection rate from leave slab toward approach slab is lower by 50% for pavements with widened slab (Ray 1981b). Also, the reduction in water ejection rate from leave slab to shoulder is 30%.

3.3.2 Effects of site factors

As mentioned earlier, the subgrade soil type and climate are the site factors in the SPS-2 experiment. The effects of site factors on concrete pavement performance are known to be significant. However, as the designer cannot control these factors, appropriate modifications should be made in the design based on an understanding of the effects of site factors. The effects of site factors, based on the literature review, are summarized below:

Environment is one of the three "best-known causes" of pavement damage, the others being traffic loads and poor materials (Hudson and Flanagan 1987). All the three causes interact to cause pavement damage; however, the extent of interaction differs based on conditions. The most important agents of environment are moisture and temperature. While moisture causes several problems including warping, base/subbase failure, freeze-thaw effects, and swelling; temperature differentials cause curling stresses in the slab. Temperature conditions at the time of paving influence the extent of locked-in gradient at the time of setting of concrete (Rao et al. 2001).

Based on a study on LTPP concrete pavements, it was found that wet-freeze (WF) climate with fine-grained soil is the "most critical" condition, while warm or dry climate with coarse-grained soil is the "most favorable" (Khazanovich et al. 1998). From the same study it was found that joint faulting is prevalent in WF climate while transverse cracking is critical in dry climates where higher thermal gradients exist.

Though the effects of environment are important, it should be noted that the environment can only exacerbate the effects due to traffic loadings, as found in a field study by Hudson and Flanagan (Hudson and Flanagan 1987).

The effect of subgrade soil type on pavement performance is often influenced by the climatic conditions. However, in general, fine-grained subgrade soil causes faulting due to greater erodibility and volume changes with moisture (Khazanovich et al. 1998). Fine-grained soils under severe climatic conditions provide non-uniform support and may cause corner cracking and pumping.

Most of the studies discussed above are limited in scope. The studies that analyzed SPS-2 data suffer from limited statistical rigor and/or from lack of enough data. The other studies that were conducted to study the effects of design features on rigid pavement performance are observational, in addition to being restricted in scope. A controlled field experiment was required to determine precisely the main and interactive effects of the strategic design and site features. The SPS-2 experiment was proposed and constructed in light of this need.

This thesis presents results on the effects of experimental factors based on a comprehensive analysis of data (contained in Release 17 of DataPave) from the ongoing SPS-2 experiment. The methodology presented in the thesis would be valid for analysis of typical in-service pavement data.

CHAPTER 4- DATA AVAILABILITY AND EXPERIMENT REVIEW

4.1. INTRODUCTION

This chapter presents a summary on data availability and a synopsis of a review of the experiment. While information about data availability is useful in defining the scope of the study, a review of the experiment with respect to the guidelines, is important in identifying deviations, if any.

Release 17 of DataPave was the primary data source for this study. Data from previous releases of DataPave, and other sources were used only to supplement the data from the Release 17. The construction information for each site was obtained from the construction reports. The essential data required for this study can be broadly classified into following categories:

- *Site Information*: site information, construction issues, climatic and traffic data.
- *Material Data*: Material type and properties for various bound and un-bound pavement layers.
- *Pavement Structure*: Layer type and thickness information and other design features such as lane width, shoulder type and dowel bar diameter etc.
- *Monitoring Data*: Longitudinal and transverse profiles, distress and deflections.

The availability of data grouped under each of the above categories is presented next, followed by a summary of a review of the experiment using the available data.

4.2. ASSESSMENT OF DATA AVAILABILITY

The variables corresponding to the SPS-2 experiment can be divided broadly into two categories- dependent variables, and independent variables. The dependent variables are those used to describe pavement response and performance. A majority of pavement responses are surface deflections from Falling Weight Deflectometer (FWD) testing. Measures of pavement performance are those that cumulate with time (e.g., cracking).

The independent variables are those that describe the design and construction factors. These can be divided mainly into main, and exogenous (or confounding) variables. Main variables are those that are controlled in the experiment, whereas the variables that have potential impact on pavement response and performance but are not controlled in the experiment design are exogenous variables. Exogenous variables that are independent of the main experiment variables are traffic and age. All other exogenous variables are associated with the main design and construction variables. These include material properties of the various pavement layers, which constitute the structural factors in the design matrix, and the climatic factors, which describe the four climatic zones in the matrix.

After identification of all the relevant variables, a database was developed for the analysis. For cases where multiple data values were available for a data element, the values were averaged to obtain a best estimate. For example, IRI values corresponding to a survey were averaged over several runs. The availability of relevant data elements is discussed in detail in the subsequent sections.

4.2.1. General Site Information

The information that is common to all sections at a test site has been categorized under this heading.

Construction Reports

The construction reports contain information related to pavement geometry, construction issues (and deviations, if any), traffic, environmental conditions during construction, and material quality control data. These reports are available for all the sites in the experiment. Details of the construction issues are available elsewhere (Desaraju 2003; Chatti, Buch et al. 2005).

Climatic data

In the LTPP database, climatic data is available from two sources- Virtual Weather Station (VWS) and Automated Weather Station (AWS). The climatic zones in LTPP are defined based on two parameters- average annual precipitation and average annual freezing index. These two variables were used to confirm the climatic classification of each site. As data for all the sites were not available from Release 17 of DataPave, DataPave 3.0 data were used to complete the data.

Traffic data

The traffic data available in the LTPP database are presented in three forms- monitored (M), estimated (E) and axle distribution (A). Traffic data availability is shown in Table 4-1. Traffic being one of the most important factors that impact pavement performance, inconsistency in traffic data was compensated, to some extent, by estimating traffic, called 'proposed' traffic (Chatti, Buch et al. 2005), for each of the sites based on the three sources of traffic data. The 'proposed' traffic was used as a covariate in all statistical analyses to adjust the dependent variable according to the variation in traffic across sites.

Traffic opening date is the date on which traffic was allowed to pass over the newly constructed test sections. This data is available in the database for all the sites. The age of a section was calculated using this date and the corresponding last distress survey date. In other words, age is defined as the latest age for which distress data are available.

Table 4- 1 Summary of traffic data availability

Site	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
4		E	M, A	M, A	M, A	E	E	NO	NO	NO	NO
5				NO	M,E,A	A	M,E,A	A	A	A	A
6	NO										
8		NO	E	M, A	M, A	M, A	A	A	A	NO	NO
10					NO	E	NO	NO	NO	NO	NO
19			NO	E	M	M,A	NO	NO	A	A	A
20	E, M	E,M,A	E, M	E	E	E	E	E	E	NO	NO
26		M, A	M, A	M	M	M	M	NO	A	A	NO
32				NO	E	M,A	NO	A	A	NO	NO
37			M, A	M, A	E, M	E,M,A	E,M,A	E,M,A	A	A	A
38			NO	E	E	E	E	E	E	E	NO
39					NO	NO	M, A	NO	A	A	A
53				NO	E	E, A	M, A	A	A	A	NO
55						NO	NO	NO	NO	A	NO

Note: 'E' indicates availability of estimated traffic data, 'M' indicates availability of monitored traffic data, and 'A' indicates availability of Axle-distribution data.

Material data

Data pertaining to materials used in the construction of pavement sections have been categorized as materials data. The data that were used for this study include the gradation of subgrade soil (percent passing #200 sieve) and PCC (mix design information and properties, and PCC strength data), apart from strength testing results of lean concrete.

Subgrade

Subgrade soil data in the form of percent passing #200 sieve (available for all sites) were used to classify subgrade soil as either "fine" or "coarse", based on Unified Classification system, and compare results with subgrade soil classification data that are available from other sources in DataPave.

Lean Concrete

The compressive strength data for LCB are available for 96 % of the sections. The 7-day compressive strength was used to compare with the specified target strength of 3.5 MPa.

Portland Cement Concrete

All the details of PCC mix design such as cement content, aggregate content (coarse and fine), water content, and additive type are available for all sites except WI (55). For most of the sites which have data, two types of mixes were used, one for each of the two levels of target 14-day flexural strength. In DE (10) more than two types of mixes were used, and PCC mix design data are available for all the sections. Though not a part of the experiment design, PCC compressive strength, split tensile strength, and modulus of elasticity are also reported in the database. The mechanical properties of concrete were recorded at 7, 14 and 365 days after casting. Compressive strength and split tensile strength data from testing of core samples are also available. Table 4-2 is a summary of data availability for PCC mechanical properties (except for flexural strength) from DataPave Release 17.

Only 52% of the sections in the SPS-2 experiment have 14-day flexural strength data. Data for sections in CA (6) and ND (38) are not available. The 14-day flexural strength data were used for comparison with specified target strengths. Table 4-3 is a summary of flexural strength data availability.

Coefficient of thermal expansion (CTE) of PCC is an important requirement for conducting a thermal analysis. CTE data are unavailable in DataPave of Release 17. Data were obtained from Portland Cement Concrete Pavements, FHWA. However, CTE data was available only for 16 sections, precluding any rigorous analysis based on the data. Table 4-4 below is a summary of CTE data obtained from FHWA.

Table 4- 2 Summary of data availability (percent of sections) for PCC properties

Site ID	Compressive Strength		Tensile Strength		Elastic Modulus
	Core	Fresh	Core	Fresh	
4	83	50	92	50	92
5	0	0	0	0	25
6	25	50	50	0	100
8	92	100	92	100	100
10	50	50	67	25	42
19	83	50	100	50	100
20	0	92	0	83	0
26	42	42	42	42	50
32	92	50	92	50	92
37	0	50	75	0	100
38	25	0	25	0	100
39	92	50	75	42	83
53	92	58	100	58	100
55	0	0	0	0	100

Table 4- 3 Summary of availability (percent of sections) PCC flexural strength data

Site ID	% of sections with data		
	14-day	28-day	365-day
4	75	75	75
5	58	58	58
6	0	0	0
8	100	100	92
10	50	50	50
19	50	50	50
20	100	100	92
26	42	42	50
32	50	50	50
37	25	33	42
38	0	42	92
39	50	50	50
53	58	58	58
55	58	58	0

Table 4- 4 CTE data obtained from FHWA

Site ID	Aggregate Type	SHRP ID	CTE, in/in/°C
5	-	0215	10.2
5	-	0220	11.3
10	Diorite	0205	11.6
10	Diorite	0208	9.2
10	Diorite	0211	9.5
19	Limestone	0224	9.6
20	Limestone	0207	10
20	Limestone	0208	10.65
32	-	0203	10.9
32	-	0208	13.9
32	-	0209	11.1
37	Granite	0203	8.9
37	Granite	0204	11.9
39	Limestone	0204	10.2
55	-	0222	8.8
55	-	0223	9.8

Pavement Structure data

All data that relates to the structure (cross-section) of the pavement sections have been categorized as pavement structure data. This data has been used to compare as-designed thickness with as-built thickness, for the sections. Information about layer type and thickness is available for all test sections in the experiment. Information about the size and spacing of dowel bars is available for all the sections except for 4 sections (0205 through 0208) in WA (53). Though not a part of the experiment design, details about the shoulders have been obtained.

Monitoring data

All data that are collected during distress surveys and during FWD testing has been categorized as monitoring data. Longitudinal profile data, distress data, faulting data, and deflection data fall under this category. These data are available for all the sections in the experiment. Table 4-5 is the summary of data availability (from Release 17 of DataPave) for all the types of data listed above.

Table 4- 5 Summary of data availability for SPS-2 experiment

Data category	Data type	Data availability, % of sections
Site information	*Construction reports*	100
	Climatic data	
	Virtual Weather Station	
	Annual Temperature	93
	Annual Precipitation	93
	Automated Weather Station	
	Monthly Temperature	93
	Monthly precipitation	93
	*Traffic data**	
	Traffic Open date	100
	Monitored	65
	Estimated	71
	Axle Distribution data	78
Materials data	*Subgrade*	
	Sieve analysis	53
	Classification	100
	Backcalculated moduli	0
	Lean Concrete Base	
	Compressive Strength	96
	Portland Cement Concrete	
	PCC mix data	100
	14-day Flexural Strength	52
	Compressive Strength	92
	Split tensile Strength	91
	Static modulus of Elasticity	78
	CTE	0
	Unit weight	63
Pavement structure	*Layer details*	
	Type	100
	Representative thickness	100
	Dowel bar details	
	Diameter	98
	Length	98
	Spacing	98
	Shoulder information	
	Type	93
	Width	93
	Thickness	93
Monitoring**	*Profile data (IRI)*	100
	Distress data	100
	Faulting data	100
	FWD data	
	Deflection	100
	Temperature during testing	100

Note:

* Monitored, Estimated, or Axle Distribution data is considered to be available for a site even if the data is available only for one year.

** Data is said to be available for a section even if it is available for just one year.

4.3. EXPERIMENT REVIEW

As mentioned earlier, guidelines were developed by LTPP for controlling variability in the experiment so as to allow for manifestation of "pure" effects. If some deviations occur, it is important that those are addressed in the analysis. So as to identify deviations, if any, in the SPS-2 experiment, a review of the experiment was conducted using the available data. The results from this review are presented here. A brief discussion on the construction issues (from construction reports) will be followed by a discussion on the deviations in the design and site features.

4.3.1. Construction Deviations based on Construction Reports

Information regarding construction issues was obtained from the construction reports. A design versus construction review for each site can be found in the appendix. Some of the major issues in the SPS-2 experiment are below:

- Shrinkage cracks in LCB were observed soon after construction at sites in AZ (4), CA (6), DE (10), MI (26), NV (32), NC (37), ND (38), and WA (53).
- PCC mixes that were different from what was stipulated were used at sites in DE (10) and NV (32). In DE, all the 550-psi PCC has been replaced with the Delaware DOT Type 'B' mix that gives a flexural strength of approximately 650 psi. Some SHRP 900-psi concrete was also replaced (sections 0202 and 0206), with 900-psi mix with 7.5-bag mix, after breaking and removing cracked PCC. In NV, The sections that were supposed to have PCC of 550-psi 14-day flexural strength have a 475-psi mix and the sections with target 14-day flexural strength of 900-psi have a 750-psi mix.
- Construction delays occurred due to bad weather at sites in MI (26) and ND (38).

- Improper size dowel bars were used at sites in CA (6) and NC (37) sites. At the site in CA (6), 32 mm and 38 mm diameter bars were used in both thinner and thicker slab sections. At the site in NC (37), all the sections were constructed with 38 mm –diameter dowel.
- Underground structures were present at sites in IA (19) and KS (20) within the monitoring length of the sections.
- Repairing (such as Partial depth repairs, full depth repairs, crack sealing, and shoulder restoration) was done to some sections [20-0201, 32-0201, and all the sections at the sites in AR (5) and ND (38)] after opening the sections to traffic.

4.3.2. Design versus Construction Review based on Data

The experiment review using the available data was done for those factors in the experiment that are bound by the guidelines. These features are subgrade soil type and climatic zone, which are site factors, and, layer thickness and flexural strength, which are design factors. In addition, a review of the status of the experiment in terms of traffic and age was performed.

Site Factors

Subgrade type: In AR (5), sections 0222 and 0223 were constructed on fine-grained soils while all the other 10 sections were constructed on coarse-grained soils. Similarly, in NV (32), sections 0201 and 0205 were built on coarse-grained soils whereas the other 9 sections were built on fine-grained soils. At the CO (8) site, 5 sections were constructed on coarse-grained soils while the other 7 were constructed on fine-grained soils. At other sites, all the sections were constructed on same type of subgrade soil.

Climatic zone: The climatic data (VWS data) were used to categorize sites into 4 climatic zones according to the LTPP definitions for climatic zones. Figure 4-1 is a scatter plot showing all the sites in the experiment and LTPP criteria (reference lines at 508 mm and 83.3 °C-day) regarding climatic zones.

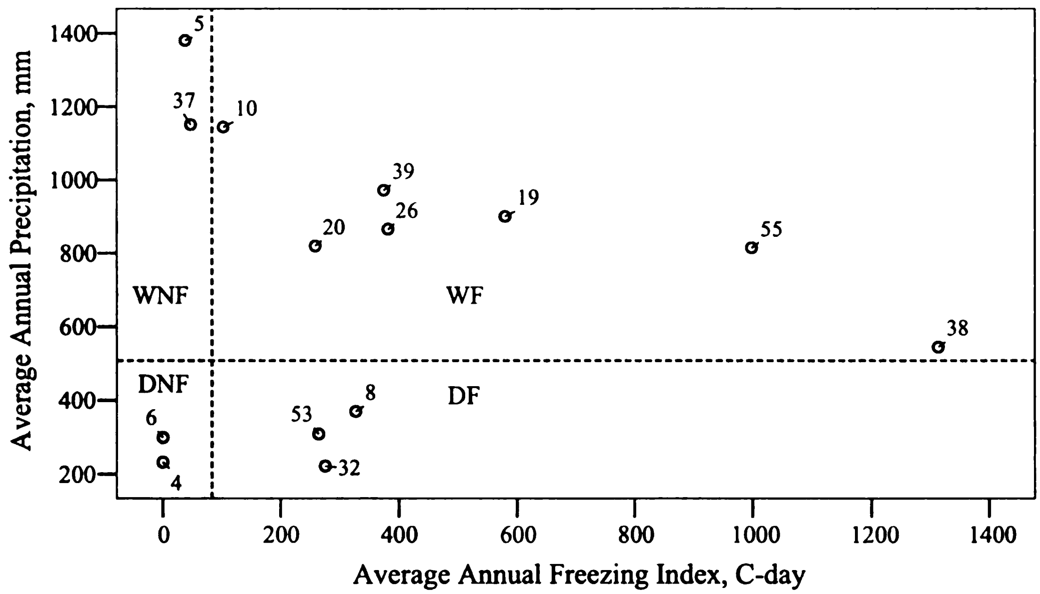


Figure 4-1 Distribution of SPS-2 sites with respect to climate

Though the SPS-2 sites were found appropriately classified, it is evident from the figure that some sites [AR (5), DE (10), NC (37), and ND (38)] are on the fringes of the climatic zones. Thus the effects of the climatic zones, as defined by LTPP, may not be easily discernible because wide variation exists within each zone.

Design Factors

PCC slab and DGAB thickness for the test sections were compared with their respective target thickness. Table 4-5 is a summary of a comparison between as-designed and as-constructed thickness, for PCC layer and the base layers.

PCC thickness: The experiment has two levels of PCC thickness- 203 mm and 279 mm. The allowable deviation from the target PCC thickness according to the guidelines is 6.4 mm (0.25 in) (SHRP, 1986). Among sections with target thickness of 203 mm, only 28 sections (33 %) conform to the allowable deviation of 6.4 mm. The remainder of the sections (67%) was built either thicker or thinner by more than 6.4 mm. Figure 4-2 is the cumulative frequency graph of PCC thickness. Among sections with a target thickness of 279 mm, 44 sections (53 %) conform to the allowable deviation of 6.4 mm. Figure 4-3 is the cumulative frequency graph showing the percent of sections and number of sections below the corresponding thickness values.

Base thickness: Though there are no guidelines limiting deviation from design thickness for LCB and PATB, the allowable deviation from target elevation for DGAB is 12.7 mm (0.5 in). Figure 4-4 is a cumulative frequency distribution of actual base thickness of DGAB sections (target thickness of 152 mm). About 80% of the sections built on DGAB have thickness that falls within the allowable range (see Table 4-6), as defined by the guidelines.

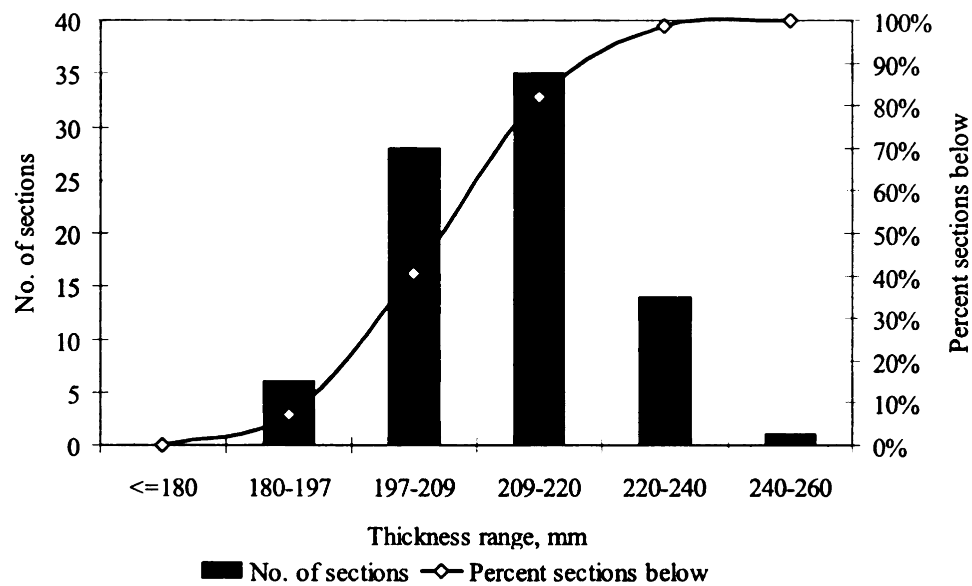


Figure 4- 2 Actual thickness of sections with target thickness of 203 mm

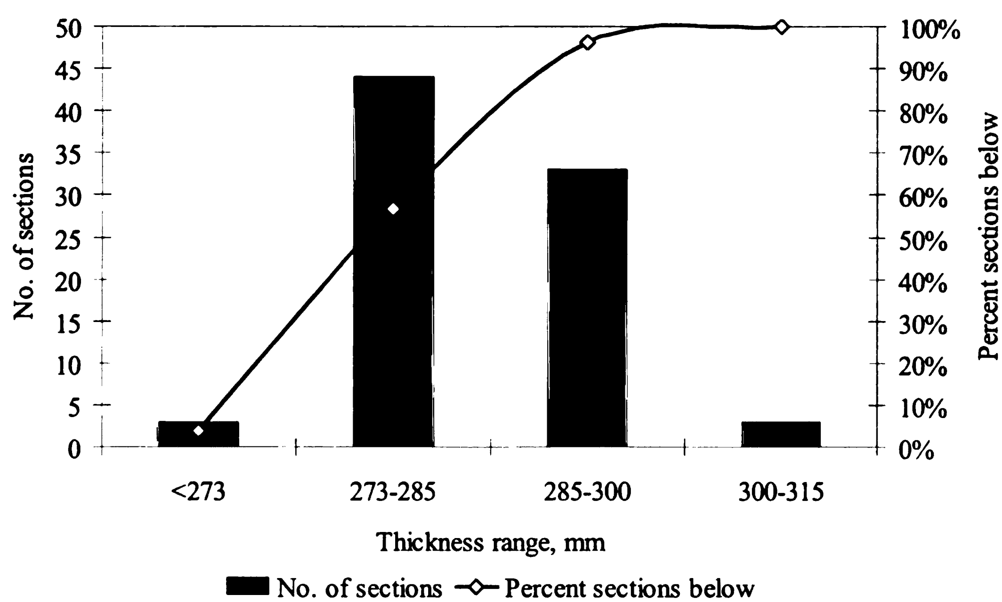


Figure 4- 3 Actual thickness of sections with target thickness of 279 mm

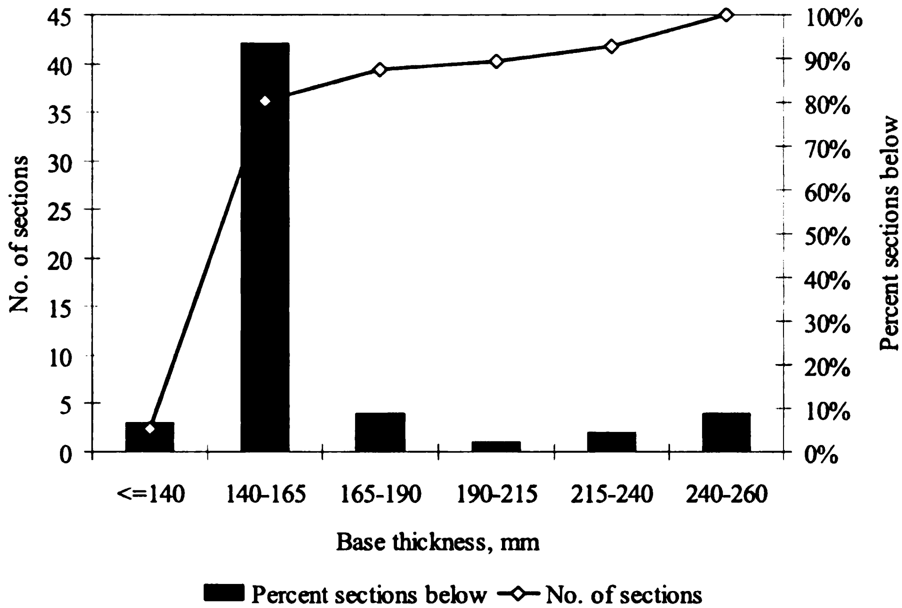


Figure 4- 4 Actual base thickness of sections on DGAB

Table 4- 6 Summary of deviation in thickness from design

Layer Type	Target Thickness, mm	Count, no. of sections	Mean, mm	Standard Deviation, mm	Coefficient of Variance, %	Below allowable range, % sections	Within allowable range, % sections	Above allowable range, % sections
PCC	203	84	212	12	5	7	33	60
	279	83	286	9	3	4	53	43
DGAB	152	56	163	34	21	4	80	16
LCB	152	56	160	10	6	-	-	-
PATB	102	55	101	14	14	-	-	-
DGAB below PATB	102	55	114	36	32	-	-	-

PCC Flexural Strength: At each site, 6 sections have a target 14-day flexural strength of 3.8 MPa (500 psi) and the other 6 sections have target 14-day flexural strength of 6.2 MPa (900 psi). Comparisons between the measured flexural strength and target 14-day strength were made. Figure 4-5 through Figure 4-10 are cumulative histograms for flexural strength at 14, 28 and 365 days.

It is evident from the plots that at 365 days most of the sections that failed to reach the target at 14 days have reached their target strengths. Among the sections with target PCC 14-day flexural strength of 3.8 MPa, 7 sections, of the 44 sections for which data are available, failed to meet the criterion of 3.4 MPa at 14-days. At 28-days, 1 of the sections failed to meet the criterion and at 365 days all the sections have met the criterion. Among sections with target 14-day PCC flexural strength of 6.2 MPa flexural strength data are available for 42 sections. Of these sections, 16 sections failed to meet the target of 5.6 MPa at 14-days. Eight sections met the criterion at 28 days and 5 more met the criterion of 5.4 MPa at 365 days.

Based on the flexural strength data available in Release 17 of DataPave, it thus seems that most of the sections met target strength not at 14-days but later. As it is safe to assume that the long-term performance is more affected by final strengths, these deviations may not affect the experiment significantly. However, if deviation from target strength were available for all sections, considering flexural strength deviation as a covariate in statistical analyses will be an option.

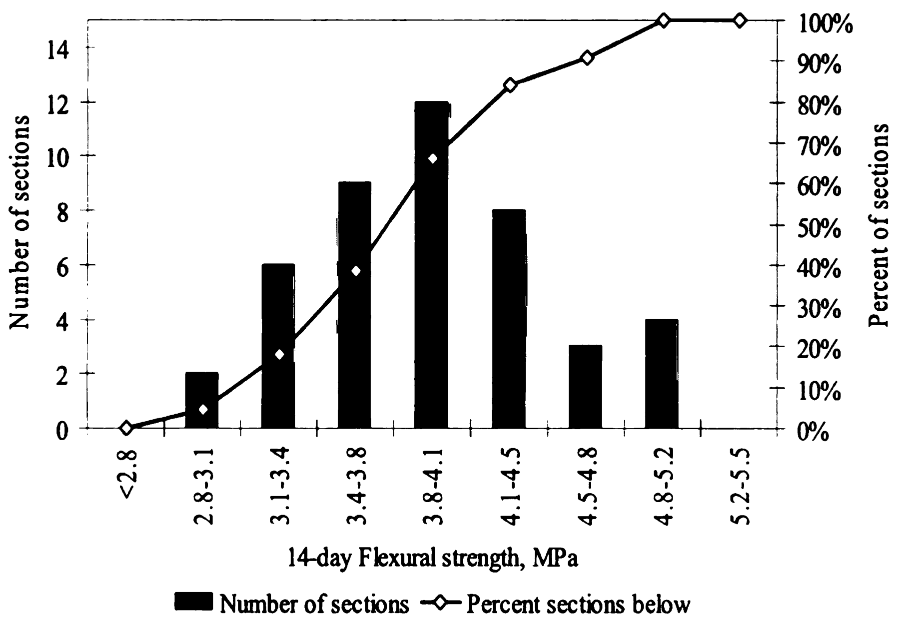


Figure 4- 5 14-day flexural strength of sections with target strength of 3.8 MPa

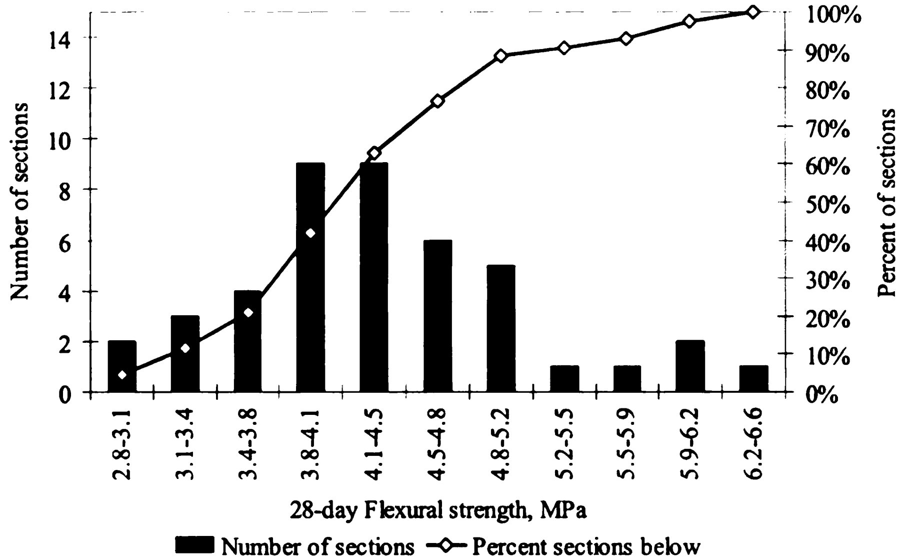


Figure 4- 6 28-day flexural strength of sections with target strength of 3.8 MPa

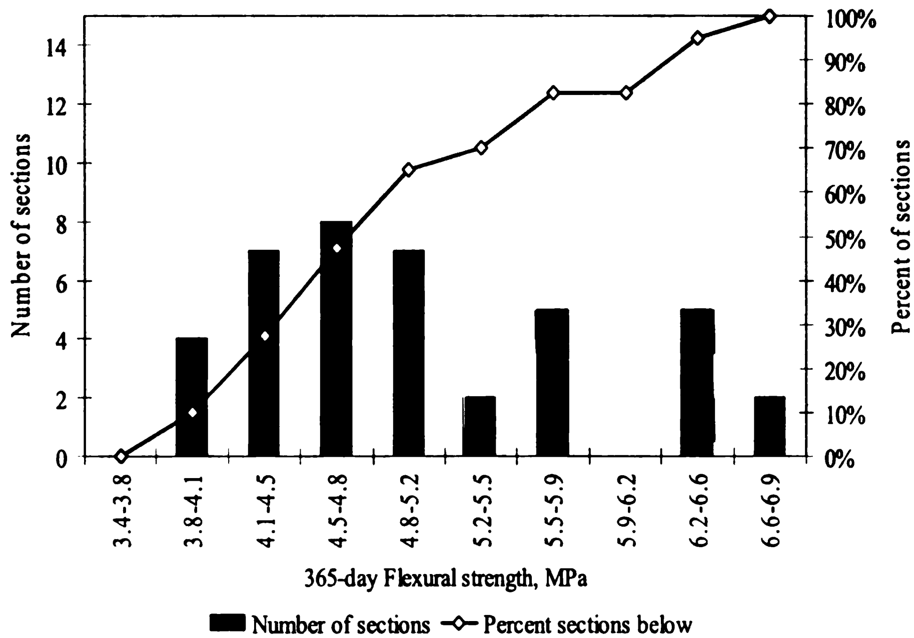


Figure 4- 7 365-day flexural strength of sections with target strength of 3.8 MPa

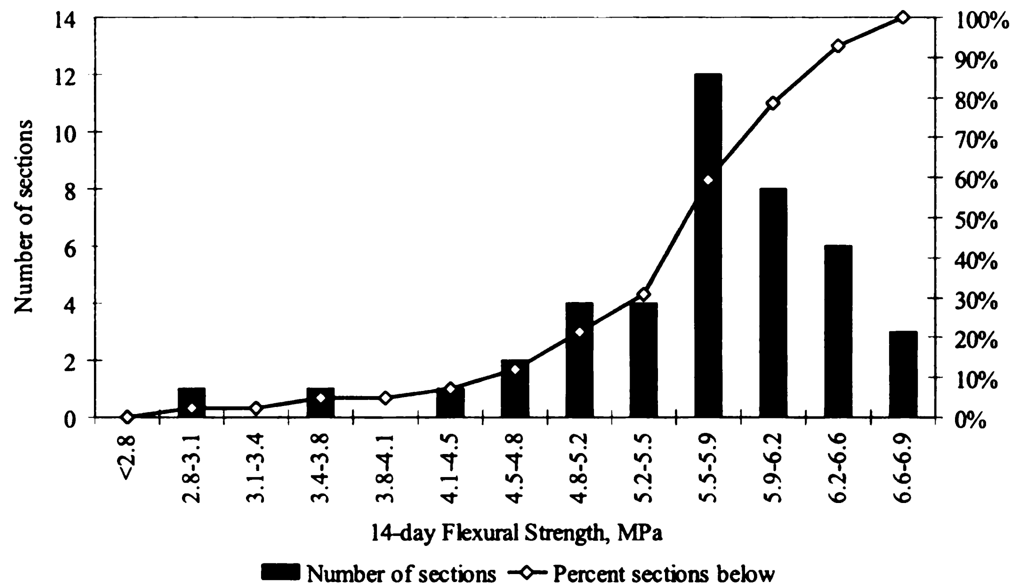


Figure 4- 8 14-day flexural strength of sections with target strength of 6.2 MPa

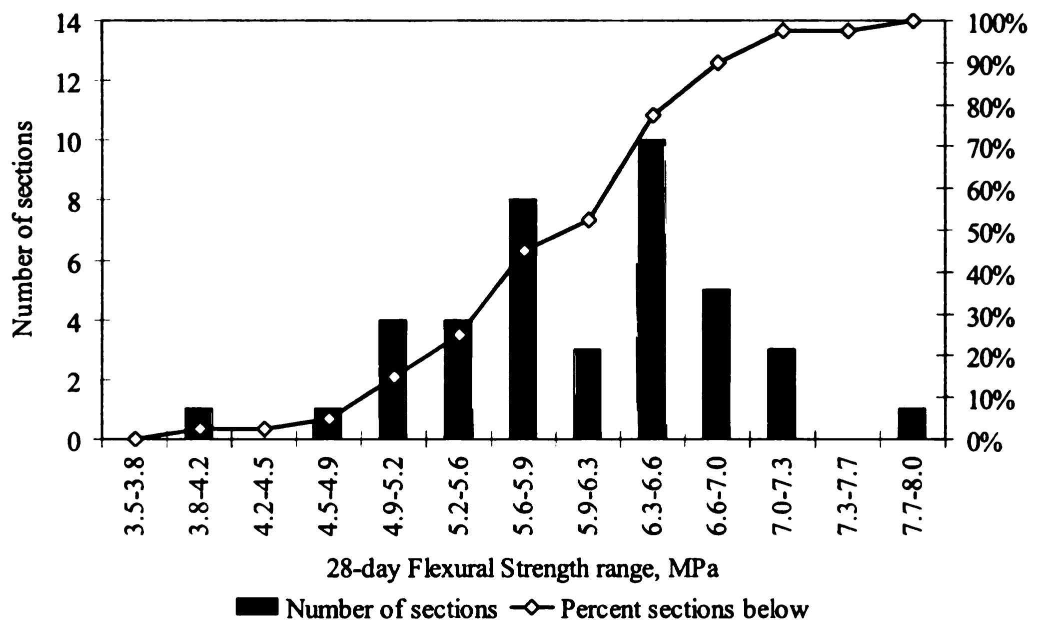


Figure 4- 9 28-day flexural strength of sections with target strength of 6.2 MPa

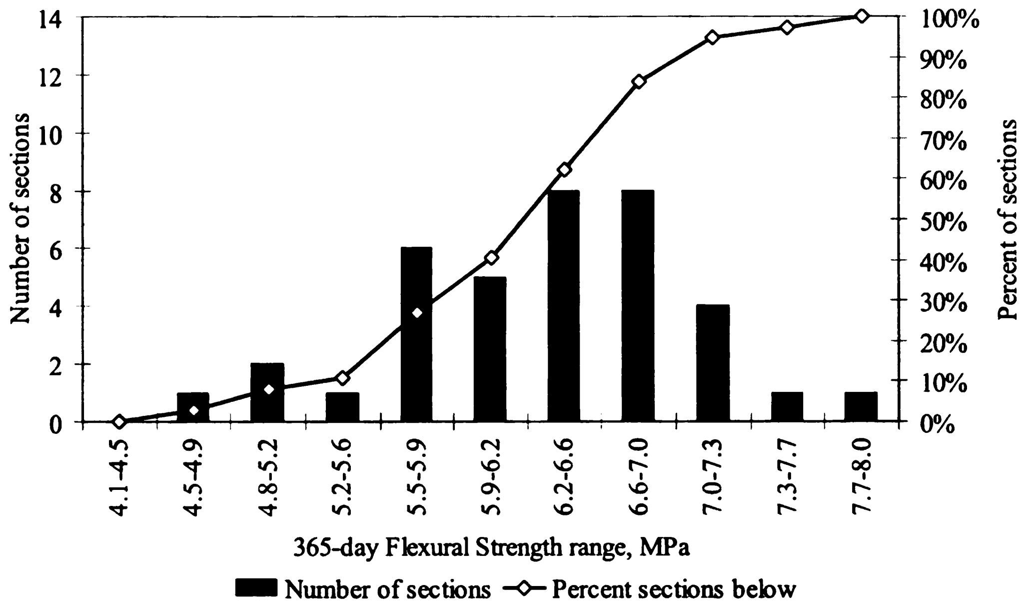


Figure 4- 10 365-day flexural strength of sections with target strength of 6.2 MPa

Miscellaneous features

Dowel diameter: It was stipulated in the guidelines (SHRP, 1986) that all the sections with 203 mm target PCC slab thickness have 32 mm diameter dowels while the sections with 279 mm have 38 mm diameter dowels. Improper size dowel bars were used at CA and NC sites. At the CA site, 32 mm and 38 mm diameter bars were used in both thinner and thicker slab sections. At the NC site, all the sections were constructed with dowels of diameter 38 mm. At all other sites no deviation was observed.

In addition to the factors discussed above, the status of the experiment in terms of age of the sites and the traffic at the sites was reviewed. Figure 4-11 shows the distribution of age among the SPS-2 sites. As mentioned before, age was calculated using the traffic open date and the latest distress survey. Similarly, Figure 4-12 shows traffic variation among the SPS-2 sites. From both the figures it is evident that there is considerable variation in age and traffic across sites.

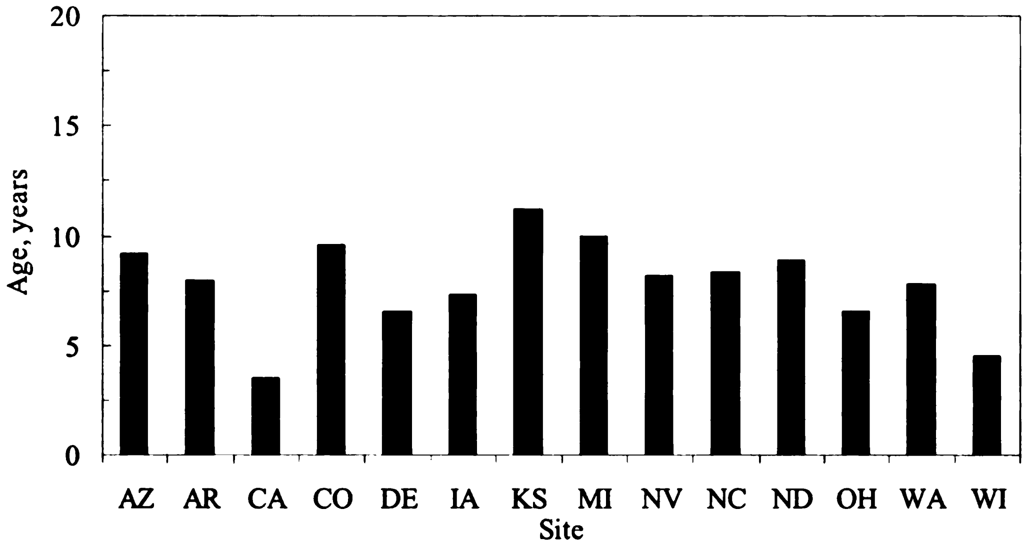


Figure 4- 11 Age distribution in the SPS-2 sites

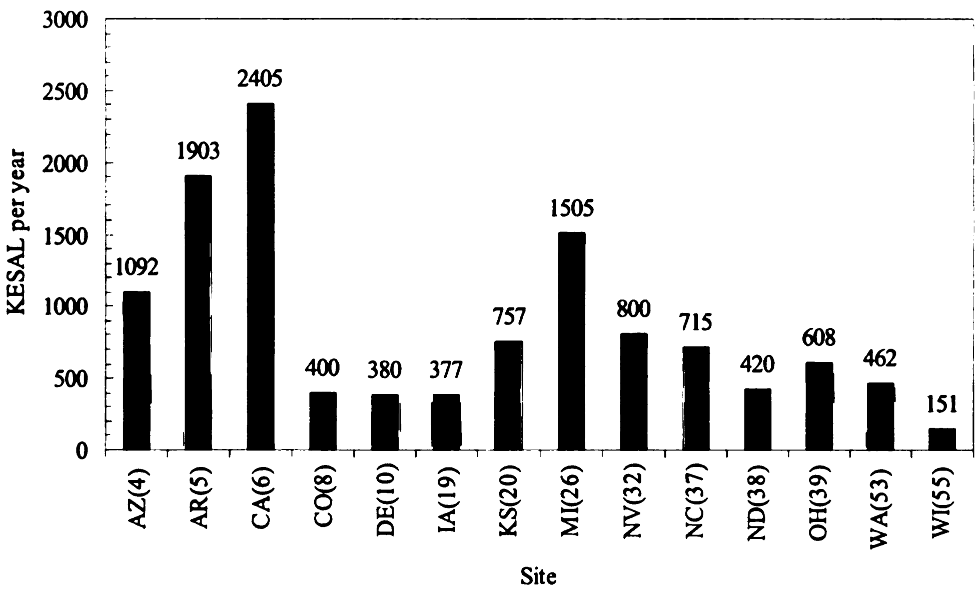


Figure 4- 12 Variation in traffic across SPS-2 sites

CHAPTER 5- EVALUATION OF KEY PERFORMANCE TRENDS

The effects of various design and construction factors on performance are manifested in the form of distresses, which are identified from condition surveys. For the LTPP studies, the condition of test sections, in terms of a suite of performance measures, is assessed from time to time and is made available through DataPave. Based on those data, a performance evaluation of the SPS-2 test sections was conducted and is presented in this chapter.

A general assessment of performance is followed by a detailed evaluation, based on "standards" developed by Khazanovich et al (Khazanovich, Darter et al. 1998). Depending on the extent of distress in the pavement sections, statistical methods were selected for analyses.

5.1. GENERAL ASSESSMENT OF PERFORMANCE

The overall performance of the SPS-2 test sections is "good". As mentioned before the age of the test sections ranges from 5 to 12 years with an average age of about 7.5 years. Given that the sections are "young", severe distress is not expected and the actual performance is in line with this expectation. Lack of distress could also be due to mild climate, over-design, and/or low traffic (Khazanovich, Darter et al. 1998).

Pumping, faulting, and cracking are the "common types of distresses" in jointed plain concrete pavements (Huang 1993). In addition to these distresses, corner breaks, blowups, spalling, durability cracking, sealant damage, and scaling are observed for rigid pavements.

While cracking occurred in about 30% of the sections, pumping occurred only in about 13% of the sections. Most of the pumping occurred at the site in Arkansas (5) where all sections but for one have length of pumping between 40 and 152 m. It is important to note that the definition of pumping in the LTPP also includes water bleeding which may not be as critical as pumping of fines along with water. In general, faulting in the SPS-2 sections is not significant.

While about 60% of the sections have spalling, only seven sections have corner breaks. Most of the spalling that was observed is longitudinal spalling, which occurred in 53% of the sections. Longitudinal spalling was found in 80% of the pavement sections that have transverse spalling. While most of the transverse spalling was low in extent, longitudinal spalling was about 8 m long on average.

None of the sections have durability cracking or blow-ups. However, scaling was observed in 13% of the sections and among those sections the average scaling is about 44 m^2. While transverse joint sealant damage, mostly of low severity, was observed in all the sections at almost all the joints, longitudinal sealant damage was observed in about 60% of the sections. On average, 162 m of sealant damage was observed in sections with longitudinal sealant damage. Longitudinal sealant damage usually accompanied pumping, in that 86% of the sections with pumping have sealant damage.

In light of this condition of the SPS-2 pavement sections, key performance measures were selected for analysis. The criteria for selection were the mechanism of distress, the relation of the distresses with the experimental factors, and the extent of occurrence of the distress. As spalling, scaling, and sealant damage are more related to PCC material and construction practices, they were not selected as key performance measures. Though pumping is a common distress type, because of low occurrence and because water bleeding was also measured as pumping, it was not selected. Hence, the main performance measures considered for analyses are cracking (transverse and longitudinal), faulting, and ride quality (IRI). Details of the performance evaluation follow.

5.2. TRANSVERSE CRACKING

Transverse cracking in LTPP is measured and presented in two forms— number of cracks and length of cracking. In each of these two forms the severity level of cracking is also measured and presented. For this study, the total number of transverse cracks was taken as the performance measure.

Among the SPS-2 sections, transverse cracking was observed in 31% of the sections. Figure 5-1 shows the distribution of cracking in the SPS-2 sections. About 65% of the cracked sections have medium severity cracking, and 37% of the cracked sections have high severity cracking. A possible explanation for the "low" occurrence of transverse cracking lies in the contraction joint spacing of 4.6 m (15-ft), which is typically considered the optimum spacing to avoid cracking (Ray 1981; Smith, Peshkin et al. 1989; Armaghani 1993; Harvey, Roesler et al. 2000).

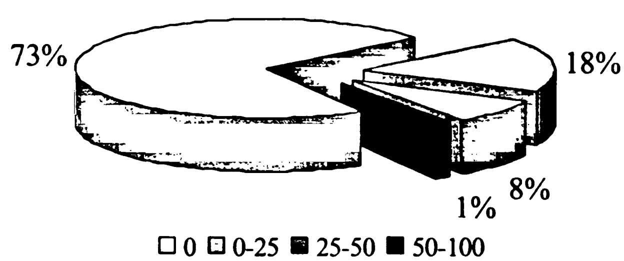


Figure 5-1 Distribution of transverse cracking (percent slabs cracked)

The site-wise occurrence of transverse cracking in the SPS-2 test sections is shown as box plots in Figure 5-2. While the box and whiskers give an idea about distribution of cracking, the horizontal line in the box is the median. It is evident from the plot that the sections in Nevada [NV (32)] have distinctly higher cracking than sections in any of the other sites. The data from the sections at this site were excluded from analyses as severe cracking at the site was premature and was related to construction issues. According to the construction report (Nichols Consulting Engineers 1998), the PCC mixes were different from the ones stipulated by the SHRP. The sections with target 14-day flexural strength of 3.8 MPa (550-psi) have a 3.3 MPa (475-psi) mix and the sections with target 14-day flexural strength of 6.2 MPa (900-psi) have a 5.2 MPa (750-psi) mix. Shrinkage cracking also occurred in the LCB and could have contributed to the outlying performance of the test sections. Excluding sections from NV, cracking was observed in 26% of the sections, with medium severity cracking in 63% of the cracked sections, and high severity cracking in 23% of the sections. Figure 5-5 and Figure 5-6 show the occurrence of cracking as a function of design and site factors. The occurrence of transverse cracking shown in these figures does not include sections from the site in NV (32). Of all the experimental factors, it seems that base type, PCC slab thickness and drainage have considerable effects on the occurrence of cracking.

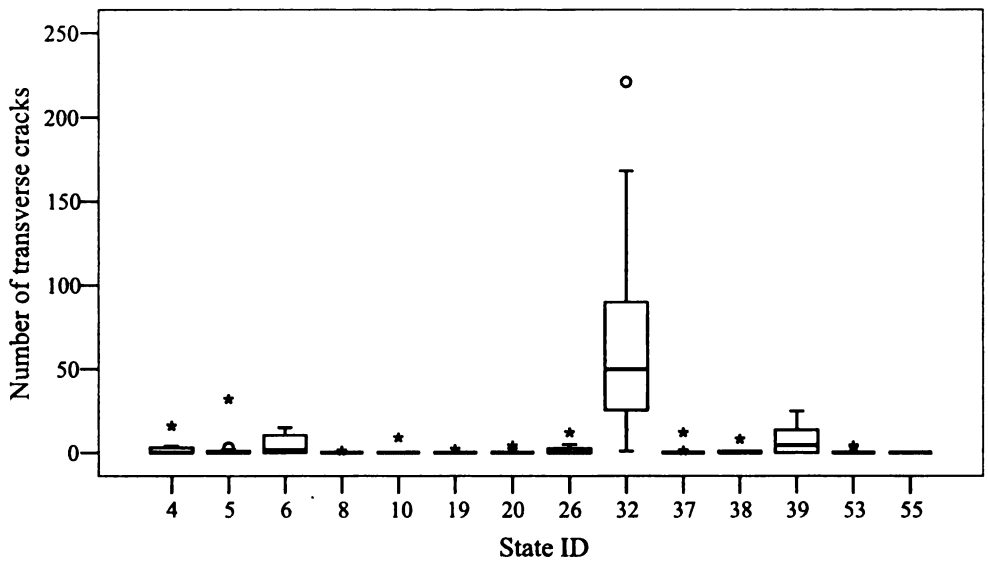


Figure 5-2 Site-wise occurrence of transverse cracking for SPS-2 test sections

The transverse cracking performance was compared to the performance criteria developed by Khazanovich et al (Khazanovich et al, 1998) for JPCP pavements. According to those criteria, for pavements that are 7.5 years old, which is the average age of sections in SPS-2, "good" performance is defined as less than 2% slabs cracked, "normal" performance is defined as 2 to 4% slabs cracked and "poor" performance is defined as more than 4% slabs cracked. The criteria were developed for transverse cracking in terms of percent slabs cracked. The percent of slabs cracked is not given directly in LTPP database. Data from faulting file (MON_DIS_JPCC_FAULT) of the data were used in conjunction with distress maps to identify crack locations and calculate the percent slabs cracked.

Based on the criteria, among sections in SPS-2 excluding ones from NV, 72% are exhibiting "good" performance, 6% are exhibiting "normal" performance while the remaining 21% are exhibiting "poor" performance.

5.3. LONGITUDINAL CRACKING

In the LTPP database, longitudinal cracking of different severity levels is presented in linear meters. For this study, total length of longitudinal cracking was taken as the performance measure. Longitudinal cracking was observed in 27% of the test sections of the SPS-2 experiment and most of the cracking, at this stage, is of low severity. Figure 5-3 shows the distribution of longitudinal cracking occurrence in all the SPS-2 sections. The site-wise occurrence of longitudinal cracking in the SPS-2 test sections is shown as box plots in Figure 5-4. As in the case of transverse cracking, the outlying performance of sections from NV (32) is evident for longitudinal cracking. In addition to sections from Nevada (NV), some sections from Arkansas [AR (5)] and Arizona [AZ (4)] have shown outlying performance. The probable reasons behind abnormal transverse cracking performance of the Nevada sections also apply to the case of high longitudinal cracking in those sections. These sections (from AR and AZ) were not excluded from analyses, as the median performance of these sections is comparable to the performance of other SPS-2 test sections. In addition, no construction deviations that could substantiate the outlying performance were documented in the construction reports.

Figure 5-7 and Figure 5-8 show the occurrence of longitudinal cracking as a function of design and site factors. These figures are based on data from all SPS-2 sections other than ones from NV site. Of all the experimental factors, it seems that base type and PCC slab thickness have considerable effects on the occurrence of cracking.

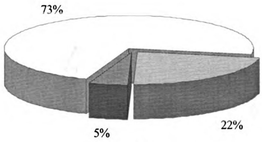


Figure 5- 3 Distribution of longitudinal cracking, m

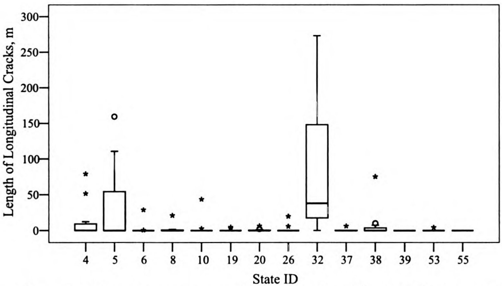


Figure 5- 4 Site-wise occurrence of longitudinal cracking in SPS-2 test sections

5.4. JOINT FAULTING

The site-wise occurrence of faulting in the test sections is shown as box plots in Figure 5-9. It is evident from the plot that less than 5 joints per section have faulting greater than 1.0 mm, in a vast majority of. Figure 5-10 shows the distribution of faulting (in terms of percent of joints that faulted more than 2 mm) in the SPS-2 test sections. Figure 5-13 and Figure 5-14 show the distribution of faulting by site factors and design factors in sections other than ones from NV. None of the factors seem to be significantly affecting the occurrence of faulting.

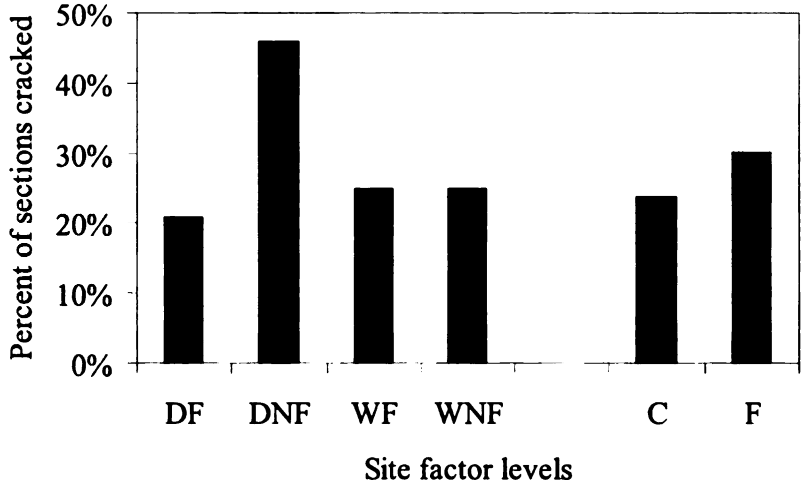


Figure 5- 5 Occurrence of transverse cracking by site factor

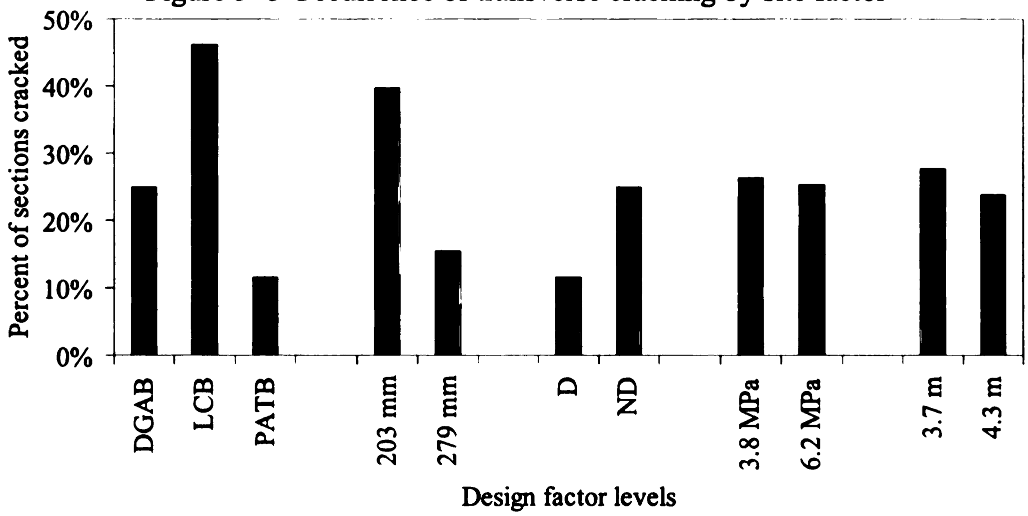


Figure 5- 6 Occurrence of transverse cracking by design factor

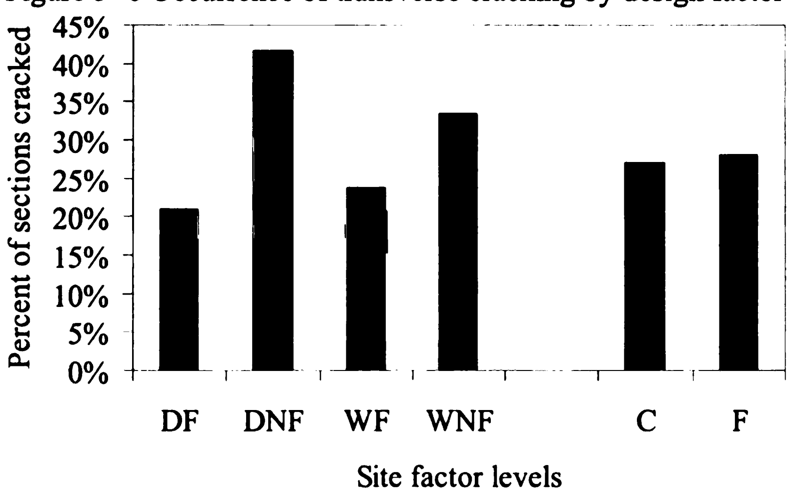


Figure 5- 7 Extent of longitudinal cracking by site factors

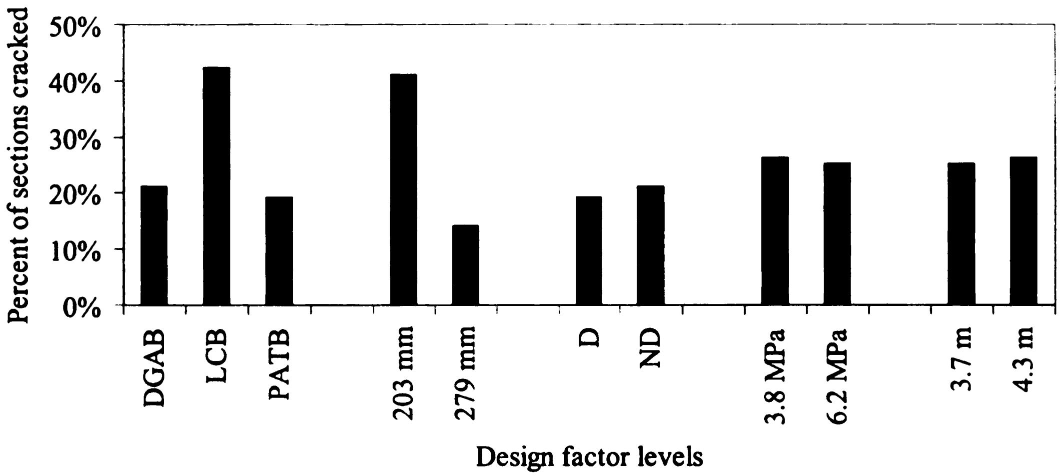


Figure 5- 8 Extent of longitudinal cracking by design factors

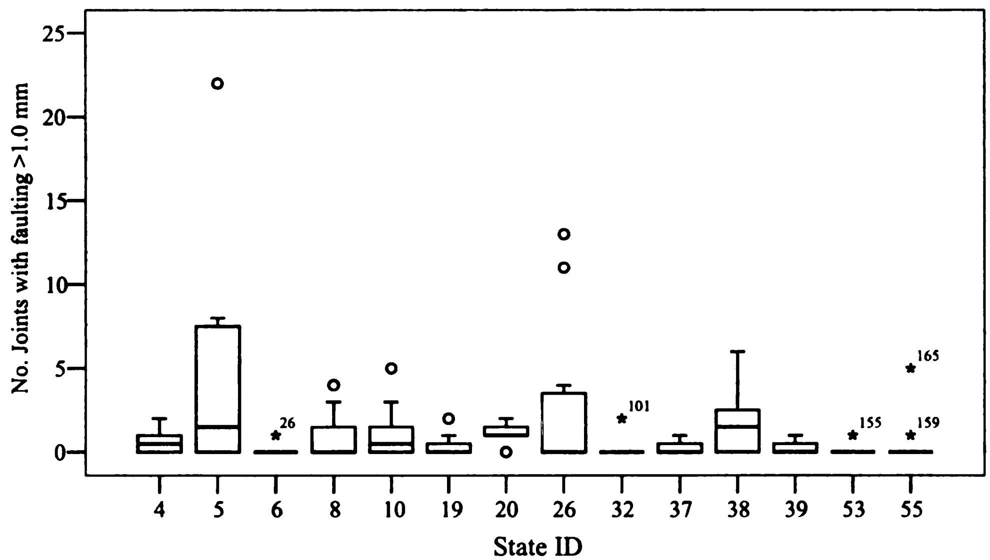


Figure 5- 9 Site-wise occurrence of faulting in SPS-2 test sections

Based on the performance criteria by Khazanovich et al (Khazanovich et al, 1998), pavements of age 7.5 years are said to be exhibiting "good" performance if the average joint faulting is less than 1.5 mm, "normal" performance if the average joint faulting is between 1.5 and 3.0 mm, and "poor" performance if the average faulting exceeds 3.0 mm.

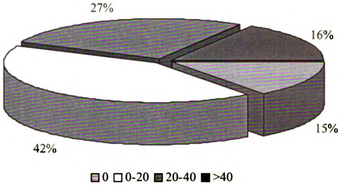


Figure 5- 10 Percent of joints that faulted >= 2.0 mm

According to these thresholds, all the SPS-2 sections except one are showing "good" performance. As mentioned earlier, the 203 mm and 279 mm test sections are provided with 32 mm (1.25-in) or 38 mm (1.5-in) dowels, respectively, and the contraction joint spacing is 4.6 m (15-ft). As the joints are doweled and the joint spacing is not large, it seems that the performance of the test sections is as expected.

In general, the extent and magnitude of faulting, as mentioned before, is "low" indicating "good" performance of a majority of the test sections. In addition, for LTPP data collection the Georgia Faultmeter, which has a least count of 1.0 mm, is used to measure faulting at joints and cracks. This least count is "large" (Selezneva et al, 2000), as typical faulting values in SPS-2 pavements are close to 1.0 mm. In light of these issues, it is too early to make reliable conclusions regarding the effects of design and/or site factors on faulting. Thus results from analysis on faulting are not presented in this thesis.

5.5. ROUGHNESS (IRI)

The site-wise status of current roughness in the test sections is shown as box plots in Figure 5-11. It is evident from the plot that for most of the sections the current roughness is less than 1.8 m/km, i.e. Present Serviceability Index (PSI) of 3.5 based on equations proposed by Hall and Correa (Hall and Correa Muñoz 1999). Also, sections from the site in Michigan [MI (26)] have higher roughness than most of the sections in the experiment. Sections 0214, 0215, 0217 and 0218 were observed to have roughness ranging between 3.2 to 4.5 m/km. Sections 0214 and 0218 were built with a roughness of 1.5 and 1.9 m/km, respectively. The sections 0215, 0217, and 0218 were decommissioned from the experiment by year 2000, due to reasons not mentioned in DataPave. However, data available in the database till the sections were decommissioned was used in this research. The status of current roughness in the test sections is given in Figure 5-12. Figure 5-15 and Figure 5-16 show the distribution of roughness by site factors and design factors. Drainage and subgrade soil type seems to be having considerable effects on roughness.

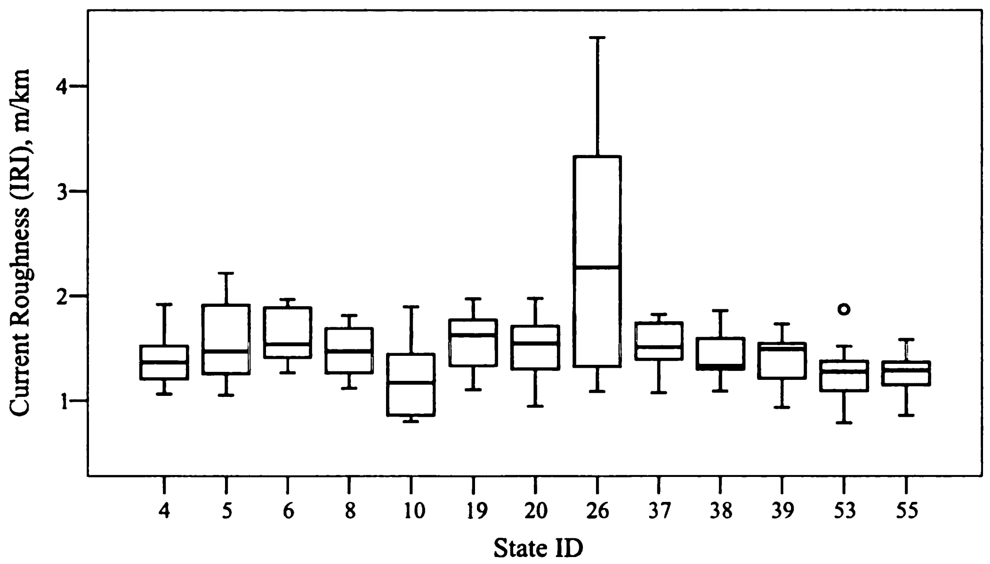


Figure 5- 11 Site-wise occurrence of final roughness values for SPS-2 test sections

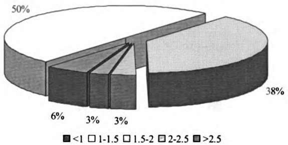


Figure 5- 12 Distribution of roughness, IRI m/ km

By Khazanovich et al (Khazanovich et al, 1998), a pavement at an age of 7.5 years, is "good" if roughness is less than 1.0 m/km and "poor" if roughness is greater than 2.0 m/km. Based on these criteria, the initial roughness of 54% of the sections is "poor" and that of the other sections is "normal". From the current roughness data, 88% of the sections are exhibiting "normal" performance and 6% of the sections each are exhibiting "good" or "poor" performance.

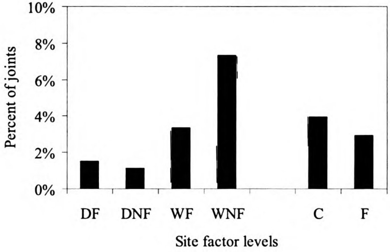


Figure 5- 13 Extent of faulting >=1.0 mm in site factors

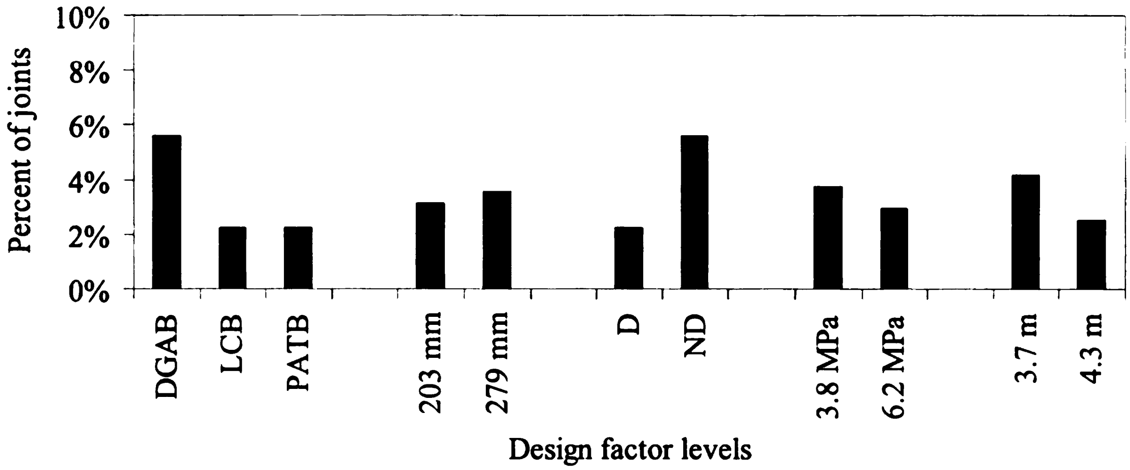


Figure 5- 14 Extent of faulting >=1.0 mm in design factors

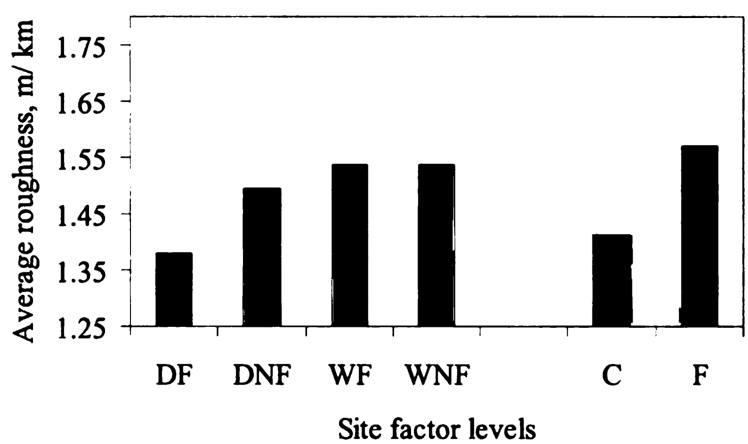


Figure 5- 15 Extent of roughness in site factors

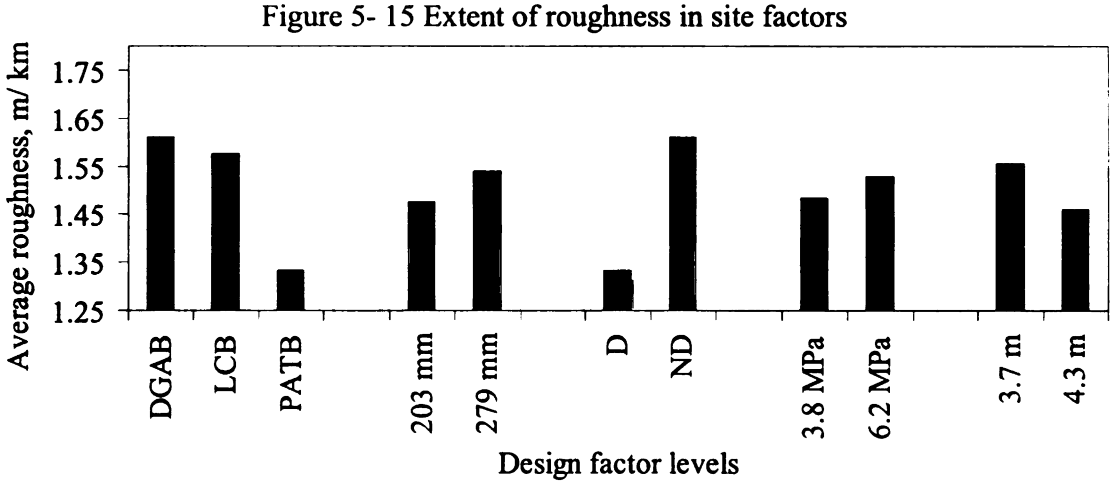


Figure 5- 16 Extent of roughness in design factors

CHAPTER 6- ANALYSIS METHODS

In this chapter, a description of the analysis methods employed for investigating the effects of experimental factors on pavement performance is presented. Broadly, the analyses were performed at two levels— site-level and network-level (or overall analysis). In the site-level analysis, as the name suggests, the effects of design factors were studied at each site and the consistency of the effects across sites was evaluated. The main advantage of such analysis is that all the sections under comparison, for a given site, were subjected to similar treatment (mainly, traffic and climate). The network-level or overall analysis was performed to make use of the wealth of data available from the SPS-2 experiment, and study the effects (main and interaction) of design and site factors on performance.

For each test section in the experiment, time-series performance data are available. Performance index (PI) has been developed to capture the entire time-series performance of a section in a single number that represents the section's performance. A brief description of PI is given first and the details of analysis methods follow.

6.1. PERFORMANCE INDICATORS

As mentioned before, the performance data are available as time-series data. In order to employ "conventional" statistical procedures that do not involve analysis of time-series data, it was necessary to develop a method to quantify the performance as a single quantity. The three options that were considered for this are: area under the performance curve (AREA), area under the performance curve normalized with age (AREA/age), and the performance index (PI). However, given the variation in age among the sites, two sections of different ages can have the same area though the older section has actually shown better performance. For example, the younger section could have significant distress over only a few years while the older one has more-or-less uniform distress over a much longer time; while the area under the curve would be the same, the older section would have exhibited much better performance.

PI was found to capture better the recent performance in comparison with AREA/age, though PI and AREA/age have a good correlation. The association between PI and AREA/age is shown in Figure 6-1 for the case of IRI, which is the performance measure to which the concept of PI was applied.

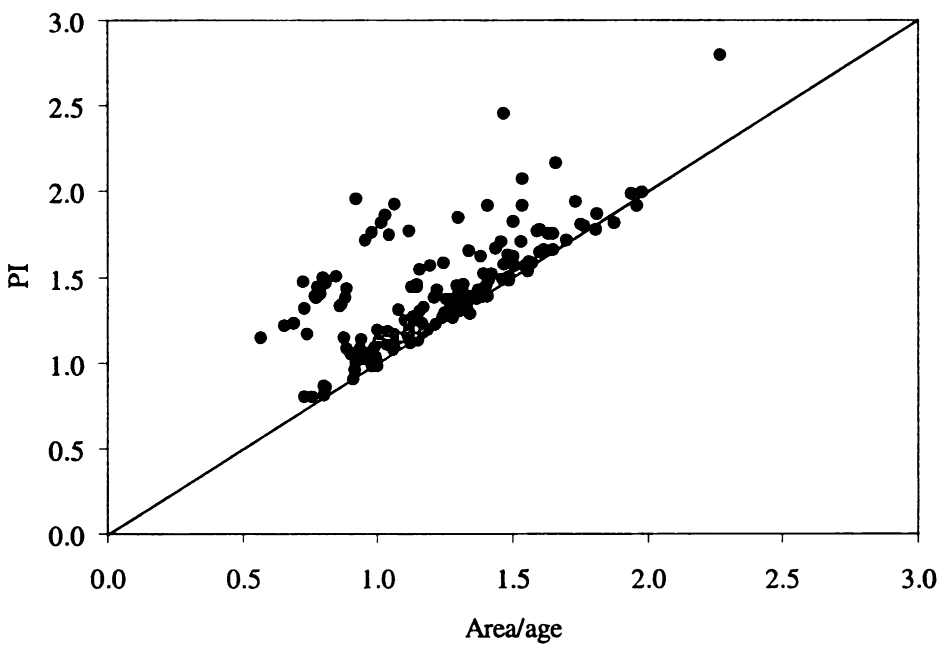


Figure 6-1 Correlation between PI and AREA/age, for IRI

PI was thus selected as it accounts for both age to initiation and the rate of growth of a distress. A detailed illustration of the reasons behind selection of PI can be found elsewhere (Chatti et al, 2005; Buch et al, 2005).

PI is defined as:

$$PI = \frac{\sum_i (t_i . y_i)}{\sum_i t_i} \qquad (1)$$

Where:

t_i = age of the section at distress measurement in year i
y_i = performance of the section at year i

Only the ages at which distress measurements were taken are included in the calculation of PI. Since PI gives greater weight to the most recent performance of a section, it may capture the most probable future trend of performance.

Although PI appears to be a viable option it has some inherent limitations. These limitations are mainly because PI is dependent on the number and timing of the distress surveys. To address this, the age of test sections was considered as a covariate in all statistical analyses of PI. Though the actual effects of traffic and age on pavement performance are quite complex (non-linear) and may not be adequately addressed by the covariates (linear adjustment), their inclusion in that manner helps in reducing bias.

6.2. SITE-LEVEL ANALYSIS METHODS

In the site-level analysis each section is evaluated in comparison with similar designs of a site. Within each site, climatic conditions and traffic loading are identical for all test sections. Thus the main advantage of this analysis is that comparisons are made among those sections that were subjected to similar loading and environmental conditions. All site-level analyses were conducted on the Performance Indices (PIs) of the sections for various performance measures. The difference in performance is assessed based on average values.

The site-level analysis consisted of series of comparisons, each focusing on the effect of a particular design factor. Comparisons were done at two levels—A and B. In level-A analyses, all designs (0201 through 0212, or 0213 through 0224) at a given site were compared such that only one factor is held common within the sections of each group. For example, in level-A analysis, the effects of PCC slab thickness [203 mm (8-in) vs. 279 mm (11-in)] were studied, within each site, by ignoring base type, drainage, PCC flexural strength, and slab width.

In level-B analyses, most of the factors are "controlled". In other words, individual sections within a given site are paired such that all but one design factor are the same, this factor being the one of interest. Comparing a given pair of sections will allow for determining the effect of the particular design factor, with the highest possible level of constraint (level-B).

The relative effects of levels within each design factor were studied based on the ratio of mean performance of the sections corresponding to a level over the mean performance of all levels of the factor.

For factors with two levels (such as PCC thickness and drainage), the relative performance of each level can range from 0 to 2, a value of 1 indicating no effect of the factor [i.e., the amount of distress (performance) corresponding to the two levels of the factor is the same]. A value less than 1 indicates better performance compared to mean performance of sections corresponding to both the levels of a factor. Consequently, a value higher than 1 indicates poor performance. The best possible performance translates to 0, and the worst possible performance translates to 2. For cases where there is no distress or same level of distress, each level of a given factor will have relative performance of 1 indicating no difference in performance. A sample calculation of relative performance is presented in Table 6-1.

For factors with more than two levels, a similar logic can be extended. The relative performance for various levels of the design factors was calculated for all the sites in the experiment, and for each performance measure.

Table 6- 1 Example calculation of relative performance for the effect of slab thickness on longitudinal cracking

8" PCC slab thickness		11" PCC slab thickness	
Section ID	Performance Index	Section ID	Performance Index
201	90.7	203	23.1
202	25.4	204	3.8
205	95.9	207	16.1
206	22.0	208	70.5
209	65.3	211	75.5
210	10.2	212	52.7
Average	51.6	Average	40.3
Mean Performance	(51.6+40.3)/2 = 46.0		
Relative performance	51.6/46.0=1.1	Relative performance	40.3/46.0=0.9

6.3. OVERALL ANALYSIS METHODS

The selection of statistical methods for analyses was mainly based on two criteria—objectives of the study, and the challenges posed by the experiment design and current performance levels. Two types of analyses were selected—magnitude-based and frequency-based. Analysis of variance (ANOVA) is a method for comparing means and is the magnitude-based analysis. Binary logistic regression (BLR) and linear discriminant analysis (LDA) are frequency-based analyses, which were used to evaluate the effects of experimental factors on the occurrence or non-occurrence of distress. These methods are briefly described below. A detailed explanation of analyses for each performance measure can be found elsewhere (Buch et al, 2005; Chatti et al, 2005).

6.3.1. Frequency-based Analysis

The average age of the SPS-2 test sections is 7.5 years. As a result, the magnitude and occurrence of distress are "low". For example, approximately 73% of the sections have not shown any transverse cracking. Though this indicates “good” performance, the absence of distress in a considerable number of sections presents challenges for statistical analysis.

Traditionally, magnitude-based methods like multi-factorial ANOVA are used to establish the impact of design and site factors on pavement performance for an experiment like SPS-2. For the normal theory least squares ANOVA to be meaningful the model residuals should (i) be normally distributed and (ii) have a constant variance. For ANOVA on transverse or longitudinal cracking, these assumptions are violated (see Figure 6-2), owing to the skewed distribution of cracking occurrence in the SPS-2 test sections. To address this issue, a logarithmic transformation could be applied to the data; however, the ANOVA would be restricted only to sections that have shown cracking, as the transformation function is not defined for a value of zero. The low occurrence of cracking limits the number of sections that can be used in such an analysis. ANOVA was used only to study the effects of the experimental factors on roughness.

The frequency-based methods are more suitable when the occurrence of distress is considerable, even though the magnitude of distress is less, because the categorization is based on occurrence only. Hence, binary logistic regression (BLR) and linear discriminant analysis (LDA) were used to study the effects of design and site factors on the occurrence of transverse and longitudinal cracking.

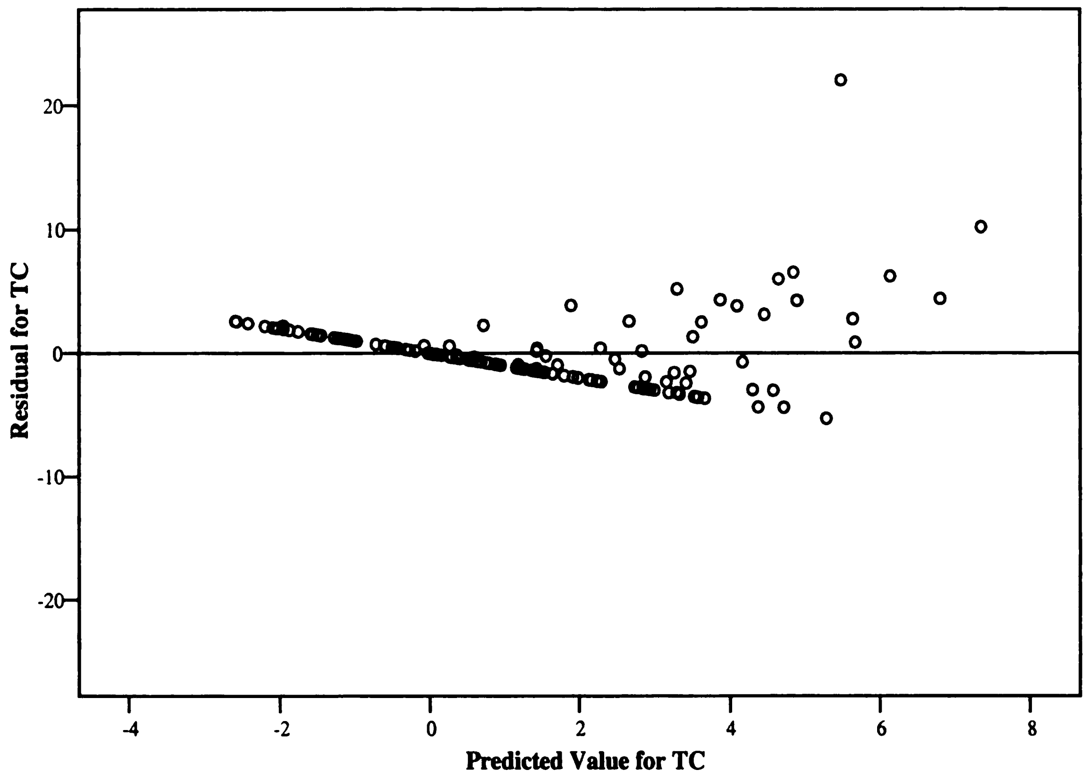


Figure 6-2 Example of violation of residual assumptions for ANOVA

BLR (Hosmer and Stanley, 2003) is used where the outcome variable is discrete. This method is based on the maximum likelihood method for estimating the parameters of interest. The interpretation of effects for various levels of the categorical (independent) variables is very convenient in terms of the odds ratio when this type of model is used. Logistic regression models are also very useful for discrimination analysis (of various groups) when categorical variables are used as independent variables. In the interpretation of results from BLR, the p-value is of primary importance as it indicates the statistical significance of the effect.

LDA (Norusis, 2005) is useful in distinguishing between two or more groups of data. This is done by identifying variables that are significant in classifying the data into the various groups. For example, in the work here, groups could include pavement sections with cracks and sections with no cracks. The method allows for determining which variables discriminate between cracked and non-cracked pavements.

6.3.2. Magnitude-based Analysis

Magnitude-based analysis was applied to roughness, which does not pose the problem of non-occurrence of distress. For the ANOVA, traffic was considered as a covariate.

The SPS-2 experiment, which is a fractional-factorial design, was rendered unbalanced because unequal numbers of sites were constructed in each zone-subgrade combination. The imbalance in the experiment resulted in a fewer or no replications for some treatments, which affects the statistical power (Kutner et al, 2005). In simple terms, the lower the power, the lower the reliability of results.

In light of these issues, a simplified analysis based on the concept of the standard deviate was performed. The performance of designs with respect to each other was evaluated using the deviation from the mean performance, which is the standard deviate. The designs were evaluated based on selected distresses, considering one distress at a time. The standard deviate was calculated for each of the twelve designs within each site by using the following equation:

$$Standard\ Deviate = \frac{(Performance\ of\ a\ given\ design - Average\ performance\ for\ the\ given\ site)}{Standard\ deviation\ of\ performance\ for\ the\ given\ site}$$

Since this measure is calculated individually for each section, considering one site at a time, it indicates the relative ranking of a section compared to other sections at the same site. This transformation adjusts for the variation in performance due to site conditions, as the sections are compared to contiguous sections at their respective sites. This method is analogous to statistical "blocking" for site effects. The standard deviate for a particular performance was used to compare the individual effects of design factors by employing one-way ANOVA on the standard deviates of the sections. These analyses were performed on data from all sections and also on subsets of data stratified by subgrade type and climate. While a lower value of standard deviate indicates better performance than the mean, a higher value indicates worse performance.

CHAPTER 7- EFFECTS OF EXPERIMENTAL FACTORS ON PAVEMENT PERFORMANCE

Findings from the statistical analyses conducted to study the effects of design and site factors on performance of the SPS-2 test sections are presented in this chapter. The performance measures that were analyzed include transverse and longitudinal cracking, and roughness (initial roughness and change in roughness). In this chapter, results from site-level analysis will be followed by results from overall analysis and comparison of designs, leading to the summary of findings. A list of all analyses conducted on the performance of SPS-2 test sections is given below:

- Site-level analyses: Evaluation of the consistency of the effects of design factors across sites.
- Overall analyses:
  a) Analysis of Variance (ANOVA)
  b) Linear Discriminant Analysis (LDA)
  c) Binary Logistic Regression (BLR)
- Comparison of designs (based on standard deviate)

7.1. EFFECT OF CONSTRUCTION ON PAVEMENT PERFORMANCE

Detailed construction guidelines were developed by LTPP for the participating agencies to minimize variability in construction across sites. The lesser variability across sites, the lower the "noise", and easier it is to determine the "pure" effects of the design factors on pavement performance. However, some deviations have occurred during construction of some sites and those issues were highlighted in the construction reports prepared by the participating agencies. Inclusion of test sections with significant construction deviations in the analysis may distort (bias) the effects of design factors.

Depending on the nature of construction issues (construction quality) the performance of a pavement is affected. Minor issues (such as minor thickness deviation in base course) may not significantly impact initial performance where as major issues (such as PCC mix issues, or drainage problems) have greater chances of affecting performance early in the life of a pavement. Hence, a construction deviation (poor quality) may be used to identify sections that may potentially show an abnormal performance.

In this study, any abnormality in early performance was used as an indicator to identify substandard sections. The performance of all the sections, over time, was observed for this purpose and those sections that had premature "failure" (in first few years of service life) were identified. In order to further investigate the construction-related performance issues, the performance, in terms of key performance measures, of all pavement sections in the experiment was examined. The analysis is discussed next with illustrations. Based on the time-series plots for all performance measures it was found that cracking (transverse and/or longitudinal) was the predominant premature "failure" for most of the pavement sections.

7.1.1. Transverse and Longitudinal Cracking

Figure 7- 1 and Figure 7- 2 show cracking in all test sections. It can be observed that some sections exhibit high initial cracking. It was found that most of the sections with this abnormal performance are from NV (32). As mentioned earlier, a wide range of construction issues (material-related) that were reported in the construction report for the site are believed to be the cause. In light of the unusual behavior of test sections at NV (32) site, data from these sections were excluded from all subsequent statistical analyses.

Figure 7- 3 and Figure 7- 4 show transverse and longitudinal cracking in all sections except those from NV (32).

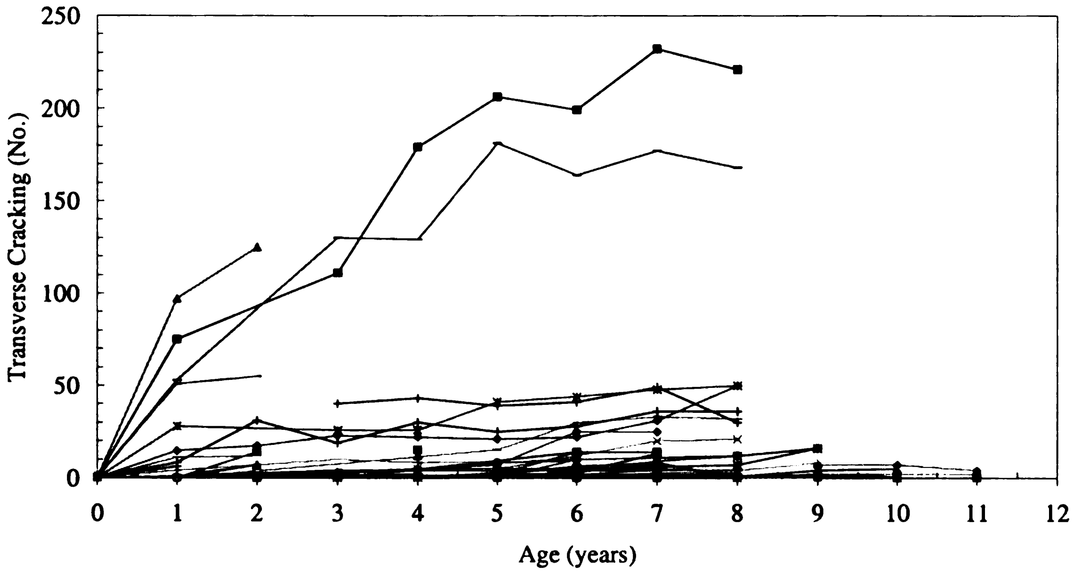


Figure 7- 1 Transverse cracking with time - All sections

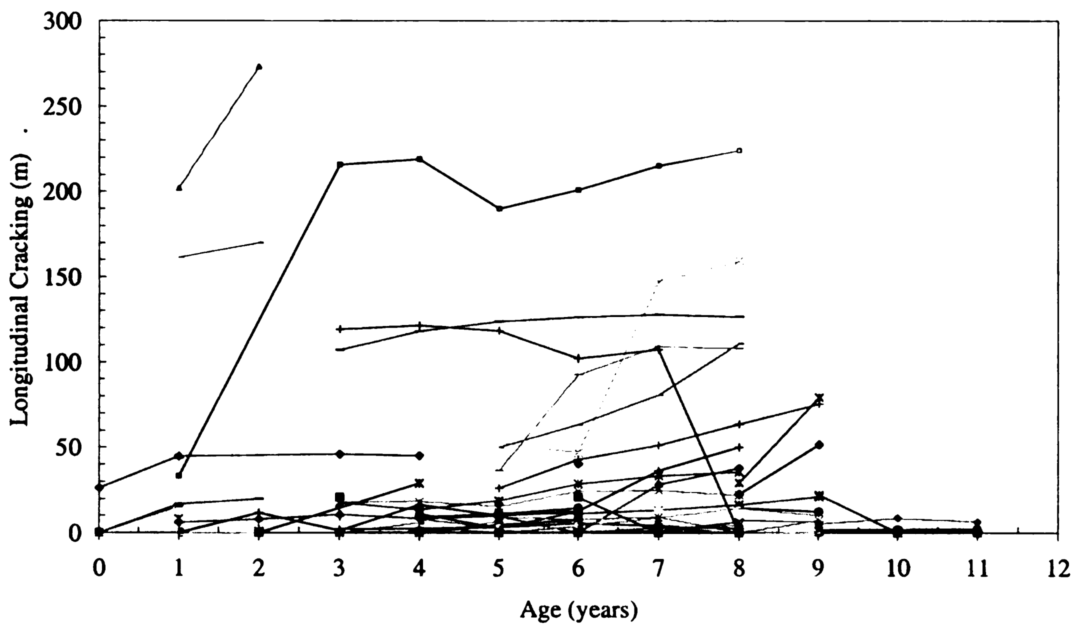


Figure 7- 2 Longitudinal cracking with time - All sections

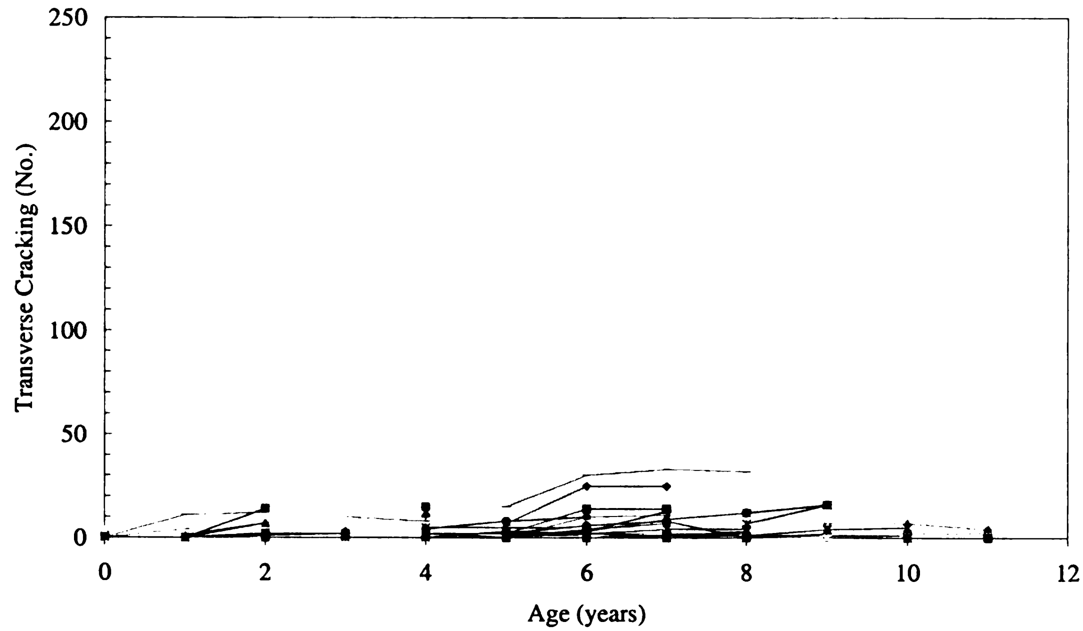


Figure 7- 3 Transverse cracking with time - Selected sections (without Nevada)

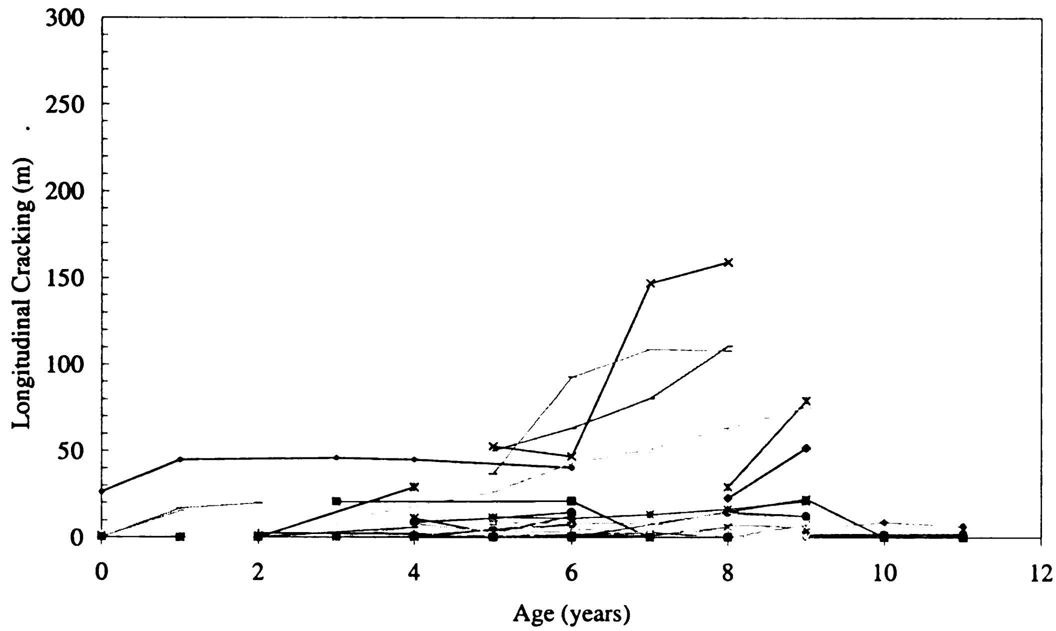


Figure 7- 4 Longitudinal cracking with time - Selected sections (without Nevada)

7.1.2. Roughness

Figure 7-5 shows the progression of roughness over time in all the SPS-2 sections except NV (32). It can be observed that only few sections have exhibited an unusual performance. Exclusion of data from these few sections was not considered necessary, as their inclusion will not impact the results significantly. Moreover, available data do not suggest any reasons behind this abnormal performance. Therefore, all the pavement sections [except those from NV (32)] were included for analysis of roughness.

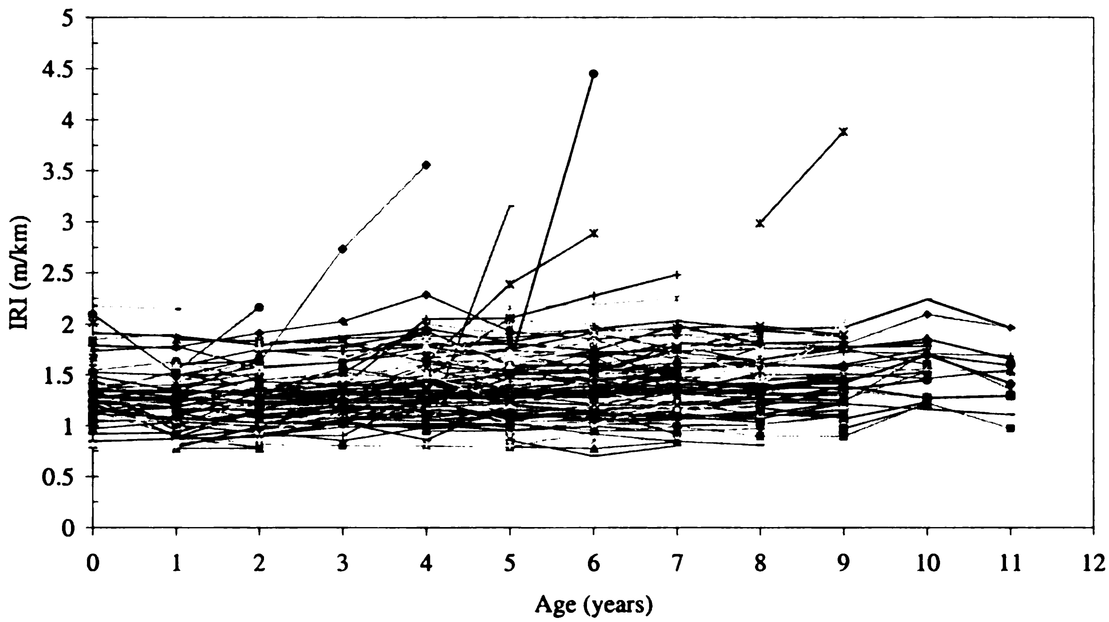


Figure 7- 5 IRI with time - Selected sections (without Nevada)

7.1.3. Drainage Issues

All the drained sections of the SPS-2 experiment were video taped to assess the condition of the drainage in late 2001 and early 2002 under the NCHRP Project 1-34C (Hall and Correa 2002). At that time, some of the sites (e.g. KS, MI, CO, AZ, and NC) were about 8 years into service, while the California site was just about 1 year old.

A subjective assessment of the quality of the drainage functioning as "good" or "poor" was reported for each section. A "poor" rating is an indication of; (i) buried lateral outlet, (ii) outlet fully blocked with silt, gravel or other debris (iii) longitudinal drains being fully blocked, or (iv) a considerable amount of standing water in the longitudinal drain. A "good" rating was given to drainage if a reasonably sufficient flow of water was evident even if some amount material was present in the drains.

The ratings assigned to each section of the experiment in Table 7-1. As shown in the table, some of the sections that were designed to be un-drained, according to the experiment design, were constructed with drainage. Hall and Correa (Hall and Correa 2002) conducted preliminary analysis of the performance of SPS-2 test sections in light of their assessment of drainage, and a brief summary of their findings are presented below:

- With respect to IRI change, larger mean differences were detected for the PATB sections with "poor" drainage than for PATB sections with "good" drainage, when un-drained and drained sections were compared. The quality of drainage is not a significant factor in the differences observed in IRI increase.
- In the analyses of transverse and longitudinal cracking in drained versus un-drained SPS-2 sections, larger mean differences were detected for PATB sections with "good" drainage functioning than for those with "poor" drainage functioning.

However, the above trends were based only on the average performance and in no case, were the differences detected statistically significant based on analysis of data from Release 17 of LTPP database.

7.2. SITE-LEVEL ANALYSES

The results obtained from site-level analyses of the SPS-2 experiment data are presented here. The concepts of performance index (PI) and relative performance were used to perform site-level analyses (details in Chapter 6). These analyses were conducted separately for transverse cracking, longitudinal cracking, and roughness (IRI).

Table 7- 1 Subjective ratings of drainage functioning for SPS-2 test sections based on video inspection results (Hall and Correa 2002)

State	Test Section ID											
	0201 0213	0202 0214	0203 0215	0204 0216	0205 0217	0206 0218	0207 0219	0208 0220	0209 0221	0210 0222	0211 0223	0212 0224
	Base Type											
	Dense-graded aggregate base				Lean concrete base				Permeable asphalt-treated base over aggregate			
	Un-drained								Drained			
4									G	G	G	G
5				P		P			P	P	P	P
6				P					G	G	G	P
8									G	P	P	P
10									P	G	P	G
19									P	P	?	?
20									G	G	G	G
26	P							P	P	?	P	?
32									G	G	G	?
37					P				P	P	P	P
38									G	G	G	G
39	?*	?*	?*	?*	?*	?*	?*	?*	G	P	G	P
53									G	G	G	G
55									?	?	?	?

[1]G= Drainage function rated as good
[2]? = Drainage outlet not found
[3]P = Drainage function rated as poor
[4]?* = Camera could not be inserted

Site-level analyses deal with each SPS-2 project separately. For each site, the climatic conditions, subgrade type (for most of the sites) and traffic are same. Construction conditions, material sources and surveys were also considered to be same for all sections within each SPS-2 site.

As described in Chapter 6, the site-level analyses consists of two types of comparisons: (i) Level-A — In this analysis all designs (201 through 212, or 213 through 224) at a given site are compared (among themselves) such that only one factor (design feature) is held common within the sections of each group under comparison; (ii) Level-B — In this analysis, most of the factors (design feature) are "controlled" for comparisons. The results from level-A and level-B comparisons, in terms of relative performance ratio, can be found in the Appendix.

Non-parametric tests (Wilcoxon Signed Ranks test and Friedman test) were performed on relative performance ratios to determine the statistical significance of the difference in relative performance ratios of different levels within each design factor. For example, the relative performance ratio corresponding to transverse cracking, for sections with 203 mm (8-inch) slab and sections with 279 mm (11-inch) slab were compared to investigate the statistical significance of the consistency of the effect of PCC slab thickness on transverse cracking across sites. A p-value less than or equal to 0.05 was considered to be indicative of a statistically significant consistency of an effect.

In site-level analyses, statistical significance of an effect needs to be interpreted as the significance of the effect's consistency across sites but not necessarily as the significance of its effect on the magnitude of distress.

In this chapter, the discussion of results for level-A and level-B analyses is presented separately. Some basic descriptive statistics regarding the performance of the test sections are also presented, to corroborate the results. Though these statistics are not at site-level they are meant to give the reader an insight about the extent of distresses.

In the SPS-2 experiment, only the test sections built on PATB were provided with in-pavement drainage. As a consequence of this, the impact of drainage alone or base type alone cannot be studied. In other words, the effect of PATB and the effect of drainage cannot be separated. Therefore, an assumption was made that DGAB and PATB are structurally the "same", and the analysis was performed by comparing performance of sections constructed on DGAB and sections constructed on PATB. It is important to note that the effect of drainage discussed in this thesis would be a result of comparison between sections on DGAB and sections on PATB. Furthermore, to study the effect of base type, the performance of sections with DGAB, sections with LCB and sections with PATB were compared. Here too the effect of PATB is combined with the effect of drainage.

7.2.1. Effect of design features on performance- Comparisons at level-A

The discussion of results from level-A analyses is presented here. These results are presented for one design feature at a time.

Drainage

To investigate the effects of drainage, sections 201 through 204, and, 213 through 216 were considered as "without drainage" and sections 209 through 212, and, 220 through 224 were considered as "with drainage". Hence it is important to note that the effects of drainage that are discussed here are from comparisons only between sections built on DGAB and sections built on PATB.

From level-A analysis, the effects of drainage on cracking and roughness are inconclusive, at this point in time. This observation should not be interpreted as drainage not having a significant impact on pavement performance in general. All the observations and conclusions need to be interpreted keeping in view the age of the test sections and the low occurrence of distresses in the SPS-2 test sections. Table 7-2 is the summary of effects of drainage on cracking (transverse and longitudinal) and roughness.

Base Type

Sections built on each of the three base types, DGAB, LCB and PATB, were compared at each site to study their relative impact on performance. Base type has a consistent effect on cracking. However, the effect is not consistent (across sites) for roughness.

Table 7-2 Effects of drainage*, based on Level-A analysis

Performance Measure	Effect	Comments
Transverse cracking	Inconclusive (p=0.299)	• In 5 of the 14 sites, no cracking occurred and the performance of sections with and without drainage is thus similar. • In 6 of the 9 sites with distressed sections, sections without drainage exhibited more cracking than ones with drainage. • Overall, 25% of sections without drainage and 12% of sections with drainage have exhibited cracking. • 21% of sections in WF zone, 13% of sections in WNF, 35% of sections in DF zone, and 19% of sections in DNF zone have exhibited cracking.
Longitudinal cracking	Inconclusive (p= 0.411)	• In 5 of the 9 sites with distressed sections, sections without drainage exhibited more cracking than ones with drainage. • In 5 of the 14 sites, no cracking occurred and the performance of sections with and without drainage is thus similar. • Overall, 21% of sections without drainage and 19% of sections with drainage have exhibited cracking. • 9% of sections in WF zone, 19% of sections in WNF, 35% of sections in DF zone, and 25% of sections in DNF zone have exhibited cracking.
Roughness (IRI)	Inconclusive (p= 0.084)	• In 11 of the 14 sites, the performance of sections with and without drainage is comparable. • Average latest roughness of sections without drainage and sections with drainage are 1.6 and 1.3 m/km.

*Effect of drainage is a result of comparison between sections built on DGAB and sections built on PATB only.

Approximately 59% of sections built on LCB have exhibited cracking compared to 38% of sections built on DGAB and 25% of sections built on PATB. Though the analysis indicates higher cracking in sections built on LCB, the conclusions need to be considered in light of the construction issues (Desaraju 2003; Chatti, Buch et al. 2005) and, the magnitude and severity of cracking. Table 7-3 is the summary of the effects of base type. The effect of base type on roughness seems to be inconclusive because at most of the sites the difference in IRI of sections built on the three base types is not considerably high. As of latest distress survey, 80% of the sections in the experiment have IRI less than 1.8 m/km. The extent and magnitude of the distresses are to be considered along with the conclusions.

Table 7- 3 Effects of base type based on Level-A analysis

Performance Measure	Effect	Comments
Transverse cracking	Consistent effect (p= 0.000)	• In all the 13 sites with distressed sections, higher cracking was observed in sections built on LCB, compared to other sections. • 25%, 46% and 12% of sections on DGAB, LCB, and PATB, respectively, exhibited cracking.
Longitudinal cracking	Consistent effect (p= 0.002)	• In 11 of the 13 sites with distressed sections, higher cracking was observed in sections built on LCB, compared to other sections. • 21%, 42% and 19% of sections on DGAB, LCB, and PATB, respectively, exhibited cracking.
Roughness (IRI)	Inconclusive (p= 0.064)	• In 10 of the 14 sites, comparable roughness was observed in all sections. • In 4 of the 14 sites, more roughness was observed in sections built on DGAB, compared to other sections. • Average latest roughness of sections on DGAB, LCB, and PATB are 1.6, 1.6 and 1.3 m/km, respectively.

PCC slab thickness

A total of 84 sections with 203 mm (8") PCC slab and 83 sections with 279 mm (11") PCC slab were compared (at site-level) for this analysis. This includes all the sections in the experiment.

The effect of slab thickness is consistent in the case of transverse and longitudinal cracking. Though a deviation from target thickness was observed in considerable number of sections (details in Chapter 4), the analysis indicates a significant effect of PCC slab thickness on cracking. Table 7-4 is the summary of effects of PCC slab thickness on cracking. It is to be noted here that 49% of cracking (transverse and/or longitudinal) has occurred in sections that were built on LCB, of which 67% of the sections are sections with 203 mm PCC slabs. These statistics suggest a noticeable effect of both slab thickness and base type. The roughness of both 203 mm PCC slab and 279 mm PCC slab sections was found to be comparable at all sites, suggesting an insignificant effect of slab thickness on roughness. The effect of PCC slab thickness on IRI is thus inconclusive.

Table 7- 4 Effects of slab thickness, based on Level-A analysis

Performance Measure	Effect	Comments
Transverse cracking	Consistent effect (p= 0.001)	• In all sites that have distressed sections (13 sites), more cracking was observed in sections with 203 mm (8 inch) PCC slab, compared to sections with 279 mm (11 inch) PCC slab. • 40% of sections with 203 mm (8 inch) PCC slab and 15% of sections with 279 mm (11 inch) PCC slab exhibited cracking.
Longitudinal cracking	Consistent effect (p= 0.020)	• In 11 of the 13 sites that have distressed sections, more cracking was observed in sections with 203 mm (8 inch) PCC slab, compared to sections with 279 mm (11 inch) PCC slab. • 41% of sections with 203 mm (8 inch) PCC slab and 14% of sections with 279 mm (11 inch) PCC slab exhibited cracking.
Roughness (IRI)	Inconclusive (p= 0.414)	• In all the sites, comparable performance was observed in all sections. • Average latest roughness of both the sections with 203 mm (8 inch) PCC slab and sections with 279 mm (11 inch) PCC slab is 1.5 m/km.

PCC flexural strength

The performance of test sections with target 14-day PCC flexural strength of 3.8 MPa and test sections with target 14-day PCC strength of 6.2 MPa was compared to study the effect of PCC flexural strength on the performance of SPS-2 sections. A total of 84 sections with 3.8 MPa concrete and 83 sections with 6.2 MPa concrete were compared. The effect of flexural strength on cracking and roughness appears to be insignificant. Comparable performance was observed in sections with higher strength concrete and lower strength concrete.

It is important to consider the deviations from target flexural strength in the sections. A detailed discussion of the deviations was presented in Chapter 4. The deviation from target PCC 14-day flexural strength was studied using the data that is available for 52% of the sections in the experiment. The average 14-day flexural strength of PCC of sections with target strength of 3.8 MPa was 3.6 MPa while in sections with target strength of 6.2 MPa was 5.6 MPa. Among sections with target flexural strength of 3.8 MPa, 34% of sections had PCC flexural strength (at 14-days) that exceeded the allowable range of 3.4 MPa to 4.2 MPa, while 16% failed to reach even the lower limit of the range. In the case of sections with target flexural strength of 6.2 MPa, 34% of sections had PCC flexural strength (at 14-days) below the allowable range, and none of the sections exceeded the range. In half of the sections with target strength of 6.2 MPa that failed to meet the lower limit of the range, the PCC strength reached the required limit at 28-days. These deviations from target strength could be a reason for comparable performance of all the pavements.

Tab-le 7-5 is the summary of effects of PCC flexural strength. At most of the sites, comparable performance (cracking) was observed for both higher strength and lower strength concrete sections. The effect is thus inconclusive. The effect of PCC flexural strength on roughness appears to be insignificant.

Slab width

The widened slab [4.3 m(14-ft)] sections were compared to those with standard slab [3.7 m (12-ft)] to study the effect of slab width on performance of the test sections. For this, 84 sections with standard slab width and 83 sections with widened slab were compared. The effect of slab width seems to be insignificant, at this point in time.

Table 7- 5 Effects of flexural strength, based on Level-A analysis

Performance Measure	Effect	Comments
Transverse cracking	Inconclusive (p=0.400)	• In 6 of the 14 sites, lower strength concrete sections exhibited higher cracking than higher strength concrete sections. • In 5 of the 14 sites, all sections have performed at comparable levels. • 26% of lower strength concrete sections and 25% of higher strength concrete sections exhibited cracking.
Longitudinal cracking	Inconclusive (p=0.944)	• In 7 of the 14 sites, lower strength concrete sections exhibited higher cracking than higher strength concrete sections. • In 5 of the 14 sites, higher strength concrete sections exhibited higher cracking than lower strength concrete sections. • 26% of lower strength concrete sections and 25% of higher strength concrete sections exhibited cracking.
Roughness (IRI)	Inconclusive (p=0.102)	• In all sites of the experiment, similar performance was observed in sections with higher strength concrete and sections with lower strength. • Average latest roughness of lower or higher strength concrete sections is 1.5 m/km.

In general, the effect of slab width on transverse cracking seems to be insignificant as widened slab sections and standard slab sections have performed similarly in most of the sites. But some effect of slab width seems to exist on longitudinal cracking. In a majority of the sites (9 of 13) slightly higher longitudinal cracking was observed in widened slab sections compared to standard slab sections. Table 7-6 is the summary of effects of slab width. The effect of slab width on roughness is inconclusive at this point in time.

7.2.2. Effect of design features- Paired Comparisons at Level-B

Level-B comparisons are those in which all possible factors other than the one of interest are controlled. The individual sections that are compared under this analysis were identified in Chapter 6. The effects of drainage, base type, and PCC slab thickness on the performance measures are presented below.

Table 7- 6 Effects of slab width based on Level-A analysis

Performance Measure	Effect	Comments
Transverse cracking	Inconclusive (p=0.222)	• In 6 of the 14 sites, sections with standard slab width exhibited higher cracking than ones with wider slab. • In 5 of the 14 sites, both standard slab width and wider slab sections have shown comparable levels of performance. • 28% and 24% of sections with standard slab width and wider slab, respectively, have exhibited cracking.
Longitudinal cracking	Inconclusive (p=0.362)	• In 9 of the 14 sites, sections with wider slab exhibited higher cracking than ones with standard slab width. • 25% and 26% of sections with standard slab width and wider slab, respectively, have exhibited cracking.
Roughness (IRI)	Inconclusive (p=0.096)	• In all sites of the experiment, similar performance was observed in sections with standard slab width and sections with wider slab. • Average latest roughness of standard slab width sections and wider slab sections are 1.6 and 1.5 m/km.

Drainage

Sections with drainage (i.e. sections with PATB) were compared with sections without drainage (sections with DGAB) controlling the effects of all other factors, namely, PCC slab thickness, slab width, and flexural strength. The effect of drainage is consistent (across sites) on transverse cracking. Slight effect was observed on roughness, whereas no effect was apparent in the case of longitudinal cracking.

For sections with 203 mm PCC slab, the effect of drainage seems to be consistent on transverse cracking. Table 7-7 is the summary of effects of drainage. The effect of drainage on longitudinal cracking is inconclusive. Sections with drainage and without drainage performed similarly in varying conditions. Among sections with 203 mm slab, a slight effect (p=0.076) appears to exist on roughness in those with standard slab width. Sections without drainage have slightly higher roughness than ones with drainage.

Base Type

Sections built on each of the three base types, DGAB, LCB and PATB, were compared at each site by controlling the effects of PCC slab thickness and slab width. A consistent effect of base type on transverse and longitudinal cracking was observed. The effect of base type on roughness is not clear.

Table 7- 7 Effect of drainage*, based on Level-B analysis

Performance Measure	Effect	Comments
Transverse cracking	Consistent effect **(p=0.034)**	• At 5 of the 7 sites with distresses sections, among sections with 203 mm PCC slab, sections without drainage cracked more than sections with drainage. • Among sections with 203 mm PCC slab, 18% and 43% of sections with drainage and without drainage have exhibited transverse cracking. • Cracking was observed only at two sites in the thicker slab sections.
Longitudinal cracking	Inconclusive	• No discernable trends were observed for longitudinal cracking. • Among sections with 203 mm PCC slab, 25% of sections with drainage and 25% of sections without drainage have exhibited longitudinal cracking.
Roughness (IRI)	Slight effect (p=0.076)	• Effect of drainage seems to be negligible as the sections with drainage and without drainage have performed similarly in most of the sites. • Among sections with 203 mm PCC slab, the average roughness of sections with drainage and without drainage are 1.3 and 1.6 m/km.

*Effect of drainage is a result of comparison between sections built on DGAB and sections built on PATB only.

On average, among sections with 203 mm PCC slab, those built on LCB have exhibited higher transverse cracking than other sections (see Table 7-8). This trend was observed in a majority of sites. Among sections with 203 mm slab and standard slab width, the trend is consistent (p=0.001) across the sites. This effect may be an "interaction effect", as the effect of base type was discernable among sections with 203 mm slab and standard slab, and not in sections with 279 mm slab.

The effect of base type on longitudinal cracking (see Table 7-8) is consistent among sections with 203 mm slab, in that sections built on LCB have higher cracking than those on other bases. The effect of base type on roughness is inconclusive.

Table 7- 8 Effect of base type on cracking, based on Level B analysis

Performance Measure	Effect	Comments
Transverse cracking	Consistent effect **(p<0.05)**	• In 9 sites, among thinner slab sections, sections built on LCB cracked more than sections on other base types. • 43%, 64% and 18% of sections on DGAB, LCB and PATB have exhibited cracking among thinner slab sections.
Longitudinal cracking	Consistent effect **(p<0.05)**	• In 8 sites, of the 12 sites at which cracking was observed, sections built on LCB exhibited more cracking sections built on other base types. • Among the thinner slab sections, 54% of sections built on LCB and 25% of other sections exhibited cracking.
Roughness (IRI)	Inconclusive	• Effect of base type seems to be negligible as all the sections performed similarly, in general.

PCC slab thickness

The performance of sections with target PCC slab thickness of 203 mm (8-in) was compared with that of sections with target PCC slab thickness of 279 mm (11-in) by controlling the effects of base type and PCC flexural strength. The effect of PCC slab thickness was consistent on cracking (transverse and longitudinal), whereas no noticeable effect was found on roughness.

The effect of PCC slab thickness is consistent, across sites, on transverse cracking. Among sections built with DGAB or LCB, sections with 203 mm slab had higher cracking than sections with 279 mm slab. Table 7-9 is the summary of effects of PCC slab thickness. In the case of longitudinal cracking, the effect was found consistent among sections built with LCB with higher cracking in sections with 203 mm slab. The effect of PCC slab thickness on roughness is inconclusive.

Table 7- 9 Effect of slab thickness on cracking, based on Level B analysis

Performance Measure	Effect	Comments
Transverse cracking	Consistent effect ($p<0.05$)	Thinner slab sections exhibit more transverse cracking than thicker slab sections, among sections with DGAB or LCB.
Longitudinal cracking	Consistent effect ($p<0.05$)	Thinner slab sections exhibit more longitudinal cracking than thicker slab, among sections with LCB.
Roughness (IRI)	Inconclusive	Effect of base type seems to be negligible as all the sections perform similarly

7.3. OVERALL ANALYSIS

The results obtained from statistical analyses performed on SPS-2 data are presented in this section. Analyses were performed on data from all sites and are thus referred to as 'overall' analyses. Linear Discriminant Analysis (LDA), Binary Logistic Regression (BLR), and Analysis of Variance (ANOVA) are the statistical methods that were employed for analyses.

The performance measures that were analyzed to investigate the impact of design and site factors on rigid pavement performance are as follows:

- Transverse cracking,
- Longitudinal cracking, and
- Roughness (IRI)- initial roughness and change in roughness.

Important factors affecting occurrence of transverse cracking, longitudinal cracking, and roughness were determined using LDA and BLR, which are frequency-based methods (details in Chapter 6). For analyses on cracking, the test sections were grouped into 2 categories— sections with cracking, and sections without cracking. In the case of IRI, a threshold of 1.5 m/km was used to separate the test sections as groups. The value corresponds to the threshold between "normal" and "poor" pavements

(Khazanovich, Darter et al. 1998) for an age of 7.5 years, which is the average age of SPS-2 test sections. Analyses were then performed to identify factors that significantly discriminate the groups.

As mentioned in Chapter 6, ANOVA was used to determine the significance of factors impacting initial roughness (IRI), and change in roughness (first survey to latest survey). ANOVA method could not be applied to transverse and longitudinal cracking as the assumption of constant variance of residuals was violated owing to occurrence of cracking in less than 30% of test sections. Wherever required, a natural logarithmic transformation of the variable of interest was applied to satisfy the assumptions of ANOVA. Traffic volume and age of test sections were considered as covariates in all analyses to adjust for the difference in traffic loading and age among the sites in the experiment.

The following is a summary of the main findings from each method of analysis. Basic statistics pertaining to the extent of occurrence of distresses are presented along with results to corroborate the results. It is suggested that the results be interpreted keeping in view the extent of distresses that occurred in the test sections. In the discussion of results, the word 'significance' needs to be interpreted as statistical significance only.

As mentioned before, all analyses were conducted without including data from the site in Nevada (32), as extensive distresses at the site are related to wide range of construction issues that occurred at the site but not to pavement performance. Inclusion of data from this site will affect results from analyses, significantly.

7.3.1. Frequency-based Methods

Two frequency-based methods were used- Linear Discriminant Analysis and Binary Logistic Regression (details in Chapter 6). The results from these analyses are as follows:

Linear Discriminant Analysis

Based on this method all the distresses were analyzed using the following thresholds for categorization of the sections.

- Transverse or longitudinal cracking: Cracked versus non-cracked
- Roughness: IRI (current)< 1.5 m/km versus IRI (current)>1.5 m/km

  IRI (initial)<1.25 m/km versus IRI (initial)> 1.25 m/km.

This analysis was aimed at identifying the experimental factors that best discriminate between distressed and non-distressed pavement sections. As the pavements in the SPS-2 experiment have not shown "high" levels of distress, this analysis will help in finding the significant design and site factors contributing to the occurrence of distresses (rather than magnitude), at this point in time. Traffic and pavement age, were considered as covariates in this analysis. Interpretation of results from this analysis is illustrated here using the results from LDA on transverse cracking. Based on the current SPS-2 data, LDA yielded the following classification model for transverse cracking:

$$\begin{aligned} Score &= -4.8 - 0.26(\mathbf{BaseType}) + 0.62(\mathbf{PCCThickness}) + 0.45(\mathbf{Drainage}) \\ &-0.14(Zone) + 0.24(LWidth) + 1.05(SG) + 0.15(FS) \end{aligned} \quad (4)$$

Group Centroids: Transverse Crack 'No'= 0.51
Transverse Crack 'Yes'= -1.47

Where:

BaseType: '1' for DGAB or PATB, '2' for LCB.
PCCThickness: '1' for target slab thickness of 203 mm, '2' for target slab thickness of 279 mm.
Drainage: '0' for No Drainage, '1' for Drainage.
Zone: '1' for WF, '2' for WNF, '3' for DF, '4' for DNF.
LWidth: '1' for 3.7 m, '2' for 4.3 m.
SG: '1' for Fine-grained, '2' for Coarse-grained.
FS: '1' for target 14-day strength of 3.8 MPa, '2' for target 14-day strength of 6.2 MPa.

In the above equation, the factors in bold are statistically significant in affecting the occurrence of transverse cracking. The equation can be interpreted by considering the group centroids and the particular effect each factor has on the score. For example, PCC slab thickness has a positive effect on the score, i.e. an increase in PCC thickness from 203 mm (code: 1) to 279 mm (code: 2) will have a positive effect on the overall score. This implies that increasing PCC slab thickness decreases the chances of cracking.

Similar results were obtained from all LDA analyses. However, for the sake of brevity only interpretations of the effects are presented in the thesis. Below are the effects of the design and site factors on pavement performance based on LDA.

Transverse cracking: The effect of drainage, base type, and target PCC thickness were significant in discriminating between cracked or un-cracked sections. Table 7-10 summarizes the effects of the design and site factors on the occurrence of transverse cracking.

In the WF zone, the effects of PCC thickness and subgrade soil type were statistically significant in discriminating between sections with cracking and without cracking. Table 7-11 summarizes effects of experimental factors based on the results of LDA on transverse cracking.

It was observed that 33% of sections with thinner slab and 14% of sections with thicker slab have exhibited cracking. Moreover, 14% of sections with thinner slab have exhibited high severity cracking where as none of the thicker slab sections exhibited high severity cracking. While 33% of sections built on fine-grained soils manifested transverse cracking, 4% of sections built on coarse-grained exhibited cracking. Also, about 22% (13 of the 60 sections) of sections built on fine-grained subgrade soils have exhibited high severity cracking while 4% (1 of the 24 sections) of the sections built on coarse-grained soils exhibited cracking.

Longitudinal cracking: The effect of target PCC thickness, base type and the climatic zone are significant in discriminating between cracked and un-cracked sections. Table 7-12 summarizes the effect of the design and site factors on the occurrence of longitudinal cracking. The effects of PCC thickness and base type, in WF zone, were statistically significant in discriminating between sections with cracking and sections with no cracking. Table 7-13 summarizes the effects of experimental factors based on the results from LDA on longitudinal cracking, in WF zone. While 19% of sections with 203 mm PCC slab have exhibited longitudinal cracking, 10% of sections with 279 mm PCC slab have exhibited cracking. Also, 7%, 25%, and 11% of sections built on DGAB, LCB and PATB, respectively, have exhibited longitudinal cracking.

Roughness: The initial and current roughness of the test sections were analyzed by categorizing the variables using the thresholds mentioned above. Table 7-14 through Table 7-17 are summaries of results from these analyses. PCC thickness was the only factor that was found to be discriminating between "smooth" and "rough" pavement sections based on the initial IRI categories. Based on LDA on current roughness, drainage, PCC thickness, and base type were found to be the significant factors.

Table 7- 10 Summary of results from LDA on transverse cracking- Overall

Factor Category	Factor	Effects on transverse cracking	p-value
Design	Drainage	Presence of drainage significantly reduces the chances of occurrence of cracking	***Yes* (0.001)**
	Target PCC thickness	Thicker PCC thickness reduces the chances of occurrence of cracking	***Yes* (0.001)**
	Base type	The type of base significantly impacts the chances of the occurrence of cracking	***Yes* (0.044)**
	Flexural Strength	No significant effect. In general, the 900-psi mixes tend to mitigate cracking.	No (0.716)
	Slab Width	No significant effect. 14-foot wide slab sections tend to inhibit cracking.	No (0.467)
Site	Climatic Zone	No significant effect. Designs constructed in Dry zones tend to crack more.	No (0.147)
	Subgrade soil type	No significant effect, however the model indicates that sections on fine subgrade soils tend to crack more than sections on coarse subgrade soils	No (0.538)

Table 7- 11 Results from LDA on transverse cracking, WF zone

Factor	Effects on transverse cracking	p-value
Drainage	No significant effect. Presence of drainage reduces the chances of occurrence of cracking	No (0.151)
Target PCC thickness	Sections with thicker PCC slabs crack significantly less	***Yes* (0.041)**
Base type	No significant effect. Sections on LCB tend to crack more.	No (0.214)
Flexural Strength	No significant effect. In general, the 900-psi mixes tend to crack more	No (1.000)
Slab Width	No significant effect. 14-foot wide slab sections tend to inhibit cracking	No (0.614)
Subgrade soil type	Sections on fine subgrade soils tend to crack significantly more than sections on coarse subgrade soils	***Yes* (0.007)**

Table 7- 12 Summary of results from LDA on longitudinal cracking

Factor category	Factor	Effects on longitudinal cracking	p-value
Design	Drainage	No significant effect. Presence of drainage increases the chances of occurrence of cracking.	No (0.180)
	Target PCC thickness	Thicker PCC thickness reduces the chances of occurrence of cracking	***Yes (0.000)***
	Base type	The type of base significantly impacts the chances of the occurrence of cracking	***Yes (0.004)***
	Flexural Strength	No significant effect. In general, the 900-psi mixes tend to mitigate cracking.	No (0.834)
	Slab Width	No significant effect. 14-foot wide slab sections tend to have more cracking.	No (0.834)
Site	Climatic Zone	Designs constructed in Dry zones tend to crack more.	***Yes (0.009)***
	Subgrade soil type	No significant effect, however the model indicates that sections on fine subgrade soils tend to crack more than sections on coarse subgrade soils	No (0.456)

Table 7- 13 Results from LDA on Longitudinal cracking, in WF zone

Factor	Effects on transverse cracking	p-value
Drainage	No significant effect. Sections with drainage have cracked more than the ones without drainage	No (0.193)
Target PCC thickness	Thicker PCC thickness significantly reduces the chances of occurrence of cracking	***Yes (0.026)***
Base type	Sections on LCB crack significantly more than other sections	***Yes (0.023)***
Flexural Strength	No significant effect. In general, the 900-psi mixes tend to crack more.	No (1.000)
Slab Width	No significant effect. 14-foot wide slab sections tend to inhibit cracking.	No (0.463)
Subgrade soil type	No significant effect, the model indicates that sections on fine subgrade soils tend to crack more than sections on coarse subgrade soils	No (0.296)

Table 7- 14 Summary of results from LDA on initial roughness

Factor category	Factor	Effects on initial roughness	p-value
Design	Drainage	Presence of drainage decreases the chances of higher initial roughness.	No (0.090)
	Target PCC thickness	Sections with thicker PCC slab have higher chances of being built rougher than thinner ones.	***Yes (0.054)***
	Base type	No significant effect. Lesser roughness was observed on sections built with PATB.	No (0.329)
	Flexural Strength	No significant effect. In general, the 900-psi mixes tend to have more roughness.	No (0.201)
	Slab Width	No significant effect. 14-feet wide slabs tend to have more roughness.	No (0.750)
Site	Climatic Zone	No significant effect. Designs constructed in Wet zones tend to have more roughness.	No (0.232)
	Subgrade soil type	No significant effect Sections on fine subgrade soils tend to have more initial roughness.	No (0.342)

Table 7- 15 Summary of results from LDA on initial roughness, in WF zone

Factor	Effects on initial roughness	p-value
Drainage	No significant effect. Presence of drainage decreases the chances of higher initial roughness.	No (0.356)
Target PCC thickness	No significant effect. Sections with thicker PCC slab have higher chances of being built rougher than thinner ones.	No (0.835)
Base type	No significant effect. Sections with PATB tend to be built smoother.	No (0.594)
Flexural Strength	No significant effect. In general, the 900-psi mixes tend to have more roughness.	No (0.190)
Slab Width	No significant effect. 12-feet wide slabs tend to have more roughness.	No (0.190)
Subgrade soil type	No significant effect. Sections on fine subgrade soils tend to have more initial roughness.	No (0.071)

Table 7- 16 Summary of results from LDA on roughness

Factor category	Factor	Effects on current (latest) roughness	p-value
Design	Drainage	Presence of drainage inhibits increase in roughness.	***Yes (0.000)***
	Target PCC thickness	Thicker PCC thickness increases the chances of higher roughness.	***Yes (0.036)***
	Base type	Sections on DGAB and LCB have higher increase in roughness.	***Yes (0.017)***
	Flexural Strength	No significant effect. In general, the 900-psi mixes tend to cause more roughness.	No (0.076)
	Slab Width	No significant effect. 12-foot wide slabs tend to have lesser roughness.	No (0.873)
Site	Climatic Zone	No significant effect. Designs constructed in Wet zones tend to have more roughness.	No (0.588)
	Subgrade soil type	No significant effect. Sections on fine subgrade soils have more roughness.	No (0.317)

Table 7- 17 Summary of results from LDA on roughness, in WF zone

Factor	Effects on current (latest) roughness	p-value
Drainage	Presence of drainage inhibits increase in roughness.	***Yes (0.008)***
Target PCC thickness	No significant effect. Thicker PCC thickness decreases the chances of higher roughness.	No (1.000)
Base type	Sections on DGAB have higher increase in roughness.	***Yes (0.032)***
Flexural Strength	No significant effect. In general, the 900-psi mixes tend to cause more roughness.	No (0.081)
Slab Width	No significant effect. 12-foot wide slabs tend to have more roughness.	No (0.193)
Subgrade soil type	No significant effect. Sections on fine subgrade soils have more roughness.	***Yes (0.004)***

Binary Logistic Regression (BLR)

The BLR model was used to model the probability of occurrence of distress for various performance measures. Thresholds similar to the ones used for LDA were used to categorize the test sections for this analysis. The results (see Table 7-18 and Table 7-19) are summarized below. The value inside parenthesis is the odds ratio between the levels of a factor. For example, an odds ratio of 3.6 for the effect of PCC slab thickness on transverse cracking means that the chances of occurrence of cracking in sections with 203 mm slab are 3.6 times the chances of occurrence of cracking in sections with 279 mm slab.

In the interpretation of the results, the p-value is of primary importance as it indicates the statistical significance of the effect. When an effect is statistically significant it can be said that the effect is not due to random error (i.e. a happenstance). Hence, irrespective of the odds ratio, a higher p-value (>0.05) will make the odds ratio less reliable.

Transverse Cracking: The BLR model for transverse cracking was significant with a p-value of 0.000. In about 89% of the cases, the model correctly differentiates cracked sections from non-cracked sections. Based on this analysis, the effects of significant factors are as follows:

- PCC slab thickness: Sections built with 203 mm PCC slab have significantly higher probability of cracking than the ones built with 279 mm PCC slab.
- Base Type: Sections built on PATB have significantly lesser likelihood of cracking than those built on LCB.

- Subgrade: Sections built on fine subgrade soils have significantly higher probability of cracking than the ones built on coarse subgrade soils.

Based on the BLR on data from sections in WF zone, the effect subgrade soil type (0.029 in BLR) was statistically significant in discriminating between sections with cracking and sections without cracking.

Longitudinal Cracking: The BLR model for longitudinal cracking was significant with a p-value of 0.000. For about 89% of the times, the model correctly differentiates cracked sections from un-cracked sections. Based on this analysis, the following factors significant affect occurrence of longitudinal cracking.

- Base Type: Sections on LCB have significantly higher chances of cracking compared to the sections with DGAB.
- PCC slab thickness: Sections with 203 mm slab have significantly higher chances of cracking than the sections with 279 mm slab.
- Climate: Sections in Dry No Freeze have significantly higher chances of cracking than Wet Freeze.

Roughness: The BLR model for initial roughness was significant with a p-value of 0.023. Moreover, 61.5% of the times, the model correctly differentiates sections with "poor" roughness from other sections. Based on this analysis, the following conclusions were made:

- Base Type: Sections built on LCB have significantly (p-value=0.040) higher probability of roughness than the ones built on PATB.
- PCC slab thickness: Sections built with thinner slab have significantly (p-value=0.038) lesser probability of being built rougher than those thicker slab.

The BLR model for latest roughness was significant with a p-value of 0.000. The model correctly differentiates sections with "poor" roughness from other sections, 78.8% of the times. Based on this analysis, base type is the significant factor for roughness. Sections built on DGAB or LCB have significantly (p-value=0.007) higher probability of roughness than the ones built on PATB. This may also be interpreted that sections with drainage have significantly lesser chances of becoming rougher compared to sections without drainage (sections on DGAB).

Table 7- 18 Summary of p-values from BLR for determining the effect of experimental factors on pavement performance measures- Overall

Experimental Factors	Transverse cracking	Longitudinal cracking	Roughness	
			Initial	Current
Drainage ·	0.083 (3.4)	0.616 (0.68)	0.28 (1.6)	0.003 (7.5)
Base type	0.073 (4.9)*	0.099 (2.7)	0.12 (2.4)	0.007
PCC thickness	0.019 (3.6)	0.001 (8.7)	0.018 (0.49)	0.381 (0.67)
Flexural Strength	0.550 (1.4)	0.825 (1.13)	0.17 (0.63)	0.077 (0.44)
Slab Width	0.389 (1.6)	0.800 (1.15)	0.687 (0.87)	0.876 (0.931)
Subgrade type	0.003 (9.5)	0.361 (1.98)	0.186 (1.73)	0.283 (1.97)
Climatic Zone	0.571	0.017 (18)	0.400	0.262

*LCB vs. PATB.

*Values in parenthesis are odds ratios.

Table 7- 19 Summary of p-values from BLR for determining the effect of experimental factors on pavement performance measures- WF Zone

Experimental Factors	Transverse cracking	Longitudinal cracking	Roughness	
			Initial	Current
Drainage	0.736 (0.74)	0.55 (0.35)	0.510 (1.5)	0.004 (47.4)
Base type	0.767	0.237	0.383	0.014
PCC thickness	0.650 (1.43)	0.084 (11.3)	0.058 (.039)	0.066 (5.05)
Flexural Strength	0.643 (0.70)	0.868 (0.84)	0.141 (0.48)	0.222 (0.37)
Slab Width	0.593 (1.49)	0.234 (4.65)	0.147 (2.1)	0.655 (1.39)
Subgrade type	0.029 (19.5)	0.488 (0.23)	0.066 (2.97)	0.368 (3.009)

*Values in parenthesis are odds ratios.

7.3.2. Analysis of Variance

ANOVA was performed on roughness of sections in the SPS-2 experiment. The analyses were performed combining data from all sections (overall) in the experiment. ANOVA was also conducted on data for sections within each zone. It should be noted that analysis that were conducted only within WF zone is presented. The other zones have two sites each and this sample size did not yield meaningful results because of less statistical "power". The effects of design factors and site factors on pavement performance are discussed next.

Effects of design factors on pavement performance

The results from this analysis are summarized in Table 7-20. Table 7-21 shows marginal means corresponding to different levels in each factor. The marginal means were back transformed using the properties of lognormal distribution based on the below formula (Haider, 2005).

$$\mu_x = \exp\left(\mu_y + \frac{1}{2}\sigma_y^{\ 2}\right)$$

The most important design factor is the base type, which has a significant effect on initial roughness (IRI_o) and change in roughness (ΔIRI). In addition to base type, IRI_o is affected by PCC slab thickness, and ΔIRI is affected by drainage and PCC thickness (slight effect). The following discussion summarizes significant effects of design factors on pavement performance:

- Effect of drainage: Pavement sections with drainage have shown significantly lower change in roughness than those without drainage.
- Effect of base type: Pavement sections with DGAB have shown the highest change in roughness while those with PATB have shown the least change in

roughness. Sections built with LCB had the highest initial roughness while other sections had comparable initial roughness.

- Effect of PCC thickness: Significantly higher initial roughness was observed on sections with 279 mm PCC slab compared to sections with 203 mm PCC slab. However, the change in roughness was slightly higher in sections with 203 mm PCC slab compared to those with 279 mm PCC slab.
- Effect of flexural strength: No significant effect of PCC flexural strength was found on roughness, at this point.
- Effect of slab width: No significant effect of slab width was found on roughness.

Similar ANOVA was performed on data from sections in the WF zone and Table 7-22 is the summary of results from the analysis. Table 7-23 shows the back transformed marginal means for all levels of design factors. As mentioned before, the results from analysis on data from other climatic zones are not presented, as limited amount of data is available for those zones. The following discussion summarizes significant effects of design factors on performance of sections in the WF zone:

- Effect of drainage: Pavement sections with drainage have shown significantly lower change in roughness than those without drainage.
- Effect of base type: Pavement sections with LCB have shown significantly higher change in roughness compared to those with PATB and with DGAB. Sections with PATB have shown the least change in roughness. Sections built with LCB were found to have the higher initial roughness compared to other sections, which have comparable initial roughness.

- Effect of PCC thickness: Significantly higher initial roughness was observed on sections with thicker PCC slab compared to sections with thinner PCC slab. However, the change in roughness was significantly higher in sections with thinner PCC slab compared to those with thicker PCC slab.
- Effect of flexural strength: Significant effect of PCC flexural strength was found on initial roughness. Sections with higher strength concrete had higher initial roughness compared to those with lower strength concrete.
- Effect of slab width: Slight effect of slab width was observed for initial roughness. Sections with standard slab width were constructed rougher.

Table 7- 20 Summary of p-values from ANOVA for determining the effects of design factors on pavement performance— Overall

Factor	Roughness (IRI)	
	ΔIRI	IRI_o
Drainage	0.002	0.373
PCC thickness	0.094	0.003
Base Type	0.009	0.037
PCC Flexural Strength	0.544	0.246
Slab Width	0.860	0.313
Site (blocked)	0.006	0.000
	N=114 R^2=0.305	N=156 R^2=0.344

Table 7- 21 Summary of marginal means from ANOVA for determining the effect of main design factors on pavement performance measures—Overall

Design Factor		Roughness (IRI)	
		ΔIRI, m/km	IRI_o, m/km
Drainage	No	0.34	1.33
	Yes	0.14	1.29
PCC thickness	8"	0.32	1.25
	11"	0.22	1.36
Base Type	DGAB	0.39	1.29
	LCB	0.30	1.37
	PATB	0.16	1.25
PCC Flexural Strength	550	0.29	1.28
	900	0.24	1.32
Slab Width	12'	0.26	1.32
	14'	0.27	1.28
MSE		1.343	0.032

Table 7- 22 Summary of p-values from ANOVA for determining the effects of design factors on pavement performance— WF Zone

Factor	Roughness (IRI)	
	ΔIRI, m/km	IRI_i, m/km
Drainage	0.012	0.688
PCC thickness	0.033	0.057
Base Type	0.004	0.557
PCC Flexural Strength	0.650	0.009
Slab Width	0.987	0.071
Site (blocked)	0.000	0.000
	N=58 R^2=0.505	N=84 R^2=0.426

Table 7- 23 Summary of marginal means from ANOVA for determining the effect of main design factors on pavement performance measures—WF Zone

Design Factor		Roughness (IRI)	
		ΔIRI, m/km	IRI_o, m/km
Drainage	No	0.30	1.32
	Yes	0.13	1.29
PCC thickness	8"	0.29	1.26
	11"	0.16	1.36
Base Type	DGAB	0.26	1.30
	LCB	0.34	1.34
	PATB	0.11	1.27
PCC Flexural Strength	550	0.20	1.24
	900	0.23	1.38
Slab Width	12'	0.22	1.35
	14'	0.22	1.26
MSE		0.947	0.033

Effect of Site Factors on Pavement Performance

Given the unbalance of the experiment, a one-way ANOVA was performed to study the main effects of the subgrade soil type (fine-grained versus coarse-grained soils) and climatic zone (wet versus dry, freeze versus no-freeze), one at a time. The p-values and mean performances from these analyses are summarized in Table 7-34 and Table 7-25, respectively. To indicate the direction of effects, "+" and "-" signs are reported along with p-values. A "+" indicates that, within a factor, the first level has exhibited more distress than the second, while a "-" indicates otherwise. For example, in the case of the effect of subgrade on roughness, "+" indicates higher roughness in pavements constructed on fine-grained soils compared to those constructed on coarse-grained soils, as fine-grained soil is the first level and coarse-grained soil is the second.

The p-values indicate that subgrade type appears to be significant in affecting the initial roughness. Pavements built on fine-grained subgrade soil showed higher initial roughness than those constructed on coarse-grained subgrade soil. Climate has a significant effect on initial roughness. Pavements constructed in "wet" climate were found to have slightly higher initial roughness compared to those in "dry" climate.

Table 7- 24 Summary of p-values from one-way ANOVA for determining the effect of site factors on pavement performance measures

Site Factor	Roughness (IRI)	
	ΔIRI, m/km	IRI_i, m/km
<u>Subgrade</u>		
Fine-grained vs. Coarse-grained	0.920 (+)	0.050 (+)
<u>Climate</u>		
Wet vs. Dry	0.406 (-)	0.052 (+)
Freeze vs. No Freeze	0.632 (-)	0.317 (-)
Wet Freeze vs. Wet No Freeze	1.000 (+)	1.000 (-)
Dry Freeze vs. Dry No Freeze	1.000 (-)	1.000 (-)

Table 7- 25 Summary of marginal means from one-way ANOVA for determining the effect of site factors on pavement performance measures

Site Factor		Roughness (IRI)	
		ΔIRI, m/km	IRI_i, m/km
Subgrade	Fine-grained	0.37	1.33
	Coarse-grained	0.38	1.25
Climate	Wet	0.35	1.33
	Dry	0.42	1.25
	Freeze	0.36	1.29
	No Freeze	0.41	1.33
	Wet Freeze	0.36	1.31
	Wet No Freeze	0.33	1.38
	Dry Freeze	0.38	1.21
	Dry No Freeze	0.50	1.29

Effect of Design Factors on Pavement Performance based on standard deviates

As explained before in Chapter 6, the experiment design and the performance of the test sections have rendered the SPS-2 experiment unbalanced. Most of the sites, 9 of the 14, in the experiment were constructed in "wet" climate of which 7 are in the WF zone. Also, all 24 unique designs were not built in every soil-climate combination. Furthermore, non-occurrence of distresses in a considerable number of sections has also contributed to the unbalance. In light of these concerns, a simplified analysis considering one design factor at a time (univariate) was performed, as in the case of analysis of the effects of site factors.

The performance of similar designs was not found to be consistent across sites indicating a considerable influence of the site conditions at each site. The site conditions that could have contributed to this variation in performance are traffic, age, construction quality, measurement variability, and material properties, apart from site factors (i.e. subgrade and environment). In order to separate the "true" effects of the experimental factors, this "noise" should be nullified.

The standard deviate indicates the relative performance of a design with respect to the other designs. As this measure was calculated for each section with respect to other sections in the same site, it indicates the relative standing of the section compared to other sections in that site. It thus helps nullify the variation in performance (due to site conditions) across sites, as the sections are weighed with respect to companion sections in each site. This approach of using the standard deviate is similar to statistical blocking, for nullifying the effects due to site conditions.

One-way (univariate) analysis of variance was performed on the standard deviates of the sections to study the effects of design factors, by considering one design factor at a time. As the SPS-2 experiment design calls for study of the effects of design factors at different site conditions, the univariate analysis was performed accordingly. The analyses were performed on data from all sections and also on subsets of data corresponding to different subgrade types, climates and combination of these. This helped in identification of the effects of design factors under different site conditions.

To study the "pure" effect of each design factor, comparisons of standard deviates were also performed by controlling for other factors, as in the case of level-B analyses (site-level). As said earlier, these comparisons were performed only on roughness. The method is not appropriate for cracking because of "low" occurrence of the distresses at this point in time. The effects of design factors, based on the above-mentioned analyses, on roughness are discussed next.

The effects of the design and site factors, in terms of standard deviate, are shown in Figure 7-7. The change in roughness was considered as the performance measure for analyses. A summary of p-values corresponding to these analyses is Table 7-26. The mean change in roughness corresponding to each comparison presented in Table 7-26 is shown in Table 7-27.

The effects of the design factors on change in roughness, based on this analysis, are presented below:

- Drainage: On the whole, the effect of drainage is statistically significant. Un-drained sections have exhibited higher change in roughness than drained sections. This effect is consistent in all sections, irrespective of subgrade soil type. In addition, the effect is more prominent in "wet" climate. Among the sections located in WF zone, those built on fine-grained soils have shown greater change in roughness compared to those built on coarse-grained soils. This effect is marginally significant.
- Base Type: As the effect of base type is confounded with the effect of drainage because of the SPS-2 experiment design, the results presented here are from

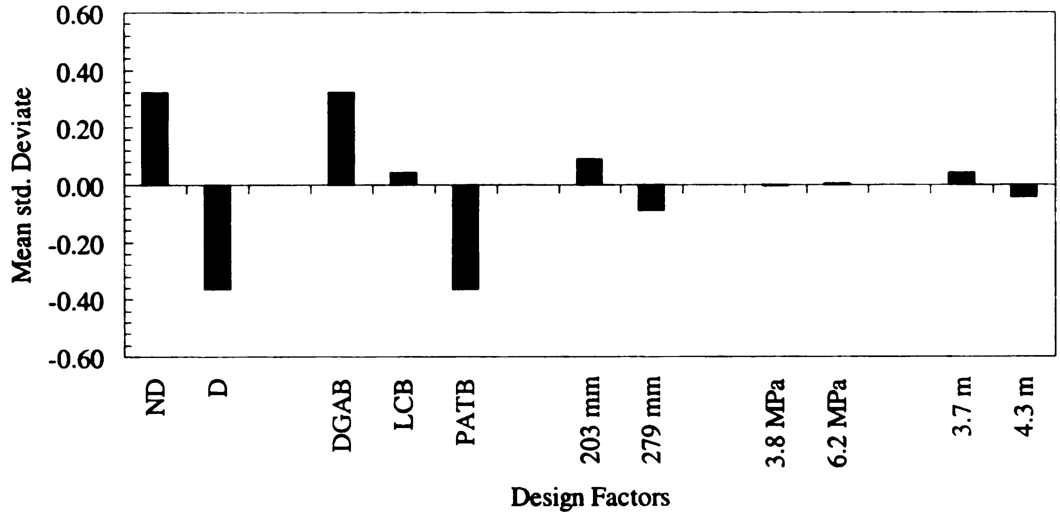
comparisons between the performance of sections built with DGAB and sections built with LCB, which are both un-drained. On average, sections with LCB have shown lower change in roughness than sections with DGAB. This effect is not statistically significant. A significant effect of base type was observed among sections located in WNF zone, in that sections with DGAB have shown higher change in roughness than those with LCB. However, this effect should be interpreted with caution, as only two sites are located in WNF zone.

- PCC slab thickness: The effect of PCC slab thickness is significant among sections built on fine-grained soils, especially when constructed in WF zone. Sections with 203 mm slab have shown higher change in roughness than those with 279 mm slab.
- PCC flexural strength: The effect of PCC flexural strength was not found to be significantly affecting roughness of the SPS-2 sections, at this point in time.
- Slab width: The effect of slab width was not found to be significantly affecting roughness of the SPS-2 sections. On average, among sections built on fine-grained soils and located in WF zone, those with standard slab width have shown higher change in roughness than those with wider slab.

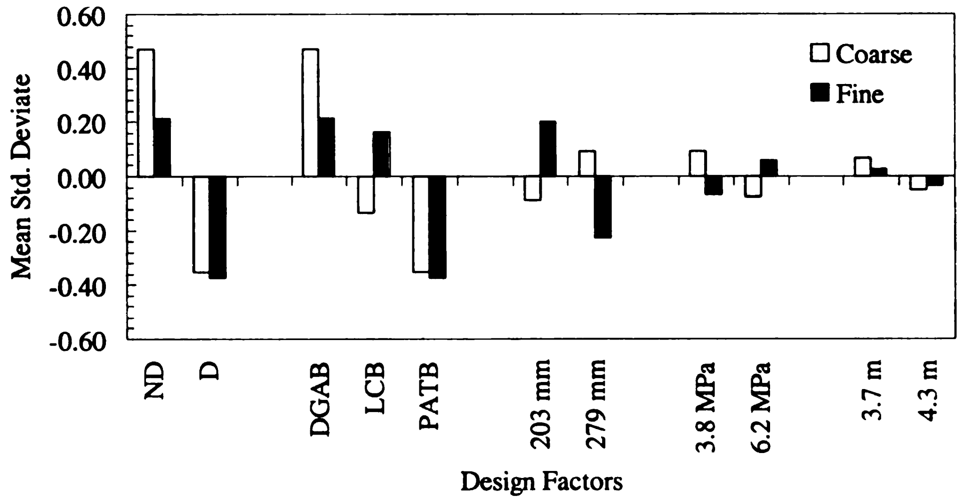
7.3.3. Comparison of Designs

The standard deviate of each section in the experiment was used to rank the designs based on their performance. For each pavement section there is a standard deviate corresponding to each of the performance measures, with respect to other sections in the same site. For each design, the standard deviates of corresponding sections at different sites were averaged to obtain the standard deviate, for each of the performance measures. The "best" designs were identified for each performance measure. Combining the performance of a design corresponding to different performance measures was considered inappropriate.

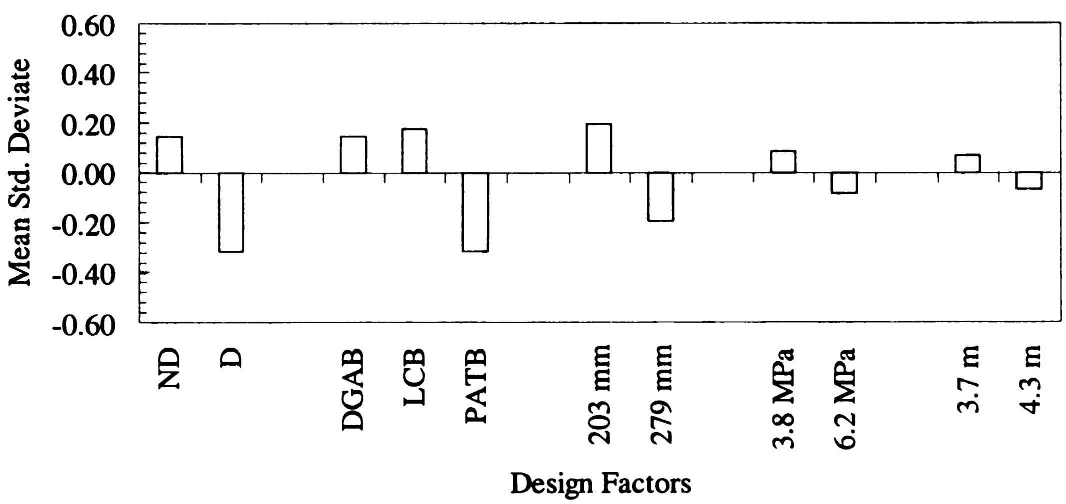
The designs that have an ID among 0201 through 0212 cannot be compared to a design with an ID among 0213 through 0224, as only one of these two sets of designs are present at a site. In other words, a site will either have designs from 0201 through 0212, or, 0213 through 0224. So, "best" designs were identified from each of the sets of designs. The design features of all the designs are given in Table 7-39 and Table 7-40.



(a) Overall



(b) By subgrade type



(c) Wet Freeze (WF) zone

Figure 7- 6 Effect of design factors on change in IRI

Table 7- 26 Summary of p-values for comparisons of standard deviates— Change in roughness

Design Factor	Comparison	Overall	By subgrade		By climatic zone				By subgrade and zone					
			Fine	Coarse	WF	WNF	DF	DNF	WF		WNF		DF	DNF
									F	C	F	C	F	C
Drainage	Drainage vs. No-Drainage	0.000	0.009	0.002	0.052	0.024	0.004	0.084	0.071	0.497	0.297	0.048	0.051	0.084
Base type	DGAB vs. LCB vs. PATB/DGAB	0.001	0.024	0.016	0.102	0.003	0.003	0.123	0.094	0.852	0.082	0.017	0.055	0.123
PCC thickness	203 mm vs. 279 mm	0.240	0.029	0.469	0.067	0.626	0.773	0.230	0.015	0.718	0.565	0.949	0.923	0.230
PCC flexural Strength	3.8 MPa vs. 6.2 MPa	0.962	0.530	0.506	0.442	0.226	0.832	0.603	0.797	0.065	0.255	0.639	0.941	0.603
Slab Width	3.7 m vs. 4.3 m	0.500	0.770	0.639	0.530	0.776	0.992	0.667	0.491	0.934	0.790	0.975	0.772	0.667

Note: Shaded cells indicate statistical significance at 90% or higher level of confidence (p<0.1).

Table 7- 27 Summary of mean change in roughness

Design Factor	Comparison	Overall	SG		Zone				WF		WNF		DF	DNF
			F	C	WF	WNF	DF	DNF	F	C	F	C	F	C
Drainage	ND	0.3	0.3	0.3	0.3	0.3	0.1	0.4	0.5	0.1	0.1	0.5	0.1	0.4
	D	0.1	0	0.1	0	0.1	-0.1	0.2	0	0	0.1	0.1	0	0.2
Base type	DGAB	0.3	0.3	0.3	0.3	0.3	0.1	0.4	0.5	0.1	0.1	0.5	0.1	0.4
	LCB	0.2	0.3	0.1	0.3	0.1	0.3	0.2	0.4	0.1	-0.1	0.2	0.3	0.2
	PATB	0.1	0	0.1	0	0.1	-0.1	0.2	0	0	0.1	0.1	0	0.2
PCC slab thickness	203 mm	0.2	0.3	0.2	0.3	0.2	0.1	0.2	0.4	0.1	0.1	0.3	0.1	0.2
	279 mm	0.2	0.2	0.2	0.2	0.1	0.1	0.3	0.2	0.1	0	0.3	0.1	0.3
PCC flexural strength	3.8 MPa	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.3	0.1	0	0.3	0.1	0.2
	6.2 MPa	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.3	0	0.1	0.3	0.1	0.2
Slab width	3.7 m	0.2	0.3	0.2	0.3	0.1	0.1	0.3	0.4	0.1	0.1	0.3	0.1	0.3
	4.3 m	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.3	0.1	0.2

Table 7- 28 Design features of designs 0201 through 0212

Design ID	Design Features				
	Drainage	Base type	Target PCC thickness (mm)	Slab Width (m)	Target 14-day flexural strength of PCC (MPa)
0201	No	DGAB	203	3.7	3.8
0202	No	DGAB	203	4.3	6.2
0203	No	DGAB	279	4.3	3.8
0204	No	DGAB	279	3.7	6.2
0205	No	LCB	203	3.7	3.8
0206	No	LCB	203	4.3	6.2
0207	No	LCB	279	4.3	3.8
0208	No	LCB	279	3.7	6.2
0209	Yes	PATB	203	3.7	3.8
0210	Yes	PATB	203	4.3	6.2
0211	Yes	PATB	279	4.3	3.8
0212	Yes	PATB	279	3.7	6.2

Table 7- 29 Design features of designs 0213 through 0224

SHRP_ID	Design Features				
	Drainage	Base type	Target PCC thickness (mm)	Slab Width (m)	Target 14-day flexural strength of PCC (MPa)
0213	No	DGAB	203	4.3	3.8
0214	No	DGAB	279	3.7	6.2
0215	No	DGAB	279	3.7	3.8
0216	No	DGAB	203	4.3	6.2
0217	No	LCB	203	4.3	3.8
0218	No	LCB	203	3.7	6.2
0219	No	LCB	279	3.7	3.8
0220	No	LCB	279	4.3	6.2
0221	Yes	PATB	203	4.3	3.8
0222	Yes	PATB	203	3.7	6.2
0223	Yes	PATB	279	3.7	3.8
0224	Yes	PATB	279	4.3	6.2

Transverse Cracking Performance

Based on the transverse cracking performance the designs are ranked as shown in Figure 7-9 and Figure 7-10. It is evident from the figures that the designs with 203 mm (8-in) PCC slab and built on a LCB (i.e. 0205, 0206, 0217 and 0218) have shown the "worst" (relative) performance, while the other sections have shown comparable performance. This is an "interaction" effect of PCC slab thickness and base type. Also, in general, sections with PATB have performed better than other sections, followed by sections with DGAB.

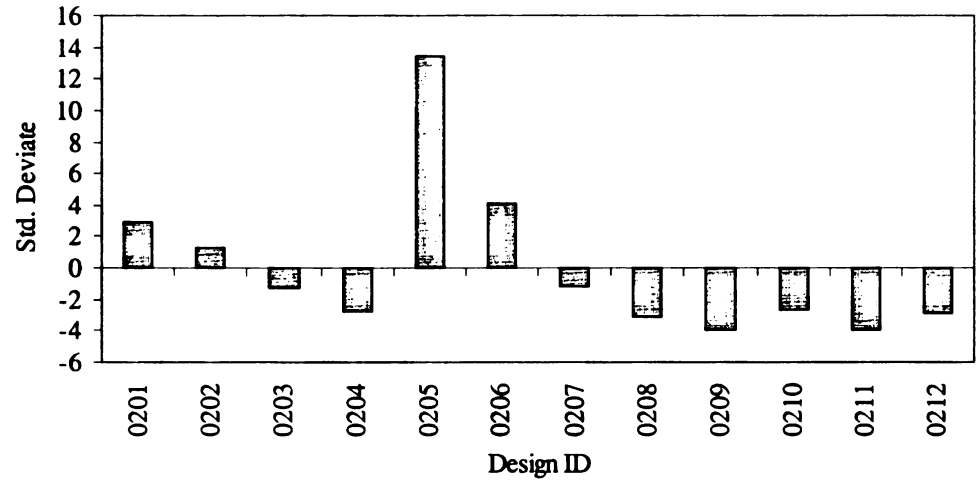


Figure 7- 7 Comparison among designs 0210 through 0212

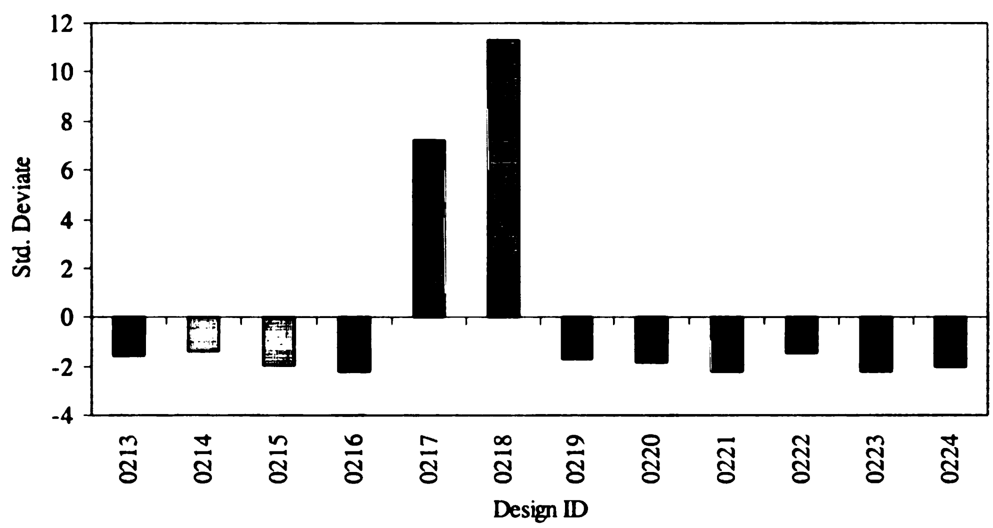


Figure 7- 8 Comparison among designs 0213 through 0224

Longitudinal Cracking Performance

The results of comparison of designs with respect to longitudinal cracking performance are shown in Figure 7-11 and Figure 7-12. As in the case of transverse cracking performance, the sections with 203 mm PCC slab and built with LCB (i.e. 0205, 0206, 0217, and 0218) have shown the worst performance. Also, in general, sections with

PATB have shown better performance than other sections, followed by sections with DGAB.

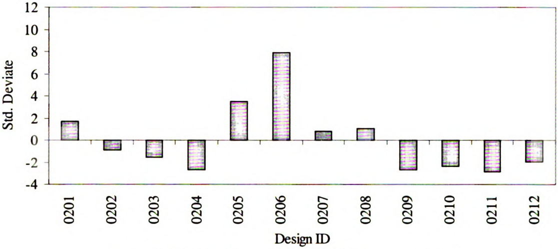


Figure 7- 9 Comparison of designs 0201 through 0212

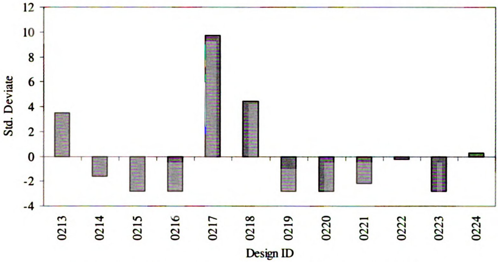


Figure 7- 10 Comparison of designs 0213 through 0224

Change in Roughness

The change in roughness, from first survey to latest survey, was taken as the performance measure for this analysis. As shown in Figure 7-13 and Figure 7-14, the change in roughness was lesser in sections with PATB, in general. On the other hand, sections with DGAB have slightly higher change in roughness compared to other sections.

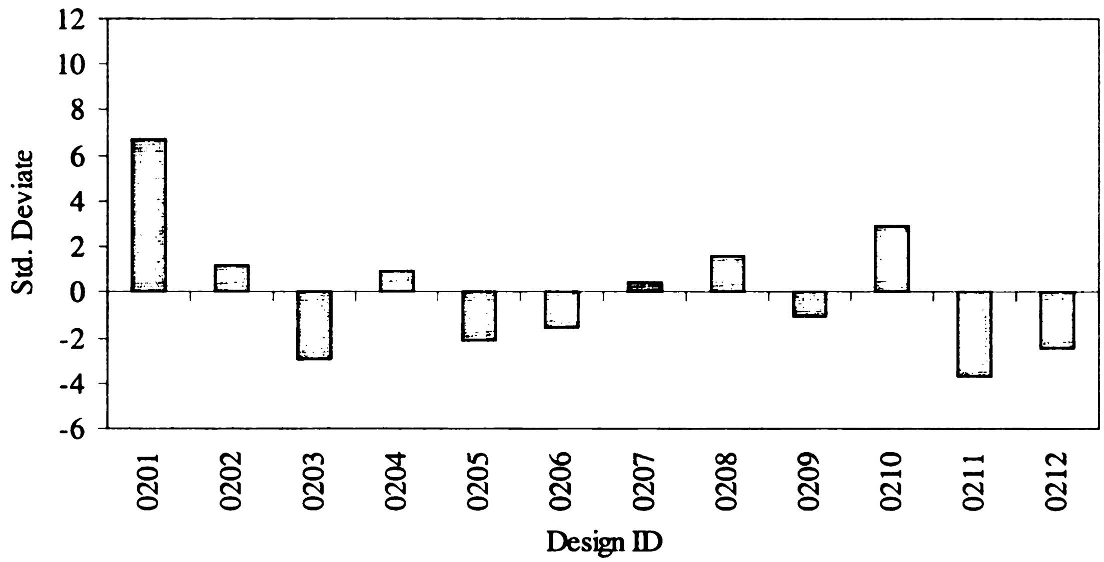


Figure 7- 11 Comparison of designs 0201 through 0212

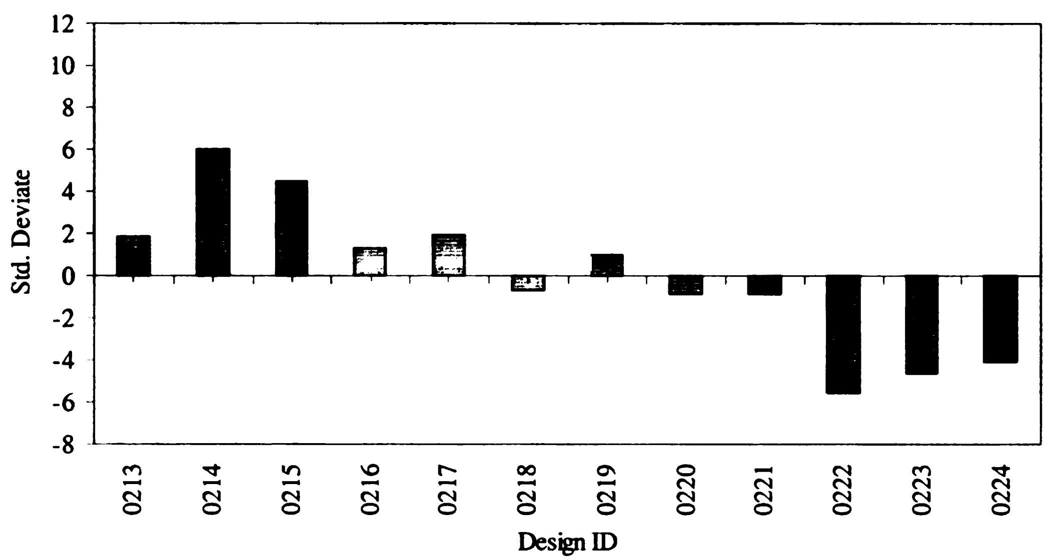


Figure 7- 12 Comparison of designs 0213 through 0224

In summary, based on the comparison of performance of the designs, PATB sections (0209 through 0212, and 0221 through 0224) are the "best" designs, especially in terms of cracking performance and change in roughness. In addition, sections with LCB (0205 through 020208, and 0217 through 0220) have shown worse cracking performance. Hence, the performance of the designs seems to be determined mainly by the type of base.

7.4. SYNTHESIS OF RESULTS FROM ANALYSES

This section summarizes all the findings from various analyses performed on the performance data of sections in the SPS-2 experiment. The methods employed in this study were explained in Chapter 6 and the results obtained from these analyses were presented above in this chapter.

As mentioned before, broadly two types of analyses (overall) were performed—magnitude-based and frequency-based. ANOVA, which is a method for comparing means, is the magnitude-based analysis. Binary Logistic Regression (BLR) and Linear Discriminant Analysis (LDA) are frequency-based analyses, which give the likelihood of occurrence and non-occurrence of distresses. The site-level analyses were used to compare the performance of pavements within each site. The results from site-level analysis were used to ascertain the consistency of the effects (of experimental factors) across all sites.

The magnitude-based methods, though powerful, are more appropriate for analyses of distresses, which have "fairly high" occurrence (roughness) and magnitude. On the other hand, the frequency-based methods are more suitable- when the occurrence of a distress is considerable though the magnitude is low (for example, transverse cracking, and longitudinal cracking).

An attempt has been made to 'summarize' the above said effects of design and site features on the performance. The results were interpreted in light of the type of analysis, and occurrence and extent of distress. ANOVA being the most "powerful" among the methods was given higher importance for distresses with "good" occurrence and/or extent (roughness). However, the results from this analysis suffer seriously in case of limited (low occurrence of distress) and unbalanced data. Therefore, in these cases, the effects of experimental features, mainly on occurrence of distresses, were investigated using BLR and LDA. The results from site-level analyses (paired comparisons and comparison of designs) and data exploration (extent of distresses) were then considered to confirm the findings. Based on the site-level analyses the consistency of effects was ascertained.

All results need to be interpreted in light of the experiment design, occurrence and extent of distresses, and analyses methods used. A "weak" effect at this point in time may become a "medium" or "strong" effect in the long term. Hence, all the conclusions are based on "mid-term" performance of the ongoing SPS-2 experiment.

The SPS-2 experiment, entitled Strategic Study of Structural Factors for Rigid Pavements, is one of nine special pavement studies in the LTPP program. The main objectives of this experiment are to determine the relative influence and long-term effectiveness of the structural factors affecting performance of jointed plain concrete pavements (JPCP). These factors include PCC slab thickness, base type, in-pavement drainage, PCC flexural strength and slab width. The key conclusions from this study are summarized below.

7.4.1. Effects of structural factors for rigid pavements — SPS-2 experiment

The effects of design and site factors on the performance of SPS-2 pavements are presented here. The structural factors include PCC slab thickness, base type, drainage, PCC flexural strength and slab width. The experiment also includes studying the secondary effects of site factors, namely subgrade type and climatic zones. The effects of the experimental factors on each performance measure are discussed below, one performance measure at a time.

Transverse cracking

The occurrence of transverse cracking among pavements with 203 mm (8-inch) PCC slab thickness is higher than that among those with 279 mm (11-inch) PCC slab thickness. Also, the occurrence of transverse cracking among pavements constructed with LCB is higher than that among those with PATB/DGAB or with DGAB. Pavements with PATB/DGAB have shown the "best" performance (least occurrence of cracking). These effects of PCC thickness and base type are statistically significant, as suggested by the frequency-based analyses. The analyses indicate a marginal effect of drainage on the occurrence of transverse cracking. Sections without drainage have slightly higher likelihood of cracking than sections with drainage.

On average, among sections built with LCB, those with 203 mm PCC slab have higher occurrence of cracking than those with 279 mm PCC slab. It is important to interpret these results in light of the construction issues, i.e. shrinkage cracking in LCB.

Pavements built on fine-grained soils have slightly higher chances for the occurrence of transverse cracking than those built on coarse-grained soils. This effect was found to be marginally significant.

Longitudinal Cracking

The occurrence of longitudinal cracking among pavements with 203 mm (8-inch) PCC slab thickness is higher than among those with 279 mm (11 inch) PCC slab thickness. Also, the occurrence of longitudinal cracking among pavements constructed with LCB is higher than among those with PATB/DGAB or with DGAB. Pavements with PATB/DGAB have shown the "best" performance (least occurrence of cracking). These effects of PCC thickness and base type are statistically significant, as suggested by the frequency-based analyses.

On average, among sections built with LCB, those with 203 mm PCC slab have higher occurrence of cracking than those with 279 mm PCC slab. It is important to interpret these results in light of the construction issues i.e. shrinkage cracking in LCB.

Faulting

The extent of faulting among the test sections of the SPS-2 experiment is low, with joint faulting less than 1 mm in 62% of the sections. Only 33% of the sections have 0 to 20% of the joints that faulted more than 1.0 mm, and just 5% of the sections have more than 20% of the joints that faulted more than 1.0 mm. A majority of SPS-2 sections seem to be exhibiting "good" performance with respect to joint faulting, at this point in time. This performance seems to be reasonable as the test sections are "young" and have doweled joints at 4.6 m (15') spacing. Therefore, the results at this point may only indicate the initial trends/observations that may not be of much practical significance.

In general, pavements with standard slab width i.e. 3.7 m (12'), have shown higher faulting than those with widened slab i.e. 4.3 m (14') wide slab. However, the effect may not be of practical significance because of the low occurrence of faulting.

It is important to note that according to the experiment design of SPS-2, sections with 203 mm PCC slabs are built with dowels of 25.4 mm diameter, whereas sections with 279 mm PCC slabs are built with dowels of 32 mm diameter. Hence, the effect of dowel diameter and the effect of PCC slab thickness on faulting are not separable.

Roughness

Pavements without drainage have shown higher change in roughness than those with drainage. Also, pavements constructed with PATB have shown lower change in IRI (ΔIRI) compared to those with DGAB or LCB, while pavements with DGAB have the highest change in roughness. These effects of drainage and base type are of statistical significance, as suggested by magnitude-based methods.

Among pavements constructed with standard slab width, sections with DGAB have shown higher ΔIRI than those with LCB or PATB. This effect is only marginally significant. Among pavements built on fine-grained soils, those with 203 mm PCC slab have higher ΔIRI than those with 279 mm PCC slab. This effect is more prominent among sections located in WF zone. Also, the effect of drainage (i.e. sections with PATB) is more prominent among sections located in WF zone and built with fine-grained soils. Among sections located in WF zone and built on fine-grained soils, those with drainage (i.e. sections with PATB) have shown lower ΔIRI compared to those without drainage. These effects are of statistical significance.

The above results suggest that the change in roughness can be inhibited by constructing pavements with PATB and drainage as compared to sections with DGAB or LCB, especially in the case of pavements built on fine-grained soils. Also, among pavements built on fine-grained soils, an increase in PCC slab thickness from 203 mm to 279 mm seems to help prevent an increase in pavement roughness.

A simplified summary of results from all analyses is given in Table 7-32. The summary is only meant to give an overall assessment of the effects. The reader is strongly recommended to peruse relevant portions of the thesis for a better understanding of all the effects. It is important to note that a "strong", "medium" or "weak" effect should only be interpreted in terms of the difference in effects at the various levels of a factor. As an example, a "strong" effect of PCC slab thickness and a "strong" effect of subgrade soil type should not be interpreted as PCC slab thickness and subgrade type having the same strength of effect.

A black circle indicates a "strong" effect; a grey circle indicates a "medium" effect, and a white circle indicates a "weak" effect. Operational significance was determined only for "strong" or "medium" effects. It should be noted that an effect can be statistically significant (meaning that it is not a coincidence) but may not be operationally/ practically significant, at this point in time.

Table 7- 30 Summary of effects of design and site factors for rigid pavements

Design Factor	Performance Measures		
	Transverse cracking	Longitudinal cracking	Roughness
Drainage	◌	○	●
PCC thickness	●	●	○
Base type	●	●	●
Flexural Strength	○	○	○
Lane Width	○	○	◌
Climatic Zone	○	●	◌
Subgrade type	◌	○	◌

Note: This table is solely for the purpose of summarizing some of the effects in a 'simple' format. The reader is urged to read relevant text in the thesis for a better understanding.

Symbol	Description
●	Strong Effect
◌	Medium Effect
○	Weak Effect

CHAPTER 8- ENVIRONMENTAL AND LOAD EFFECTS ON RIGID PAVEMENTS

8.1. INTRODUCTION

The SPS-8 experiment of the LTPP program is aimed at studying the effects of environment, in the absence of heavy loads, on pavement performance. Newly constructed flexible and rigid pavements are included in the experiment. A detailed description of the experiment design can be found elsewhere (Hanna, Tayabji. et al. 1994). Data from the rigid pavement sections from this experiment were used to investigate the effects of environment and traffic on rigid pavement performance. While the effects of environment were studied based on comparisons among the pavement sections in the SPS-8 experiment, the effects of traffic were deduced from comparisons between similar sections in SPS-8 and SPS-2 experiments. This chapter contains observations regarding the effects of environment and traffic on rigid pavement performance, based on the comparisons mentioned above. An introduction to the SPS-8 experiment is followed by details of the comparisons and observations based on the comparisons.

8.2. DESCRIPTION OF THE SPS-8 EXPERIMENT

The SPS-8 experiment was designed to evaluate the effects of environment on pavement performance, in the absence of heavy traffic loads. The study examines the effects of climatic factors and subgrade type (frost-susceptible, expansive, fine, and coarse) on pavement sections incorporating different designs of flexible and rigid pavements, which are subjected to very limited traffic as measured by ESAL accumulation. The study design stipulates that the traffic volume on the test sections be at least 100 vehicles per day and not more than 10,000 ESALs in a year.

Table 8-1 shows the experiment design matrix for SPS-8. Rigid pavement test sections consist of 203 mm (8") and 279 mm (11") doweled JPCP slabs on 152 mm (6") DGAB. These sections are identified as XX-0807 to XX-0812, where 'XX' is the site code and the first two digits of the SHRP ID, i.e. '08', stand for the SPS-8 experiment. The sections with SHRP ID that ends with an odd number have a target PCC slab thickness of 203 mm, while the others have a target PCC slab thickness of 279 mm. An alphabet is introduced before the SHRP ID in case the section belongs to a second site constructed in the same state.

Table 8- 1 SPS-8 Experiment Design

Pavement Type	AC/PCC Thickness, mm	Base Thickness, mm	WF			WNF			DF			DNF		
			A	F	C	A	F	C	A	F	C	A	F	C
Flexible	102	203	x	x	x	x	x	x	x	x	x	x	x	x
	178	306	x	x	x	x	x	x	x	x	x	x	x	x
Rigid	203	153	x	x	x	x	x	x	x	x	x	x	x	x
	279		x	x	x	x	x	x	x	x	x	x	x	x

A: Active subgrade soil (either frost susceptible or swelling type relative to climatic zone)
F: Fine-grained subgrade soil
C: Coarse-grained subgrade soil

Each section is constructed as uniform as is practical over a length of 183 m (600 feet) to allow 152 m (500 feet) for monitoring purposes and 15 m (50 feet) at each end for destructive testing. The guidelines also stipulate that an asphalt concrete, untied PCC, or bituminous surface-treated aggregate shoulder must be constructed as part of the test section. The shoulder should extend at least 0.9 m (3 feet) outside the edge of the travel lane and should be constructed according to participating highway agency practice. The concrete used for the surface layer has to have a target average 14-day flexural strength of 3.8 MPa (550 psi). Moreover, no subsurface drainage is to be provided to the pavements in the experiment. The other construction guidelines for the experiment are the similar to the SPS-2 experiment (see Chapter 2).

8.3. CURRENT STATUS OF SPS-8 RIGID PAVEMENTS

Table 8-2 shows the current status of the SPS-8 experiment, as per Release 17 of DataPave. While the minimum required number of rigid pavement sections to fulfill the proposed experiment criteria is 24, only 14 rigid pavement sections are currently in the experiment, distributed over 6 sites. There are two sites [Missouri (29) and Ohio (39)] in Wet Freeze zone, two sites [Arkansas (5) and Texas (48)] in Wet No Freeze zone, and two sites [Colorado (8) and Washington (53)] in Dry Freeze zone. There are no sites in the Dry No Freeze zone. An active subgrade soil can be coarse-grained or fine-grained. A section that is 'active' is not categorized as 'fine' or 'coarse', but as 'active'. Subgrade soil type at a site was determined based on the data provided in the construction reports.

Table 8- 2 Distribution of rigid pavement sections in the SPS-8 experiment

Pavement Type	AC/PCC Thickness	Base Thickness	WF			WNF			DF			DNF		
			A	F	C	A	F	C	A	F	C	A	F	C
Rigid	203 mm	152 mm	x	x		x	x			x	x			
	279 mm		x	x		x	x			x	x			

Each 'X' indicates presence of one or more sections fulfilling the criteria of the cell

8.4. DATA AVAILABILITY

Table 8-3 is a summary of data availability for the rigid pavement sections in the SPS_8 experiment.

8.4.1. Construction Reports

As in the case of SPS-2 sites, the construction reports contain information about the construction process, geometric layout, construction issues, etc. Construction reports are available for all the six sites in the SPS-8 experiment. A summary of the site-specific information can be found elsewhere (Chatti, Buch et al. 2005).

8.4.2. Climate Data

The data on climate at the SPS-8 sites are available from Automated Weather Stations (AWS) and not from Virtual Weather Stations (VWS). This information was used to calculate average annual temperature and precipitation at the sites. The classification of the sites in different climatic zones was confirmed with the available data.

8.4.3. Traffic Data

Table 8-4 is a summary of the traffic data available for the rigid pavement sections in SPS-8 experiment. The traffic on the sections in Ohio (39) is higher than the stipulated upper limit, which is 10,000 ESAL. Traffic data are also available from the construction reports of the sites. A summary of traffic data obtained from construction reports is Table 8-5. The AADT for sections in AR (5), MO (29), and WA (53) is below the lower limit of 100 vehicles/day.

8.5. DESIGN VERSUS ACTUAL CONSTRUCTION REVIEW

Figure 8-1 and 8-2 show the PCC slab thickness deviations for the two thickness levels (the horizontal lines indicate target values). Sections at MO and OH have slabs with considerable deviation from target thickness. Similarly Figure 8-3 shows the deviations in the base layer thickness (the horizontal line indicates target value). Section 48-A808, and the sections at the sites in Arkansas (5) and Washington (53) were built with lesser than stipulated base thickness.

The experiment design stipulates that the target 14-day flexural strength of the PCC slab concrete be 3.8 MPa (550 psi). Figure 8-4 (the horizontal line indicates target value) is a summary of concrete test data for each section. PCC in all the sections met the stipulated flexural strength. All sections except 8-0811 exceeded the target strength.

8.6. DISTRESS OCCURRENCE

The distresses in SPS-8 sections as of Release 17 have been summarized in Table 8-6. Faulting occurred in all the sections except the ones at the WA (53) site. In 12 of the 14 sections in the experiment, less than 40% of the joints have measurable faulting. In half of the sections, 3 to 20% of the joints faulted more than 1.0 mm. Figure 8-5 shows the distribution of IRI in SPS-8 sections. A detailed evaluation of distress in SPS-8 sections is presented in the next section.

Table 8- 3 Summary of data availability for SPS-8 experiment –Rigid pavements

Data category	Data type	Data Availability, % of sections
Site location information	*Construction reports*	100
	Climatic data	
	Virtual Weather Station	
	Annual Temperature	0
	Annual Precipitation	0
	Automated Weather Station	
	Monthly Temperature	7
	Monthly precipitation	7
	*Traffic data**	
	Traffic Open date	0
	Monitored	14
	Estimated	14
	Axle Distribution	0
Materials data	*Subgrade*	
	Sieve analysis	100
	Atterberg Limits	100
	Classification	100
	Lean Concrete Base	
	Compressive Strength	0
	Portland Cement Concrete	
	PCC mix data	100
	Flexural Strength	71
	Compressive Strength	86
	Split tensile Strength	86
	Static modulus of Elasticity	86
	CTE	0
Pavement structure	*Layer details*	
	Type	100
	Representative thickness	100
	Dowel bar details	
	Diameter	0
	Length	0
	Spacing	0
	Shoulder information	
	Type	100
	Width	100
	Thickness	100
Monitoring**	Profile data (IRI)	100
	Distress data	100
	Faulting data	100

*Monitored, Estimated, or Axle Distribution data is considered to be available for a site even if the data is available only for one year.

**Data is said to be available for a section even if it is available for just one year.

Table 8- 4 Summary of available traffic data

Site ID	SHRP ID	Year	Traffic (ESAL)
8	0811	1997	1000 (Estimated)
8	0811	1998	1000 (Estimated)
8	0811	1999	1000 (Estimated)
8	0812	1997	1000 (Estimated)
8	0812	1998	1000 (Estimated)
8	0812	1999	1000 (Estimated)
39	0809	1997	66824 (Monitored)
39	0810	1997	69317 (Monitored)

Table 8- 5 Summary of traffic data available from the construction reports

Site ID	2-way AADT used to calculate design traffic, vehicles/ day	Design ESAL, KESAL/ yr
5	38	Not Available
8	2500	12.95
290800	50	96.5
29A800	118	Not Available
39	500	Not Available
48	Not Available	2.15
53	60	182.5

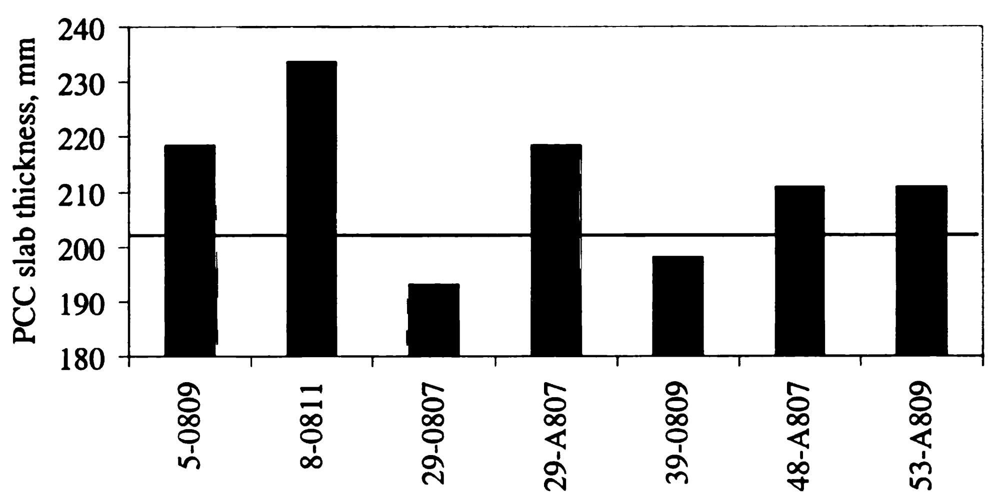


Figure 8- 1 Thickness deviations in sections with target PCC thickness of 203 mm

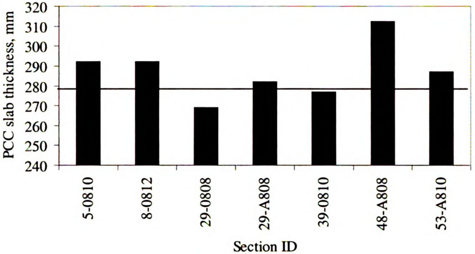


Figure 8- 2 Thickness deviations in sections with target PCC thickness of 279 mm

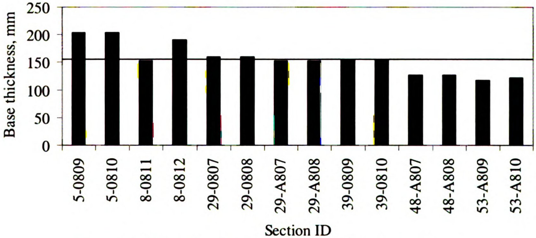


Figure 8- 3 Deviation from target base thickness of 152 mm

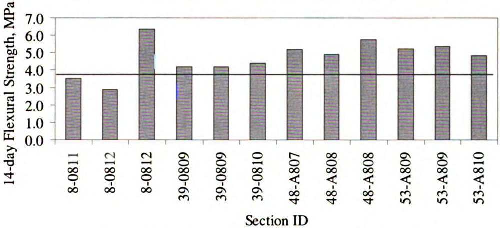


Figure 8- 4 Average 14-day flexural strength of PCC

Table 8- 6 Distresses in SPS-8 sections

Site ID	SHRP ID	Trans. Cracks	Long. Cracks	Corner Breaks	Long. Spalling Length	Trans. Spalling	Trans. Spall Length	Scaling No.
5	809	0	0	0	46.2	0	0	0
5	810	0	0	0	37.5	0	0	0
8	811	5	7.7	1	0	2	0.8	1
8	812	0	0	0	0	0	0	0
29	807	3	0.5	0	37.4	1	0.5	0
29	808	0	0	0	4.5	0	0	0
29	A807	0	0	0	0	0	0	0
29	A808	0	0	0	0	0	0	0
39	809	1	0	0	0.7	0	0	0
39	810	0	0	0	78.8	0	0	0
48	A807	0	0	0	0	0	0	0
48	A808	0	0	0	0	0	0	0
53	A809	0	0	0	0	0	0	0
53	A810	0	0	0	0	1	0.4	0

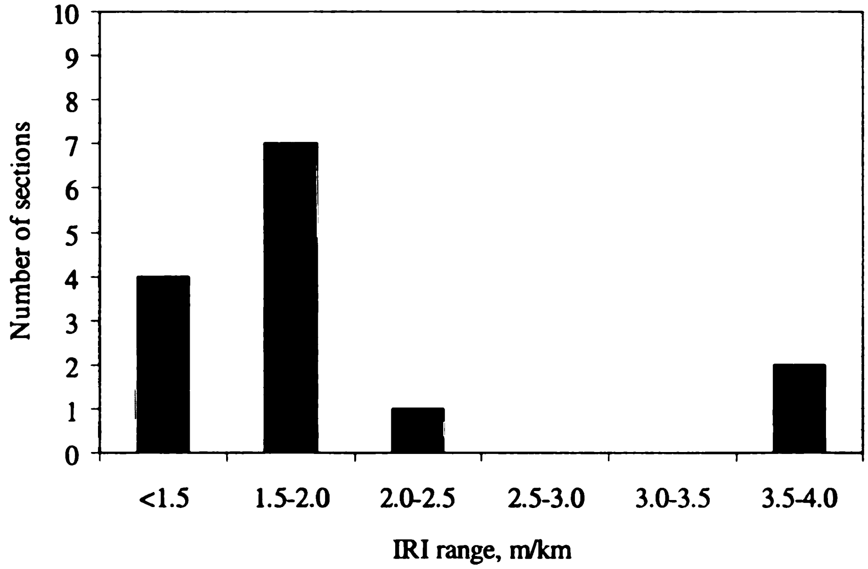


Figure 8- 5 Current IRI in SPS-8 sections

8.7. ANALYSES AND RESULTS

As mentioned before, comparisons were performed among the SPS-8 sections and also between similar sections in SPS-2 and SPS-8 experiments. The results from these comparisons are presented in this section.

The SPS-8 sites are 4 to 9 years old, according to Release 17 of DataPave, with an average age of 7 years. In light of the absence of heavy traffic, SPS-8 sections are not expected to exhibit severe structural distress at this point in time. In line with this expectation, low levels of distress were observed on the test sections.

No sign of pumping, blow-ups, map cracking or durability cracking were observed on the test sections. Cracking (transverse and/or longitudinal), mostly of low or medium severity, was observed in four sections. Spalling was found in eight sections and most of the spalling occurred at longitudinal joints. Longitudinal spalling ranged from 1 m to 79 m while transverse spalling was less than 1 m. Scaling and corner break occurred on section 8-0811 only. Only the sections at the Colorado site, 8-0811 and 8-0812, have polished aggregate of 302 and 214 m^2, respectively. Severe construction issues (poor climatic conditions during construction), as mentioned in the construction report (Nichols Consulting Engineers 1998), could be the reason behind the outlying performance of the test sections.

Keeping in view the number of sections constructed for SPS-8 experiment (14 rigid pavements in 6 sites) and the extent distresses at present, statistical analysis as in the case of the SPS-2 experiment is not applicable. In future when enough distress occurs at the SPS-8 sections, non-parametric tests may be applied, given that only 14 sections exist in the experiment.

For this study, simple mean comparisons (only for sections that exhibited distresses) were performed to identify the effects of environment and traffic on various performance measures. The site-level and overall analyses, which are comparisons among the SPS-8 sections, are followed by a comparison between the performance of similar sections from SPS-2 and SPS-8 experiments. Some initial trends obtained from these comparisons are reported below.

8.7.1. Site-Level Analysis

The site-level analysis of the SPS-8 rigid pavements was done based on the PI and the relative performance concepts (see Chapter 6), as in the case of SPS-2 experiment. At the site-level, roughness and transverse joint sealant damage were analyzed to investigate the effects of the main site factors (climatic zone and subgrade type) on performance. It was observed that the roughness of sections constructed in the dry freeze zone is lesser than those constructed in the wet zones. Furthermore, sections in the wet freeze zone are smoother than the ones in the wet no-freeze zone. Also, transverse joint sealant damage appeared to be more prevalent in the wet zones as compared to the dry freeze zone.

8.7.2. Overall Analysis

The initial trends that show the effect of SPS-8 experimental factors on various performance measures will be discussed in this section. These comparisons were carried out only for those performance measures that were exhibited to some extent in the rigid pavement sections.

Transverse Cracking: Figure 8-6 and 8-7 show the average transverse cracking length by experimental factors. Only three of the fourteen sections have transverse cracking, ranging from 1 to 5 cracks. Cracking was not observed in any of the pavements constructed with thicker PCC slab and in any of the pavements constructed on coarse-grained subgrade soil. Average transverse cracking was found to be more on sections located in DF zone, which was contributed by section 0811 of site CO (8). The CO(8) site is the oldest (10 years) in the experiment and "very poor" climatic conditions prevailed during the construction (Nichols Consulting Engineers 1998).

Longitudinal Spalling: Figure 8-8 shows the average longitudinal spalling length by experimental factors, for rigid pavements. Six of the fourteen sections have longitudinal spalling ranging from 1 to 79 m with an average of 34 m. Spalling was not observed in any of the pavements located in the DF zone and in any of the pavements constructed on coarse-grained subgrade soil. Average spalling was found to be more in sections located in WNF zone. Also pavements with thicker PCC slab have shown slightly more spalling than those with thinner PCC slab. Among the pavements built on fine-grained soils, those built on active soils have exhibited slightly more spalling than those built on non-active subgrade soil (see Figure 8-9).

Wheel Path Joint Faulting: Average percent of joints that faulted more than 1 mm, by experimental factors, is shown in Figure 8-10. Seven sections have faulting of more than 1.0 mm at one or more joints. Among these sections, on average, 8% of the joints faulted more than 1 mm, with a range of 3 to 21% of joints. Average percentage of joints that faulted more than 1 mm was found to be more on sections located in WNF zone. Also pavements constructed on active subgrade soil have shown slightly more faulting than those constructed on others. Among the pavements built on coarse-grained soils, those built on active soils have exhibited more faulting than those built on non-active subgrade soil (see Figure 8-11).

Roughness: The average roughness in the SPS-8 sections by experimental factors is shown in Figure 8-12. The average initial IRI of the SPS-8 rigid pavement sections is 1.8 m/km, with a range of 1.0 to 3.6 m/km. The average change in IRI for rigid pavements is 0.1 m/km with a range of 0.0 to 0.7 m/km. Average roughness was found to be higher for sections located in WNF zone. Also pavements constructed on active subgrade soil have shown slightly higher IRI than those constructed on others. Among the pavements built on coarse-grained soils, those built on active soils have exhibited higher IRI than those built on non-active subgrade soil (see Figure 8-13). It may be noted that similar trends were observed for faulting and roughness, which may suggest a cause-effect relation among these performance measure.

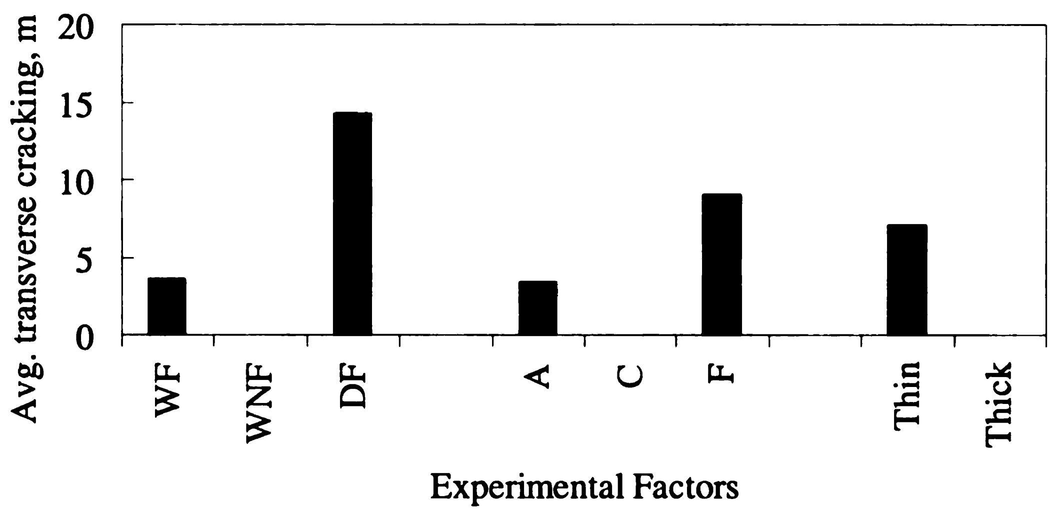


Figure 8- 6 Average transverse cracking by experimental factors

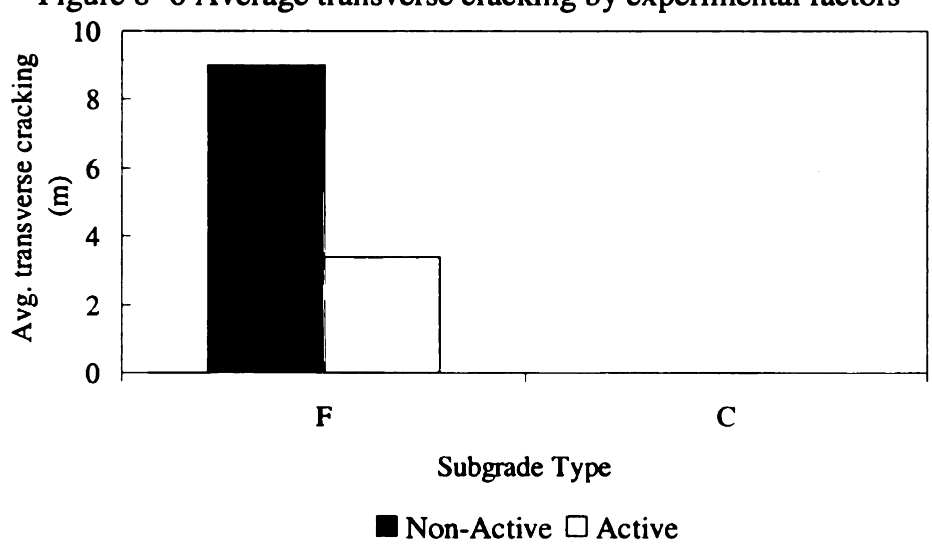


Figure 8- 7 Average transverse cracking by subgrade type

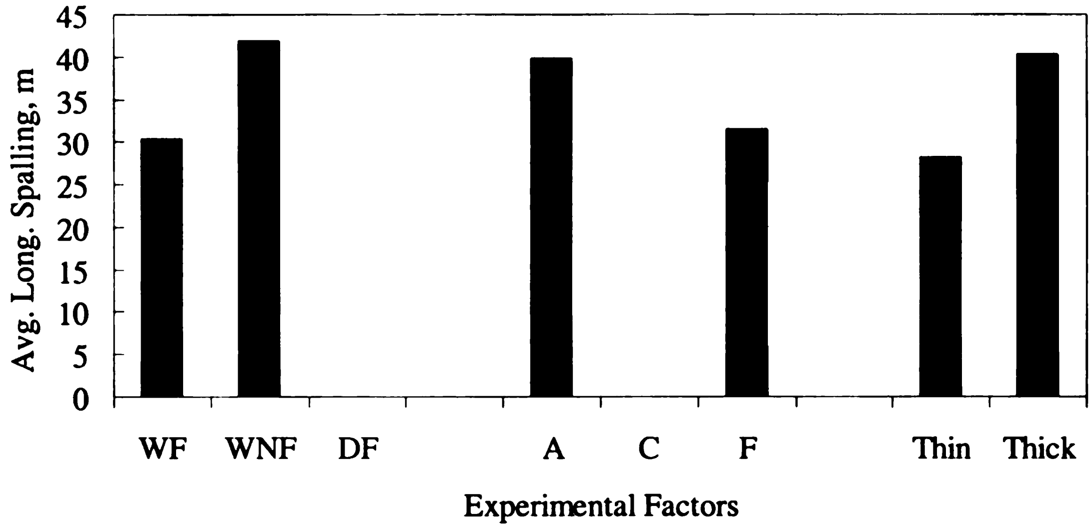


Figure 8- 8 Average long. spalling by experimental factors

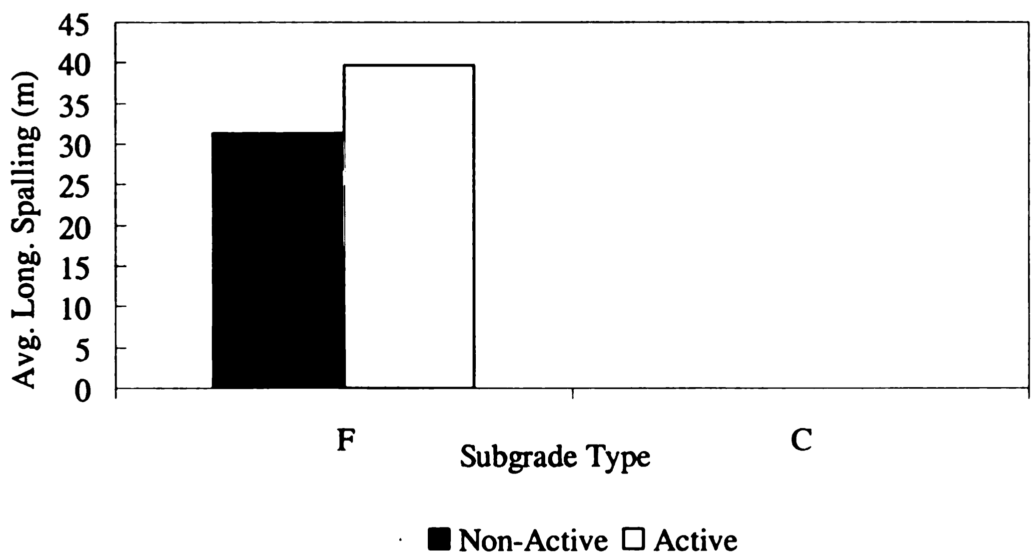


Figure 8- 9 Average long. spalling by subgrade type

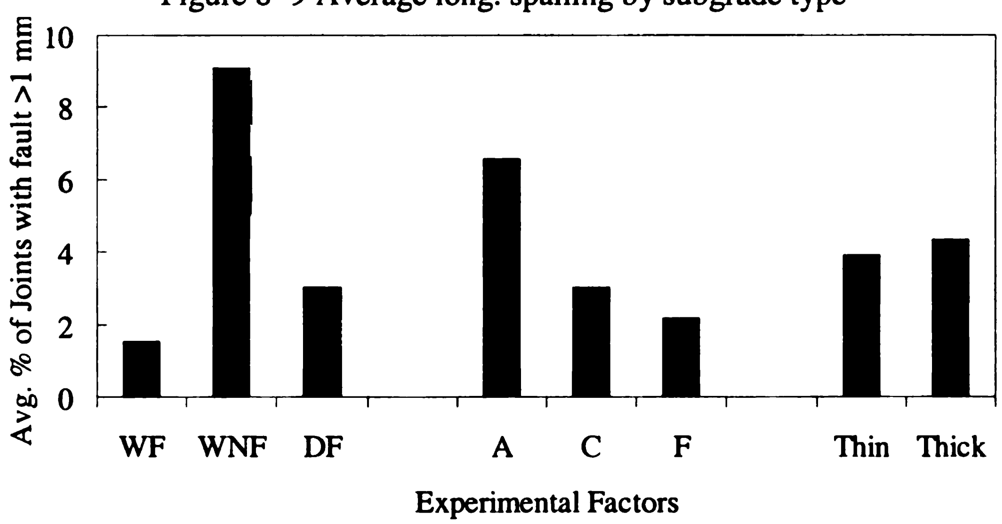


Figure 8- 10 Faulting performance by experimental factors

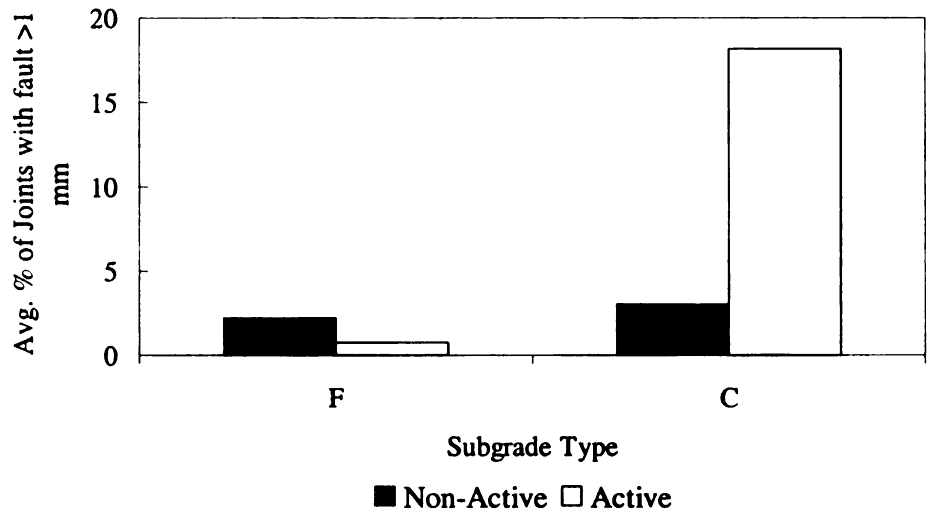


Figure 8- 11 Faulting performance by subgrade type

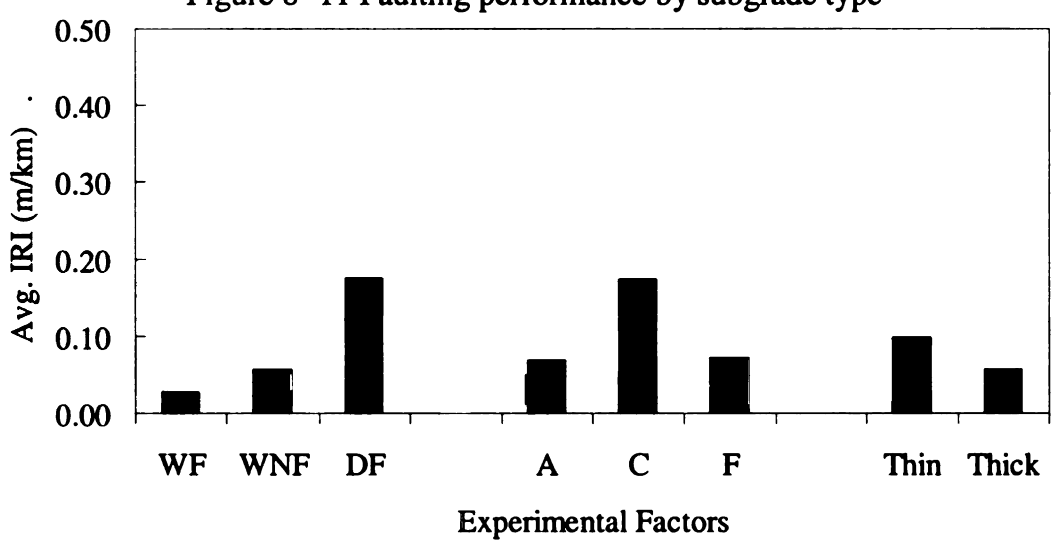


Figure 8- 12 Average IRI by experimental factors

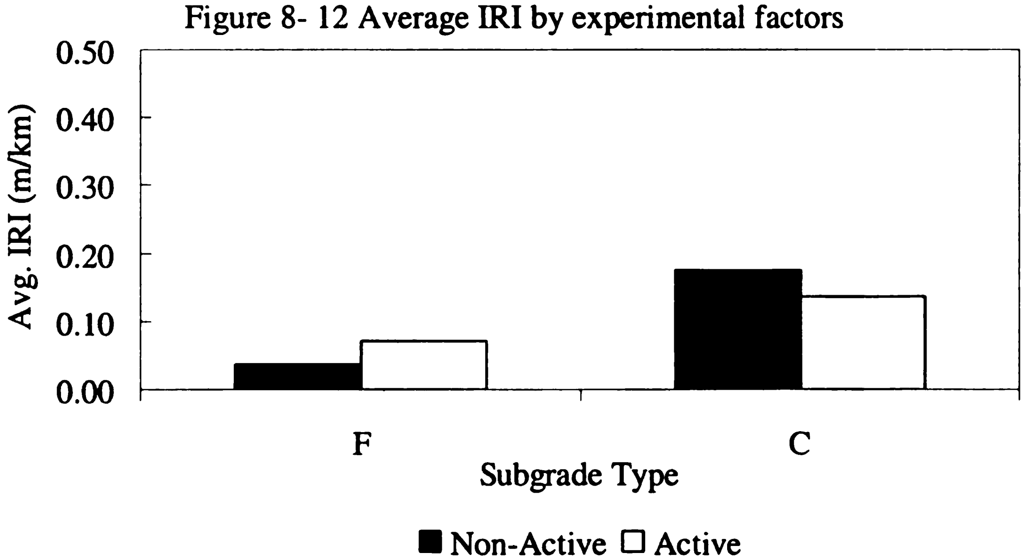


Figure 8- 13 Average IRI by subgrade type

8.7.3. Comparison between Similar Designs of SPS-8 and SPS-2 Experiments

Owing to similarities in the design features of sections in the SPS-8 and SPS-2 experiments, comparisons can be performed among the similar sections to study the effects of traffic on rigid pavement performance. The sections 0201, 0203, 0213 and 0215 of the SPS-2 experiment are similar in design (i.e. target PCC slab thickness, target PCC flexural strength, base type and thickness, and drainage conditions) to the sections in the SPS-8 experiment. Also some sites in the SPS-8 experiment are located in states that also have SPS-2 sites. These states include Arkansas (5), Colorado (8), Ohio (39) and Washington (53). In these states, the sections of SPS-2 those are similar in design to the sections in SPS-8 are most similar because of identical climatic conditions.

In each climatic zone, similar sections from SPS-2 and SPS-8 experiments were compared to identify the effect of traffic on pavement performance in that climatic zone. The effect of traffic in each climatic zone can be compared to understand how environmental conditions affect the influence of traffic on pavements. It is expected that the SPS-2 pavement sections exhibit much higher distress as compared to those in the SPS-8 experiment. The sections from Nevada were excluded from this exercise for the same reason for which they were excluded from all analyses of SPS-2 data.

In general, the distress in SPS-8 sections is lesser than that of SPS-2 sections. The low distresses exhibited by the SPS-8 sections and the setup of the SPS-8 experiment preclude application of rigorous statistical analyses. Hence subjective evaluation was performed based on the magnitude and occurrence of distress. Though faulting data for all the sections is also available, statistical analysis is not expected to yield meaningful results as considerable faulting ($\geq$3.0 mm) occurred only in three sections (only at few joints).

In the Dry Freeze zone, except for section 8-0811 in which many types of distresses occurred, no major distress was exhibited in the SPS-8 sections. The distresses in the section 8-0811 could thus be due to some issues other than environment alone. But the comparable SPS-2 sections have exhibited wide range of distresses implying the effect of traffic.

In the Wet Freeze zone, based on the comparisons between the sections of SPS-2 and SPS-8, which are from the same state, it can be said that similar distresses occurred in the sections. But this could be due to traffic of 68000 ESAL/yr (approximately) on the SPS-8 sections, which is much higher than the stipulated traffic of 10000 ESAL/year. From the comparisons between the SPS-2 and SPS-8 sections that are from Wet Freeze zone, the effect of traffic appeared more clear as the SPS-2 sections exhibited a great variety of distresses but the SPS-8 sections showed no distresses (except for transverse cracking which could be due to higher than stipulated traffic). The SPS-2 sections also showed considerable distress at the same age as that of the SPS-8 sections in Missouri.

In the Wet No Freeze zone, the SPS-2 sections exhibited a wide range of distresses (including pumping) compared to the SPS-8 sections. Significant faulting ($\geq$3.0 mm) occurred extensively in the SPS-2 sections but negligible number of joints faulted to 3.0 mm in SPS-8. The SPS-2 sections also showed considerable distress at the same age as that of the SPS-8 section. From the faulting data it can be said that, the influence of climate was more in the Wet No Freeze zone as, higher number of joints in SPS-2 sections faulted more than 3.0 mm compared to joints in SPS-8 sections.

8.8. SUMMARY OF RESULTS

Currently a total of 14 rigid pavement sections, in 6 sites, are present in the experiment. There are 6, 4 and 4 pavement sections in WF, WNF, and DF climatic zones, respectively. Three pavement sections were constructed on coarse-grained soils among which 2 sections are on "active" and one section is on "non-active" soil. Also, 11 pavement sections were built on fine-grained soil, among which 4 sections are on "active" soils and 7 sections are on "non-active" soils. These test sections have an average age of about 7 years. The distresses are too "low" for any meaningful conclusions to be made, at this point in time. Some observations based on initial trends, as of Release 17.0, are as follows:

- Longitudinal spalling, on average, was noticed more in sections located in "wet" climate.
- Spalling was not observed in any of the pavements located in the DF zone and in any of the pavements constructed on coarse-grained soil.
- Transverse cracking was not observed in any of the pavements constructed with thicker PCC slabs and in any of the pavements constructed on coarse-grained subgrade soils.

Based on the comparison between similar sections in SPS-2 and SPS-8 experiment, the effect of traffic seems to be prominent. The effect seemed to be more important in the case of sections situated in wet climates, especially in the Wet No-Freeze zone. The results are in line with those observed in a study by Hudson and Flanagan (Hudson and Flanagan 1987).

CHAPTER 9- CONCLUSIONS

This chapter contains a summary of findings from a comprehensive evaluation of the SPS-2 experiment, based on data from Release 17 of DataPave. Findings from an evaluation of rigid pavement sections in the SPS-8 experiment are also presented here. A brief description of the experiments, their current status, and other information detailed in preceding chapters are also discussed in this chapter. The conclusions are followed by limitations of the findings and recommendations for future data collection and research.

A detailed description of the experiment design and the current status of the SPS-2 experiment were presented in Chapter 2. The experiment is a fractional-factorial design that is aimed at finding the relative influence of strategic design features on performance of rigid pavements, in different site conditions (subgrade soil type and climate). The design features include PCC slab thickness, base type, PCC flexural strength, drainage, and slab width (sometimes referred to as lane width).

Each site within the SPS-2 experiment has 12 pavement test sections, each section representing a different structural design. There are fourteen sites that are distributed throughout the United States by climatic zones (wet-freeze, wet-no-freeze, dry-freeze and dry-no-freeze) and subgrade type (fine and coarse-grained). A review of the current status (details in Chapter 2) of the experiment indicated some deviations from the intended experiment design.

A summary of data availability for the SPS-2 experiment was presented in Chapter 4. The as-constructed details of design features and site factors obtained from the LTPP database and construction reports were compared to the target values. The deviations that were observed (in flexural strength, slab thickness, etc.) were reported in the chapter. Key performance trends of the test sections were evaluated and the findings were presented in Chapter 5. Depending on the extent of distress in the pavement sections, statistical methods were selected for analyses. The analysis methods employed for this study were detailed in Chapter 6.

All results obtained from analyses of performance of the SPS-2 sections were presented and discussed in Chapter 7. The performance measures considered for the analyses are transverse cracking, longitudinal cracking, and roughness [as expressed by the international roughness index (IRI)].

The average age of test sections in the experiment is 7.5 years with a range of 5 to 12 years. It may thus be said that the pavements are "fairly young", and high occurrence and levels of distress may not be expected at this point in time. Thus, all conclusions from the analyses presented in this thesis should only be interpreted as "mid-term" performance findings. However, the findings are expected to be valid for coming years as early life performance has an important bearing on long-term performance.

The details of experiment design, analysis and findings of the SPS-8 experiment were presented in Chapter 8. The experiment was designed to study effects of environment on pavement performance, in the absence of heavy traffic. The experimental factors include climate and subgrade soil type. A total of 14 rigid pavement sections at 6 sites were constructed for the experiment. The average age of the rigid pavement sections in SPS-8 experiment is 7 years with a range of 4 to 10 years.

A majority of results from these analyses should be interpreted with caution in light of the "low" occurrence of distresses in the test sections. It is suggested that the conclusions be considered while keeping in view the limitations, as explained later in this chapter.

9.1. EFFECTS OF STRUCTURAL FACTORS FOR RIGID PAVEMENTS — SPS-2 EXPERIMENT

The SPS-2 experiment, entitled *Strategic Study of Structural Factors for Rigid Pavements*, is one of nine Specific Pavement Studies in the LTPP program. The key conclusions regarding the influence of the experimental factors, based on this study, are summarized below.

It should be noted that the effects presented herein are statistically significant unless mentioned otherwise; however, they may not be of practical significance at this point in time. While statistical significance indicates whether an effect is a happenstance, the practical significance of the effect matters next.

Transverse cracking: Among the SPS-2 sections, transverse cracking was observed in 31% of the sections. About 65% of the cracked sections have medium severity cracking, and 37% of the cracked sections have high severity cracking. Most of the sections in the experiment are thus exhibiting "good" performance. The effects of design and site features on transverse cracking are as follows:

- The occurrence of transverse cracking among pavements with 203 mm (8-inch) PCC slab thickness is higher than among those with 279 mm (11-inch) PCC slab.
- The occurrence of transverse cracking among pavements constructed with LCB is higher than that among those with PATB/DGAB or with DGAB. Pavements with PATB/DGAB have shown the "best" performance (least occurrence of cracking).
- Sections without drainage have slightly higher likelihood of cracking than sections with drainage.

- On average, among sections built with LCB, those with 203 mm PCC slab have higher occurrence of cracking than those with 279 mm PCC slab. It is important to interpret these results in light of the construction issues, i.e. shrinkage cracking in LCB.
- Pavements built on fine-grained soils have slightly higher chances for the occurrence of transverse cracking than those built on coarse-grained soils.

Longitudinal Cracking: Longitudinal cracking was observed in 27% of the test sections of the SPS-2 experiment and most of the cracking, at this stage, is of low severity. As in the case of transverse cracking, majority of test sections are exhibiting "good" performance. The effects of design and site features on longitudinal cracking are as follows:

- The occurrence of longitudinal cracking among pavements with 203 mm PCC slab is higher than among those with 279 mm PCC slab.
- The occurrence of longitudinal cracking among pavements constructed with LCB is higher than among those with PATB/DGAB or with DGAB. Pavements with PATB/DGAB have shown the "best" performance (least occurrence of cracking).
- On average, among sections built with LCB, those with 203 mm PCC slab have higher occurrence of cracking than those with 279 mm PCC slab. It is important to interpret these results in light of the construction issues i.e. shrinkage cracking in LCB.

Faulting: A majority of SPS-2 sections are exhibiting "good" performance with respect to joint faulting, at this point in time. Only 33% of the sections have 0 to 20% of the joints that have faulting of more than 1.0 mm, and 5% of the sections have more than 20% of the joints that have faulting more than 1.0 mm. In addition, for LTPP data collection the Georgia Faultmeter, which has a least count of 1.0 mm, is used to measure faulting at joints and cracks. This least count is "large" (Selezneva et al, 2000), as typical faulting values in SPS-2 pavements are close to 1.0 mm. In light of these issues, it is too early to make reliable conclusions regarding the effects of design and/or site factors on faulting.

Roughness: About 56% of the sections have current roughness less than 1.5 m/km, and 38% of the sections have current roughness between 1.5 and 2.0 m/km. The effects of design and site features on roughness are as follows:

- Pavements constructed with PATB have shown lower change in IRI (ΔIRI) compared to those with DGAB or LCB, while pavements with DGAB have the highest change in roughness, especially in the case of sections with standard slab width.
- Among pavements built on fine-grained soils, those with 203 mm PCC slab have higher ΔIRI than those with 279 mm PCC slab. This effect is more prominent among sections located in WF zone.
- Among sections located in WF zone and built on fine-grained soils, those with drainage (i.e. sections with PATB) have shown lower ΔIRI compared to those without drainage.

The above results suggest that the change in roughness can be inhibited by constructing pavements with PATB and drainage as compared to sections with DGAB or LCB, especially in the case of pavements built on fine-grained soils. Also, among pavements built on fine-grained soils, an increase in PCC slab thickness from 203 mm to 279 mm seems to help prevent an increase in pavement roughness.

9.2 ENVIRONMENTAL AND LOAD EFFECTS ON RIGID PAVEMENT PERFORMANCE

The SPS-8 experiment is entitled *Strategic Study of Environmental Effects in the Absence of Heavy Loads for Flexible and Rigid Pavements*. The study examines the effect of climate and subgrade type (active, fine, and coarse) on pavement sections incorporating different flexible and rigid pavements, which are subjected to very limited traffic as measured by ESAL accumulation.

The SPS-8 pavements have "low" occurrence and extent of distresses, at this point. Most of the pavements in the experiment are performing at comparable levels. The observations presented here are just based on average performance of the distressed pavements. The observations, presented below, need to be considered as initial trends in light of these limitations.

Longitudinal spalling, on average, was higher in sections located in "wet" climate. Spalling was not observed in any of the pavements located in the DF zone and in any of the pavements constructed on coarse-grained subgrade soil. Transverse cracking was not observed in any of the pavements constructed with thicker PCC slabs and in any of the pavements constructed on coarse-grained subgrade soils.

Based on the comparison between similar sections in SPS-2 and SPS-8 experiment, the effect of traffic is clear. The effects seem to be more important in the case of sections situated in wet climates, especially in the Wet No-Freeze zone.

9.3 LIMITATIONS OF THE EXPERIMENTS AND ANALYSES

All the above findings/observations on the effects of design and construction features on pavement performance should be considered in light of the limitations discussed herein. These limitations can be broadly classified under two categories—experiment-related and data-related.

9.3.1 EXPERIMENT-RELATED ISSUES

- The SPS-2 and SPS-8 experiments, which are fractional-factorial designs, were rendered unbalanced because unequal numbers of sites were constructed in each zone-subgrade combination. This unbalanced design limits the "power" of the experiments. In the SPS-2 experiment, 7 sites are located in the WF zone compared to 2, 3 and 2 in WNF, DF, and DNF zones, respectively. Furthermore, in some of the sites not all sections were constructed on the same subgrade soil type [for example, NV (32)].
- The SPS-2 experiment has 12 designs constructed per site. Hence, the experiments do not have any "true" (statistical) replication of designs. In other words, though two sites (with 12 designs at each site) are located in a climate-subgrade soil combination, the traffic, age, and material-related properties vary between the sites.
- The variation in age of the sites is considerably high for the experiments. If the sites were reasonably similar in age, the findings would be more reliable. It should be noted that age of the test sections was included as a covariate in all statistical analyses to address the above issue to some extent.

- In the SPS-2 experiment, in-pavement drainage was provided only for sections built with PATB. Moreover, all sections with PATB were provided with drainage. As a result of this, the effect of PATB and the effect of drainage are inseparable (confounded).
- The sections with 203 mm (8-inch) thick PCC slabs have dowels of 32 mm (1.25-inch) diameter and sections with 279 mm (11-inch) thick PCC slabs have dowels of 38 mm (1.5-inch) diameter. The effect of PCC slab thickness, especially on faulting, is thus not "pure".
- Only the lower limit for traffic volume was specified for the SPS-2 experiment. This resulted in considerable variability in traffic across sites.

9.3.2 DATA-RELATED ISSUES

- Reasonably accurate monitored traffic data is not available for all the sites in the experiments. This has further complicated the issue of controlling for traffic.
- Large measurement variability was observed, over time, for some of the distresses (faulting in SPS-2). This variability has made the time-series trends unclear for some of the performance measures.
- Though thorough construction guidelines were developed by the LTPP to minimize construction variability across sites, some deviations occurred. These deviations along with the material variability have added to the variability in performance across sites. If material-related information were available for all the sections, the issues caused by performance variability could be better addressed.
- Backcalculated layer moduli are unavailable for most of the sections. Some of the material-related issues could be dealt with if the data were present.

- The data regarding the coefficient of thermal expansion (CTE) of concrete is not available in the DataPave IMS database (Release 17.0). Therefore, CTE of concrete could not be considered in the analyses.

9.4 RECOMMENDATIONS FOR FUTURE DATA COLLECTION AND RESEARCH

Based on the above issues and the experience of the authors with the LTPP data, recommendations for future data collection and research are given below.

1) Reasonably accurate monitored traffic data should be made available for all the sites to allow for better adjustment of traffic loading variation across sites.
2) All the core sections of the experiment should be closely monitored until failure or to a stage when the long-term performance (at least 15-20 years) has been captured.
3) The core sections should be strictly supervised to prevent any maintenance activity, as per the experiment designs. This will ensure that the actual long-term performance of the pavements is observed.
4) Most of the test sections will soon enter a critical stage in their service life; in light of this, to reap maximum benefits from the experiments, the sections should be monitored at regular intervals and with greater accuracy.
5) Hall and Correa (Hall and Correa 2002) have identified issues regarding in-pavement drainage for. The findings from this study should be considered for inclusion in the DataPave IMS database. This may help study the effect of in-pavement drainage more accurately.

6) Some of the sections have shown premature "failure". These sections should be considered for exclusion from DataPave, as they do not contribute to the study of long-term pavement performance.

7) Some of the sites in the SPS-2 experiment are very close to the thresholds (regarding average annual precipitation and freeze index) defined for delineation of climatic zones. The definitions of the climatic zones may need reconsideration in light of this.

8) The definition of pumping, in the case of the SPS-2 experiment, should be revisited to allow for its inclusion in future studies.

9) Accurate material data should be made available for all the sections of the experiments to allow for addressing the variability in material quality across sites. Also, backcalculated layer moduli data should be made available for all sections in DataPave to help perform mechanistic analyses.

10) Most of the construction-related issues are available only from construction reports. These issues and/or deviations should be better highlighted well within the DataPave database.

11) The spatial location of some distresses (such as cracking) is sometimes important for research. It is practically cumbersome for the users to obtain distress maps and interpret the spatial location of the distresses. It is therefore recommended that each section be "discretized" (segmented) for data collection and the related data be made available in DataPave. This would greatly decrease the level of subjectivity in the data.

12) In general, the extent of distresses on the SPS-8 test sections is "low", at this point in time. The performance data should thus be collected for sufficiently long time (15 to 20 years for all the sections in the experiment) to capture the effects of environment. A meaningful statistical analysis may then be performed to study the effects of environment.

APPENDIX

Table 1 Level-A analysis on transverse cracking

Transverse Cracking				Drainage		Base type			PCC slab thickness, in		PCC Flexural Strength, psi		Lane width, feet	
Traffic	**State**	**Climatic Zone**	**Subgrade**	**Y**	**N**	**DGAB**	**LCB**	**PATB**	**8**	**11**	**550**	**900**	**12**	**14**
400	**8**	**DF**	**C+F**	2.0	0.0	0.0	2.5	0.5	2.0	0.0	0.0	2.0	2.0	0.0
800	**32**	**DF**	**F+C**	0.3	1.7	1.2	1.6	0.2	1.2	0.8	1.1	0.9	1.0	1.0
462	**53**	**DF**	**F**	1.0	1.0	0.0	3.0	0.0	1.3	0.7	1.2	0.8	0.5	1.5
1092	**4**	**DNF**	**C**	1.0	1.0	0.0	3.0	0.0	1.8	0.2	0.9	1.1	1.1	0.9
2405	**6**	**DNF**	**C**	0.0	2.0	1.3	1.7	0.0	1.8	0.2	1.1	0.9	1.1	0.9
380	**10**	**WF**	**C**	1.0	1.0	0.0	3.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0
377	**19**	**WF**	**F**	1.0	1.0	0.0	3.0	0.0	2.0	0.0	1.9	0.1	0.1	1.9
757	**20**	**WF**	**F**	0.0	2.0	3.0	0.0	0.0	2.0	0.0	1.5	0.5	1.5	0.5
1505	**26**	**WF**	**F**	0.0	2.0	0.9	2.1	0.0	1.9	0.1	0.3	1.7	1.8	0.2
420	**38**	**WF**	**F**	2.0	0.0	0.0	2.9	0.1	1.7	0.3	1.8	0.2	0.1	1.9
608	**39**	**WF**	**F**	0.4	1.6	1.1	1.6	0.3	1.8	0.2	0.9	1.1	1.1	0.9
151	**55**	**WF**	**C**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1903	**5**	**WNF**	**C**	0.0	2.0	0.2	2.8	0.0	2.0	0.0	0.2	1.8	1.8	0.2
715	**37**	**WNF**	**F**	1.5	0.5	0.1	2.7	0.2	2.0	0.0	1.8	0.2	1.8	0.2

Table 2 Level-A analysis on longitudinal cracking

Longitudinal Cracking				Drainage		Base type			PCC slab thickness, in		PCC Flexural Strength, psi		Lane width, feet	
Traffic	**State**	**Climatic Zone**	**Subgrade**	**Y**	**N**	**DGAB**	**LCB**	**PATB**	**8**	**11**	**550**	**900**	**12**	**14**
400	**8**	**DF**	**C+F**	1.4	0.6	0.1	2.7	0.2	2.0	0.0	1.9	**0.1**	0.1	1.9
800	**32**	**DF**	**F+C**	0.2	1.8	1.2	1.6	0.1	1.5	0.5	0.9	1.1	0.8	1.2
462	**53**	**DF**	**F**	1.0	1.0	0.0	3.0	0.0	2.0	0.0	0.0	2.0	0.0	2.0
1092	**4**	**DNF**	**C**	0.5	1.5	0.9	1.8	0.3	2.0	0.0	1.6	0.4	0.4	1.6
2405	**6**	**DNF**	**C**	1.0	1.0	0.0	3.0	0.0	0.0	2.0	0.0	2.0	2.0	0.0
380	**10**	**WF**	**C**	2.0	0.0	0.0	2.9	0.1	0.2	1.8	2.0	0.0	0.2	1.8
377	**19**	**WF**	**F**	1.5	0.5	0.7	0.0	2.3	1.2	0.8	0.5	1.5	0.7	1.3
757	**20**	**WF**	**F**	0.0	2.0	2.1	0.9	0.0	1.9	0.1	1.5	0.5	1.6	0.4
1505	**26**	**WF**	**F**	0.0	2.0	0.7	2.3	0.0	2.0	0.0	0.2	1.8	1.8	0.2
420	**38**	**WF**	**F**	1.8	0.2	0.0	2.7	0.3	1.8	0.2	1.6	0.4	0.3	1.7
608	**39**	**WF**	**F**	1.0	1.0	0.0	3.0	0.0	2.0	0.0	0.0	2.0	0.0	2.0
151	**55**	**WF**	**C**	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1903	**5**	**WNF**	**C**	0.0	2.0	1.2	1.8	0.0	2.0	0.0	1.4	0.6	0.6	1.4
715	**37**	**WNF**	**F**	0.8	1.2	0.3	2.5	0.2	2.0	0.0	1.8	0.2	1.8	0.2

Table 3 Level-A analyses on IRI

Roughness (IRI)				Drainage		Base type			PCC slab thickness, in		PCC Flexural Strength, psi		Lane width, feet	
Traffic	**State**	**Climatic Zone**	**Subgrade**	**Y**	**N**	**DGAB**	**LCB**	**PATB**	**8**	**11**	**550**	**900**	**12**	**14**
400	**8**	**DF**	**C+F**	1.1	0.9	0.8	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0
800	**32**	**DF**	**F+C**	0.8	1.2	1.2	1.0	0.8	1.0	1.0	0.9	1.1	1.1	0.9
462	**53**	**DF**	**F**	1.0	1.0	1.0	1.1	0.9	1.0	1.0	1.0	1.0	1.0	1.0
1092	**4**	**DNF**	**C**	0.9	1.1	1.2	0.9	0.9	1.0	1.0	1.1	0.9	1.0	1.0
2405	**6**	**DNF**	**C**	0.9	1.1	1.1	1.0	1.0	0.9	1.1	1.0	1.0	1.0	1.0
380	**10**	**WF**	**C**	1.0	1.0	1.0	1.1	0.9	0.9	1.1	0.9	1.1	1.2	0.8
377	**19**	**WF**	**F**	1.1	0.9	1.0	0.9	1.1	1.0	1.0	1.0	1.0	1.1	0.9
757	**20**	**WF**	**F**	1.0	1.0	0.9	1.1	0.9	0.9	1.1	1.0	1.0	1.1	0.9
1505	**26**	**WF**	**F**	0.7	1.3	1.2	1.1	0.7	1.1	0.9	0.9	1.1	1.1	0.9
420	**38**	**WF**	**F**	1.0	1.0	1.0	1.0	1.0	0.9	1.1	1.0	1.0	1.0	1.0
608	**39**	**WF**	**F**	1.0	1.0	1.0	1.1	0.9	1.1	0.9	1.0	1.0	1.0	1.0
151	**55**	**WF**	**C**	1.0	1.0	1.1	0.9	1.1	1.0	1.0	0.9	1.1	1.0	1.0
1903	**5**	**WNF**	**C**	0.8	1.2	1.2	1.0	0.8	1.0	1.0	0.9	1.1	0.9	1.1
715	**37**	**WNF**	**F**	0.9	1.1	1.0	1.2	0.8	1.0	1.0	1.0	1.0	1.0	1.0

Table 4 Level-B analysis on transverse cracking- Effect of PCC Slab Thickness

Climatic Zone	State	Subgrade Type	Effect of PCC thickness											
			D				ND							
			PATB				DGAB				LCB			
			12		14		12		14		12		14	
			8	11	8	11	8	11	8	11	8	11	8	11
DF	8	C		X		X	X			X		X		
		F	X		X			X	X		X		1.0	1.0
	32	C					X				X			
		F	X		1.8	0.2		X	0.5	1.5		X	1.8	0.2
	53	F	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0	1.0	1.0
DNF	4	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.8	0.2	1.8	0.2
	6	C	1.0	1.0	1.0	1.0	2.0	0.0	1.7	0.3	1.8	0.2	1.8	0.2
WF	10	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0	1.0	1.0
	19	F	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0	2.0	0.0
	20	F	1.0	1.0	1.0	1.0	2.0	0.0	2.0	0.0	1.0	1.0	1.0	1.0
	26	F	1.0	1.0	1.0	1.0	1.5	0.5	2.0	0.0	2.0	0.0	1.0	1.0
	38	F	1.0	1.0	0.0	2.0	1.0	1.0	1.0	1.0	0.0	2.0	1.9	0.1
	39	F	0.5	1.5	2.0	0.0	1.2	0.8	2.0	0.0	2.0	0.0	2.0	0.0
	55	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WNF	5	C	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0	2.0	0.0	2.0	0.0
	37	F	1.0	1.0	2.0	0.0	2.0	0.0	1.0	1.0	2.0	0.0	1.0	1.0

Table 5 Level-B analyses on transverse cracking- Effect of Drainage

Climatic Zone	State	Subgrade Type	Effect of Drainage							
			8				11			
			12		14		12		14	
			D	ND	D	ND	D	ND	D	ND
DF	8	C		X			1.0	1.0	1.0	1.0
		F	0.3	1.7	1.0	1.0		X		X
	32	C		X						
		F	X		0.5	1.5		X	0.1	1.9
	53	F	0.0	2.0	0.0	2.0	1.0	1.0	0.0	2.0
DNF	4	C	0.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0
	6	C	0.0	2.0	0.0	2.0	0.0	2.0	1.0	1.0
WF	10	C	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0
	19	F	0.0	2.0	0.0	2.0	1.0	1.0	1.0	1.0
	20	F	0.0	2.0	0.0	2.0	1.0	1.0	1.0	1.0
	26	F	0.0	2.0	0.0	2.0	0.0	2.0	1.0	1.0
	38	F	1.0	1.0	0.0	2.0	0.0	2.0	1.3	0.7
	39	F	0.1	1.9	0.5	1.5	0.6	1.4	1.0	1.0
	55	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WNF	5	C	0.0	2.0	0.0	2.0	1.0	1.0	1.0	1.0
	37	F	0.0	2.0	2.0	0.0	1.0	1.0	1.0	1.0

Table 6 Level-B analyses on Transverse Cracking- Effect of Base Type

Clim. Zone	State	Subgrade Type	Effect of Base Type											
			8						11					
			12			14			12			14		
			D	ND		D	ND		D	ND		D	ND	
			PATB	DGAB	LCB	PATB	DGAB	LCB	PATB	DGAB	LCB	PATB	DGAB	LCB
DF	8	C		X					1.0		1.0	1.0	1.0	
		F	0.3		1.7	1.0	1.0	1.0		X				X
	32	C		0.3	1.7									
		F	X			0.4	0.8	1.8		0.8	1.2	0.1	2.7	0.2
	53	F	0.0	0.0	3.0	0.0	0.0	3.0	1.0	1.0	1.0	0.0	0.0	3.0
DNF	4	C	0.0	0.0	3.0	0.0	0.0	3.0	0.0	0.0	3.0	0.0	0.0	3.0
	6	C	0.0	1.1	1.9	0.0	1.5	1.5	0.0	0.0	3.0	1.0	1.0	1.0
WF	10	C	0.0	0.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	19	F	0.0	0.0	3.0	0.0	0.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0
	20	F	0.0	3.0	0.0	0.0	3.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0
	26	F	0.0	0.6	2.4	0.0	3.0	0.0	0.0	3.0	0.0	1.0	1.0	1.0
	38	F	1.0	1.0	1.0	0.0	0.0	3.0	0.0	0.0	3.0	1.5	0.0	1.5
	39	F	0.0	0.8	2.2	0.4	1.2	1.4	0.5	2.5	0.0	1.0	1.0	1.0
	55	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WNF	5	C	0.0	0.0	3.0	0.0	1.6	1.4	1.0	1.0	1.0	1.0	1.0	1.0
	37	F	0.0	0.1	2.9	3.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 7 Level-B analysis on IRI- Effect of PCC Slab Thickness

Climatic Zone	State	Subgrade Type	Effect of PCC thickness											
			D				ND							
			PATB				DGAB				LCB			
			550		900		550		900		550		900	
			8	11	8	11	8	11	8	11	8	11	8	11
DF	8	C		X		X			1.0	1.0		X		
		F	X		X		1.0	1.0			X		0.9	1.1
	32	C					X				X			
		F	1.0	1.0	X			X	1.0	1.0		X	1.0	1.0
	53	F	1.1	0.9	0.9	1.1	1.0	1.0	0.9	1.1	1.0	1.0	1.1	0.9
DNF	4	C	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.1	0.9	1.1	1.0	1.0
	6	C	0.8	1.2	0.9	1.1	0.8	1.2	0.9	1.1	0.9	1.1	0.9	1.1
WF	10	C	1.0	1.0	0.8	1.2	1.1	0.9	0.7	1.3	1.0	1.0	0.6	1.4
	19	F	0.8	1.2	1.2	0.8	0.8	1.2	1.0	1.0	1.1	0.9	1.1	0.9
	20	F	0.9	1.1	0.9	1.1	1.1	0.9	0.8	1.2	0.9	1.1	0.9	1.1
	26	F	1.0	1.0	1.1	0.9	0.9	1.1	1.3	0.7	1.1	0.9	1.2	0.8
	38	F	1.0	1.0	0.8	1.2	0.8	1.2	0.8	1.2	1.0	1.0	1.0	1.0
	39	F	0.9	1.1	1.0	1.0	1.1	0.9	1.2	0.8	1.0	1.0	1.0	1.0
	55	C	1.0	1.0	1.2	0.8	1.0	1.0	1.0	1.0	0.9	1.1	0.9	1.1
WNF	5	C	1.0	1.0	0.8	1.2	1.0	1.0	1.1	0.9	1.0	1.0	0.9	1.1
	37	F	1.0	1.0	1.1	0.9	0.9	1.1	1.1	0.9	1.0	1.0	0.9	1.1

Table 8 Level-B analysis on IRI- Effect of Drainage

Climatic Zone	State	Subgrade type	Effect of Drainage							
			8				11			
			12		14		12		14	
			D	ND	D	ND	D	ND	D	ND
DF	8	C		X			X		1.2	0.8
		F	X		1.1	0.9		X		X
	32	C		X						
		F	X		0.8	1.2		X	1.1	0.9
	53	F	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.1
DNF	4	C	0.9	1.1	0.8	1.2	0.9	1.1	0.9	1.1
	6	C	1.0	1.0	0.9	1.1	0.9	1.1	1.0	1.0
WF	10	C	0.8	1.2	1.1	0.9	1.0	1.0	0.9	1.1
	19	F	1.1	0.9	1.1	0.9	1.1	0.9	0.9	1.1
	20	F	0.8	1.2	1.2	0.8	1.1	0.9	0.9	1.1
	26	F	0.6	1.4	0.8	1.2	0.7	1.3	0.8	1.2
	38	F	1.1	0.9	1.0	1.0	0.9	1.1	1.1	0.9
	39	F	0.9	1.1	0.9	1.1	1.0	1.0	1.1	0.9
	55	C	1.1	0.9	1.0	1.0	1.0	1.0	0.8	1.2
WNF	5	C	0.7	1.3	0.8	1.2	0.9	1.1	0.9	1.1
	37	F	0.9	1.1	0.9	1.1	0.9	1.1	0.8	1.2

Table 9 Level-B analysis on IRI- Effect of Base Type

Clim. Zone	State	Subgrade Type	Effect of Base type											
			8						11					
			12			14			12			14		
			D	ND		D	ND		D	ND		D	ND	
			PATB	DGAB	LCB	PATB	DGAB	LCB	PATB	DGAB	LCB	PATB	DGAB	LCB
DF	8	C		X					1.0		1.0	1.2	0.8	
		F	1.0		1.0	1.0	0.8	1.2		X				X
	32	C		1.2	0.8									
		F	X			0.9	1.2	0.9		1.1	0.9	1.0	0.9	1.1
	53	F	1.0	1.0	0.9	0.7	0.8	1.5	0.9	1.0	1.1	0.9	1.1	1.1
DNF	4	C	1.0	1.1	1.0	0.9	1.3	0.9	0.9	1.2	0.9	0.9	1.1	0.9
	6	C	1.0	1.0	0.9	0.9	1.0	1.1	0.9	1.1	1.1	1.0	1.0	1.0
WF	10	C	0.7	1.1	1.1	1.1	1.0	0.9	1.0	0.9	1.1	0.8	1.0	1.2
	19	F	1.2	0.9	0.9	1.0	0.8	1.2	1.2	1.0	0.8	1.0	1.1	0.9
	20	F	0.8	1.2	1.0	1.1	0.7	1.2	1.0	0.8	1.2	0.9	1.0	1.1
	26	F	0.6	1.3	1.1	0.8	1.1	1.1	0.8	1.3	0.9	0.8	1.1	1.1
	38	F	1.0	0.9	1.1	1.0	0.9	1.1	0.9	1.2	0.9	1.1	1.0	0.9
	39	F	0.8	1.1	1.1	0.8	1.1	1.1	0.9	0.9	1.2	1.1	0.9	1.1
	55	C	1.2	1.0	0.8	1.1	1.1	0.7	1.0	1.0	1.0	0.8	1.2	1.0
WNF	5	C	0.7	1.4	0.9	0.8	1.1	1.0	0.8	1.1	1.1	0.9	1.0	1.0
	37	F	0.8	0.9	1.2	0.9	1.1	1.0	0.8	0.9	1.3	0.8	1.1	1.1

Table 10 Level-B analysis on Longitudinal Cracking- Effect of PCC slab thickness

Climatic Zone	State	Subgrade Type	Effect of PCC thickness											
			D				ND							
			PATB				DGAB				LCB			
			550		900		550		900		550		900	
			8	11	8	11	8	11	8	11	8	11	8	11
DF	8	C		X		X			1	1		X		
		F	X		X		2	0			X		1.0	1.0
	32	C					X				X			
		F	1.3	0.7	X			X	1.8	0.2		X	1.8	0.2
	53	F	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0
DNF	4	C	2.0	0.0	1.8	0.2	2.0	0.0	1.0	1.0	2.0	0.0	2.0	0.0
	6	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0	0.0	2.0
WF	10	C	2.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	0.1	1.9	1.0	1.0
	19	F	1.0	1.0	0.9	1.1	2.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0
	20	F	1.0	1.0	1.0	1.0	2.0	0.0	1.0	1.0	2.0	0.0	1.7	0.3
	26	F	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0	2.0	0.0	2.0	0.0
	38	F	1.0	1.0	0.0	2.0	0.0	2.0	1.4	0.6	2.0	0.0	2.0	0.0
	39	F	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	0.0
	55	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WNF	5	C	1.0	1.0	1.0	1.0	2.0	0.0	1.0	1.0	2.0	0.0	2.0	0.0
	37	F	1.0	1.0	2.0	0.0	2.0	0.0	2.0	0.0	2.0	0.0	1.0	1.0

Table 11 Level-B analysis on Longitudinal Cracking- Effect of Drainage

Climatic Zone	State	Subgrade Type	Effect of drainage							
			8				11			
			12		14		12		14	
			D	ND	D	ND	D	ND	D	ND
DF	8	C		X			X		1.0	1.0
		F	X		1.1	0.9		X		X
	32	C		X						
		F	X		0.3	1.7		X	0.1	1.9
	53	F	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
DNF	4	C	2.0	0.0	0.4	1.6	1.0	1.0	2.0	0.0
	6	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WF	10	C	2.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0
	19	F	2.0	0.0	0.0	2.0	1.0	1.0	2.0	0.0
	20	F	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0
	26	F	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0
	38	F	0.0	2.0	1.0	1.0	0.0	2.0	2.0	0.0
	39	F	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	55	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WNF	5	C	1.0	1.0	0.0	2.0	1.0	1.0	1.0	1.0
	37	F	0.0	2.0	1.4	0.6	1.0	1.0	1.0	1.0

Table 12 Level-B analysis on Longitudinal Cracking- Effect of Base Type

Climatic Zone	State	Subgrade type	Effect of Base type											
			8						11					
			12			14			12			14		
			D	ND		D	ND		D	ND		D	ND	
			PATB	DGAB	LCB	PATB	DGAB	LCB	PATB	DGAB	LCB	PATB	DGAB	LCB
DF	8	C		X					1.0		1.0	1.0	1.0	
		F	2.0		0.0	0.1	0.1	2.0		X				X
	32	C		0.6	1.4									
		F	X			0.2	1.1	1.7		0.8	1.2	0.1	2.5	0.4
	53	F	1.0	1.0	1.0	0.0	0.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0
DNF	4	C	0.5	0.0	2.5	0.3	1.1	1.6	0.0	0.0	3.0	2.0	0.0	1.0
	6	C	0.0	0.0	3.0	1.0	1.0	1.0	0.0	0.0	3.0	1.0	1.0	1.0
WF	10	C	1.0	0.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	3.0
	19	F	3.0	0.0	0.0	0.0	3.0	0.0	1.0	1.0	1.0	3.0	0.0	0.0
	20	F	0.0	2.8	0.2	0.0	0.0	3.0	0.0	0.0	3.0	1.0	1.0	1.0
	26	F	0.0	0.8	2.2	0.0	0.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0
	38	F	0.0	0.1	2.9	0.0	0.0	3.0	0.0	3.0	0.0	2.9	0.1	0.0
	39	F	1.0	1.0	1.0	0.0	0.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0
	55	C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
WNF	5	C	0.0	0.0	3.0	0.0	1.7	1.3	0.0	0.0	3.0	1.0	1.0	1.0
	37	F	0.0	0.2	2.8	2.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0

SITE WISE SUMMARIES

Arizona (4)

Site Description

The site in Arizona is located in the eastbound direction of I-10, approximately 35 miles west of Phoenix between Tonopah and State Spur on route 85, in Maricopa County. The other inventory data for the sections are summarized in Table 1.

Table 1 Inventory data for AZ (4)

Site code	4
Climatic zone	Dry No Freeze
Average annual precipitation	232 mm
Average annual freezing index	0.0 °C-days
Traffic open date	1st of October 1993
'Proposed' traffic	1092 KESALs/year
Subgrade soil type	Coarse grained
Inside shoulder type	PCC
Outside shoulder type	PCC

Construction Issues

According to the construction report, no major problems were encountered during construction. The following are the main construction issues encountered at the site:

- In the construction of DGAB, AASHTO No. 57 coarse aggregate was utilized in as the backfill material in the pavement base drain.
- The geotextile wrapped around the PATB edge was short and could have caused intrusion of soil from adjacent DGAB.
- Transverse drains were installed perpendicular rather than in a herringbone fashion.

- Transverse cracking in the LCB layer was observed in sections 4-0217, 4-0218, 4-0219 and 4-0220 prior to the placement of the slab.
- Longitudinal tie bars were placed uncoated and also the bars were smaller (20" long) than specified (30").
- PCC slump variations and segregation occurred in several test sections.

Site Status

The deviations in the design and/or site features at this site are explained here. No deviations in the site factors have been observed at the site. As planned, the site has coarse-grained roadbed soil and it is situated in the Dry No Freeze climatic zone. A summary of the status of the design features of the site is Table 2. Only one section, 4-0222, has been constructed thicker/thinner by more than 0.5". All the other design features have been constructed as intended in the SPS-2 design.

Table 2 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	7.9	DGAB	No	14	Yes
0214	8	8.3	DGAB	No	12	Yes
0215	11	11.3	DGAB	No	12	Yes
0216	11	11.2	DGAB	No	14	Yes
0217	8	8.1	LCB	No	14	Yes
0218	8	8.3	LCB	No	12	Yes
0219	11	10.8	LCB	No	12	Yes
0220	11	11.3	LCB	No	14	Yes
0221	8	8.2	PATB	Yes	14	Yes
0222	8	**8.6**	PATB	Yes	12	**No**
0223	11	11.1	PATB	Yes	12	Yes
0224	11	10.7	PATB	Yes	14	Yes
Flexural Strength, psi	Target	Std. Dev.	Actual (average)		Average Within 10%?	
	550	10	572		Yes	
	900	58	837		Yes	

Data Availability

A summary of the data available for the sections in this site is Table 3. The section 4-0213 is a seasonal monitoring section and that could be the reason for the higher amount of data available for that section.

Table 3 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	6	6	8	5
0214	6	6	8	4
0215	18	18	10	40
0216	6	6	8	5
0217	6	6	8	5
0218	6	6	8	5
0219	6	6	8	5
0220	6	6	8	5
0221	6	6	8	5
0222	6	6	8	5
0223	6	6	8	5
0224	6	6	8	4

Arkansas (5)

Site Description

The site, a four lane divided highway, is located on the westbound lanes of I-30 in Hot Spring County, Arkansas. The other inventory data of the site in Arkansas have been summarized in Table 4. It is to be noted that there is a discrepancy in the notation of the sections between DATAPAVE and the construction reports. The sections were numbered from 5-0213 to 5-0224 in DATAPAVE while the sections were numbered from 5-0201 to 5-0212 in the construction reports. However the notation in DATAPAVE was used during the analysis.

Table 4 Inventory data for AR (5)

Site code	5
Climatic zone	Wet No Freeze
Average annual precipitation	1381 mm
Average annual freezing index	38 °C-days
Traffic open date	1st of November 1995
'Proposed' traffic	1903 KESALs/year
Subgrade soil type	Coarse grained
Inside shoulder type	AC
Outside shoulder type	AC

Construction Issues

Only a few construction issues occurred during the construction of the section at this site. They are as follows:

- The dowel basket assembly that got "entangled" with the paver had to be removed while the paving operations were halted.
- The longitudinal joints at the site were not sealed until early 1997 and pumping was evident at the joints by that time.

Site Status

Though as per the design the sections at this site are to be founded on fine-grained soils, most of the sections (i.e. except 0222 and 0223) have been built on coarse-grained subgrade soils. The subgrade soil type for each test section has been decided based on four different sources of information in the LTPP database- TST_L05B, SPS2_LAYER, TST_SS04_UG08, and TST_SS01_UG01_UG02. The data from SPS2_LAYER has been found to be contradictory with the data from other sources for most of the sections at this site. The construction report has indicated that the site has all the sections on fine-grained subgrade soil. A decision has been made considering all the sources. But, as planned, the site has been constructed in a Wet No Freeze climatic zone. Table 5 is a summary of the status of all the design factors. Sections 0213 and 0215 have been constructed with a PCC thickness deviation of at least 0.5 inch. Also the average 14-day flexural strength of the PCC at the sections with target strength of 900-psi has been found to be lesser by more than 10% the target.

Table 5 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	**7.4**	DGAB	No	14	**No**
0214	8	8.4	DGAB	No	12	Yes
0215	11	**11.5**	DGAB	No	12	**No**
0216	11	11	DGAB	No	14	Yes
0217	8	8.3	LCB	No	14	Yes
0218	8	8.2	LCB	No	12	Yes
0219	11	11.1	LCB	No	12	Yes
0220	11	10.7	LCB	No	14	Yes
0221	8	8.3	PATB	Yes	14	Yes
0222	8	8.3	PATB	Yes	12	Yes
0223	11	10.9	PATB	Yes	12	Yes
0224	11	10.9	PATB	Yes	14	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	30	545		Yes	
	900	226	**666**		**No**	

Maintenance construction was done on all the sections at this site. Longitudinal lane-shoulder joints, transverse joints, and cracks were sealed as maintenance. The maintenance work was done in 1997 and 2002, and resulted in the change of 'construction number' in the database since those years.

Data Availability

Table 6 is the summary of the monitoring data available from the LTPP database. Though the site is more than 8 years old, the data available is only for four or five tests.

Table 6 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	5	5	4	4
0214	5	5	4	4
0215	5	5	4	4
0216	5	5	4	4
0217	5	5	4	4
0218	5	5	4	4
0219	5	5	4	4
0220	5	5	4	4
0221	5	5	4	4
0222	5	5	4	4
0223	5	5	4	4
0224	5	5	4	4

California (6)

Site Description

The project at this site is the youngest of all the sites in the SPS-2 experiment. It is located on the northbound truck lane of SR 99, Delhi (Merced County), California. The test sections were built as part of a realignment of SR 99 and a conversion to a four-lane freeway. The other inventory data are summarized in Table 7.

Table 7 Summary of inventory data

Site code	6
Climatic zone	Dry No Freeze
Average annual precipitation	299 mm
Average annual freezing index	0.2 °C-days
Traffic open date	1st October 2000
'Proposed' traffic	2405 KESALs/year
Subgrade soil type	Coarse-grained
Inside shoulder type	AC
Outside shoulder type	PCC

Construction Issues

No major problems were encountered during construction of the pavement sections at the site. The main construction issues are as follows:

- Cracks developed at several places in the LCB layer right after placement because the curing compound was not placed properly.
- Considerable segregation occurred in the LCB layer, due to large aggregate used in mix.
- The PATB layer was bladed, following an inspection, to make the surface uniform.

- The sides of the PATB material were completely covered by the overlaying PCC material and the cement paste rendered the PATB almost ineffective. Later it was cleaned up 'sufficiently'.
- Unlike in other sites of the SPS-2 experiment, two levels in dowel diameter, 32 mm and 38 mm, exist in sections with target PCC slab thickness of 203 mm and in sections with target PCC slab thickness of 279 mm.

Site Status

No deviations in the site factors have been observed at the site. As planned, the site has coarse-grained roadbed soil and it is situated in the Dry No Freeze climatic zone. A summary of the status of the design features of the site is Table 8. Only one section, 4-0211, has been constructed thicker by at least 0.5". The lane width of test section with target of 14 ft was found to be 13 ft (Table: SPS_GENERAL). The data of testing on the PCC of the slab are not available from the database. All the other design features have been constructed as intended in the SPS-2 design.

Table 8 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0201	8	8.2	DGAB	No	12	Yes
0202	8	7.7	DGAB	No	13	**No**
0203	11	11.4	DGAB	No	13	**No**
0204	11	11.4	DGAB	No	12	Yes
0205	8	8.3	LCB	No	12	Yes
0206	8	8.1	LCB	No	13	**No**
0207	11	11.4	LCB	No	13	**No**
0208	11	10.8	LCB	No	12	Yes
0209	8	8.3	PATB	Yes	12	Yes
0210	8	8.2	PATB	Yes	13	**No**
0211	11	**11.5**	PATB	Yes	**13**	**No**
0212	11	11.2	PATB	Yes	12	Yes
	Target	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
Flexural Strength, psi	550	N.A.	N.A.		-	
	900	N.A.	N.A.		-	

Data Availability

A summary of the data available for the sections in this site is Table 9.

Table 9 Summary of status of available data

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0201	3	3	3	2
0202	3	3	3	2
0203	3	3	3	2
0204	2	2	3	1
0205	3	3	3	2
0206	3	3	3	2
0207	3	3	3	2
0208	3	3	3	2
0209	3	3	3	2
0210	3	3	3	2
0211	3	3	3	2
0212	3	3	3	2

Colorado (8)

Site Description

The site in Colorado was constructed on I-76 (east bound) near Adams County in Denver, Colorado. Six sections (0213 through 0216, 0218 and 0219) were a part of reconstruction project and the other six sections were a part of new alignment project. The other inventory data of the site have been summarized in Table 10.

Table 10 Summary of inventory data

Site code	8
Climatic zone	Dry Freeze
Average annual precipitation	370 mm
Average annual freezing index	327 °C-days
Traffic open date	1st of November 1993
'Proposed' traffic	400 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	PCC
Outside shoulder type	PCC

Construction Issues

According to the construction report of the site, six sections each were constructed in 'cut' and on 'fill'. Sections 0213, 0214, 0215, 0216 and 0221 were constructed on fills. The Phase 1 of construction included the construction of the new alignment and the Phase 2 of the construction was reconstruction of I-76. The major construction issues at the site are as follows:

- Subgrade pumping occurred on several sections during Phase 1 construction due to wet weather and high water table at some locations.
- Many PATB sections had too many fines in the mix. The mat in section 0221 was replaced due to this problem.

- In section 0218, construction was stopped sometimes due to delay in delivery of material and equipment. The dowel basket assembly was torn up at station 141+50 but not replaced in this section.

Site Status

The deviations in the design and/or site features at this site are explained here. The site is one of the three sites in the SPS-2 experiment that have sections on both fine-grained and coarse-grained subgrade soils. The site has five test sections (0214, 0216, 0219, 0223, and 0224) on coarse-grained soils and the other seven sections on fine-grained soils. As a majority of the sections have fine-grained soils, the site has been categorized under fine-grained subgrade soil type (see Table 10). But according to the SPS-2 experiment design, the site was supposed to be having coarse-grained subgrade soils only. This is the major deviation from design at this site. A summary of the status of the design features of the site is Table 10.

Table 11 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	**8.7**	DGAB	No	14	**No**
0214	8	8.4	DGAB	No	12	Yes
0215	11	11.4	DGAB	No	12	Yes
0216	11	**11.8**	DGAB	No	14	**No**
0217	8	**8.6**	LCB	No	14	**No**
0218	8	7.7	LCB	No	12	Yes
0219	11	11.1	LCB	No	12	Yes
0220	11	11.1	LCB	No	14	Yes
0221	8	8.3	PATB	Yes	14	Yes
0222	8	**8.7**	PATB	Yes	12	**No**
0223	11	**11.8**	PATB	Yes	12	**No**
0224	11	**11.7**	PATB	Yes	14	**No**
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	45	526		Yes	
	900	58	906		Yes	

Six of the twelve sections have PCC thickness exceeding the respective target PCC thickness by more than 0.5 inch. The target 14-day flexural strength has been met, based on average 14-day flexural strength values.

Data Availability

A summary of the data available for the sections in this site is Table 12. The initial faulting and distress survey was conducted only in 1996 though the section was opened to traffic in 1993.

Table 12 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	5	5	7	5
0214	4	4	7	5
0215	5	5	7	5
0216	4	4	7	5
0217	6	6	8	7
0218	7	7	8	7
0219	7	7	8	7
0220	7	7	8	7
0221	7	7	8	7
0222	7	7	8	7
0223	7	7	8	7
0224	7	7	8	7

Delaware (10)

Site Description

The site is located on US 113 between Milford and Georgetown, Delaware. The site was included in the additional two southbound lanes to an initial to-lane roadway. Within the area of the site, there is an intersecting highway that is assumed to cause only insignificant impact on truck traffic through the test sections. Other inventory data has been summarized in Table 13.

Table 13 Summary of inventory data

Site code	10
Climatic zone	Wet Freeze
Average annual precipitation	1144 mm
Average annual freezing index	103 °C-days
Traffic open date	1st of May 1996
'Proposed' traffic	430 KESALs/year
Subgrade soil type	Coarse grained
Inside shoulder type	AC
Outside shoulder type	AC

Construction Issues

A variety of construction issues have been reported in the construction report. Problems were encountered with weather and poor performance of concrete in some test sections. The main issues have been summarized below:

- All the 550-psi PCC has been replaced with the Delaware DOT Type 'B' mix that gives a flexural strength of approximately 650 psi. Extensive cracking (poor performance) prompted the Delaware DOT officials to take this decision.
- Some 900-psi concrete was also replaced (sections 0202 and 0206), with 900-psi mix with 7.5-bag mix, after breaking and removing cracked PCC.

- Also 900-psi mix was found hard finish during paving operations.
- Concrete patching was done at many locations where cracks appeared on the PCC.
- Transverse shrinkage cracks appeared in LCB before PCC was laid.
- During construction of the LCB, depressions occurred due to stoppage of the paver. Transverse cracks were observed at some of these depressions.
- "High spots" were milled before paving was done for some of the sections.
- Edge drains did not extend to the full length of the PATB in section 0211.
- A transverse construction joint was placed within section 0212.
- The road was opened to traffic before all the joints were sealed.

Site Status

As said above, the 550-psi SHRP mix has been replaced with Delaware DOT Type 'B' mix after the 550-psi SHRP mix was found to be performing poorly (shrinkage cracking). This is the main deviation at this site. A summary of the status of the design factors at this site is in Table 14. Seven of the twelve test sections have been built with PCC layers thicker than their respective target thickness, by at least 0.5 in. Also, the flexural strength of the PCC of the sections are different from the target strength by more than 10%.

Table 14 Summary of status of design factors

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0201	8	8.3	DGAB	No	12	Yes
0202	8	**8.8**	DGAB	No	14	**No**
0203	11	**11.7**	DGAB	No	14	**No**
0204	11	11	DGAB	No	12	Yes
0205	8	**9.2**	LCB	No	12	**No**
0206	8	**8.9**	LCB	No	14	**No**
0207	11	11.3	LCB	No	14	Yes
0208	11	**12.1**	LCB	No	12	**No**
0209	8	8.2	PATB	Yes	12	Yes
0210	8	8.3	PATB	Yes	14	Yes
0211	11	**11.8**	PATB	Yes	14	**No**
0212	11	**12.4**	PATB	Yes	12	**No**
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	101	**657**		**No**	
	900	152	**757**		**No**	

Data Availability

A summary of the data available for the sections in this site is Table 15.

Table 15 Summary of data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0201	7	7	7	5
0202	6	6	7	4
0203	6	6	7	4
0204	6	6	7	4
0205	5	5	7	4
0206	5	5	7	4
0207	6	6	7	4
0208	6	6	7	4
0209	7	7	7	5
0210	5	5	7	4
0211	5	5	7	4
0212	6	6	7	4

Iowa (19)

Site Description

The site is located in the northbound lanes of U.S. 65 in central Iowa, northeast of Des Moines. The project was included in the relocation of the U.S. 65 in both the northbound and southbound lanes. A summary of other inventory data is in Table 16.

Table 16 Summary of inventory data

Site code	19
Climatic zone	Wet Freeze
Average annual precipitation	901 mm
Average annual freezing index	580 °C-days
Traffic open date	1st of December 1994
'Proposed' traffic	377 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	AC
Outside shoulder type	AC

Construction Issues

No major construction problems have occurred during construction of the report, as per the construction report. Some of the main issues are as follows:

- In six of the twelve sections at the site (0213, 0214, 0215, 0217, 0219, and 0221), underground structures were located. The depth of the structures has a range of 2.4 m to 12.2 m, with reference to the profile grade.
- At least 0.3 m of geotextile was removed from the longitudinal edge of the sections because of the low permeability of the geotextile.
- During placement of the PCC slab for the test section 0222 incorrect dowel baskets were placed. The section was thus relocated to avoid this area.

Site Status

Five sections (0215, 0216, 0221, 0223, and 0224) have been built with PCC thickness greater than corresponding target PCC thickness by a margin of 0.5 in. Also the average 14-day flexural strength of the sections is lesser than the corresponding target flexural strength by a margin greater than 10% of the target flexural strength. Table 17 is a summary of the status of the design features at the site.

Table 17 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	8.5	DGAB	No	14	Yes
0214	8	8.4	DGAB	No	12	Yes
0215	11	**11.8**	DGAB	No	12	**No**
0216	11	**11.6**	DGAB	No	14	**No**
0217	8	8.1	LCB	No	14	Yes
0218	8	8.2	LCB	No	12	Yes
0219	11	11.2	LCB	No	12	Yes
0220	11	11.4	LCB	No	14	Yes
0221	8	**9.4**	PATB	Yes	14	**No**
0222	8	8.3	PATB	Yes	12	Yes
0223	11	**11.7**	PATB	Yes	12	**No**
0224	11	**11.6**	PATB	Yes	14	**No**
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	**31**	467		**No**	
	900	**47**	753		**No**	

Data Availability

A summary of the available monitoring data for the sections at this site is in Table 18. Though the site is almost 10 years old, the deflection data is available only for about 4 tests, on an average.

Table 18 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	6	6	8	4
0214	5	5	8	3
0215	6	6	8	3
0216	6	6	8	3
0217	6	6	8	4
0218	6	6	8	4
0219	6	6	8	4
0220	6	6	8	4
0221	6	5	8	4
0222	5	5	7	3
0223	5	5	8	3
0224	5	5	8	3

Kansas (20)

Site Description

The site is located in the westbound driving lane of Interstate 70 near Abilene in Dickinson County. The project was included in the reconstruction of I-70 and was built on fill. The other inventory data are summarized in Table 19.

Table 19 Summary of inventory data

Site code	20
Climatic zone	Wet Freeze
Average annual precipitation	820 mm
Average annual freezing index	259 ^{o}C-days
Traffic open date	1st of August 1992
'Proposed' traffic	757 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	PCC
Outside shoulder type	PCC

Construction Issues

The main construction issues encountered at this site are as follows:

- Underground structures were present at the site in sections 0208 through 0212 and 0204. The drains were at least 1.5 m below the pavement surface.
- Two partial-depth repairs were done to the test section 0204 in the year 1995.
- Vertical curves exist within the limits of the site.
- PATB was difficult to place. Excess PATB was removed with a trimmer.
- Existing subbase and shoulder material was retained.
- Subgrade was dried up prior to construction using Type 'C' Fly Ash.

Site Status

Table 20 is the summary of the status of design factors at the site. Two sections, 0202 and 0209, have at least 0.5 inches as deviation from target PCC slab thickness. Test section 0202 has been built 0.6" thinner and 0209 has been built 0.5" thicker than corresponding target thicknesses. Also the average 14-day flexural strength of the sections with target 14-day modulus of rupture as 550-psi is more than 10% higher than the target (see Table 20).

Partial depth repairing was performed on section 0201 in the year 2995 resulting in a change in 'construction number' for the section since that year.

Table 20 Summary of status of the design factors

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0201	8	7.7	DGAB	No	12	Yes
0202	8	**7.4**	DGAB	No	14	**No**
0203	11	11.1	DGAB	No	14	Yes
0204	11	11.3	DGAB	No	12	Yes
0205	8	7.8	LCB	No	12	Yes
0206	8	7.9	LCB	No	14	Yes
0207	11	11.3	LCB	No	14	Yes
0208	11	11	LCB	No	12	Yes
0209	8	**8.5**	PATB	Yes	12	**No**
0210	8	8.3	PATB	Yes	14	Yes
0211	11	11.1	PATB	Yes	14	Yes
0212	11	10.9	PATB	Yes	12	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	47	**613**		**No**	
	900	50	843		Yes	

Data Availability

Table 21 is the summary of the monitoring data availability. Though the site is about 12 years old, the monitoring data available is for less than or equal to six tests for distress and deflection data. Also, unlike in the case most of the sections in the experiment, the faulting data and distress data are not available to the same extent in this site.

Table 21 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0201	6	4	11	4
0202	6	4	12	3
0203	6	4	12	3
0204	6	4	12	4
0205	6	4	12	4
0206	6	4	12	4
0207	6	4	12	4
0208	6	4	12	4
0209	5	3	12	3
0210	6	4	12	4
0211	6	4	12	4
0212	6	4	12	4

Michigan (26)

Site Description

The Michigan SPS-2 site is located on the US 23 (Ottawa Lake, Monroe County), which is a rural principal arterial. The project was included in the reconstruction of US 23. Consear Road bisects the site. Most of the sections were constructed on fills. Some of the sections (0218 and 0219) were constructed on a superelevation. The other inventory data for the site has been summarized in Table 22.

Table 22 Summary of inventory data

Site code	26
Climatic zone	Wet Freeze
Average annual precipitation	866 mm
Average annual freezing index	382 ^{o}C-days
Traffic open date	1st of November 1993
'Proposed' traffic	1505 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	AC
Outside shoulder type	AC

Construction Issues

The major construction issues, from the construction report, at the Michigan site are as follows:

- The traffic flow over all of the test sections is not uniform as Consear road bisects the site.
- Moisture content of the compacted subgrade was not maintained in the range of 85 to 120% of the optimum moisture content on sections 0213 through 0220.
- The DGAB for section 0221 segregated.

- The Geotextile fabric did not extent to the stipulated minimum depth of 1' under the pavement.
- Rutting (1/2" to 1-3/4") occurred in PATB due to traffic that was allowed to pass over the outside shoulder area of PATB during construction.
- A transverse construction joint was located in the LCB of section 0218.
- Longitudinal cracking of LCB was observed in 0217 and 0220, which could be due to the paving machines that were allowed to operate from the outside shoulder area.
- LCB in sections 0218, 0219 and 0220 and PCC in sections 0215 and 0219 had lesser than 1" of slump, which is the stipulated value.
- Embankment clay dried out and desiccation cracks appeared
- Rutting developed from 0-15 to 0+15 near the inner wheel path and 0-02 to 0+15 in the outer wheel path of 0221
- Transverse shrinkage cracks appeared in LCB soon after construction
- Extra amount of water entered the pavement structure since this section is located on superelevation, which drains toward the outside shoulder.
- PCC Concreting delayed by a month in 0216

Site Status

Table 23 is the summary for the status of the design features of the sections at this site. Four of the twelve sections (0213, 0214, 0217, and 0218) were built with PCC thickness deviation of at least 0.5 in. The average 14-day modulus of rupture of PCC of the sections with target 14-day strength of 550-psi is greater than the target by a margin of 10% of the target strength (see Table 23).

Table 23 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	**8.6**	DGAB	No	14	**No**
0214	8	**8.9**	DGAB	No	12	**No**
0215	11	11.2	DGAB	No	12	Yes
0216	11	11.4	DGAB	No	14	Yes
0217	8	**8.5**	LCB	No	14	**No**
0218	8	**7.1**	LCB	No	12	**No**
0219	11	10.9	LCB	No	12	Yes
0220	11	11.1	LCB	No	14	Yes
0221	8	8.2	PATB	Yes	14	Yes
0222	8	8.4	PATB	Yes	12	Yes
0223	11	11	PATB	Yes	12	Yes
0224	11	11.2	PATB	Yes	14	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	30	**617**		**No**	
	900	4	973		Yes	

Sections 0213, 0215, 0217 and 0218 were de-assigned from the experiment in the years 1999, 2000, 1999, and 1998.

Data Availability

A summary of the extent of monitoring data available in the LTPP database for the site is Table 24. Though the site is about 11 years old, the deflection data is available for only 3 to 6 tests. Unlike in the case of other sites, this site has high variation in the extent of available data among the test sections. The section 0218 has the least amount of data.

Table 24 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	5	4	6	5
0214	6	6	10	5
0215	5	5	7	4
0216	8	7	10	5
0217	4	3	5	4
0218	3	3	4	3
0219	7	7	10	5
0220	8	7	9	5
0221	9	8	9	6
0222	7	7	10	5
0223	8	8	10	5
0224	8	7	10	4

Nevada (32)

Site Description

The site is located in north central Nevada, in the outer eastbound lane of Interstate 80, in Humboldt and Lander Counties. The other inventory data are summarized in Table 25.

Table 25 Summary of inventory data

Site code	32
Climatic zone	Dry Freeze
Average annual precipitation	222 mm
Average annual freezing index	276 °C-days
Traffic open date	1st of September 1995
'Proposed' traffic	800 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	PCC
Outside shoulder type	PCC

Construction Issues

The Nevada site has many serious construction issues according to the construction report. The PCC layer had a wide range of construction issues. It is highly unlikely, according to the construction report, that any of the sections will last the intended life for the experiment. A majority of the problems with the PCC paving came as a result of the mixes being significantly different from those typically used. Major construction issues, from the construction report, are as follows:

- The site was constructed after removal of an existing AC pavement. After removal of then existing AC layer, cement treated base, and DGAB, it was found that the subgrade was 'unsuitable' as per NDOT specifications. For this, lime stabilization was done to the top one foot of the in-situ subgrade soil.

- Higher deflections were observed in stabilized subgrade soil of sections 0201, 0205, 0207, and 0209, compared to that of other sections
- The PCC consisted of mixes different from the ones stipulated by the SHRP. The sections that were supposed to have PCC of 550-psi 14-day flexural strength have a 475-psi mix and the sections with target 14-day flexural strength of 900-psi have a 750-psi mix. This change was made to the design as it was found difficult to attain the 900-psi strength stipulated by SHRP, with locally available materials.
- Sections 0205, 0207 and 0208 had shrinkage cracking in the LCB before paving operations were carried out.
- Section 0212 had severe cracking following paving and was removed in 1995. The section was replaced with nonconforming materials and thus was removed from the experiment. Also sections 0203, 0205, and 0208 had shrinkage cracks following paving.

Site Status

Table 26 is the summary of status of the design features at this site. Six of the eleven sections (see Table 25) have been built with PCC slab thicker than target thickness at least by a margin of 0.5 in. Also the average 14-day flexural strength of the sections is more than 10% (of target strength) below the target strength.

Full-depth repairing was conducted on section 0201 in 1999 and 2000. This has been reported in the database as a rehabilitation construction event. In addition sections 0202 and 0206 have been de-assigned from the experiment in 1997.

Table 26 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0201	8	**9.2**	DGAB	No	12	**No**
0202	8	8.2	DGAB	No	14	Yes
0203	11	**11.9**	DGAB	No	14	**No**
0204	11	**11.8**	DGAB	No	12	**No**
0205	8	**8.5**	LCB	No	12	**No**
0206	8	7.8	LCB	No	14	Yes
0207	11	10.9	LCB	No	14	Yes
0208	11	11	LCB	No	12	Yes
0209	8	**8.9**	PATB	Yes	12	**No**
0210	8	**10.1**	PATB	Yes	14	**No**
0211	11	11.3	PATB	Yes	14	Yes
0212	11	-	-	-	-	-
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	33	**490**		**No**	
	900	87	**730**		**No**	

Data Availability

Table 27 is a summary of extent of monitoring data available for the sections at this site.

Table 27 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0201	7	7	7	6
0202	2	2	2	2
0203	7	7	7	4
0204	8	8	7	17
0205	7	7	7	6
0206	2	2	2	2
0207	7	7	7	4
0208	7	7	7	4
0209	8	8	7	5
0210	8	8	7	6
0211	7	7	7	4
0212	-	-	-	-

North Carolina (37)

Site Description

The site is located in the southbound lanes of U. S. 52 near Lexington, N. C. It is a four lane divided highway. There is an interchange to US 64 on the site and 0204 is on the south of the interchange. The other inventory data are summarized in Table 28.

Table 28 Summary of inventory data

Site code	37
Climatic zone	Wet No Freeze
Average annual precipitation	1151 mm
Average annual freezing index	47 °C-days
Traffic open date	1st of July 1994
'Proposed' traffic	715 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	PCC
Outside shoulder type	PCC

Construction Issues

No major construction issues have occurred at the site, according to the construction report. The main construction issues are as follows:

- Shrinkage cracks occurred at several locations in LCB before paving was done. Cracks were covered with tar paper before paving. Repairing was done to the PCC slabs that had cracks that reflected from LCB.
- The PATB layer was placed 5" thick instead of 4" thick in 0209 and 0210.
- All sections in the site were constructed with dowels with diameter of 38 mm. The stipulation requires dowels with diameter of 25 mm for sections with 203

mm-thick PCC slab and dowels with diameter of 38 mm for sections with 279 mm-thick PCC slab.

- Cement or lime stabilization was done to top 7 or 8 inches of the subgrade for sections 0204 and 0207.
- The DGAB and LCB extended only to two feet from the pavement edge and not to the shoulder edge as stipulated for SPS-2.
- Edge drains were located at a two-feet offset from the pavement edge instead of at 8-feet, which is an SPS-2 specification. Stone was used as trench backfill instead of PATB.
- Shoulders were made of Econocrete instead of asphalt concrete.
- In section, 0203, a contraction joint was located in LCB.
- No compaction was done around the TDR probes in section 0201. This may cause post construction settlement of the pavement.

Site Status

A summary of the status of the design features at the site is Table 29. Sections 0201, 0202, 0207, 0209 and 0210 were constructed at least 0.5" thicker than their respective target thickness. The flexural strength data is available only for three sections. Sections with target 14-day flexural strength of 550-psi have average 14-day flexural strength higher than target by a margin of more than 10% (of target strength).

Table 29 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0201	8	**9**	DGAB	No	12	**No**
0202	8	**8.9**	DGAB	No	14	**No**
0203	11	11.2	DGAB	No	14	Yes
0204	11	11.2	DGAB	No	12	Yes
0205	8	8	LCB	No	12	Yes
0206	8	8.4	LCB	No	14	Yes
0207	11	**11.6**	LCB	No	14	**No**
0208	11	11.2	LCB	No	12	Yes
0209	8	**8.6**	PATB	Yes	12	**No**
0210	8	**9.1**	PATB	Yes	14	**No**
0211	11	11.4	PATB	Yes	14	Yes
0212	11	10.9	PATB	Yes	12	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	61	**693**		**No**	
	900	N/A	850		Yes	

Data Availability

A summary of monitoring data availability is Table 30. The large extent of data available for the section 0201 could be because the section is a DLR and SMP section.

Table 30 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0201	8	9	9	47
0202	5	6	9	4
0203	5	6	9	4
0204	5	5	9	4
0205	5	6	9	4
0206	5	6	9	4
0207	5	6	9	4
0208	5	5	8	4
0209	7	8	9	7
0210	5	6	9	4
0211	5	6	9	4
0212	5	5	9	4

North Dakota (38)

Site Description

The site is located in the eastbound lanes of I-94 in eastern North Dakota, west of Fargo. I-94 is a rural interstate. Table 31 is a summary of other inventory data. The project is reconstruction of an existing PCC pavement.

Table 31 Summary of inventory data

Site code	38
Climatic zone	Wet Freeze
Average annual precipitation	545 mm
Average annual freezing index	1313 °C-days
Traffic open date	1st of November 1994
'Proposed' traffic	420 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	AC
Outside shoulder type	AC

Construction Issues

The site is located on a flat terrain, which is part of the old Lake Agassiz. The extremely wet clay soils delayed the construction during rains. The project opening was thus delayed by more than a month. The key observations from the construction report are as follows:

- The LCB was hard to place. For this the mix was changed to increase the strength of this layer.
- Shrinkage cracks in LCB reflected on the PCC layer in section 0217 and the cracks were sealed.
- The PATB was difficult to place, as it was very "fluid".

Site Status

The status of the design features at the site is summarized in Table 32. No data for 14-day flexural strength of PCC is available in the LTPP database (Release 17). All the sections have been constructed with actual PCC thickness deviation (from target thickness) less than 0.5".

Rehabilitation repairing was done to all the sections of the site. AC shoulder restoration was done to all the sections in the year 1997. Partial-depth repairing was done to section 0217 in 1998 and in 1999. Partial-depth repairing was also done in 1999 in 0216.

Table 32 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	8.2	DGAB	No	14	Yes
0214	8	7.9	DGAB	No	12	Yes
0215	11	11	DGAB	No	12	Yes
0216	11	11.2	DGAB	No	14	Yes
0217	8	7.9	LCB	No	14	Yes
0218	8	7.9	LCB	No	12	Yes
0219	11	10.9	LCB	No	12	Yes
0220	11	10.9	LCB	No	14	Yes
0221	8	8.1	PATB	Yes	14	Yes
0222	8	8.2	PATB	Yes	12	Yes
0223	11	11.1	PATB	Yes	12	Yes
0224	11	10.8	PATB	Yes	14	Yes
Flexural Strength, psi	Target	Std. Dev.	Actual (average)		Average Within 10%?	
	550	N/A	N/A		-	
	900	N/A	N/A		-	

Data Availability

Table 33 is the summary of the extent of monitoring data available for the sections in this site. Though the site is about 10 years old, the IRI and FWD data is available only for 5 tests each.

Table 33 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	7	7	5	5
0214	6	6	5	5
0215	6	5	5	5
0216	6	5	5	5
0217	7	7	5	5
0218	6	6	5	5
0219	6	6	5	5
0220	6	6	5	5
0221	7	7	5	5
0222	6	6	5	5
0223	6	6	5	5
0224	6	6	5	5

Ohio (39)

Site Description

The Ohio site is located in the northbound lanes of U. S. 23 in Delaware County, central Ohio. The four-lane highway is a rural arterial.

Table 34 Summary of inventory data

Site code	39
Climatic zone	Wet Freeze
Average annual precipitation	972 mm
Average annual freezing index	375 °C-days
Traffic open date	1st of October 1996
'Proposed' traffic	608 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	AC*
Outside shoulder type	AC

*Section 0211 has a PCC shoulder

Construction Issues

According to the construction report, no major construction problems and/ or deviations have occurred at this site.

Site Status

Table 35 is summary of the status of design features at the site. A substantial deviation from the target flexural strengths is to be noted. The average 14-day flexural strength of sections with 550-psi as target strength is much higher than the target and that of the sections with target strength as 900-psi is much lesser than 900-psi.

Table 35 Summary of status of design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0201	8	7.9	DGAB	No	12	Yes
0202	8	8.3	DGAB	No	14	Yes
0203	11	10.9	DGAB	No	14	Yes
0204	11	11.1	DGAB	No	12	Yes
0205	8	8	LCB	No	12	Yes
0206	8	7.9	LCB	No	14	Yes
0207	11	11.1	LCB	No	14	Yes
0208	11	11	LCB	No	12	Yes
0209	8	8.1	PATB	Yes	12	Yes
0210	8	8	PATB	Yes	14	Yes
0211	11	11.4	PATB	Yes	14	Yes
0212	11	10.6	PATB	Yes	12	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	56	**684**		**No**	
	900	153	**614**		**No**	

Moreover, the average 14-day flexural strength PCC in sections with target strength of 550-psi is greater than that of PCC of sections with target strength of 900-psi.

Data Availability

Table 36 is a summary of the extent of monitoring data available for the test sections at this site. Section 0204 is a SMP section. This could be the reason for higher extent of data available for the section.

Table 36 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0201	5	5	8	8
0202	5	5	8	7
0203	5	5	8	8
0204	6	6	8	21
0205	5	5	8	9
0206	4	4	8	7
0207	4	4	8	8
0208	4	4	8	8
0209	5	5	8	8
0210	5	5	8	7
0211	5	5	8	8
0212	5	5	8	6

Washington (53)

Site Description

The site is located in the northbound lanes of SR 395 in eastern Washington. The route is an urban principal arterial.

Table 37 Summary of other inventory data

Site code	53
Climatic zone	Dry Freeze
Average annual precipitation	308 mm
Average annual freezing index	265 °C-days
Traffic open date	1st of November 1995
'Proposed' traffic	462 KESALs/year
Subgrade soil type	Fine grained
Inside shoulder type	AC
Outside shoulder type	AC

Construction Issues

The major observations from the construction report are as follows:

- Average moisture content of the subgrade soil was 5.8% below optimum.
- Construction traffic provided compaction effort.
- The section 0203 that was built on cut has most variation in deflections, as observed from the FWD testing.
- Section 0207 had a high compressive strength of LCB compared to other sections, which could be due to the low water-cement ratio.
- In sections 0209 and 0212, the embankment soil was accidentally placed on shoulder and because of this the PATB voids could have been clogged. Also during paving, the PCC slurry that spilled over the PATB in shoulder, though scrapped off later, could have clogged the PATB voids.

- Patching was done to the fabric of edge drains in 0209 and 0212.
- Surface voids appeared immediately due to the mix being unconsolidated.
- Following paving, shrinkage cracks appeared throughout the section 0206.

Site Status

The status of the design features has been summarized in Table 38. Five of the twelve sections have deviation of at least 0.5" from the respective target PCC thickness. All the five sections have been built at least 0.5" thicker than the respective target thickness. Also, the average 14-day flexural strength of the sections with target 14-day flexural strength of 550-psi is below the 10% (of target strength) error range.

Table 38 Summary of status of design factors

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	**8.7**	DGAB	No	14	**No**
0214	8	8.3	DGAB	No	12	Yes
0215	11	11.1	DGAB	No	12	Yes
0216	11	11.2	DGAB	No	14	Yes
0217	8	**8.5**	LCB	No	14	**No**
0218	8	**8.6**	LCB	No	12	**No**
0219	11	11.1	LCB	No	12	Yes
0220	11	11.2	LCB	No	14	Yes
0221	8	**9**	PATB	Yes	14	**No**
0222	8	8.3	PATB	Yes	12	Yes
0223	11	**11.8**	PATB	Yes	12	**No**
0224	11	11.3	PATB	Yes	14	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	55	**485**		**No**	
	900	35	831		Yes	

Data Availability

Table 39 is the summary of monitoring data availability.

Table 39 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	8	8	8	6
0214	8	8	8	6
0215	8	8	8	5
0216	8	8	8	6
0217	8	8	8	6
0218	8	8	8	6
0219	8	8	8	6
0220	8	8	8	6
0221	8	8	8	6
0222	8	8	8	6
0223	8	8	8	6
0224	8	8	8	6

Wisconsin (55)

Site Description

The site is located on the westbound and eastbound STH-29, a rural arterial road, in Marathon County, Wisconsin. The other inventory data are summarized in Table 40.

Table 40 Summary of inventory data

Site code	55
Climatic zone	Wet Freeze
Average annual precipitation	815 mm
Average annual freezing index	998 °C-days
Traffic open date	1st of November 1997
'Proposed' traffic	151 KESALs/year
Subgrade soil type	Coarse grained
Inside shoulder type	No data
Outside shoulder type	No data

Construction Issues

No major construction issues exist for the site. The main issues are as follows:

- Undisturbed soil samples could not be obtained for testing, as the project was a replacement of a PCC pavement. The PCC slab was removed and fill was placed.
- A stiff or rigid layer exists below 20 feet.

Site Status

Table 44 is a summary of the status of the design features of the sections at the site. Section 0222 was constructed 0.5" thicker than the target thickness of 8". The average 14-day flexural strength of the sections with target 14-day strength of 550-psi is higher by 10% of the target strength.

Table 41 Summary of status of the design features

SHRP ID	Slab Thickness, in.		Base Type	Drainage	Lane Width, ft	As designed?
	Design	Actual				
0213	8	8.5	DGAB	No	14	Yes
0214	8	8.4	DGAB	No	12	Yes
0215	11	11.3	DGAB	No	12	Yes
0216	11	11.1	DGAB	No	14	Yes
0217	8	8.2	LCB	No	14	Yes
0218	8	8.4	LCB	No	12	Yes
0219	11	11.3	LCB	No	12	Yes
0220	11	11.2	LCB	No	14	Yes
0221	8	8.3	PATB	Yes	14	Yes
0222	8	**8.5**	PATB	Yes	12	**No**
0223	11	11.3	PATB	Yes	12	Yes
0224	11	11.4	PATB	Yes	14	Yes
Flexural Strength, psi	**Target**	**Std. Dev.**	**Actual (average)**		**Average Within 10%?**	
	550	28	**633**		**No**	
	900	53	884		Yes	

Data Availability

Table 42 is a summary of the monitoring data available for the sections at the site. Though the site is about seven years old, the distress data and FWD data are available for only three tests.

Table 42 Summary of monitoring data availability

SHRP ID	Monitoring data availability, No. of surveys			
	Distress		IRI	FWD
	Manual	Faulting		
0213	3	3	7	3
0214	3	3	6	3
0215	3	3	7	3
0216	3	3	7	3
0217	3	3	7	3
0218	3	3	7	3
0219	3	3	7	3
0220	3	3	7	3
0221	3	3	7	3
0222	3	3	7	3
0223	3	3	7	3
0224	3	3	7	3

REFERENCES

Armaghani, J. M. "Factors Affecting Performance of Concrete Pavements." *5th International Conference on Concrete Pavement Design and Rehabilitation*, 33-45.

Brown, S. (1979). "Design of Pavements with Lean Concrete Bases." *Transportation Research Record*, 725, 51-58.

Buch, N., Chatti, K., Haider, S. W., Pulipaka, A., Lyles, R. W., and Gilliland, D. "Statistical Challenges presented by the SPS-2 Experiment and Data." *8th International Conference on Concrete Pavements*, Colorado, USA.

Cedergren, H. R. (1988). "Why All Important Pavements Should Be Well Drained." *Transportation Research Record*, 1188, 56-62.

Chatti, K., N. Buch, et al. (2005). Final Report, LTPP Data Analysis: Influence of Design and Construction Features on the Response and Performance of New Flexible and Rigid Pavements. Washington DC., NCHRP.

Desaraju, P. (2003). "Influence of Design and Construction Features on the Response and Performance of SPS-2 Test Sections," Thesis, Master of Science, Michigan State University, East Lansing.

Elkins, G. E., Schmalzer, P., Thompson, T., and Simpson, A. (2003). "Long Term Pavement Performance Information Management System Pavement Performance Database User Guide." FHWA.

Fleckenstein, L. J., and Allen, D. L. (1996). "Evaluation of Pavement Edge Drains and Their Effect on Pavement Performance." *Transportation Research Record*, 1519, 28-35.

Forster, S. F. "HIPERPAV- Guidance to Avoid Early-Age Cracking in Concrete Pavements." *Fifth CANMET/ACI International Conference on Durability of Concrete*, Barcelona, Spain, 1109-1122.

Forsyth, R. A., Wells, G. K., and Woodstrom, J. H. (1987). "Economic Impact of Pavement Subsurface Drainage." *Transportation Research Record*, 1121, 77-85.

Gharaibeh, N. G., and Darter, M. I. (2001). "Benefits and Costs of Jointed Plain Concrete Pavement Design Features." *Transportation Research Record*, 1778, 1-8.

Grater, S., McCullough, F., and Zollinger, D. (1999). "Developing 21st Century Specifications for Portland Cement Concrete Pavements." Recent Developments in Design and Specification of Concrete Pavement Systems, American Concrete Institute, Farmington Hills, MI.

Hagen, M. G., and Cochran, G. R. (1996). "Comparison of Pavement Drainage Systems." *Transportation Research Record*, 1519, 1-10.

Haider, S. W., "The Use of Long-Term Pavement Performance Data for Quantifying the Relative Effects of Structural and Environmental factors on the Response and Performance of New Flexible Pavements," in Department of Civil and Environmental Engineering, Ph. D. Dissertation. Michigan State University, 2005.

Hall, K. T. and C. Correa (1999). Estimation of Present Serviceability Index from International Roughness Index. 78th Annual Meeting of the Transportation Research Board, Washington, D. C.

Hall, K. T., and C. Correa (2003). "Effects of Subsurface Drainage on Performance of Asphalt and Concrete Pavements." *NCHRP's Report No. 499.*

Hanna, A. N., Tayabji., S. D., and Miller, J. S. (1994). "SHRP-LTPP Specific Pavement Studies: Five-Year Report." SHRP-P-395, Strategic Highway Research Program, National Research Council.

Hansen, W., Jensen, E. A., and Mohr, P. (2001). "The Effects of Higher Strength and Associated Concrete Properties on Pavement Performance." *FHWA-RD-00-161*, FHWA, U. S, Department of Transportation.

Hansen, W., Mohamed, A. R., Byrum, C. R., and Jensen, E. "Effect of High Strength Concrete on Pavement Performance." *Material Science of Concrete- The Sidney Diamond Symposium*, 191-204.

Harvey, J., Roesler, J., Farver, J., and Liang, L. (2000). "Preliminary Evaluation of Proposed LLPRS Rigid Pavement Structures and Design Inputs." *FHWA/CA/OR-2000/02*, Pavement Research Center, Institute of Transportation Studies, University of California at Berkeley, Berkeley, CA.

Huang, Y. H. (1993). Pavement Analysis and Design. New Jersey, Prentice Hall.

Hudson, W. R. and P. R. Flanagan (1987). "An Examination of Environmental Versus Load Effects on Pavements." *Transportation Research Record 1121,* 34-39.

Jiang, Y. J., and Darter, M. I. (2001). "Structural Factors of Jointed Plain Concrete Pavements: SPS-2 - Initial Evaluation and Analysis." *FHWA-RD-01-167*, FHWA.

Khazanovich, L., Darter, M., Bartlett, R., and McPeak, T. (1998). "Common Characteristics of Good and Poorly Performing PCC Pavements." *FHWA-RD-97-131*, FHWA, U. S. Department of Transportation.

Kutner, M. H., Christopher, J. N., John, N., and William, L. (2005). Applied Linear Models, McGraw-Hill, Irwin.

Mallela, J., Titus-Glover, L., and Darter, M. I. (2000). "Considerations for Providing Subsurface Drainage in Jointed Concrete Pavements." *Transportation Research Record*, 1709, 1-10.

NCHRP. (2002). "Research Results Digest No. 268."

NCHRP[1-37A] (2004). Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Champaign, IL, ARA Inc., ERES Consultants Division.

Nichols Consulting Engineers, C. (1998). Colorado SPS-8 Construction Report, Colorado Department of Transportation.

Nichols Consulting Engineers, C. (1998). Materials Sampling, Field Testing, and Laboratory Testing Plan- SHRP SPS-2 Projects, Nevada Department of Transportation.

Norusis, M. J., SPSS 12.0: Statistical Procedures Companion. NJ.: Prentice Hall, 2003.

Perera, R. W., and Kohn, S. D. (2001). "LTPP Data Analysis: Factors Affecting Pavement Smoothness." *Project No. 20-50 (8/13)*, NCHRP.

Peshkin, D. G., Smith, K. D., Darter, M. I., and Arnold, C. J. (1989). "Performance Evaluation of Experimental Pavement Designs at Clare." *Transportation Research Record*, 1227, 24-33.

Rao, C., Barenberg, E. J., Snyder, M. B., and Schmidt, S. "Effects of Temperature and Moisture on the Response of Jointed Concrete Pavements." *7th International Conference of Concrete Pavements*, 23-38.

Ray, G. K. "35 years of Pavement Design and Performance." *2nd International Conference on Concrete Pavement Design*, 3-8.

Ray, M. A. "European Synthesis on drainage, sub-base erodibility, and load transfer." *2nd International Conference on Concrete Pavement Design*, 27-39.

Ring III, G. W. "Drainage of Concrete Pavement Structures." *1st International Conference on Concrete Pavement Design and Rehabilitation*, 365-378.

Selezneva, O., Jiang, J., and Tayabji, S. D. (2000). "Preliminary Evaluation and Analysis of LTPP Faulting Data, Final Report." *FHWA-RD-00-076*, FHWA.

SHRP. (1986). "Final Report for Strategic Highway Research Program Research Plans." NCHRP Project 20-20, Transportation Research Board, Washington, DC.

SHRP. (1990). "Specific Pavement Studies Experimental Design and Research Plan for Experiment SPS-2, Strategic Study of Structural Factors for Rigid Pavements." National Research Council, Washington DC.

Smith, K. D., Mueller, A. L., Darter, M. I., and Peshkin, D. G. (1990). "Performance of Jointed Concrete Pavements." *FHWA-RD-89-137*, FHWA, U. S. Department of Transportation.

Smith, K. D., Peshkin, D. G., Darter, M. I., and Mueller, A. L. "Effect of design features on concrete pavement performance." *4th International Conference on Concrete Pavement Design and Rehabilitation*, 23-44.

Smith, K. D., Wade, M. J., Yu, H. T., and Darter, M. I. "Design Considerations For Improved JPCP Performance." *6th International Conference on Concrete Pavement Design and Materials for High Performance*, 89-109.

Springenschmid, R., and Fleischer, W. "Developments in the Design and Construction of Concrete Pavements for German Expressways (Autobahns)." *7th International Conference on Concrete Pavements*, 437-450.

Suthahar, N., Ardani, A., and Morain, D. (2000). "Early Evaluation of LTPP Specific Pavement Studies-2 in Colorado." *CDOT-DTD-R-00-2000-2*, Colorado Department of Transportation, Denver, CO.

Tart Jr., R. G. (2000). "Pavement Distress and Roadway Damage caused by Subsurface Moisture and Freezing Temperatures- Case Histories from Alaska." *Transportation Research Record*, 1709, 91- 97.

Voigt, G. F. (2000). "Specification Synthesis and Recommendations for Repairing Uncontrolled Cracks that Occur During Concrete Pavement Construction." American Concrete Pavement Association, Skokie, IL.

Vongchusiri, K., Buch, N., Desaraju, P., and Salama, H. "An Evaluation of LTPP SPS-2 Sections in Michigan." *Maintenance and Rehabilitation of Pavements and Technological Control*, Portugal.

Wade, M. J., Smith, K. D., Yu, T., and Darter, M. I. (1995). "Monitoring of European Concrete Pavements." *Transportation Research Record*, 1478, 90-99.

Wu, S. (1992). "Concrete Pavement Performance: A 23-year Report (Abridgement)." *Transportation Research Record*, 1370, 39-42.

Wu, S.-S., and Qian, Y. "Effect of Base Type on Concrete Slabs Response to Loading." *6th International Conference on Concrete Pavement Design and Materials for High Performance*, 339-358.