Design and Construction of PCC Pavements, Volume II: Design Features and Practices That Influence Performance of Pavements

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LTPP

FOREWORD

This report documents the results of analysis of site conditions, design features, and construction practices that influence the performance of portland cement concrete (PCC) pavements. The analysis was done using Long-Term Pavement Performance (LTPP) data.

The positive outcomes of this study are the recommendations for improving PCC pavement design. This report discusses the effect of various site conditions on the development and progression of several common PCC pavement distresses. It also documents how to minimize distress through the use of design features and construction techniques.

This report is important to everyone who designs, constructs, and manages pavements.

Charles J. Nemmers, P.E.
Director
Office of Engineering
Research and Development

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16. Abstract

A study has been conducted to evaluate and analyze portland cement concrete (PCC) pavements in order to develop recommendations for the design and construction of long-lived concrete pavements. It involved a detailed evaluation and analysis of the PCC pavement data in the Long-Term Pavement Performance (LTPP) database using statistical techniques to determine the design features and construction practices that have a beneficial effect on long-term performance.

The study focused on the development of practical recommendations that can be easily implemented by highway agencies to increase pavement life. This volume describes and provides information on design features and construction practices that improve pavement performance. A key focus was to develop canonical discriminant functions that can be used to discriminate between groups of pavements in the sense of being able to tell them apart. The pavements were grouped according to their performance classification, namely, above expectation, as expected, and below expectation. The canonical functions consist of linear combinations of the variables that describe and quantify the pavement design features, site conditions, and construction practices.

This report is the second in a series of three volumes on the study. The other volumes are as follows:

FHWA No.	Vol No.	Short Title
FHWA-RD-98-052	I	Summary of Design Features and Construction Practices That Influence Performance of Pavements
FHWA-RD-98-113	III	Improved PCC Performance Models

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AC	asphalt concrete
ANOVA	analysis of variance
C_d	drainage coefficient
CRCP	continuously reinforced concrete pavement
Dowdia	dowel diameter
D32	average annual number of days with temperature below 32 °C
E_{PCC}	elastic modulus of PCC slab
ESAL	equivalent single axle load
FI	freezing index
Ftcyc	average annual number of air freeze-thaw cycles
FWD	falling weight deflectometer
GPS	general pavement studies
h_{PCC}	PCC slab thickness
IRI	international roughness index
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement
JTSP	joint spacing or PCC slab length
k	modulus of subgrade reaction
LTPP	Long-Term Pavement Performance
PCC	portland cement concrete
TEMP	temperature
Wtdys	average annual number of wet days

1. INTRODUCTION

Background

A major goal of the Long-Term Pavement Performance (LTPP) study is the development of recommendations for improving the design and construction of new and reconstructed pavements. This is emphasized in two of the six objectives that were established for the LTPP study in 1985 by the Pavement Advisory Committee of the Strategic Highway Research Program (SHRP). They are as follows:

- Determine the effects of loading, environment, material properties, construction, and maintenance on pavement distress and performance.
- Determine the effects of design features on pavement performance.

An attempt was made to develop such recommendations in the early analysis of the LTPP data that were available in 1992.[1] Due to the limited amount of data that were available, a complete analysis to develop useful practical recommendations for pavements was not possible; however, the research provided several useful insights into the database and provided guidelines on future data analysis and research efforts.

Since the 1992 study, there have been major improvements to the LTPP database. With these improvements have come some new opportunities for the evaluation and analysis of pavement data to meet some of the specific objectives of the LTPP study. More importantly, enough data are now available in the LTPP database to permit significant analyses to meet some specific regional and local needs. Such targeted research is perhaps the most appropriate way to harvest the best products out of the LTPP database.

Project Scope

This study was designed to investigate the evaluation of portland cement concrete (PCC) pavements in the LTPP database to meet some of the specific needs of the States that have been sponsoring and participating in the LTPP program. It involves an evaluation and analysis of the PCC pavement data in the LTPP database to determine the design features, climatic variables, and construction practices that influence performance of rigid pavements. The two specific objectives of the study include:

- Examining and analyzing the PCC pavement LTPP data to determine design, climate, and construction variables that influence performance.
- Developing specific recommendations for improving the design and construction of PCC pavements.

The project scope was refined to exclude specific recommendations for the maintenance and rehabilitation of PCC pavements because of the lack of available data. Emphasis was placed on the development of national recommendations (as opposed to regional ones) because of constraints in the availability of data.

Scope of Report

This report is the second in a series of three volumes on this study. The other two reports are as follows:

Volume I	–	Summary of Design Features and Construction Practices That Influence Performance of Pavements
Volume III	–	Improved PCC Performance Models

Volume II provides results of extensive data analysis and research work that was conducted in this study. Volume II addresses the preliminary work done in evaluating the influence of the site, specific design features, and construction practices on the long-term performance of concrete pavements using the LTPP database, and volume III provides information on improved distress and roughness prediction models that were developed using the LTPP database. The results obtained from volumes II and III were used to develop a summary of design features and construction practices that influence performance of pavements, presented in volume I.

After this introduction, the report provides a discussion of the approach used for performance evaluation in this study in chapter 2. Chapters 3, 4, and 5 present an evaluation of the effects of site conditions, design features, and construction practices on PCC pavement performance with the use of transverse joint faulting, transverse cracking, and roughness, respectively, as a measure of distress and, hence, performance, and chapter 6 concludes the report. Transverse joint spalling and corner breaks were not considered for this kind of analysis (empirical statistical analysis) because there were not enough pavement sections with these distresses. A comprehensive overview of the LTPP PCC data used in this study is presented in appendix A of this report, and a discussion of past research findings on factors that influence pavement performance is presented in appendix B.

2. METHOD OF PERFORMANCE EVALUATION

Introduction

Pavement performance is determined based on criteria related to the rate of occurrence of distress, the severity of the distress, and the detrimental effect of the given distress on the pavement's ability to serve its function. Several attempts have been made in the past to develop procedures and criteria for evaluating pavement performance and, in the process, determine the effects of design features, site conditions, and construction practices on performance.[1,2,3] Most of these studies involved the use of simple univariate and bivariate plots of the data to establish trends in the severity of a given distress as a function of design features, site conditions, and construction variables. The development of performance prediction models and a comprehensive sensitivity analysis is also an effective procedure for identifying key factors affecting performance.

Results from some of the past pavement performance evaluation studies were reviewed as part of this study to determine the following:

- Variables that have significant effect on distresses and, hence, performance.
- Interactions between quantitative variables that have a significant effect on distresses.
- Mechanistic clusters that have an effect on the occurrence and rate of progression of distress.
- Procedures used to determine which pavements are performing better than expected, as expected, and worse than expected.

Table 1 shows the site, design, and construction (explanatory) pavement variables that have been found in previous studies to have a significant effect on PCC distresses. The effect of these variables on pavement performance were investigated further by conducting a preliminary analysis of bivariate plots of distress versus traffic and consequently a more detailed and comprehensive canonical discriminant analysis and analysis of variance. The plots showed clearly the effects of the variables on the development and progression of distress. The procedure for pavement performance evaluation for this study is in five parts and can be summarized as follows:

1. A literature review of past pavement evaluation studies that is presented in appendix B of this report.
2. Preliminary evaluation of data using graphical techniques such as univariate (presented in appendix A) and bivariate plots.
3. Classification of pavement sections within the database based on performance criteria.

Table 1. Proposed variables to be investigated for each prediction model.

Design Features, Site Conditions, and Construction Practices	Joint Faulting	Transverse Cracking	Roughness
Pavement age	✓	✓	✓
Slab thickness	✓	✓	✓
Joint spacing	✓	✓	✓
Drainage	✓		
Base type	✓	✓	✓
Cumulative ESAL's*	✓	✓	✓
Effective joint opening	✓		
Corner deflection	✓		
Freezing index	✓	✓	✓
Edge support	✓		✓
Subgrade type	✓	✓	✓
Annual precipitation	✓	✓	✓
Bearing stress	✓		
Dowel diameter	✓		
Slab stress		✓	✓
PCC modulus of rupture		✓	✓
PCC elastic modulus	✓		✓
PCC compressive strength	✓		
Average monthly temperature	✓	✓	✓
Thornthwaite index	✓	✓	✓
Static k-value	✓	✓	✓
Steel percentage		✓	✓
Reactive aggregate			✓
Joint sealant type	✓		
Sealant damage	✓		
Load transfer type	✓		
Freeze-thaw cycles			✓

* ESAL = Equivalent single axle load.

4. Developing a procedure for determining pavement performance on the basis of known quantitative design, climate, and construction variables (canonical discriminant analysis).
5. An analysis of variance (ANOVA) to determine variables that have a significant influence and effect on distress and, therefore, performance.

This chapter reviews the approach used in this report for evaluating pavement sections according to performance and determining the significant design features, site conditions, and construction practices that influence pavement performance.

Preliminary Statistical Analysis (Univariate and Bivariate Analysis)

For both performance model development and performance evaluation, an extensive univariate and bivariate analysis of the database was necessary. This served two purposes: to determine the condition of the database used in analysis and to confirm trends determined from past pavement performance evaluation studies, model development efforts, and mechanistic analysis.

Univariate Analysis

Univariate analysis is the determination of the basic statistics of the LTPP data elements such as the total number of sections, sections with missing data, and the mean, mode, median, and standard error estimate of the mean of the data element. Other tests include a test for the normality of the data, skewness, and kurtosis. Plots, in the form of a histogram or bar chart, can be used to show visually the distribution of a given data element or variable. The ideal data element distribution for statistical analysis is a normal distribution. However, the distribution of most of the data elements used in the analysis is skewed. Univariate analysis and plot are efficient techniques for identifying such data elements and correcting them where possible. Also, statistical techniques that are insensitive to skewness may be used for analysis. Figures 1 and 2 show examples of normally distributed data and skewed data. The results of the comprehensive univariate analysis performed as part of this study are presented in appendix A of this report.

Bivariate Analysis

Bivariate statistics measure the degree of dependence between two variables (dependent and independent). They also show the trends and changes in the value of the dependent variable as the independent variable is varied. For this study, the dependent variable is a distress variable and the independent variable is a design, climate, construction, or any other kind of variable or cluster of variables that could influence pavement performance.

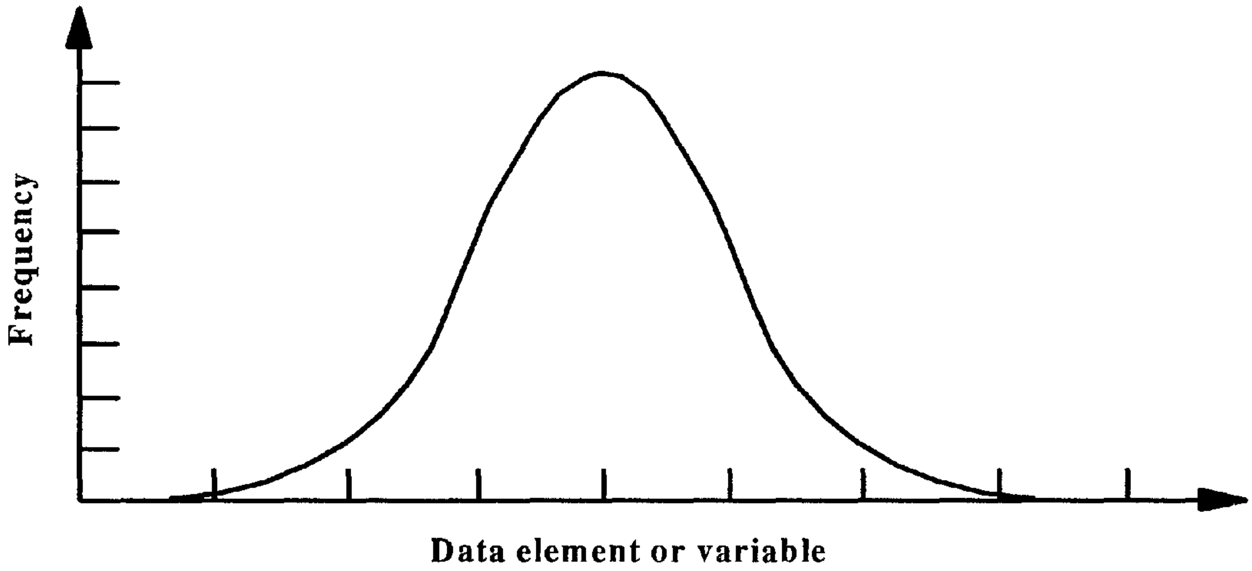


Figure 1. Normally distributed data.

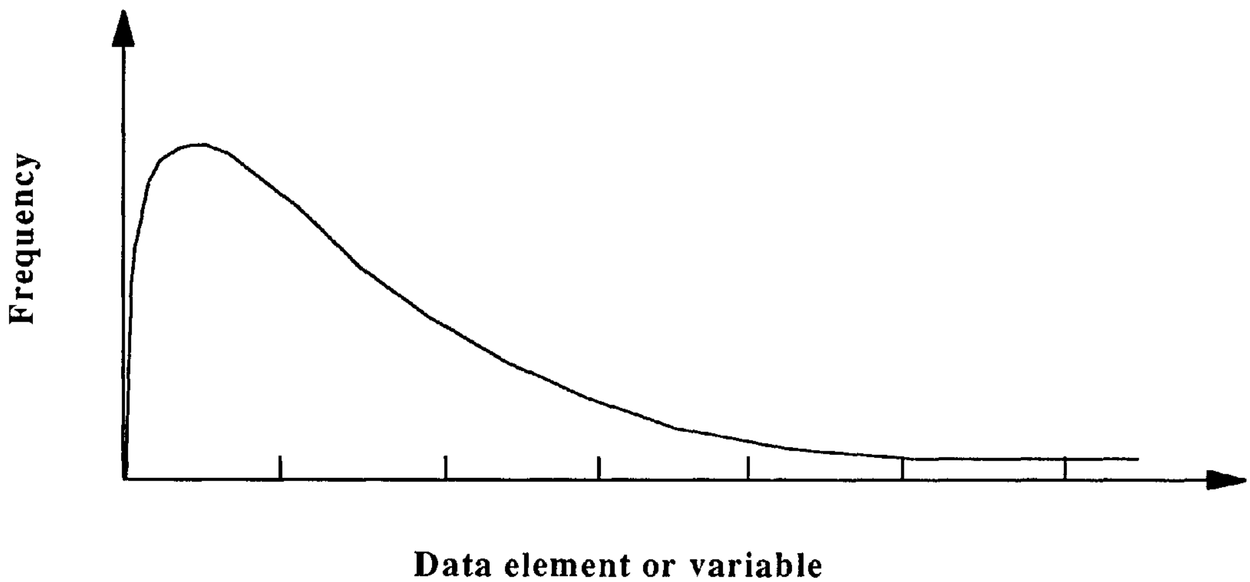


Figure 2. Data that are skewed or deviating from normal.

Results of the bivariate analysis were presented in the form of plots of the independent variables against distress and simple statistical regression curves (linear) showing trends and correlations. The plots showed visually the trends between the independent variable and distress. They were used to determine if the trends were reasonable and as expected from mechanistic analysis, engineering judgment, and past empirical analysis. The bivariate plots were also used to identify potential outliers. Plots of this kind can be confounded by the effects of other independent variables not considered. This could lead to obtaining contradictory and misleading results. Observations from bivariate plots are therefore preliminary in nature and therefore not conclusive. For this study, more sophisticated statistical tools such as canonical discriminant analysis and analysis of variance were used to develop recommendations for pavement design and construction.

Canonical Discriminant Analysis

Canonical discriminant analysis begins with the desire to statistically distinguish between two or more groups of observations. These groups are defined by the particular research situation.[1, 2] Some examples of groups of observations would be as follows:

- Group 1—Pavements with faulting less than 10 mm.
- Group 2—Pavements with faulting greater than or equal to 10 mm.

With measurements on several quantitative variables, canonical discriminant analysis derives a linear combination of variables that has the highest possible multiple correlation with the groups. The coefficients of the linear combination are the canonical coefficients or canonical weights. The variable defined by the linear combination is the canonical variable. Several other canonical variables can be obtained by finding the linear combination uncorrelated with the first canonical variable that has the highest possible multiple correlation with the groups.

To distinguish between the groups the researcher selects a collection of discriminating variables that measure the characteristics on which the groups are expected to differ. For instance, in the faulting example, data on the pavement design, site conditions, and construction techniques such as base or subgrade type, traffic, load transfer system, joint construction method, and precipitation that potentially could influence faulting may be useful for canonical discriminant analysis. The mathematical objective of canonical discriminant analysis is to weight and linearly combine the discriminating variables in some fashion so that the groups are forced to be statistically distinct as possible. In order words we want to be able to discriminate between the groups in the sense that we tell them apart. Normally, no single variable will perfectly discriminate between the two faulting levels given in the example; however, by taking several variables and mathematically combining them it is possible to obtain a single discriminant variable that is a linear combination of the pavement properties that clearly demarcates between the two levels of faulting. For pavement performance evaluation, canonical discriminant analysis can be an efficient tool for evaluating the performance of newly designed pavements given the pavement site, design, and construction features.

Canonical discriminant analysis in this study involved the classification of existing pavement sections in the LTPP database according to performance and then using the data in the development of canonical functions based on the pavement's design, site, and construction properties. The methods for classifying the pavement and developing the canonical functions are discussed in the following sections.

Performance Classification of Pavements

To perform a more detailed statistical analysis on the data to determine variables affecting performance, the different pavement sections within the LTPP database had to be classified using a variable that defined them based on performance. The observations were classified as expected, below, and above expected performance.

Several studies in the past have used expert opinion to classify pavement performance. One such study used a graphical approach, which involved defining and plotting the boundaries between three levels of performance (good, normal, poor) for each distress type for a given pavement's age since construction. The criteria for differentiating between good, normal, and poor performance and defining the boundaries for the different classes of performance were recommended by pavement experts over a 20-year period. The objective was to identify design features that contribute to good and poor performance.[4] For this study, pavement performance was classified by considering the relevant design, climatic, and construction variables that influence the occurrence and severity of the distress. The classification procedure is best explained by the example below.

Consider a pavement designed and constructed using appropriate design techniques and construction procedures to withstand 20 million ESAL applications over a 20-year period for the given site and climatic conditions. We expect the pavement to have a minimum useful life of 20 years; that is, we expect the pavement to perform adequately for at least 20 years, without any major occurrence of distress. We also expect damage to the pavement resulting in distress to accumulate both from the repeated axle loads applied to the pavement and repeated climate-related stresses. Within the 20-year useful design life of the pavement, we expect the severity of both damage and distress to approach but remain below critical levels. Classifying or quantifying performance for such a pavement is based on whether the pavement performs as expected. The most practical method for determining this is to compare the actual distress measured for a pavement with a given age and traffic load applications and expected distress. The expected distress is estimated from distress prediction models and expert opinion. Pavements can thus be categorized based on the comparison of actual and expected distress as follows:

- Pavements with measured distress equal to predicted distress or within a 90 percent confidence interval are classified as "expected."
- Pavements with measured distress less than the lower limit of the 90 percent confidence interval of predicted distress are classified as "above expectation."
- Pavements with measured distress greater than the upper limit of the 90 percent confidence interval of predicted distress are classified as "below expectation."

Table 2 presents this concept in another format. The most appropriate method for determining the expected distress values of pavement sections is the use of existing pavement performance models. Performance models are multi-dimensional, taking several design, climate, and construction variables into consideration for predicting the expected level of distress. Because of potential errors that are certain with every model, a confidence interval should be used to define a range for the expected level of distress. This will limit the potential for misclassification. It must be noted that the expected distress level of a pavement with similar features may vary according to age and traffic loading. A detailed procedure for pavement performance classification is presented in the next section.

Pavement Performance Classification Procedure

Pavement performance classification was determined using models developed as part of this study. The information required for classification is as follows:

1. Determine the actual distress severity from the database.
2. Use pavement performance models or expert opinion to determine the expected distress severity level for a pavement section with the given design, climate, and construction features.
3. Determine the standard estimate of error (SEE) for the model being used in the analysis.
4. Using the standard error estimate and expected distress value, determine the 90 percent confidence interval (C.I.) for the expected distress (90% C.I. = 1.645*SEE).

Using information from the LTPP database, performance models, and engineering judgment, the pavement sections in the LTPP database used for this study were classified as follows:

Table 2. Procedure of pavement performance evaluation.

Age, yr	Traffic, ESAL's	Expected Faulting, mm	Actual Faulting, mm	Performance Classification
20	10 million	2.5	0.25	Above expectation
20	10 million	2.5	2.5	Expected
20	10 million	2.5	6	Below expectation

- A pavement section with a measured distress severity greater than the expected confidence interval band (measured distress > expected distress + 1.645*SEE) is classified as performing below expectation.
- A pavement section with a measured distress severity within the confidence interval band is classified as expected (expected distress - 1.645*SEE < measured distress < expected distress + 1.645*SEE).
- A pavement section with a measured distress severity below the confidence level band (measured distress < expected distress) - 1.645*SEE) is said to be performing better than expected or above expected.

The procedure outlined for pavement performance evaluation is shown graphically as figure 3.

Canonical Functions

Canonical discriminant analysis is a dimension reduction technique related to principal component analysis and canonical correlation.[5, 6, 7] Given a classification variable such as pavement performance and the quantitative variables such as the design, climate, and construction features of the pavement, canonical discriminant analysis derives canonical variables related to the classification variable for canonical functions (linear combination of the quantitative variables). The canonical functions summarize between class variation and discriminate between pavements based on the classification variable (in this case, pavement performance). The procedure for implementing this technique is summarized as follows and shown in figure 4.[5, 6]

- Identify and define potential quantitative design, climatic, and construction variables.
- Identify missing data and potential data problems, such as normality, and implement remedies as required.
- Assemble the database and classify the pavement sections within the database into the expected, below expected, and above expected performing pavement sections (classification variables).

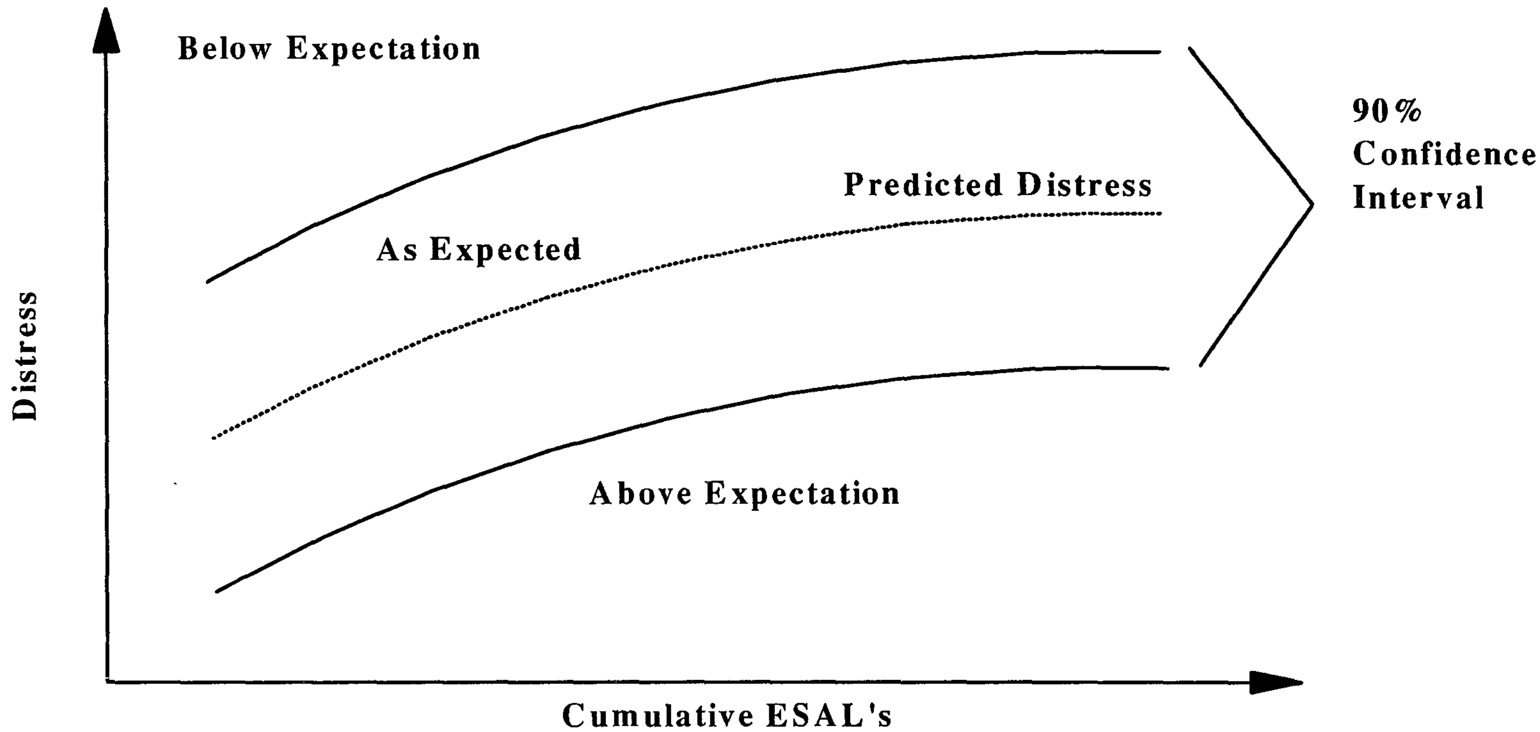


Figure 3. Graphical representation of pavements performing as expected, below, and above expectation.

- Perform canonical discriminant analysis on the data to obtain canonical functions and variables.
- Check canonical functions and variables for significance, misclassification, and collinearity using diagnostic and other statistics.
- Determine the range of values of canonical variables for the different performance classes.

The use of the canonical discriminant analysis technique to classify pavement performance is illustrated with the following example plot of two canonical functions, CAN1 and CAN2, shown as figure 5. The plot shows pavement sections classified as A, B, C, and D. Pavements classified as A are located in quadrant 1, B is in quadrant 2, C is in quadrant 3, and D is in quadrant 4 of the plot.

Therefore, for a pavement section with given design features, site conditions, and construction practices, the quadrant in which the plot of CAN1 and CAN2 lies determines the performance class to which that pavement belongs. The performance class can be varied by varying the values of the input variables for the canonical functions and thus could be useful in determining the performance class of newly designed pavements.

Analysis of Variance

ANOVA models are versatile statistical tools for studying the relation between a dependent variable and one or more independent variables.[8] They do not require making assumptions about the nature of the statistical relation nor do they require that the independent variables be quantitative. ANOVA models are used for applications where the effects of one or more independent variable on the dependent variable are of interest. Independent variables in the models for ANOVA are mostly called factors or treatments. This section of the report presents the basic ANOVA procedures used in this study for determining the effects of several factors or treatments (independent variables such as slab thickness and annual precipitation) on the dependent variable, distress.

ANOVA Procedure

The procedure for the ANOVA analysis is summarized as follows:

1. Transform continuous variables within the LTPP database into classification variables.
2. Develop ANOVA models for predicting distress.
3. Perform test of hypothesis using the models developed.

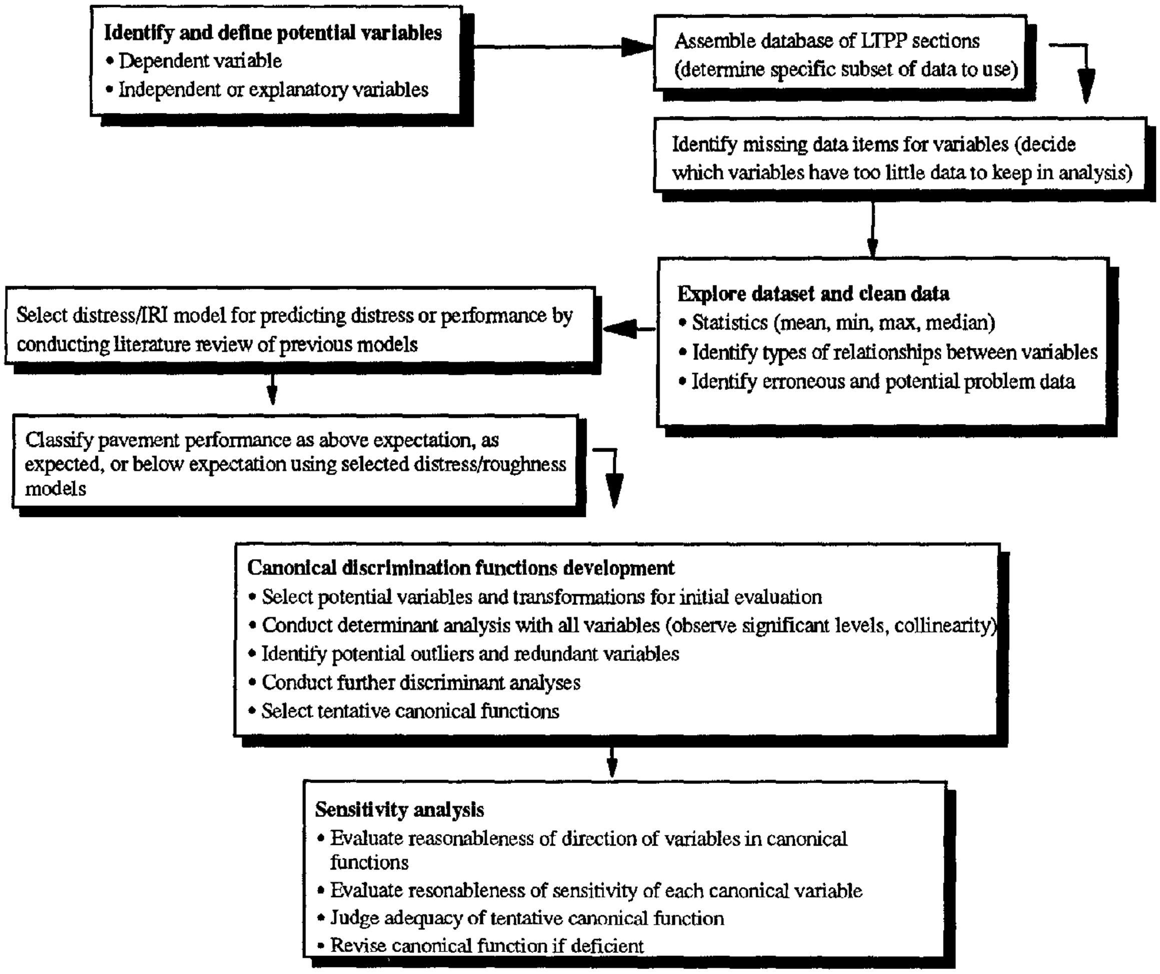


Figure 4. Flow chart showing canonical discriminant analysis procedure.

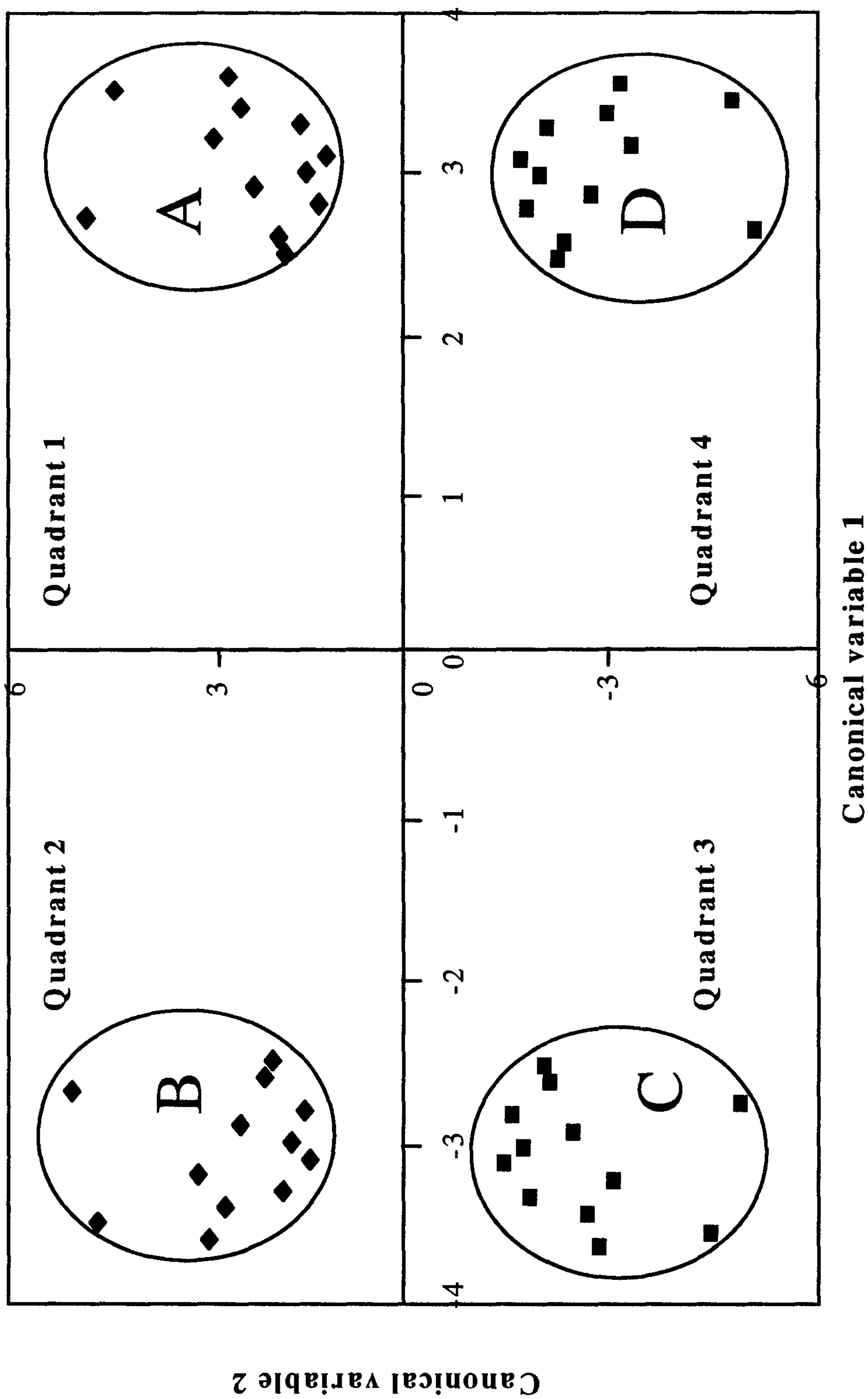


Figure 5. Typical plot of canonical variables.

The procedure outlined is simple and suits the purposes of most simple analysis of variance. The different elements of the procedure are explained in the following sections.

Data Transformation

Most of the data elements in the LTPP database used as treatments or factors in ANOVA are continuous. Using them as presented in the database will result in the consideration of the effect of several factor levels on the given distress (e.g., PCC slab thickness = 200, 210, 220, 230, ..., 260 mm). To avoid such a situation, and also to decrease the number of levels of a given factor such as slab thickness, the data elements were transformed into classification or indicator variables. An example is shown below:

- Class A or 0, PCC slab thickness < 220 mm.
- Class B or 1, PCC slab thickness ≥ 220 mm.

The qualitative variable defining the ranges of pavement PCC slab thickness was then used in the ANOVA model to determine the effect of slab thickness on pavement performance.

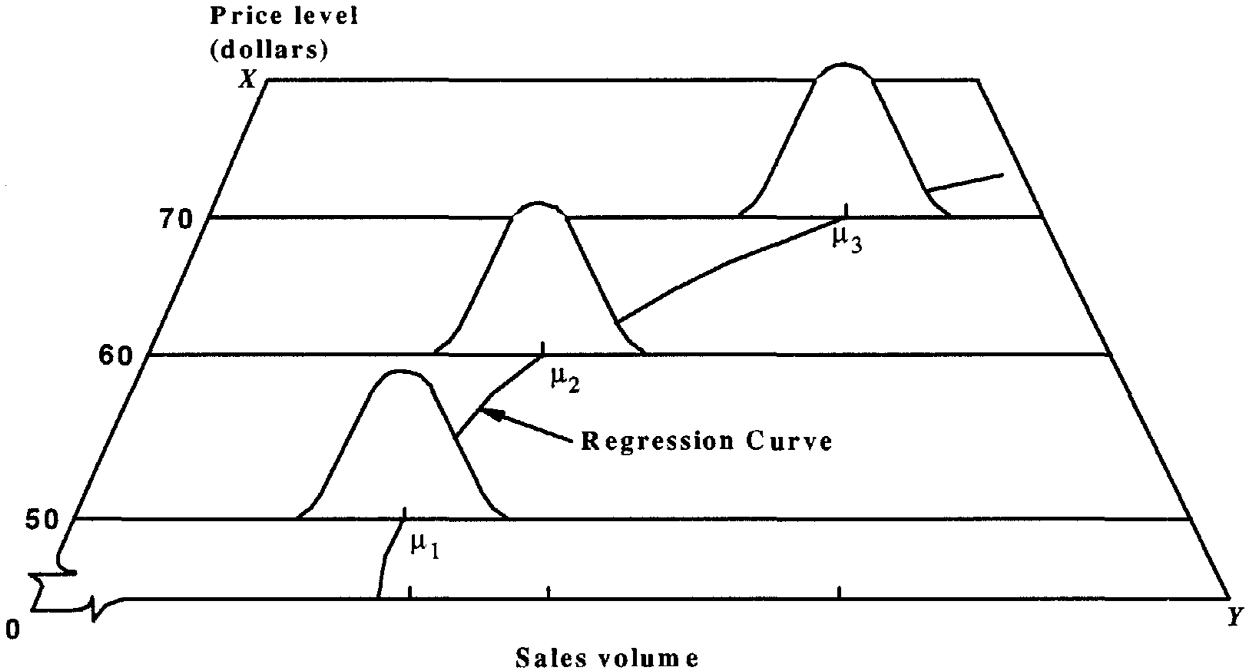
ANOVA Models

ANOVA models are a basic type I statistical model.[8] They are concerned, like regression models, with the statistical relation between one or more independent variables and a dependent variable. Like regression models, ANOVA models are appropriate for both observational data and data based on formal experiments. Further, like the usual regression models, the dependent variable for ANOVA models is a quantitative variable. However, they differ from ordinary regression models in two key respects. First, the independent variables in the ANOVA model can be qualitative (geographic location, wet, dry, freeze, nofreeze). Second, if the independent variables are quantitative, no assumption is made in the ANOVA models about the nature of the statistical relation between them.[8]

The difference between ANOVA models and regression models is illustrated by the plots shown in figure 6. Shown in figure 6a is the regression model for a pricing study involving three different price levels, X = $50, $60, and $70. For each level of the independent variable, there is a probability distribution of sales volume. The means of these probability distributions fall on the regression curve, which describes the statistical relation between price level and mean sales volume.

The ANOVA model for the same study is shown in figure 6b. The three price levels are shown as separate distributions, each leading to a probability

(a) Regression Model



(b) Analysis of Variance Model

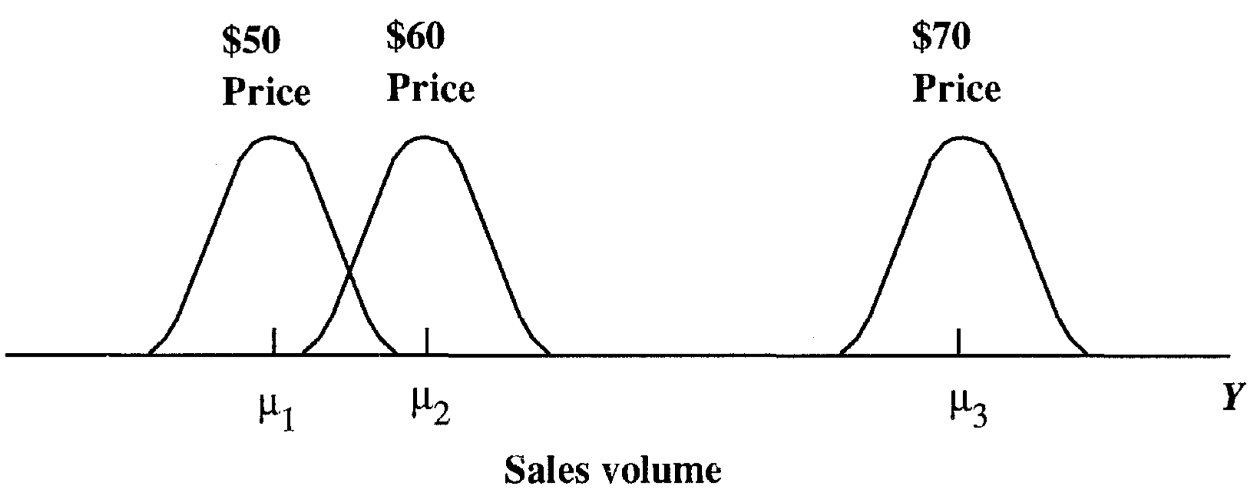


Figure 6. Relation between regression and analysis of variance models.[8]

distribution of sales volumes. The quantitative differences in the three price levels and their statistical relation to expected sales volume are not considered.

Hypothesis Testing

The goal of the ANOVA is to compare means of the response variable (distress) for various combinations of the classification variables (design, site, and construction properties). The effect and significance of the variables on performance can be confirmed or verified by comparing the level of significance of the variables to a predetermined level of significance, called p-value. ANOVA determines if there is a statistical difference in the mean values of the distress for the different classes of the independent variables in the model.(8) The mean level of the distress for the different classes gives an indication of whether the independent variable has a positive or negative effect on the distress. The following example illustrates the ANOVA technique.

Pavement PCC thickness: class A (less than 220 mm)
class B (greater than 220 mm)

Distress level : class A $= \mu_A$
class B $= \mu_B$

The significance of the effect of PCC thickness on the given distress is determined by the following test of hypothesis:

Null hypothesis, H_o: $\mu_A = \mu_B$
Alternative hypothesis, H_A: $\mu_A \neq \mu_B$

Based on a significance level (p-value) of 5 percent (0.05), of less than 0.05 rejects the null hypothesis, whereas a result greater than 0.05 confirms the null hypothesis. A comparison of the magnitude of the means determines the nature of the effect of the pavement property (in this case, PCC thickness).

Summary of Methods of Performance Evaluation

Bivariate plots, canonical discriminant analysis, and analysis of variance are statistical tools useful in determining, preliminarily, trends between dependent and independent variables, and the effect of various design, site, and construction features on pavement performance. These statistical tools will be applied throughout this report to determine the effects of site conditions, design features, and construction practices on distress formation and progression in PCC pavements and, thus, PCC pavement performance.

3. EVALUATION OF SITE CONDITIONS, DESIGN FEATURES, AND CONSTRUCTION PRACTICES THAT INFLUENCE JPCP FAULTING

Introduction

Many of the primary design features, site conditions, and construction practices that influence PCC pavement performance are identified in appendix B. They include the site conditions of traffic, climate, and subgrade support, as well as the specific design features that are incorporated into the pavements to improve performance, such as PCC slab thickness, the presence of dowels, and drainage facilities.

A prioritized list of the design features, site conditions, and construction practices (relevant to each distress type) proposed for investigation with LTPP data was presented in table 1 of chapter 2 of this report. Some of these data elements identified during the literature review are not available in the LTPP database; however, those available will be investigated to determine their effect on performance. The list of key site conditions, design features, and construction practices available in the LTPP database, and identified as having the potential to influence the development and progression of faulting, is presented in table 3. This list was not meant to be exhaustive, and any other variables that were found to significantly influence faulting at the preliminary stage of faulting were investigated.

This chapter presents the results of a preliminary bivariate analysis and canonical discriminant analysis used to identify the data elements that influence PCC pavement faulting. A comprehensive univariate analysis, which was the first step in analyzing the data, is presented in appendix A of this report. For the bivariate analysis, the effects of individual design features and site conditions were investigated separately. The data were further divided, when possible, to observe the effect of climate. The design of experiments to be analyzed was based on engineering judgment in order to keep the individual evaluation data sets a minimum size. This reduced the possibility of insufficient data for analysis. Each experiment was specific to the distress data type being investigated and is described in detail in later sections of this chapter.

Also, an analysis of variance was performed to confirm where possible the trend observed in the preliminary stages of the analysis. It must be noted therefore that, with the exception of the results from the analysis of variance, results and discussions presented from the bivariate analysis and canonical discriminant analysis can be misleading because of the influence of other variables not considered in this kind of preliminary analysis.

Table 3. Key design features, site conditions, and construction practices available in LTPP database for transverse joint faulting.

Design Features, Site Conditions, and Construction Practices	Joint Faulting
Pavement age	✓
Slab thickness	✓
Joint spacing	✓
Drainage facilities	✓
Base type	✓
Cumulative ESAL's (traffic)	✓
Effective joint opening*	✓
Corner deflection*	✓
Freezing index	✓
Edge support	✓
Subgrade type	✓
Annual precipitation	✓
Bearing stress*	✓
Dowel diameter	✓
PCC elastic modulus	✓
PCC compressive strength	✓
Average monthly temperature range	✓
Static k-value	✓
Joint sealant type	✓
Load transfer type	✓
Freeze-thaw cycles	✓
Dowel placement method	✓
Transverse joint forming method	✓

* Data elements were calculated from other original data elements in the LTPP database.

Preliminary Evaluation of Transverse Joint Faulting Data

As indicated in appendix B, the development of transverse joint faulting in both jointed plain concrete pavements (JPCP) and jointed reinforced concrete pavements (JRCP) pavements is greatly influenced by the presence of dowels and the amount of heavy traffic load applications. Based on the assumption that the presence of dowels has more of an influence on the development of faulting than pavement type, the JPCP and JRCP LTPP data were analyzed together.

Level 1 Investigations

The data were divided into subsets of doweled and undoweled sections, defined as the Level 1 analysis. The analysis at this stage was to determine the influence of dowels on faulting of PCC jointed pavements. The results are presented in the next section of this chapter.

Influence of Presence of Dowels

Figure 7 shows a plot of average edge faulting versus cumulative ESAL's for all doweled and undoweled JPCP and JRCP sections in the LTPP database. Linear trends were fit through the data in order to more clearly observe the trends. The available LTPP data indicate that, on average, undoweled JPCP and JRCP sections experience more faulting than doweled sections. A visual inspection of the data appears to indicate that the presence of dowels is much more important in minimizing faulting than dowel bar diameter.

The effect of the presence of dowels was further investigated by determining the effect of pavement location and dowels on performance. This involved investigating the influence of dowels in the various climatic regions in the United States. Figure 8 shows plots of faulting versus traffic in ESAL's for the climatic regions. Only the wet-freeze and wet-nofreeze climatic regions contained enough sections to compare doweled and undoweled sections. For both of these regions, the undoweled sections clearly exhibited more faulting than the doweled sections.

No trends were distinguishable for the dry-freeze and dry-nofreeze regions. An investigation of undoweled sections by climatic region showed about the same amount of faulting for those sections in the dry-freeze, wet-freeze, and wet-nofreeze regions. The undoweled sections in the dry-nofreeze region, however, exhibited much smaller faulting values than the undoweled sections in the other three regions. Doweled sections in the wet-freeze and wet-nofreeze regions appeared to develop about the same amount of faulting.

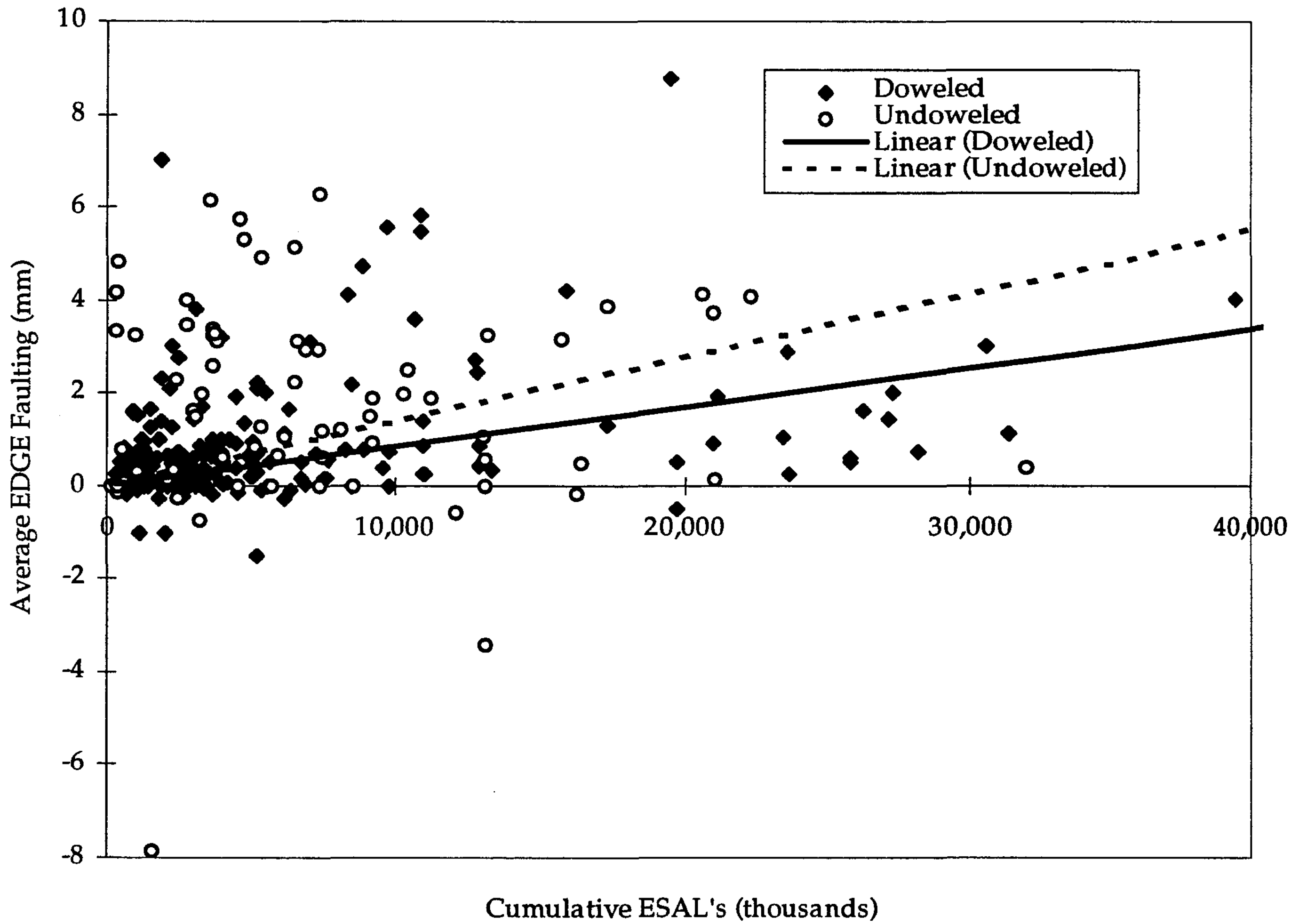


Figure 7. Plot of faulting versus cumulative ESAL's for doweled and undoweled PCC pavements.

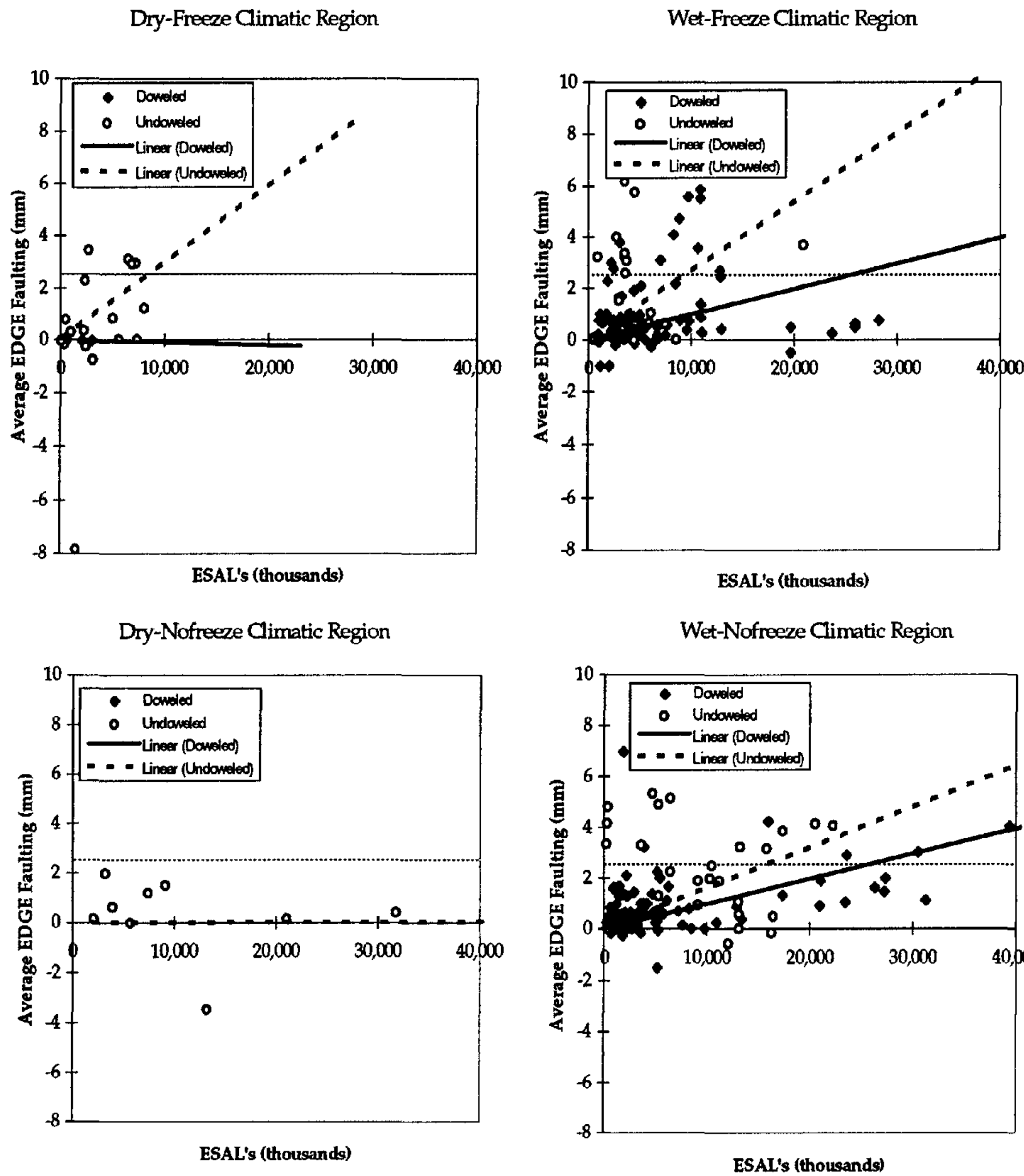


Figure 8. Plots showing the influence of the presence of dowels and climatic region on the faulting of JPCP and JRCP sections.

Level 2 Investigations

Level 2 investigations of the faulting data consisted of further dividing the Level 1 subsets into smaller data sets based on many of the possible influential site and design features identified in table 3. A summary of the Level 1 and Level 2 variables chosen for the faulting investigation is presented in table 4. The trends discussed and presented are those of the raw LTPP data. Each Level 2 variable is investigated by plotting the observed joint faulting data (expressed as the average transverse joint faulting for the section in millimeters) versus the cumulative ESAL's as determined from regression equations of the LTPP annual traffic data. The preliminary analysis consisted of creating plots showing the influence of each Level 2 variable at each Level 1 definition (doweled or undoweled) for all of the data observations, regardless of climatic region. Lines were fit through the data to more easily identify the trends. To observe any differences in the influence of the Level 2 variables between climatic regions, these plots were then recreated by using only the data in each climatic region (when data were available).

The conclusions and inferences drawn at the bivariate analysis stage are preliminary. There is a great possibility at this stage of the analysis for some of the results to be misleading because of confounding effects and interactions between the data elements. The results of these analyses are summarized and presented below.

Influence of Site Conditions

The Level 2 investigation involved analyzing the effect of several site-related variables on faulting of doweled and undoweled jointed PCC pavements, namely, freezing index, freeze-thaw cycles, average annual precipitation, average annual temperature range, average annual number of wet days, subgrade type, and the modulus of subgrade reaction. The variables were divided into the following categories for investigation:

- Freezing index: < 270 and ≥ 270 °C days.
- Annual freeze-thaw cycles: < 70 and ≥ 70.
- Average annual precipitation: < 1 and ≥ 1 m/yr.
- Average annual temperature range: < 11 and ≥ 11 °C.
- Average annual number of wet days: < 125 and ≥ 125 days.
- Subgrade type: fine or coarse-grained.
- Modulus of subgrade reaction: < 40.7 and ≥ 40.7 kPa/mm.

Effect of Freezing Index

For pavements with dowels, freezing index appeared to have no significant effect

Table 4. Level 1 and 2 design features, site conditions, and construction practices used in the evaluation of transverse joint faulting data.

Pavement Types	**Level 1 Variables**	**Level 2 Variables**
JPCP and JRCP	Presence of dowels	Freezing index
		Average annual precipitation
		Average annual freeze-thaw cycles
		Average annual temperature range
		Average annual number of wet days
		Subgrade type
		Backcalculated static k-value
		Slab thickness
		Average transverse joint spacing
		Dowel diameter
		Presence of subsurface drainage
		Presence of edge drains
		Base type
		PCC elastic modulus
		Presence of widened lane (lane width)
		Outside shoulder type
		Presence of transverse joint sealant
		Type of transverse joint sealant
		Transverse joint forming method
		Dowel placement method

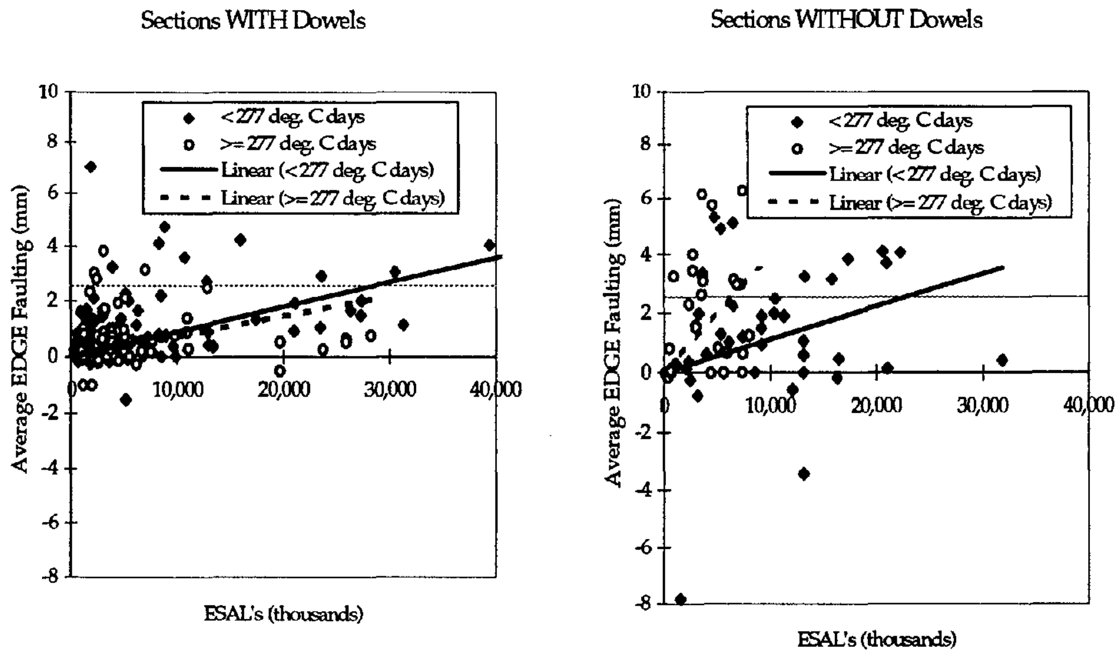


Figure 9. Plots of JPCP and JRCP transverse joint faulting versus traffic for different freezing index categories (all climatic regions).

on the level of faulting. However, undoweled pavements subjected to a freezing index ≥ 270 °C days exhibited a larger amount of faulting than those sections subjected to a freezing index < 270 °C days. The plots of faulting versus traffic showing the influence of freezing index are presented figure 9.

Effect of Average Annual Freeze-Thaw Cycles

The level of faulting in doweled sections again did not appear to be influenced by the level of change in average annual freeze-thaw cycles. However, undoweled sections subjected to freeze-thaw cycles ≥ 70 per year exhibited a significantly larger amount of faulting than those sections subjected to < 70 per year. Figure 10 presents plots of faulting versus traffic showing the influence of freeze-thaw cycles.

Effect of Average Annual Precipitation

For those sections with dowels, no significant change in faulting was observed for the two different annual precipitation categories. However, the same did not hold true for the undoweled sections. The undoweled sections subjected to greater than 1 m of average annual precipitation exhibited much more faulting (on average) than those sections subjected to less than 1 m. Figure 11 presents plots of faulting versus traffic showing the influence of average annual precipitation.

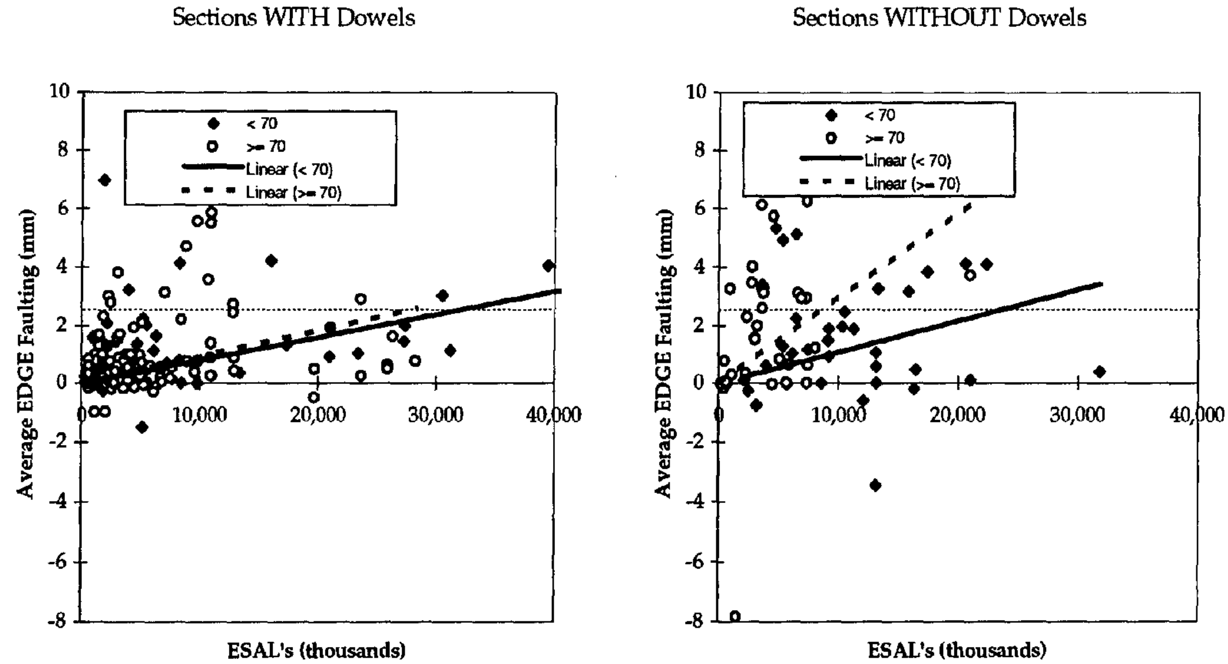


Figure 10. Plots of JPCP and JRCP transverse joint faulting versus traffic for different levels of freeze-thaw cycles (all climatic regions included).

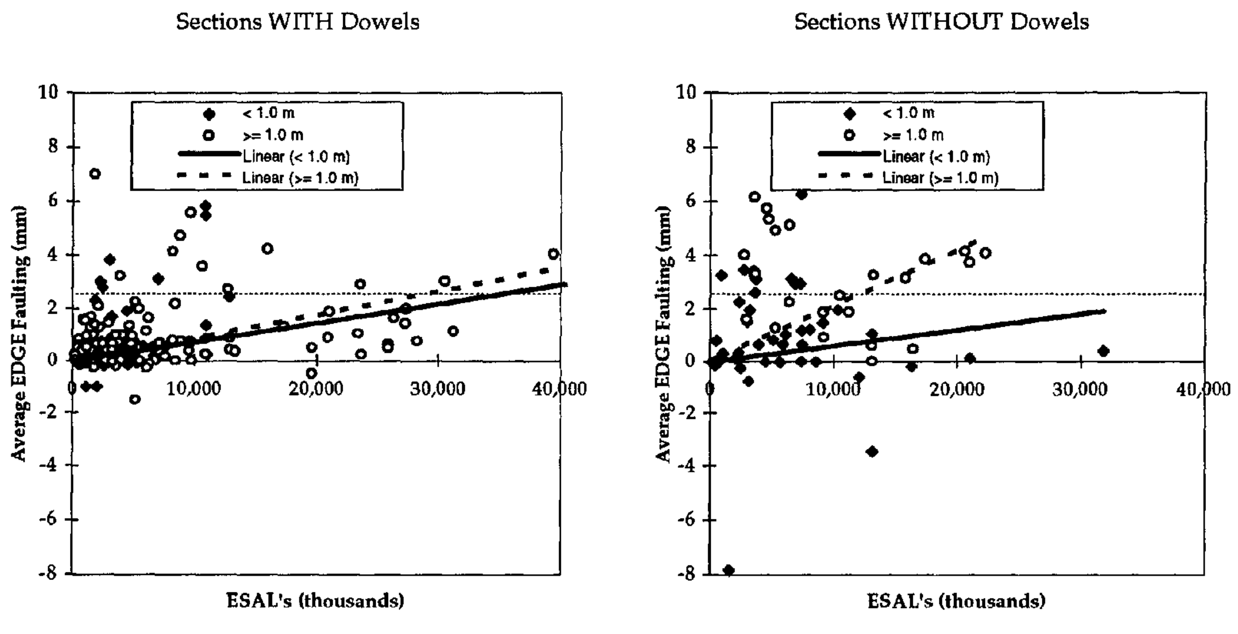


Figure 11. Plots of JPCP and JRCP transverse joint faulting versus traffic for different levels of average annual precipitation (all climatic regions included).

Effect of Average Annual Temperature Range

Changes in the average annual temperature range appeared to have little effect on the faulting of doweled sections. However, undoweled LTPP sections subjected to an annual temperature range < 11 °C showed more faulting (on average) than those undoweled sections subjected to a range of ≥ 11 °C. Figure 12 presents plots of faulting versus traffic showing this influence of average annual temperature range.

Effect of Average Annual Number of Wet Days

An investigation of the influence of the average annual number of wet days on transverse joint faulting showed that it significantly influenced faulting. Doweled and undoweled JPCP and JRCP subjected to ≥ 125 wet days per year consistently developed more faulting (on average) than those subjected to < 125 wet days per year. Figure 13 presents plots of faulting versus traffic showing this influence of average annual number of wet days.

Effect of Subgrade Type

A Level 2 analysis of subgrade type involved further separating the JPCP and JRCP doweled and undoweled sections by subgrade type (coarse-grained and fine-grained). The results showed that doweled sections with fine-grained subgrades had more faulting than those with coarse-grained subgrades. The undoweled sections appeared to have the opposite trend, with the sections with coarse-grained subgrade soils experiencing more faulting. This may be due to the fact that close to 90 percent of the undoweled JPCP pavements were located in wet or freeze regions, which could influence the magnitude of observed faulting. A visual inspection of the data showed that the highest individual faulting values were observed for those sections with fine-grained soils. Figure 14 contains plots showing the influence of subgrade type category on the faulting of JPCP and JRCP doweled and undoweled sections.

An analysis of the sensitivity of JPCP and JRCP transverse joint faulting data to subgrade type and climatic region was limited to the wet-freeze and wet-nofreeze climatic regions because of the lack of data in the dry-freeze and dry-nofreeze climatic regions. Both doweled and undoweled sections in the wet-freeze climatic region showed more faulting for those sections with fine subgrade soils. The regressions fit through the data in the wet-nofreeze region showed no sensitivity to subgrade type for the doweled sections, whereas for the undoweled sections, pavements with coarse-grained subgrade soils exhibited more faulting than those sections with fine-grained subgrade soils. Figure 15 contains plots showing the influence of subgrade type on the faulting of JPCP and JRCP doweled and undoweled sections in the wet-freeze and wet-nofreeze climatic regions.

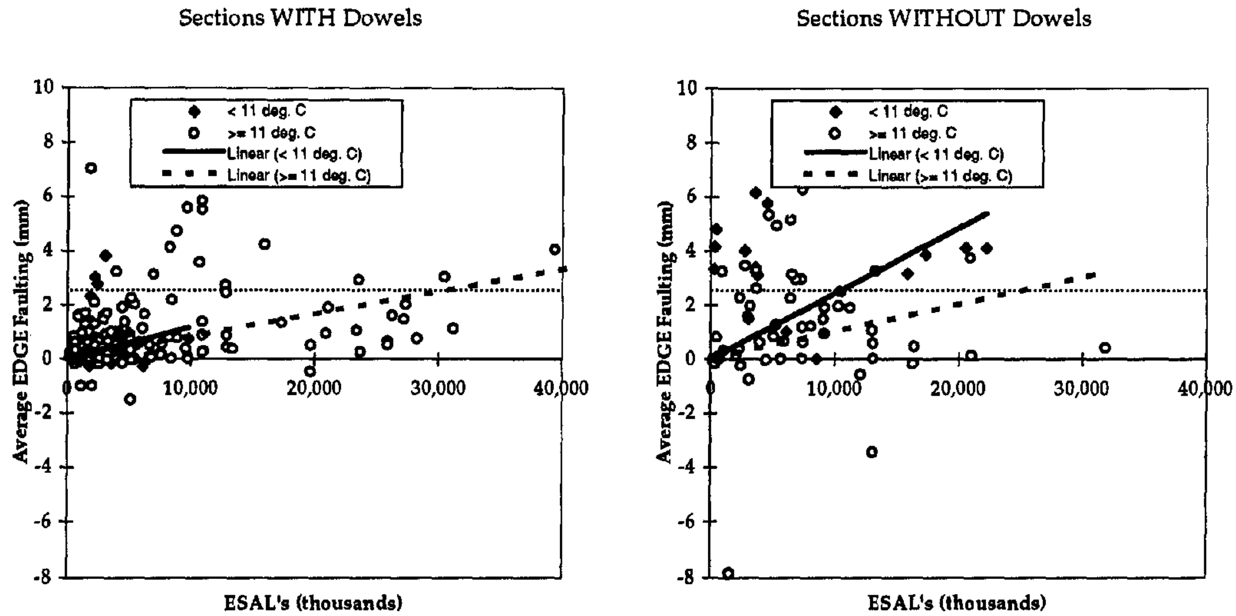


Figure 12. Plots of JPCP and JRCP transverse joint faulting versus traffic for different levels of average annual temperature range (all climatic regions included).

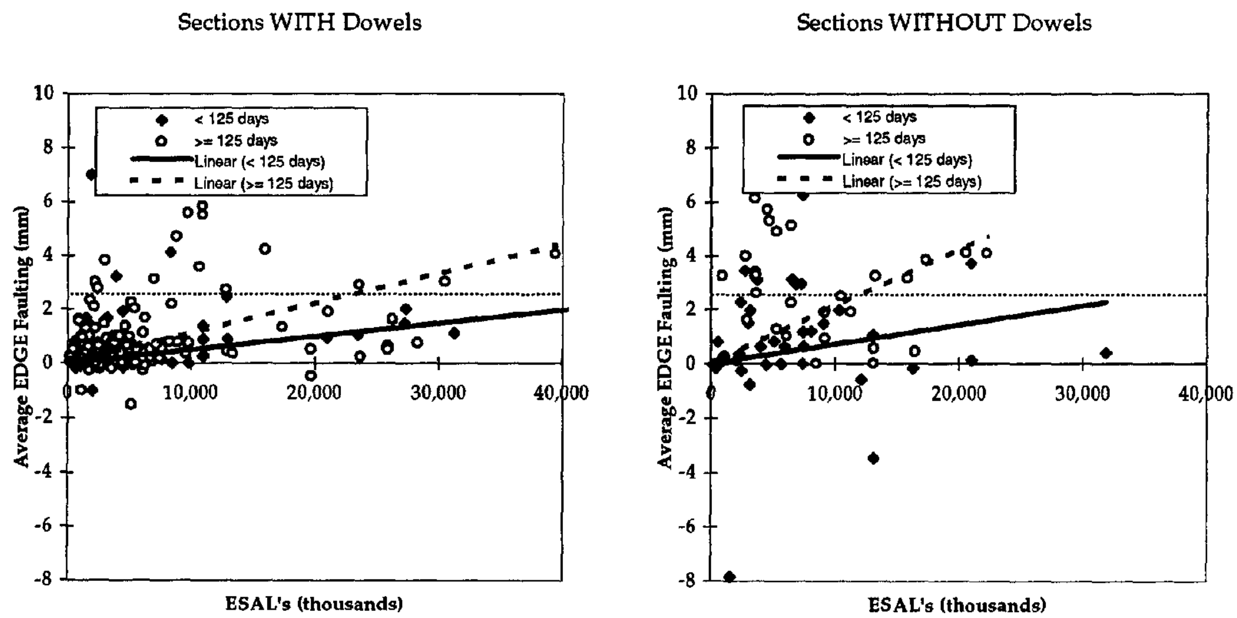


Figure 13. Plots of JPCP and JRCP transverse joint faulting versus traffic for different levels of average annual number of wet days (all climatic regions included).

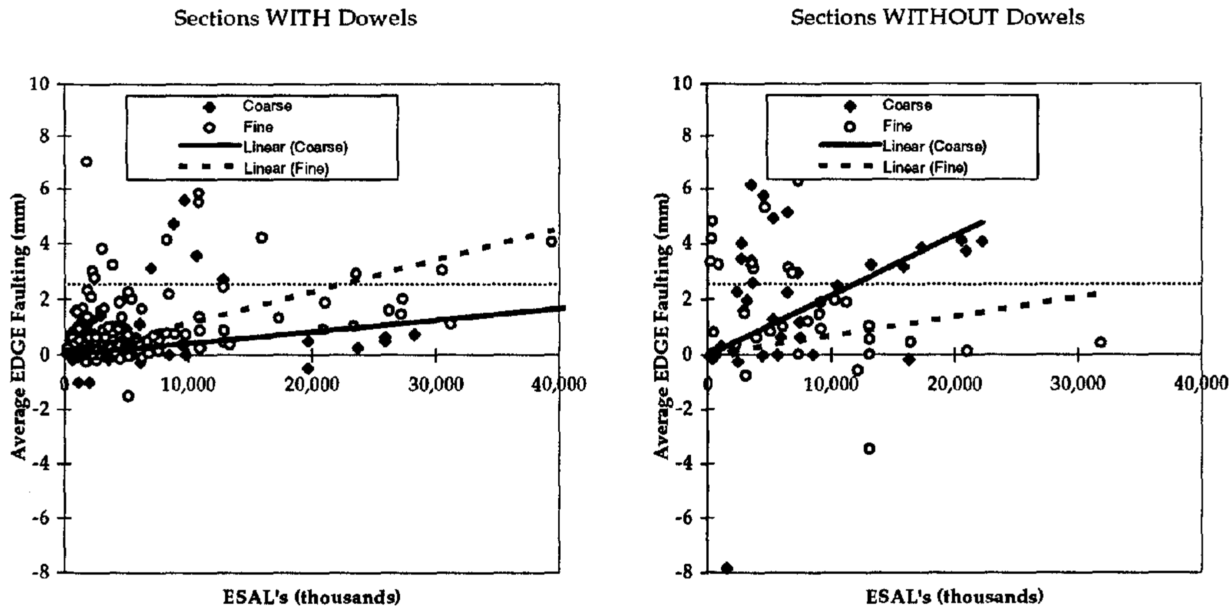


Figure 14. Plots of JPCP and JRCP transverse joint faulting versus traffic for different subgrade type categories (all climatic regions included).

Effect of Modulus of Subgrade Reaction (Backcalculated Static k-value)

The influence of two different static k-value levels (k-value < 40.75 kPa/mm and ≥ 40.75 kPa/mm) on JPCP and JRCP transverse joint faulting data was investigated for both doweled and undoweled LTPP sections. The results showed that doweled sections with k-values in the < 40.75 kPa/mm category had slightly more faulting than those with larger k-values. The undoweled sections appeared to have the opposite trend, with the sections with k-values ≥ 40.75 kPa/mm experiencing more faulting.

This, however, does not appear to be significant and may require further statistical analysis. Figure 16 contains plots showing the influence of k-value category on the faulting of JPCP and JRCP sections (all climatic regions are included). An analysis of the sensitivity of JPCP and JRCP transverse joint faulting data to subgrade k-value and climatic region was again limited by the lack of data in the dry-freeze and dry-nofreeze regions. However, both doweled and undoweled sections in the wet-freeze climatic region showed more faulting for those sections with k-values less than 40.75 kPa/mm.

Figure 17 contains plots showing the influence of subgrade k-value category and climatic region on the faulting of doweled and undoweled sections in the wet-freeze and wet-nofreeze climatic regions.

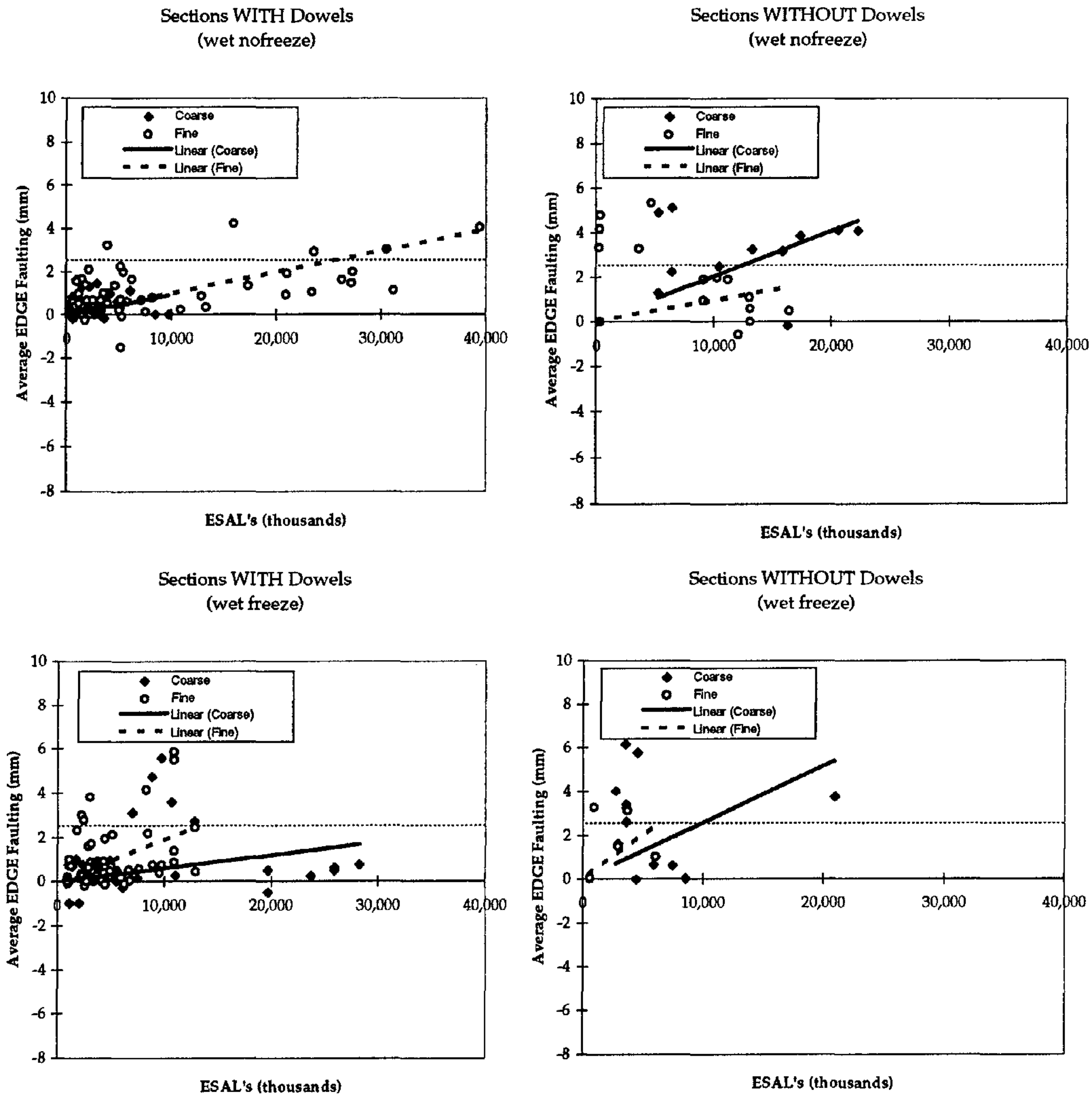


Figure 15. Plots showing the influence of subgrade type, dowels, and climate on faulting of JPCP and JRCP.

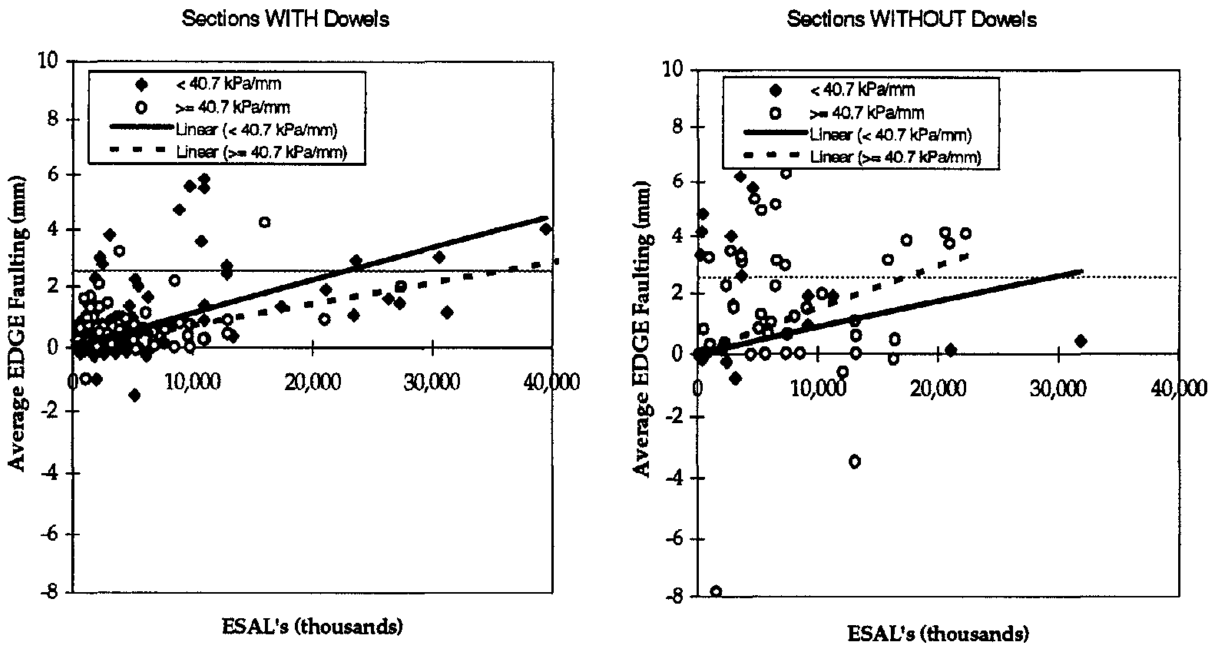


Figure 16. Plots showing the influence of k-value on the faulting of JPCP and JRCP.

Influence of Design Features

The Level 2 investigation involved analyzing the effect of several design features on faulting of doweled and nondoweled jointed PCC pavements, namely, slab thickness, joint spacing, presence of edge drains, base type, PCC elastic modulus, presence of widened lanes, outside shoulder type, and joint sealant type. The variables were divided into the following categories for investigation:

- Slab thickness.
- Joint spacing.
- Presence of edge drains.
- Base type.
- PCC elastic modulus.
- Presence of widened lanes.
- Outside shoulder type.
- Joint sealant type.

Effect of Slab Thickness

A Level 2 analysis of the effects of slab thickness on transverse joint faulting involved separating the JPCP and JRCP doweled and undoweled sections into two different slab thickness categories (thickness < 250 mm and $\geq$ 250 mm).

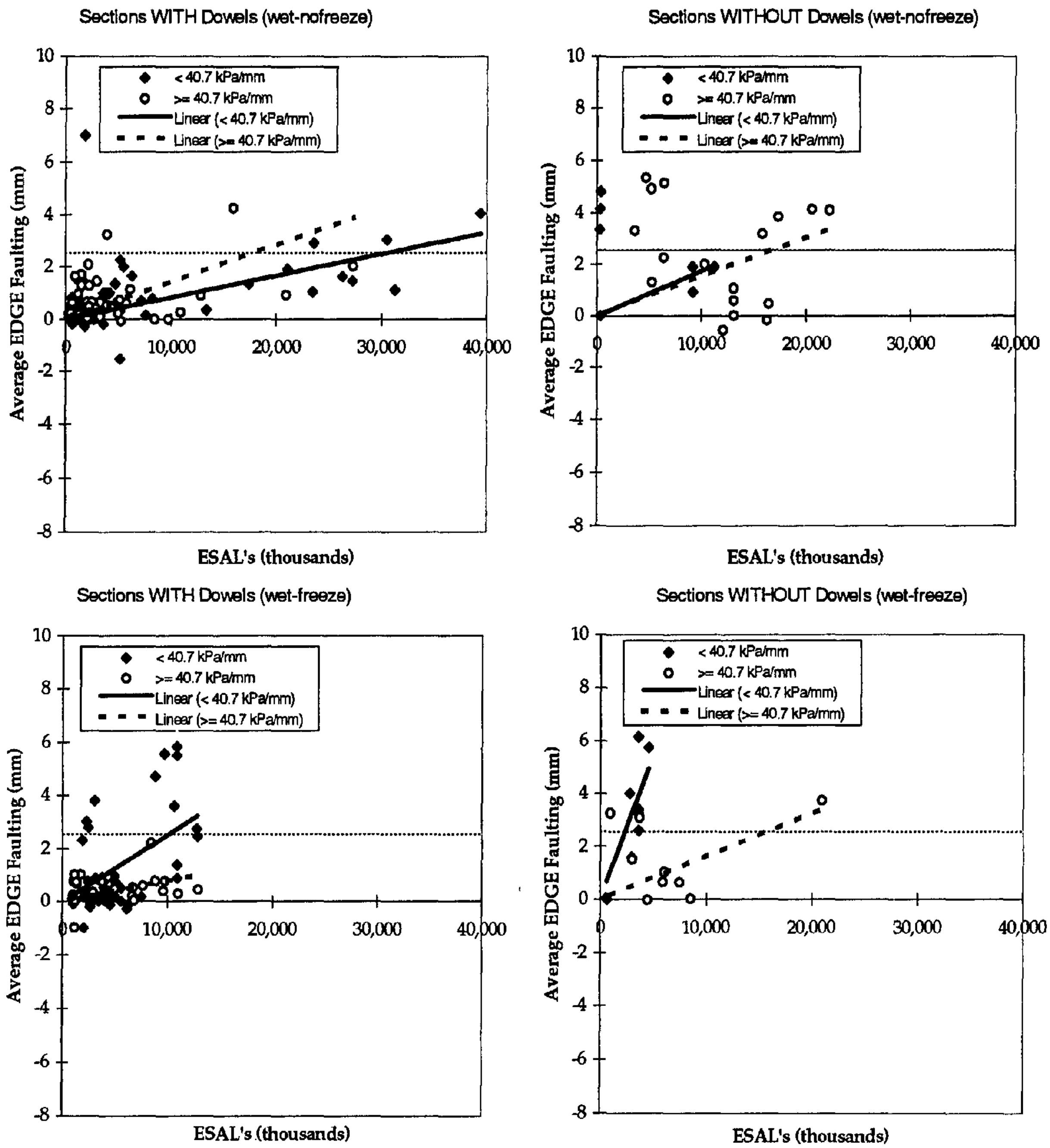


Figure 17. Plots showing the influence of k-value, dowels, and climate on the faulting of JPCP and JRCP.

The data showed that faulting was not influenced greatly by slab thickness. The doweled sections with slab thickness ≥ 250 mm showed slightly more faulting than the thinner sections, while the linear regressions fit through the undoweled sections showed no difference in the faulting between the sections in each thickness category. Figure 18 contains plots showing the influence of slab thickness category and presence of dowels on the faulting of JPCP and JRCP LTPP sections (all climatic regions are included).

An analysis of the sensitivity of doweled and undoweled transverse joint faulting data to thickness category and climatic region was limited by the lack of data in some regions. There were not enough data to make any statements about trends in the dry-nofreeze region (doweled and undoweled sections) or the doweled sections in the dry-freeze region. The data that were available showed that thickness level did not have a significant influence on the faulting of undoweled pavements in the dry-freeze region or doweled and undoweled pavements in the wet-nofreeze region.

Doweled pavements in the wet-freeze region showed more faulting for thicker pavements, and the undoweled pavements in this region showed slightly more faulting for the thinner sections. Figure 19 contains plots showing the influence of thickness category and climatic region on the faulting of undoweled JPCP and JRCP LTPP sections. Figure 20 contains plots showing the influence of thickness category and climatic region on the faulting of doweled JPCP and JRCP LTPP sections.

Average Transverse Joint Spacing

The influence of two different average transverse joint spacing levels (joint spacing ≤ 4.6 m and > 4.6 m) on JPCP transverse joint faulting was investigated for both doweled and undoweled LTPP sections. The data showed that faulting was generally higher for both doweled and undoweled sections in the category where joint spacing was < 4.6 m. Figure 21 contains plots showing the influence of joint spacing category on the faulting of doweled and undoweled JPCP LTPP sections (all climatic regions are included).

Available data showed that doweled sections with joint spacing ≤ 4.6 m generally exhibited more faulting than those sections with longer joint spacing in the wet-freeze and wet-nofreeze regions. No consistent trends were identified between climatic regions for the available undoweled JPCP LTPP sections. These data showed that faulting was greater for the JPCP sections with joint spacing ≤ 4.6 m in the wet-freeze region, but the opposite was true in the dry-freeze and wet-nofreeze regions, where the sections with longer joint spacing exhibited more faulting. Figures 22 and 23 contain plots showing the influence of joint spacing category and climatic region on the faulting of doweled and undoweled JPCP LTPP sections, respectively.

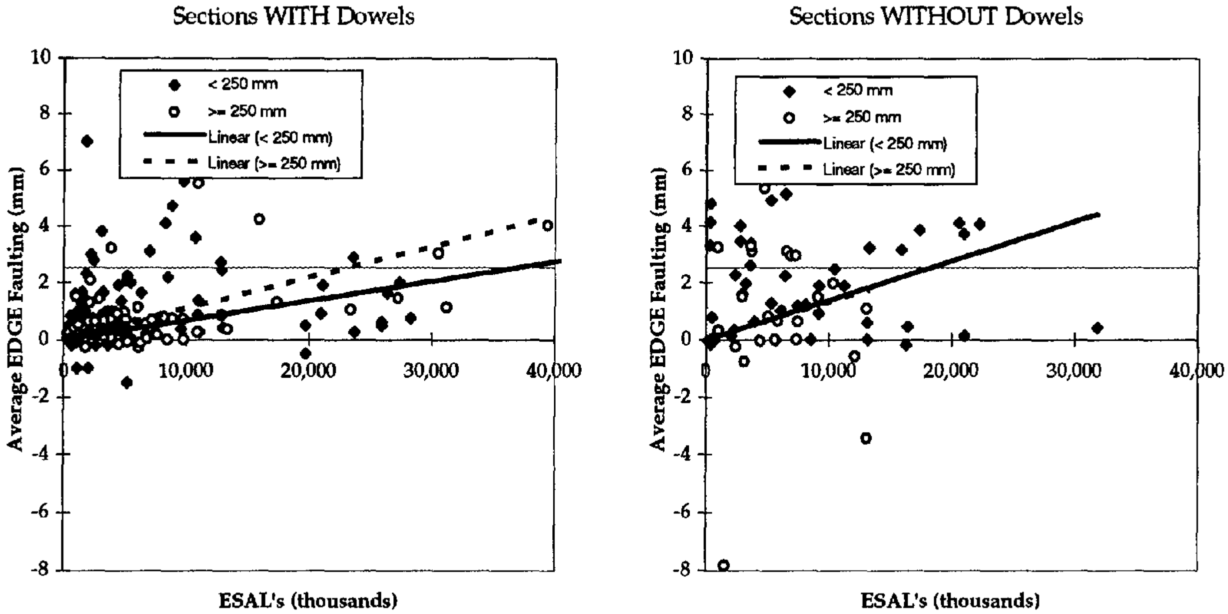


Figure 18. Plots showing the influence of thickness and dowels on faulting of JPCP and JRCP.

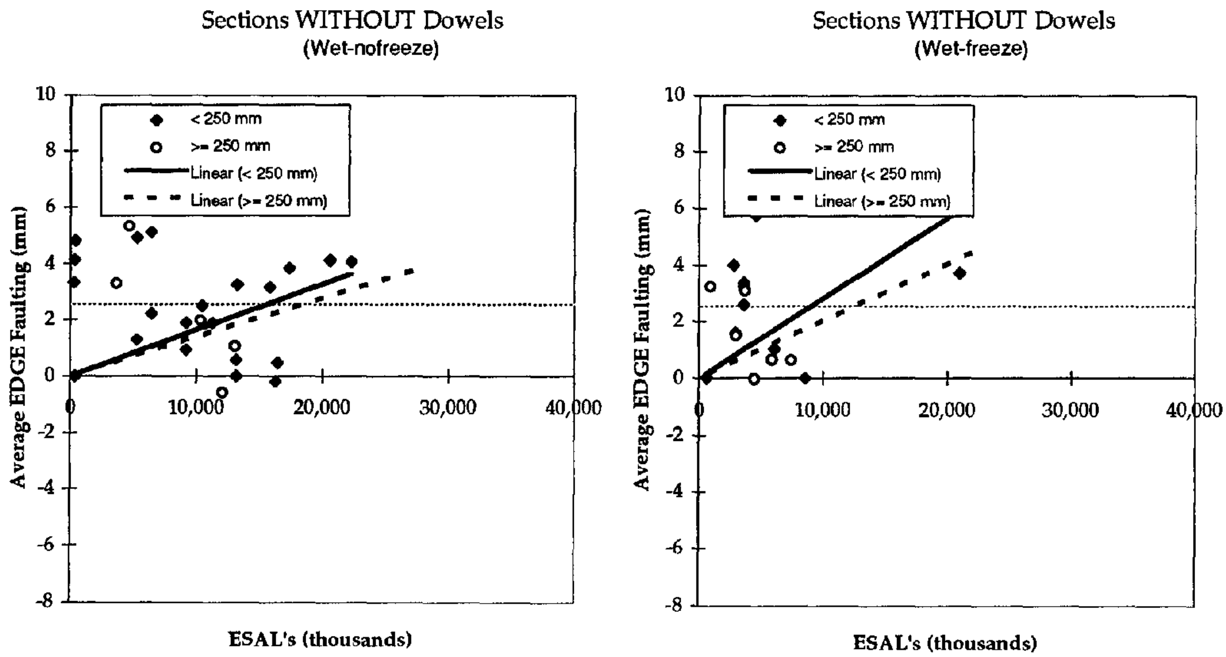


Figure 19. Plots showing the influence of thickness and climate on the faulting of undoweled JPCP and JRCP.

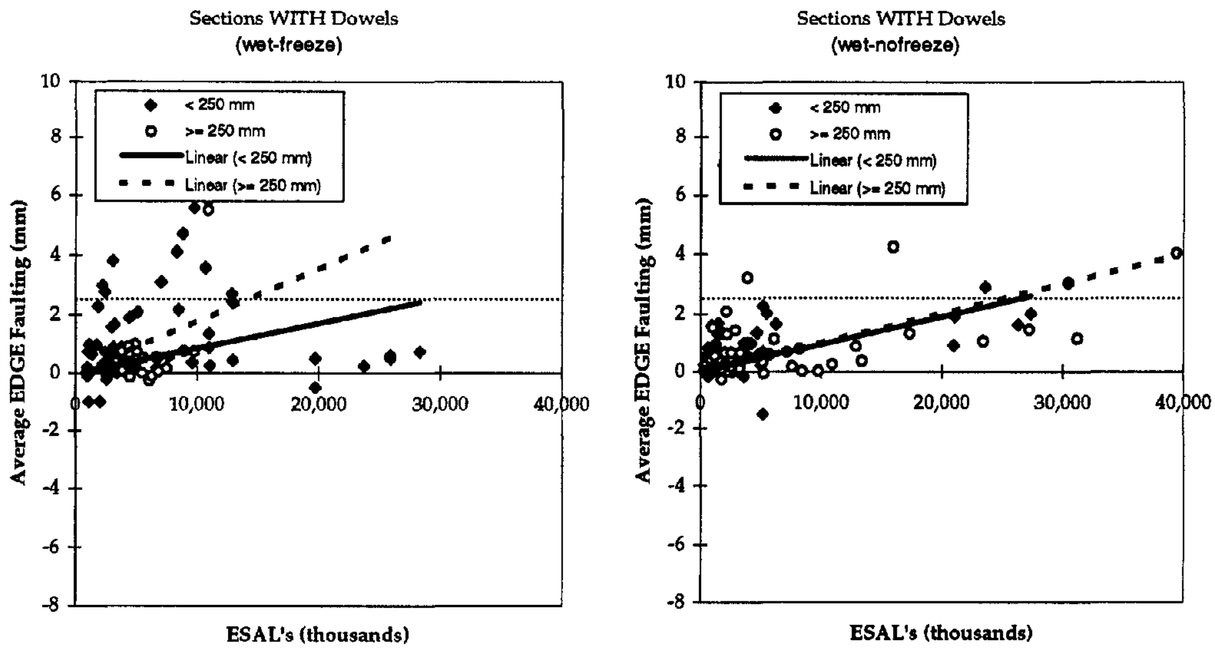


Figure 20. Plots showing the influence of thickness and climate on the faulting of doweled JPCP and JRCP.

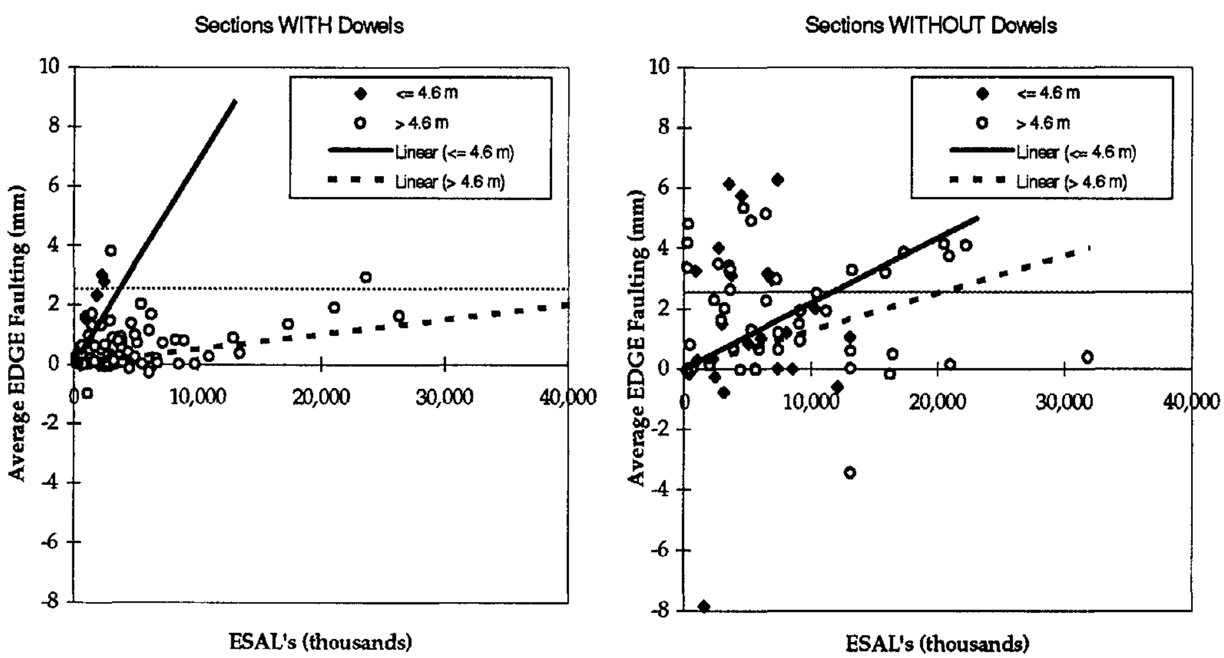


Figure 21. Plots showing the influence of joint spacing on the faulting of doweled and undoweled JPCP.

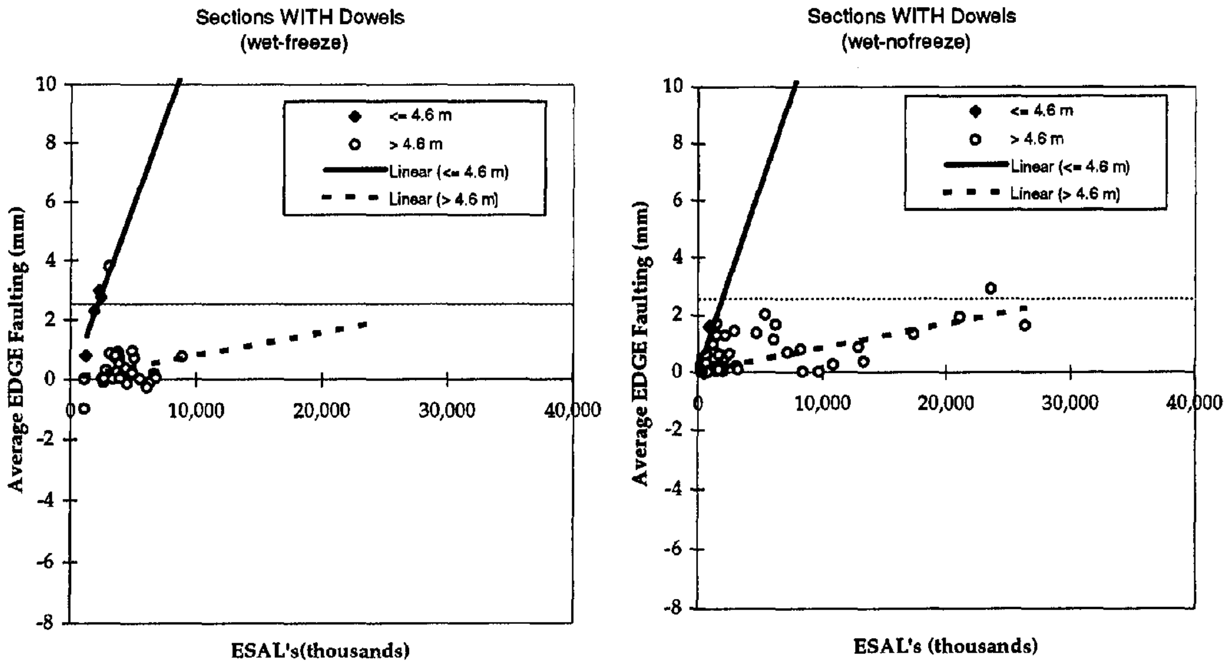


Figure 22. Plots showing the influence of joint spacing and climate on faulting of doweled JPCP.

Effect of Presence of Edge Drains

The presence of edge drains had no effect on the development of transverse joint faulting for doweled or undoweled JPCP and JRCP LTPP sections. However, a visual inspection of the data showed that the majority of high faulting data points came from sections without edge drains, as expected (see figure 24). An analysis of the sensitivity of transverse joint faulting data to the presence of edge drains and climatic region was conducted. No analysis could be made about the influence of edge drains in the dry regions because they lacked enough data. Edge drains had virtually no effect on the doweled sections in the wet-freeze or wet-nofreeze regions. However, a visual inspection of the data showed that the undoweled sections without edge drains in these regions exhibited more faulting than those sections constructed with edge drains. Figure 25 contains plots showing the influence of edge drains and presence of dowels on the faulting of JPCP and JRCP LTPP sections in the wet-freeze and wet-nofreeze regions.

Effect of Base Type

The influence of two different base type categories (granular and stabilized) on JPCP and JRCP transverse joint faulting data was investigated for both doweled and undoweled LTPP sections. The data showed that faulting was generally higher for

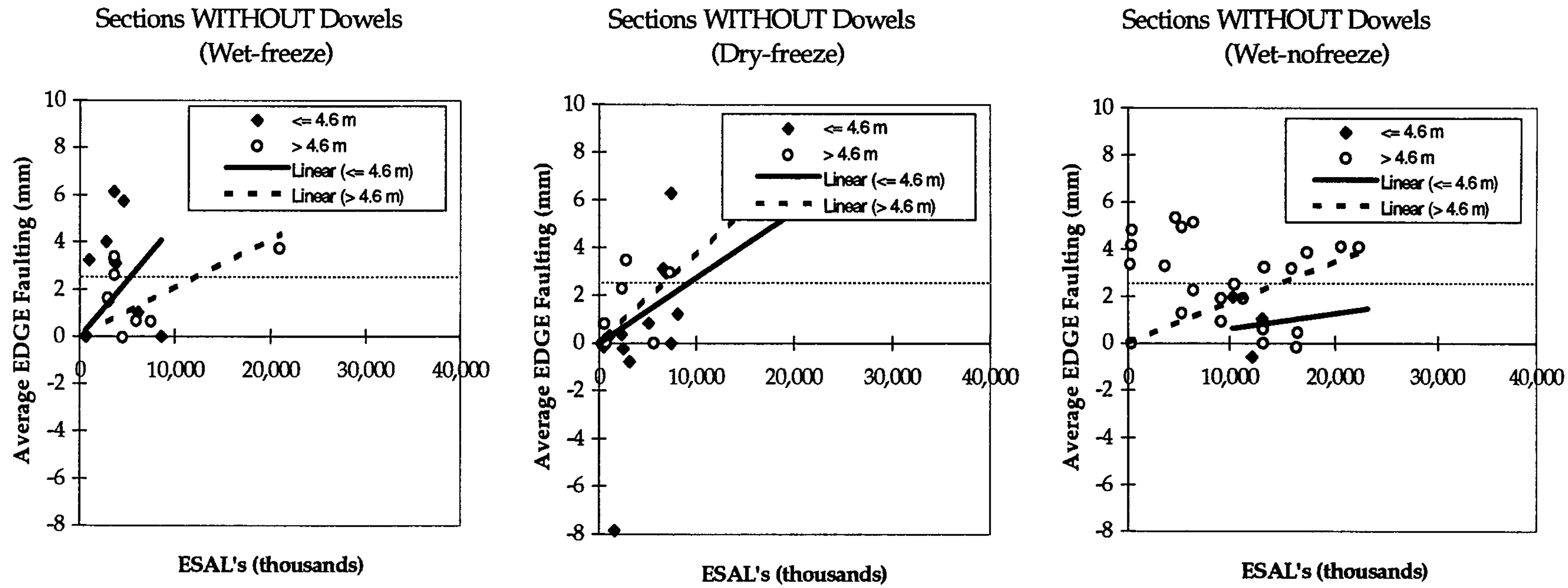


Figure 23. Plots showing the influence of joint spacing and climate on faulting of undoweled JPCP.

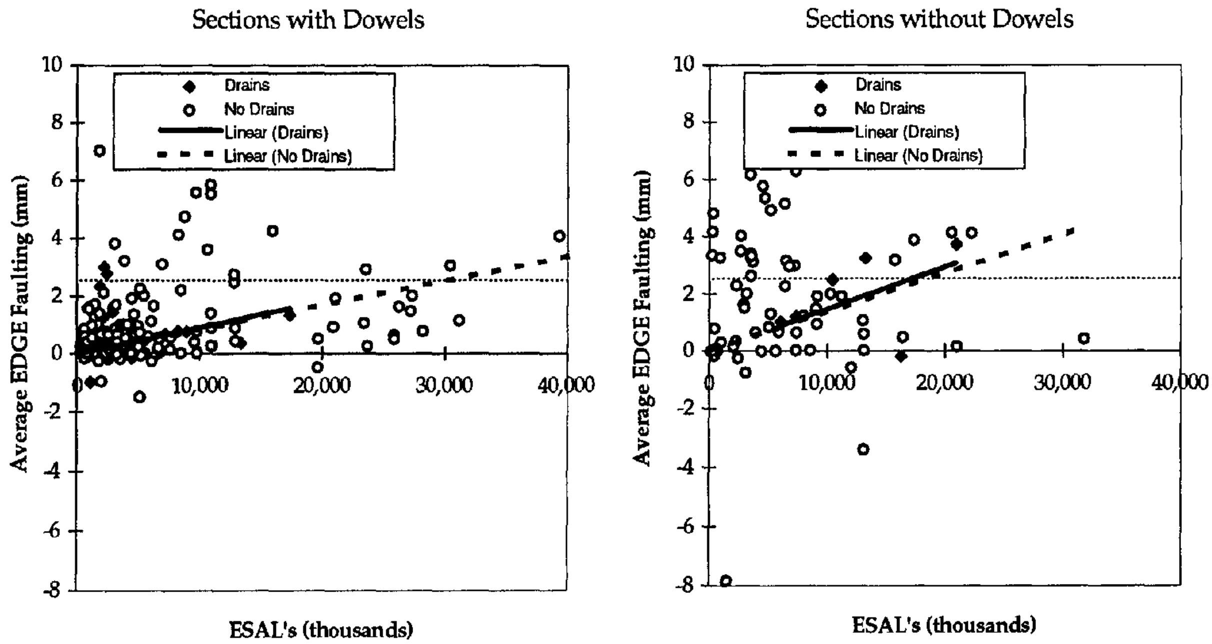


Figure 24. Plots showing the influence of edge drains on faulting of dowel and undoweled JPCP and JRCP sections.

doweled and undoweled sections with granular base types. The difference appears to be more dramatic for undoweled sections, as expected. These conclusions are supported by linear trends and visual inspections of the data shown in figure 26.

An investigation of the influence of base type category and climatic region on the transverse faulting of JPCP and JRCP sections was completed for the available LTPP data. For the doweled sections, base type category was found to have no significant influence on development of transverse joint faulting in the wet-freeze or wet-nofreeze climatic regions. No conclusions could be made about the doweled sections in the dry climatic regions due to insufficient data. For the undoweled sections, base type category did not appear to have a significant influence on faulting in the dry-freeze or wet-nofreeze climatic regions. It did, however, appear to show a trend for the undoweled sections in the wet-freeze region.

For this region, sections with granular base types appeared to exhibit more faulting than those with stabilized base types. No conclusions were made about the undoweled sections in the dry-nofreeze region because of insufficient data. Figures 27 and 28 contain plots showing the influence of base type category and climatic region on the faulting of doweled and undoweled sections, respectively.

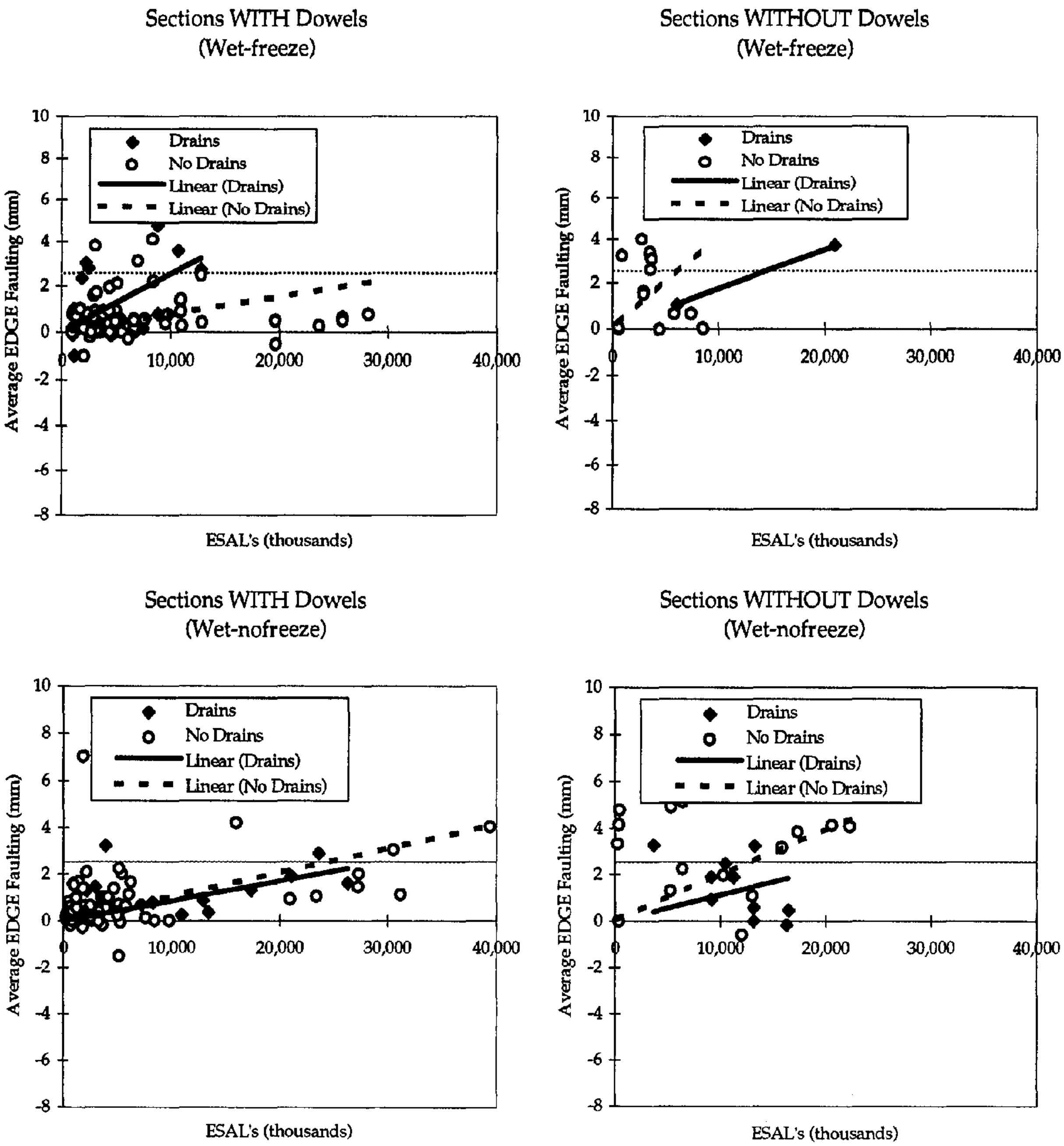


Figure 25. Plots showing the influence of dowels and climate on JPCP and JRCP faulting in wet-freeze and wet-nofreeze regions.

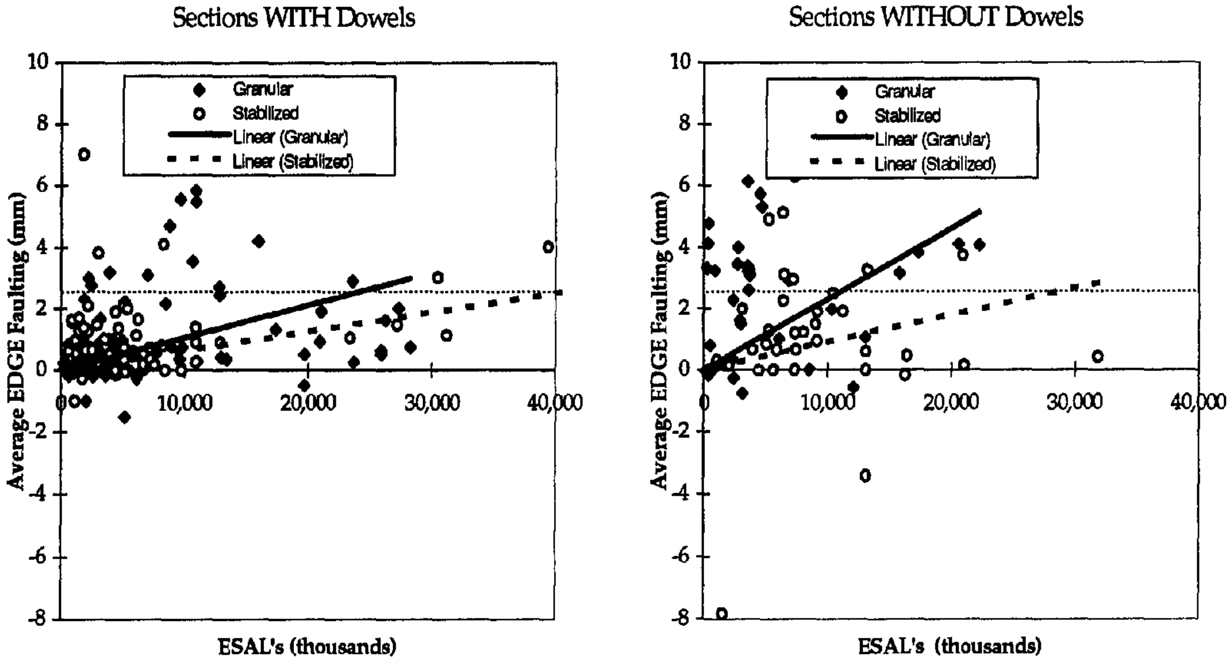


Figure 26. Plots showing the influence of base type and dowels on faulting of JPCP and JRCP.

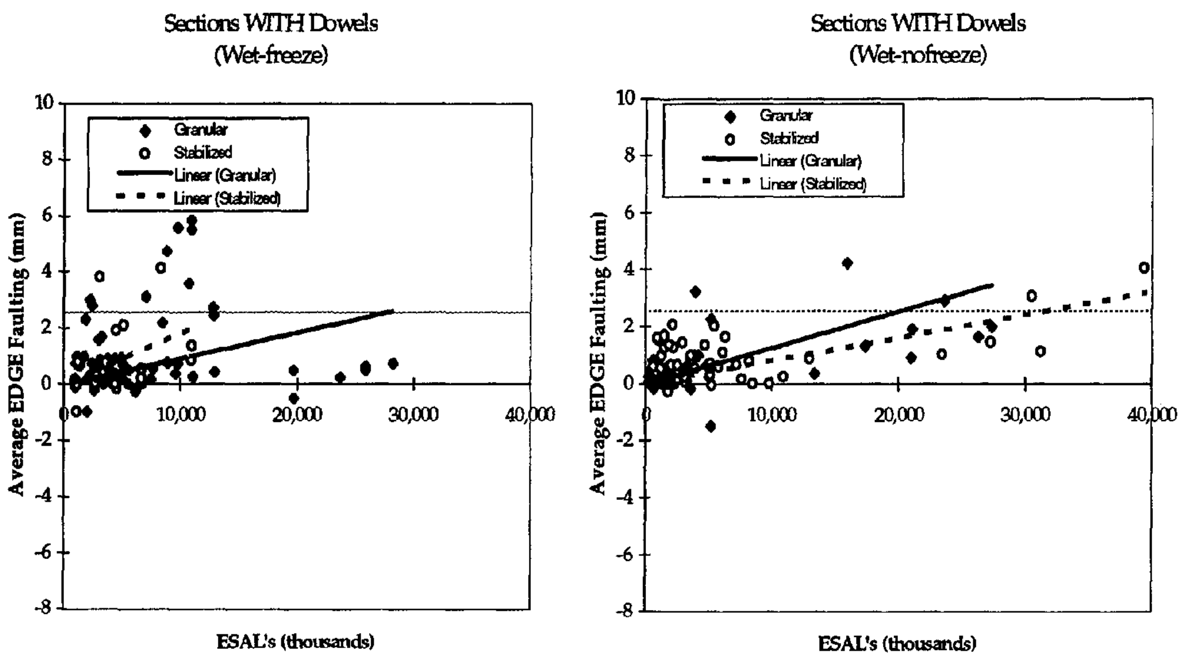


Figure 27. Plots showing the influence of base type and climatic region on faulting of doweled JPCP and JRCP sections.

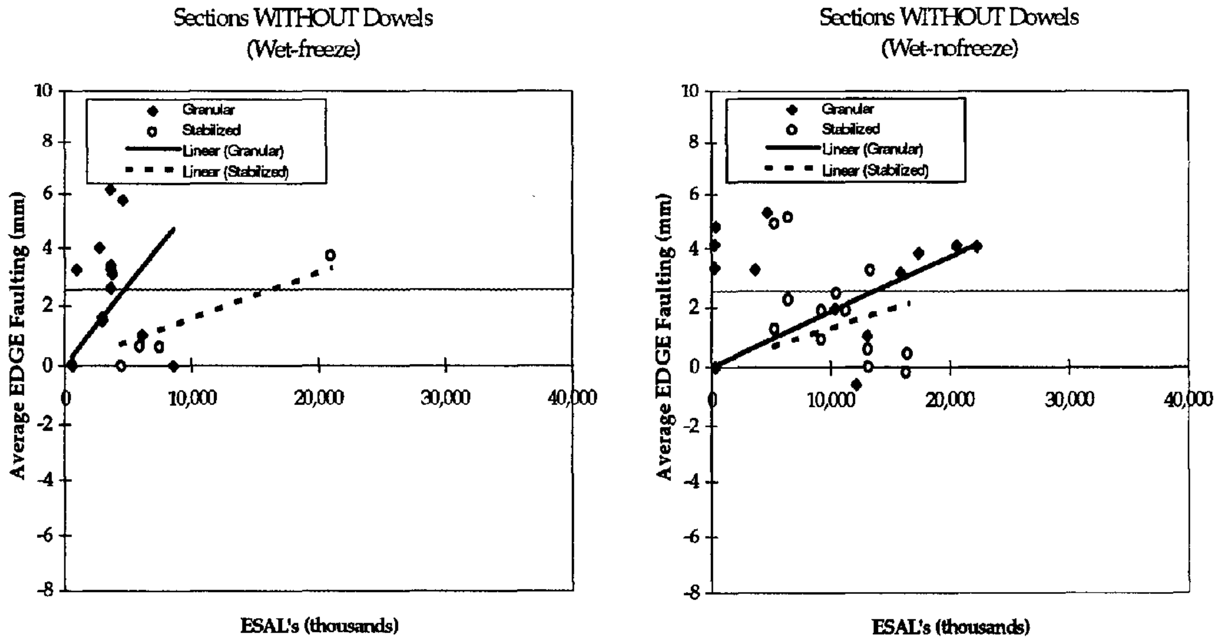


Figure 28. Plots showing the influence of base type and climatic region on faulting of undoweled JPCP and JRCP sections.

Effect of PCC Elastic Modulus

The influence of two different PCC elastic modulus (laboratory-measured) levels (E_{PCC} < 27.6 MPa and ≥27.6 MPa) on JPCP and JRCP transverse joint faulting data was investigated for both doweled and undoweled LTPP sections. The linear trends through the data showed that faulting was generally higher for sections where the PCC elastic modulus was in the higher category ($E_{PCC} \geq$ 27.6 MPa). A visual inspection of the data appeared to show that this impact was greater for the doweled than the undoweled sections. Figure 29 shows the influence of PCC elastic modulus category on faulting of doweled and undoweled JPCP and JRCP.

Presence of Widened Lane (Lane Width)

The influence of two different lane width categories (lane width = 3.6 m and ≥ 3.6 m) on JPCP and JRCP transverse joint faulting was investigated for both doweled and undoweled sections. The data showed that faulting was generally less for those doweled and undoweled sections with widened lanes. Figure 30 contains plots showing the influence of lane width category on the faulting of doweled and undoweled JPCP and JRCP.

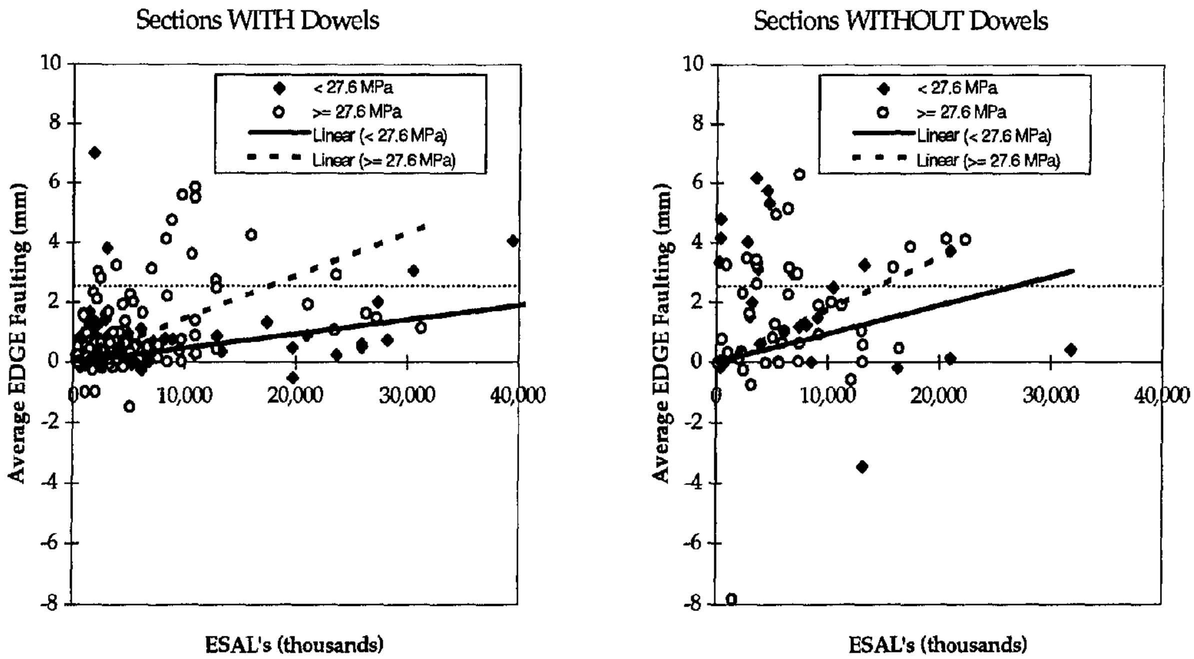


Figure 29. Plots showing the influence of PCC elastic modulus on faulting of doweled and undoweled JPCP and JRCP (all climatic regions included).

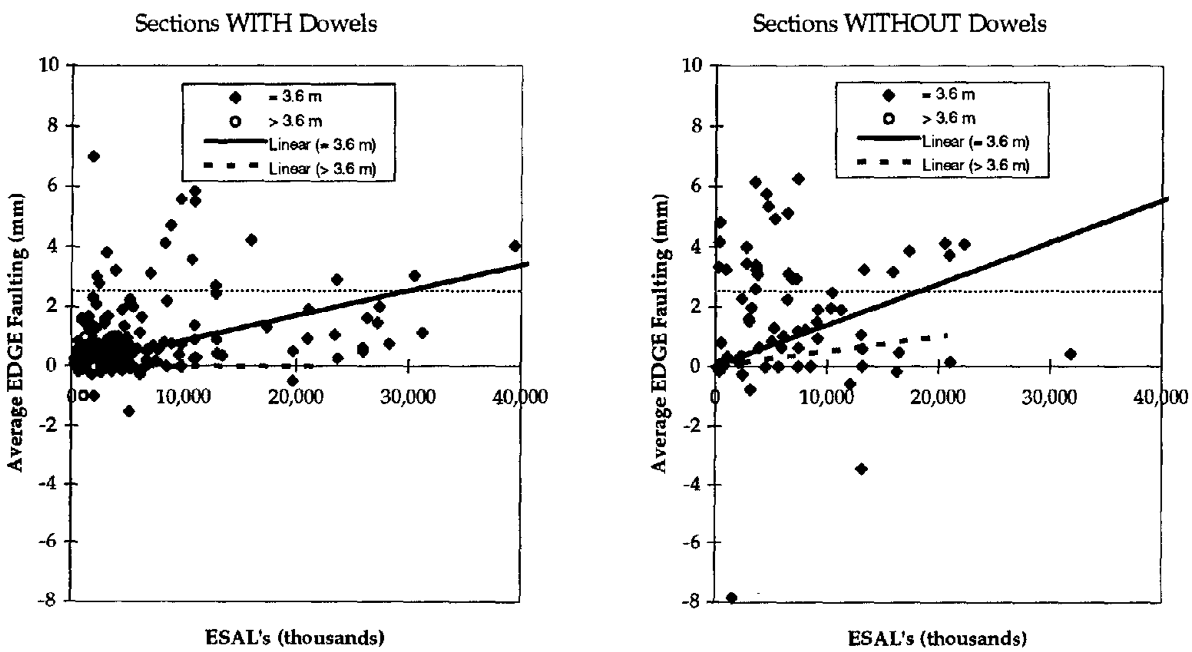


Figure 30. Plots showing the influence of lane width on faulting of doweled and undoweled JPCP and JRCP sections.

Effect of Outside Shoulder Type

The influence of two different outer shoulder types (PCC and non-PCC) was investigated for both doweled and undoweled JPCP and JRCP LTPP sections. The linear trends through the doweled section data showed that faulting was generally higher for the sections with non-PCC shoulder types, as expected. The opposite trend was observed for the undoweled LTPP sections. Undoweled LTPP sections with PCC shoulders developed more faulting on average than those undoweled sections with non-PCC shoulders. Figure 31 contains plots showing the influence of outside shoulder type category on the faulting of doweled and undoweled JPCP and JRCP LTPP sections (data from all climatic regions are included).

Effect of Transverse Joint Sealant

Linear trends suggest that greater transverse joint faulting developed for doweled sections with unsealed joints and undoweled sections with sealed joints. For both cases, the difference between sealed and unsealed joints did not appear to be that significant. Figure 32 contains plots showing the influence of joint sealant on the faulting of doweled and undoweled JPCP and JRCP LTPP sections (data from all climatic regions are included). An analysis of the sensitivity of transverse joint faulting data to the presence of joint sealant and climatic region did not reveal any clear trends because of the lack of data in many regions.

Effect of Joint Sealant Type

The investigation of the influence of joint sealant type showed that the majority of the doweled sections with large faulting values were from sections with asphalt or rubberized asphalt joint sealant. These trends hold true for both the wet-freeze and wet-nofreeze climatic regions (limited data were available for the sections in the regions with dry conditions). No obvious trends of the faulting of the undoweled sections on the basis of joint sealant could be determined for the data in all climatic regions.

However, a breakdown of the data by climatic region showed that the majority of the high faulting values experienced by undoweled sections in the wet-freeze region were from sections with asphalt or rubberized asphalt joint sealant. The majority of the high faulting values experienced by undoweled sections in the wet-nofreeze region were from sections with a preformed joint sealant. Figure 33 contains plots showing the influence of joint sealant type on the faulting of doweled and undoweled JPCP and JRCP LTPP sections (data from all climatic regions are included).

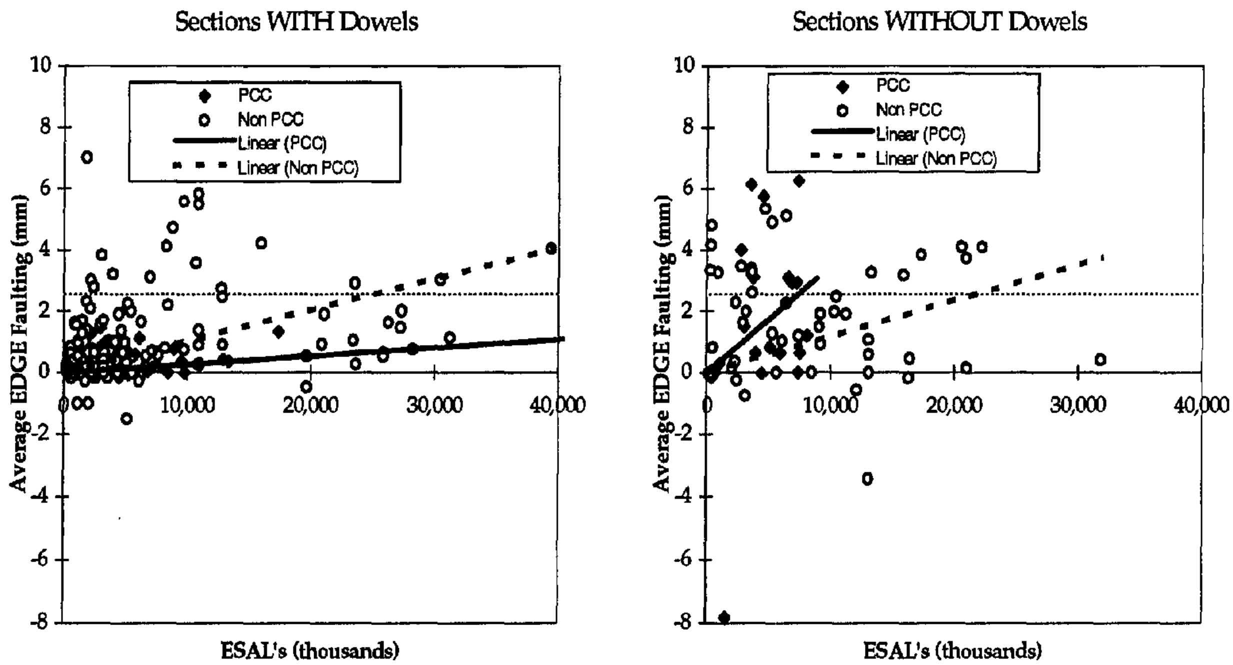


Figure 31. Plots showing the influence of shoulder type on faulting of doweled and undoweled JPCP and JRCP.

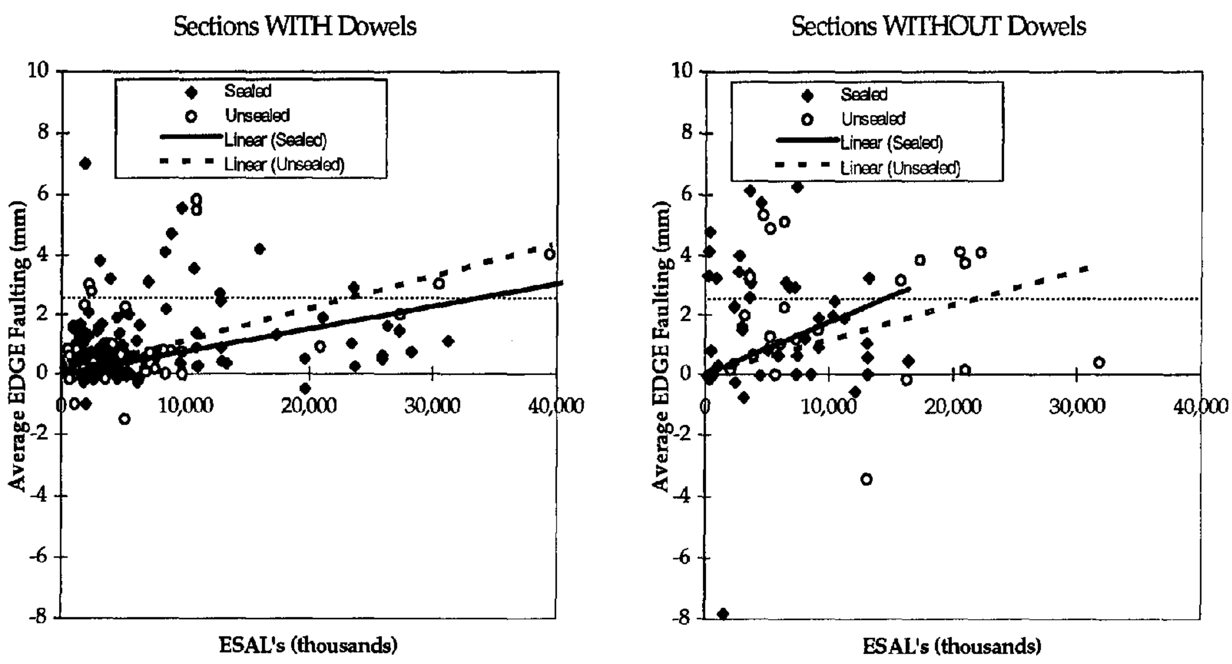


Figure 32. Plots showing the influence of joint sealant on faulting of doweled and undoweled JPCP and JRCP.

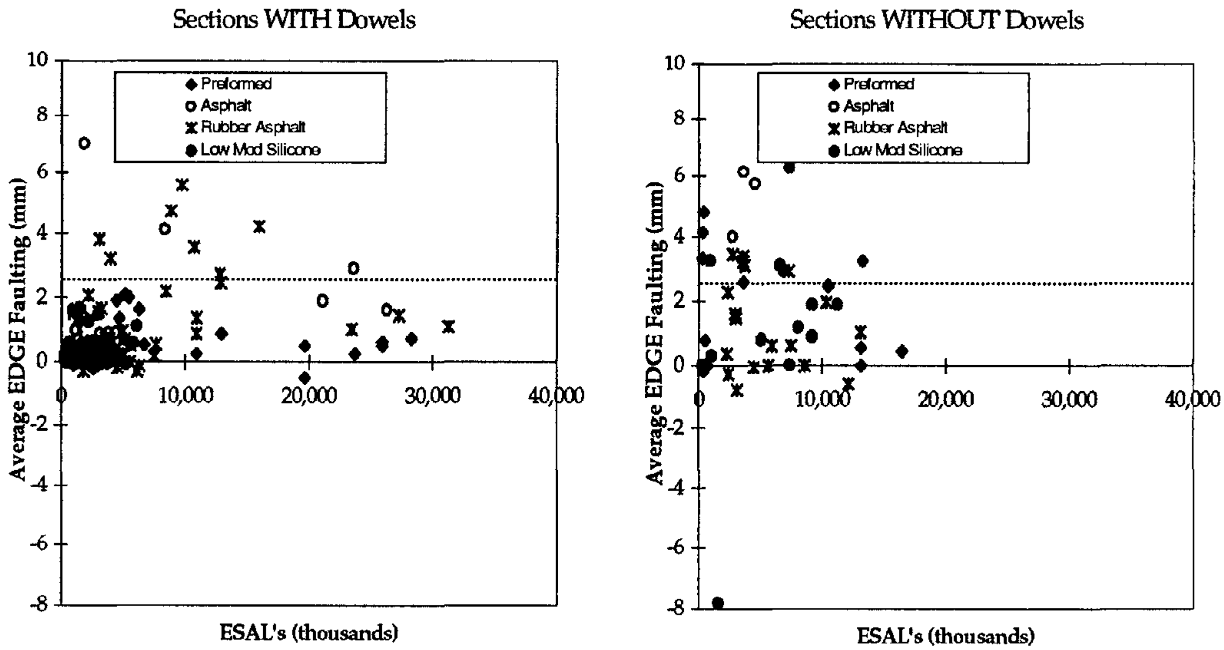


Figure 33. Plots showing the influence of joint sealant type on faulting of doweled and undoweled JPCP and JRCP.

Figure 34 contains plots showing the influence of joint sealant type and climatic region on the faulting of doweled and undoweled JPCP and JRCP LTPP sections.

Influence of Construction Practices

The Level 2 investigation involved analyzing the effect of the two main construction practices that influence faulting, transverse joint forming method and dowel placement method. The data available for this stage of the analysis were limited. Therefore, more data will be required for further analysis. Using the data available currently, the results of the bivariate analysis are as follows.

Effect of Transverse Joint Forming Method

The influence of transverse joint forming method on the development of faulting was investigated for doweled and undoweled pavements. Three different joint forming methods were observed for the available LTPP data—plastic insert, metal insert, and sawed. For the doweled sections, a comparison of metal inserts to sawed joints showed that more faulting developed for those sections constructed using metal inserts. The analysis of the undoweled sections showed that those sections with plastic inserts exhibited significantly less faulting than those with sawed joints.

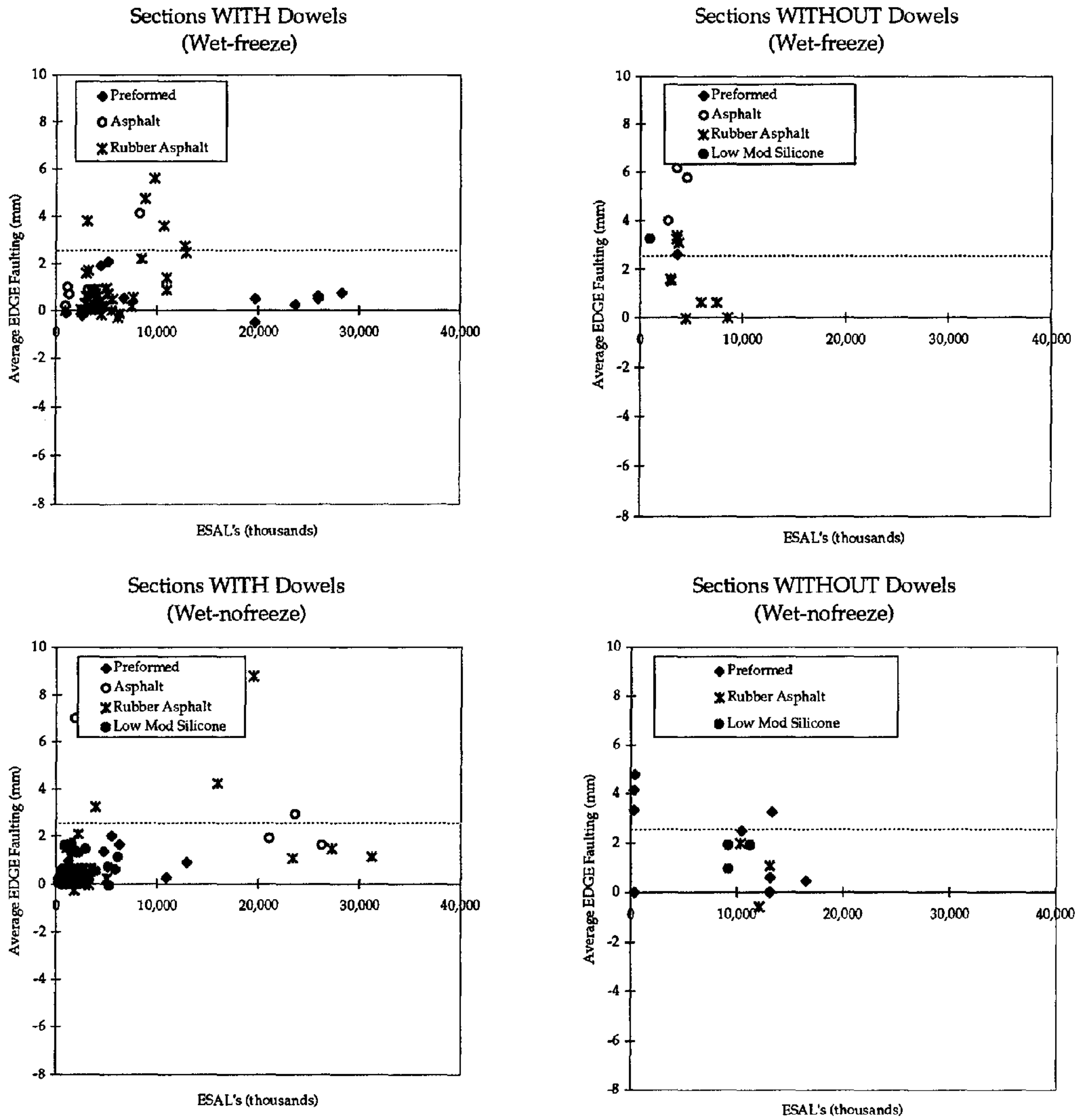


Figure 34. Plots showing the influence of joint sealant type and climatic region on the faulting of doweled and undoweled JPCP and JRCP.

A secondary analysis of the influence of climatic region on these data sets was not completed due to insufficient data. Figure 35 contains plots showing the influence of transverse joint forming method and presence of dowels on the transverse joint faulting of JPCP and JRCP LTPP sections (data from all climatic regions were included).

Effect of Dowel Placement Method

The influence of dowel placement method on the development of transverse joint faulting was also investigated for doweled (JPCP and JRCP) pavements. Two different dowel placement methods were observed for the available LTPP data—baskets and inserted using a mechanical dowel bar inserter. The data showed that those sections in which the dowels were mechanically inserted exhibited significantly more joint faulting (on average) than those placed using traditional baskets. Most of the data used for this analysis were for pavements built over 10 years ago. It is possible to obtain different results from pavement built recently using newer dowel bar inserter equipment. Figure 36 contains a plot showing the influence of dowel placement method on the transverse joint faulting of doweled JPCP and JRCP LTPP sections (data from all climatic regions were included).

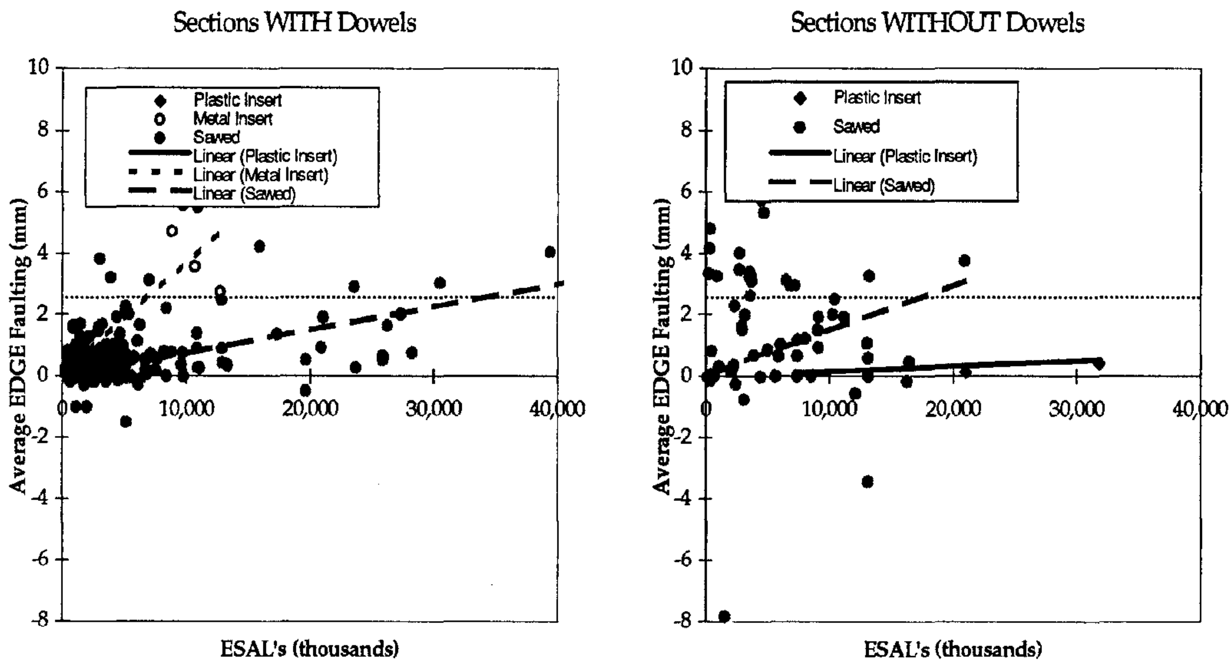


Figure 35. Plots showing the influence of transverse joint forming method and dowels on the transverse joint faulting of JPCP and JRCP.

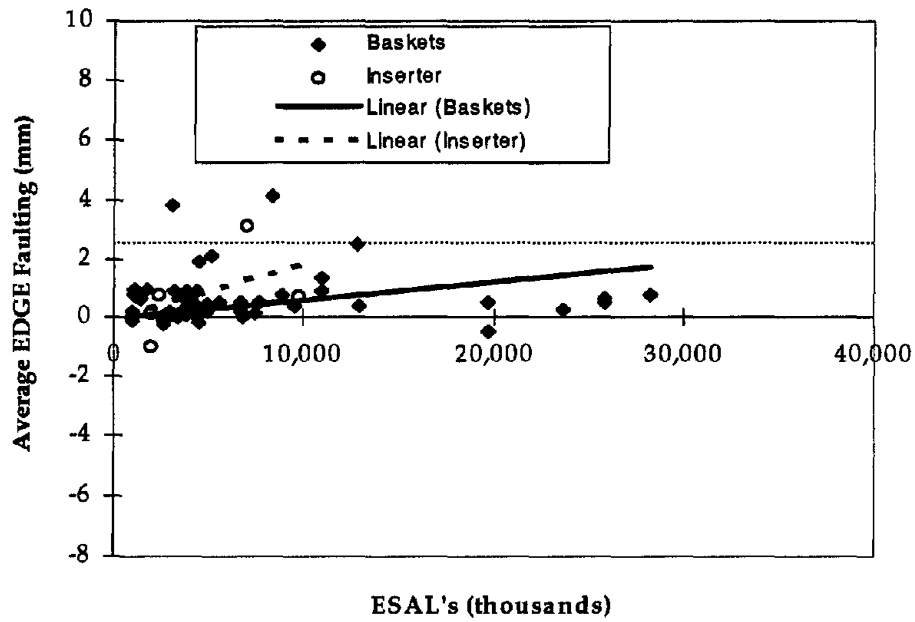


Figure 36. Plot showing the influence of dowel placement method on transverse joint faulting of JPCP and JRCP.

Canonical Discriminant Analysis for Faulting

Canonical Functions

The canonical functions were developed using the SAS statistical software.[5,6,7,8] Following are two canonical variables, CANF1 and CANF2, developed and used to classify pavements according to performance:

$$\text{CANF1} = -0.032\text{MINT} + 0.154\,\text{STYP} - 1.02\,\text{SKEW} - 1.35\text{WET} - 0.57 + 0.004\text{DRAIN} + 0.0074\text{RLS} + 0.04\text{DOW} + 0.0011\text{KVAL} \quad (1)$$

$$\text{CANF2} = 0.016\text{MINT} + 0.03\text{STYP} + 0.27\text{SKEW} + 2.15\text{WET} + 0.288 - 0.437\text{DRAIN} + 0.004\text{RLS} - 0.07\text{DOW} + 0.011\text{KVAL} \quad (2)$$

where

MINT = annual average minimum temperature, °C
STYP = shoulder type, 1 = rigid, 0 = others
SKEW = skew joint, presence = 1, 0 = otherwise

WET	=	wet region, wet = 1, 0 = otherwise
DRAIN	=	presence of drain, present =1, 0 = otherwise
RLS	=	radius of relative stiffness, mm
DOW	=	dowel bar diameter, mm
KVAL	=	modulus of subgrade reaction, kPa/mm

The mean values of CANF1 and CANF2 for the expected, below, and above expected categories are given in table 5. A plot of CANF1 versus CANF2 for each observation of the data used in the analysis is shown in figure 37. The plot clearly demarcates the areas (CANF1, CANF2) where the pavements in the different performance categories are located. This is in agreement with the mean values of the canonical variables for the different categories. The areas of the pavement performance categories are summarized as follows:

- The canonical variable CANF1 was greater than 0.5 for pavements classified as performing above expectation.
- The canonical variable CANF1 was less than 0.5 for pavements classified as performing as expected or below expectation.

Summary

The results of the canonical discriminant analysis show that CANF1 is a canonical variable that distinguishes between pavements performing above expectation and the other performance categories. An in-depth look at the canonical function for predicting CANF1 shows that the function is generally in agreement with engineering principles and past studies. Pavements with higher CANF1 values tend to perform better in faulting than those with smaller CANF1 values. An increase in the minimum temperature, the use of skewed joints, and pavements located in wet environments decrease pavement performance, while the use of rigid shoulders, a higher radius of relative stiffness, dowels, and a higher modulus of subgrade reaction results in higher CANF1 values and, hence, better performing pavements.

Table 5. Class means for canonical variables CANF1 and CANF2.

Category	CANF1	CANF2
Expected	-0.64	-0.8
Below Expectation	-0.80	1.56
Above Expectation	2.12	0.09

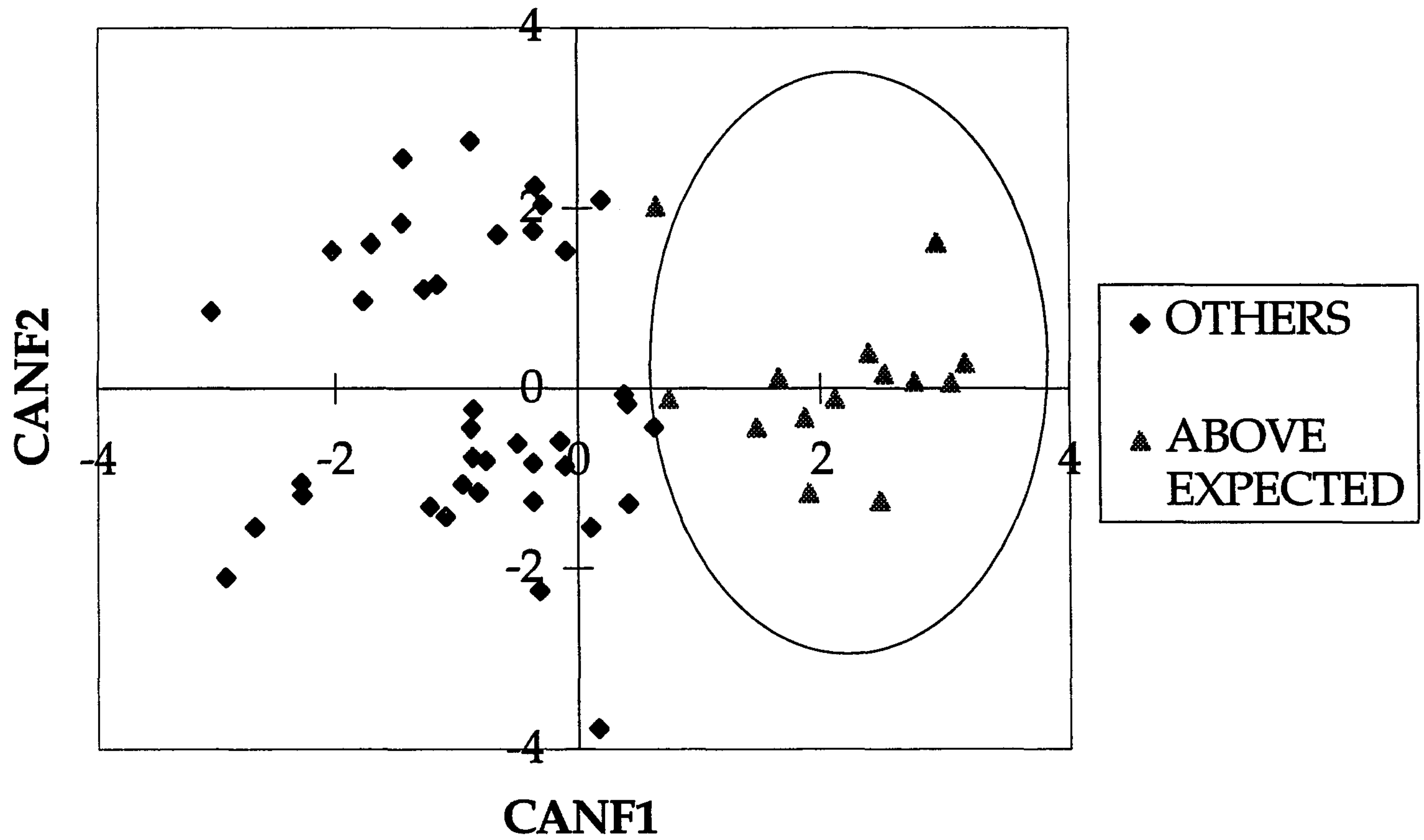


Figure 37. A plot of CANF1 versus CANF2 for each observation.

Also, pavements located in dry regions or pavement in wet regions with adequate drainage facilities experienced less faulting. All these trends are reasonable and are in agreement with past research results.

Analysis of Variance for JPCP Faulting

A comprehensive analysis of variance was performed to determine the effect and significance of each design feature and site condition variable on faulting. The ANOVA procedure was also used to compute the mean faulting for each design feature and site condition used in the ANOVA. The mean faulting was calculated for the different classification levels of each variable. Multiple comparison test of the means (Duncan's Test) was then used to determine if there were significant differences between the mean faulting distress levels for the different classes of a given design feature or site condition variable. Table 6 is a summary of the analysis of variance Duncan's multiple range test results. Table 6 shows clearly the variables that have a significant effect on faulting. Table 7 is a summary of variables that, though not significant, show quite a difference in mean faulting values for different class levels and thus potentially could affect faulting in more carefully controlled experiments. The effects of the variables are discussed in the next few sections.

Influence of Site Conditions

Effect of Annual Number of Wet Days

The results presented in table 6 show that pavements located in areas with a high number of wet days are more likely to experience faulting. This is in agreement with past studies that have shown that pumping of the underlying pavement materials is directly related to excess moisture in the pavement and is a major cause of erosion and faulting. Pavements located in such areas will need to be designed with materials that are less susceptible to erosion, such as stabilized permeable bases or high-quality stabilized bases.

Effect of Subgrade Type

The ANOVA results showed that even though the difference in measured faulting for pavements with fine or coarse subgrade was not significant, pavements with coarse subgrades experienced less faulting than pavements with fine subgrades. Coarse subgrades in general provide greater permeability and therefore less free water available for erosion.

Table 6. Summary of analysis of variance results for faulting.

Variable	Classification	Faulting, mm	Duncan Class*	Significant Difference
Annual number of wet days	less than 100	0.02	A	Yes
	100 to 140	0.06	A	
	greater than 140	0.11	B	
Base elastic modulus, MPa	less than 690	0.073	A	Yes
	690 to 6900	0.09	A	
	greater than 6900	0.025	B	
Joint coefficient, J	less than 3.2	0.03	A	Yes
	greater than 3.2	0.07	B	
Presence of dowel	no dowels	0.08	A	Yes
	dowels	0.02	B	
Radius of relative stiffness, mm	less than 890	0.05	A	Yes
	890 to 1150	0.08	A	
	greater than 1150	0.03	B	
Drain	no edge drain	0.07	A	Yes
	edge drain	0.03	B	
Pavement type	JPCP on untreated	2.85	A	Yes
	JPCP on treated	1.4	B	
	JPCP on non-AC	0.97	C	
	JPCP over unbound	0.91	C	
	JPCP on AC treated	0.37	D	
Load transfer system	aggregate interlock	1.77	A	Yes
	Dowels	0.46	B	
Drainage coefficient, C_d	less than 1	0.084	A	Yes
	greater than 1	0.05	B	

* Duncan's multiple range test; those with the same letter are not significantly different.

Table 7. Summary of analysis of variance results for variables that potentially influence faulting.

Variable	Classification	Faulting, mm	Duncan Class*	Significant Difference
Wet	wet areas	0.075	A	No
	dry areas	0.044	A	
Base type	not stabilized	0.073	A	No
	stabilized	0.054	A	
Skew joints	no skew joint	0.08	A	No
	skew joints	0.061	A	
PCC thickness, mm	less than 240 mm	0.064	A	No
	greater than 240 mm	0.060	A	
Freeze	freeze areas	0.064	A	No
	no-freeze areas	0.060	A	
Subgrade type	fine	0.064	A	No
	coarse	0.060	A	
Joint forming method	sawed	1.10	A	No
	plastic insert	0.56	A	
Dowels placement method	other methods	1.72	A	Yes
	mechanically installed	0.68	B	
	preplaced on baskets	0.27	C	

* Duncan's multiple range test; those with the same letter are not significantly different.

Effect of Wet and Freeze Climates

The mean faulting values for pavements located in both wet and freeze areas show that pavements located in extreme climates tend to experience more faulting. This is a reasonable result, since an increase in precipitation generally corresponds to higher pumping and faulting. The ANOVA test also shows that pavements in areas with precipitation of more than 1 m experience more faulting than those in areas with precipitation less than 1 m. This again confirms the relationship between moisture and faulting. Pavements in areas with high rates of precipitation (greater than 1 m/yr) should be designed with adequate drainage facilities to reduce moisture damage.

Influence of Design Features

Effect of Base Modulus

Table 6 shows that pavements with a higher base elastic modulus experienced less faulting. This is because an increase in base modulus results in less deflections of the PCC slab joints. Stabilized bases have higher moduli than granular untreated bases, and lean concrete bases have higher moduli than PCC- or AC-treated bases.

Effect of the Presence of Dowels

The ANOVA results show clearly that pavements with dowels perform better than those without. Dowels provide load transfer across the joints of adjacent slabs, and load transfer reduces deflections at the joints.

Effect of Radius of Relative Stiffness

Table 6 shows that pavements with a higher radius of relative stiffness experienced less faulting. This is a reasonable result because it is known from mechanistic analysis that pavements with higher radius of relative stiffness values have less corner deflections and, thus, less pumping and faulting. The variable radius of relative stiffness is obtained from several design variables and is defined as follows:

$$\ell^4 = E*h^3 / [12*k(1-\mu^2)]$$

where

E = PCC elastic modulus, kPa
h = PCC thickness, mm
k = modulus of subgrade reaction, kPa/mm
μ = Poisson's ratio

The values of these design variables should be selected to increase the radius of relative stiffness, thereby increasing performance.

Effect of Drains and Drainage Coefficient

The ANOVA analysis shows that the provision of drains to a pavement generally reduces the occurrence and severity of faulting. This can be explained by the fact that adequate drainage reduces the amount of free water within the pavement structure, thereby reducing the potential for pumping and the erosion of underlying pavement materials. Providing a base material that enhances drainage also reduces faulting. This is shown by the fact that an increase in the pavement base drainage coefficient reduces faulting. The use of stabilized free draining bases should therefore reduce faulting.

Effect of Base Type

The ANOVA results showed that, even though the difference in measured faulting for pavements with or without stabilized bases was not significant, pavements with stabilized bases experienced less faulting than pavements with unstabilized bases. This is because stabilized bases are less erodible and reduce the potential of pumping.

Effect of Skewed Joints and PCC Thickness

The analysis shows that pavements with skewed joints experienced less faulting than those without. The use of skewed joints is a means of enhancing load transfer. This is true especially for JPCP with undoweled joints. It enhances load transfer because wheels of the same axle strike the joints at different times, reducing the impact of a given axle load on the joint. Pavements with thicker PCC slabs also experienced less faulting. Thicker PCC slab thickness increases the strength of the pavement, reducing deflections and, hence, pumping and faulting.

Effect of Pavement Type

The pavement types with slab placed directly on the subgrade material showed the highest amount of faulting. This is because subgrade materials in general tend to be weaker than base materials and other pavement material types. Past studies have shown that treated subgrades are not strong enough to prevent pumping. Also, subgrade materials tend to contain a higher percentage of fine material than base materials or stabilized materials, and this increases the potential for such materials to pump, resulting in faulting.

Effect of Load Transfer System

The ANOVA analysis shows that the best form of load transfer is through the use of dowels and not aggregate interlock. Pavements with aggregate interlock experienced a greater level of faulting than those without. This agrees with the ANOVA results for the effect of design features, which shows that pavements with dowels perform better than those with other kinds of load transfer devices.

Influence of Construction Practices

Results of the comprehensive ANOVA and Duncan's multiple comparison test are presented in tables 6 and 7. A summary of the significant construction variables that influence faulting are discussed in the next few sections.

Effect of Dowel Placement Method

The ANOVA analysis results show that pavements with dowels placed from preplaced baskets experience about a third of the faulting as do pavements with dowels placed mechanically. This may be due to the care taken by workmen in placing the dowels manually. As noted in earlier sections of this chapter, most of the data used for this analysis were for pavements built more than 10 years ago. It is possible to obtain different results from pavements built quite recently using newer dowel bar inserter methods and equipment.

Effect of Joint Forming Method

The pavements with joints formed by plastic insert experienced far less faulting than those with sawed joints. This may be due to the fact that sawing PCC slabs introduces weaknesses into the pavement structure.

Summary

Using univariate analysis (appendix A), bivariate analysis, canonical discriminant analysis, and ANOVA, the design and climatic variables that influence the occurrence and severity of faulting in JPCP have been analyzed. According to the results of the analysis, pavements with strong or stiff foundations tend to develop less faulting. This is shown by the fact that pavements with higher radius of relative stiffness and pavements constructed on coarse and stronger base material experience less faulting and therefore performed better. Also, the presence of dowels resulted in better performance because dowels enhanced load transfer and decreased deflections.

The analysis also showed that pavements located in climates with higher annual number of wet days and with extreme climate performed worse than did those in milder climates. These observations are reasonable and could serve as basic guidelines for pavement design and evaluation and for the prevention of faulting. Also, the canonical function CANF2 can be a useful tool in classifying newly designed pavements and to check preliminarily for adequate performance through the pavement's design life.

The construction features that influence faulting are all related to the pavement joint. The ANOVA result shows that the joint forming method, dowel placement method, and load transfer mechanism all influence faulting. Using the right methods of load transfer, such as dowels and joint formation, will therefore minimize or eliminate faulting and enhance performance.

4. EVALUATION OF SITE, DESIGN, AND CONSTRUCTION VARIABLES THAT INFLUENCE TRANSVERSE CRACKING

Introduction

The primary design features, climate, and site conditions that influence PCC transverse cracking were identified in appendix B. They include the site conditions of traffic, climate, and subgrade support, as well as the specific design features that are incorporated into pavements to reduce cracking, such as PCC slab thickness, the presence of dowels, and drainage facilities.

A prioritized list of the features and practices (relevant to each distress type) proposed for investigation with LTPP data was presented in table 1 of chapter 2 of this report. The list of data elements available in the LTPP database for transverse cracking is presented in table 8. This list was not meant to be exhaustive, and any other variables that were found to significantly influence JPCP transverse cracking were investigated thoroughly. The first step in the performance evaluation analysis was a comprehensive univariate analysis, which is presented in appendix A. This chapter presents the results of a preliminary bivariate analysis, canonical discriminant analysis, and ANOVA to identify the data elements that influence transverse cracking and, hence, pavement performance.

For the bivariate analysis, the effects of individual design features were investigated separately for each pavement type. As a step toward developing specific regional recommendations, the data were further divided based on the four climatic regions in order to observe any regional differences. Because there are relatively few data sections in the LTPP database, engineering judgment was used to make some intelligent divisions of the data in order to keep the individual evaluation data sets a reasonable size. Each of these divisions is specific to the distress data type being investigated and is explained in greater detail in later sections of this chapter.

Preliminary Evaluation of Transverse Cracking Data

Jointed plain concrete pavements typically develop fatigue cracks caused by traffic loading. Repeated traffic loading at the slab edge, midway between transverse joints, results in the development of critical stresses at the bottom of the JPCP. The damage caused by the critical stresses accumulates over time and eventually causes a transverse crack to develop approximately midway between the joints. Slab thickness was chosen as the most important pavement characteristic influencing JPCP transverse (fatigue) cracking; therefore, it is the appropriate variable for Level 1 analysis.

Table 8. Key design features, site conditions, and construction practices available in LTPP database for transverse cracking.

Data Element	Transverse Cracking
Pavement age	✓
Slab thickness	✓
Joint spacing	✓
Drainage	✓
Base type	✓
Cumulative ESAL's	✓
Freezing index	✓
Edge support*	✓
Subgrade type	✓
Annual precipitation	✓
PCC modulus of rupture	✓
PCC elastic modulus	✓
PCC compressive strength	✓
Average monthly temperature range	✓
Static k-value	✓
Steel percentage	✓
Freeze-thaw cycles	✓
Paver type	✓
Curing method	✓
Transverse joint forming method	✓

* Data elements were calculated from other original data elements in the LTPP database.

The conclusions and inferences drawn at the bivariate analysis stage are preliminary. There is a great possibility at this stage of the analysis for some of the results to be misleading because of confounding effects and interactions between the data elements. The results of these analyses are summarized and presented as follows.

Transverse Cracking Level 1 Investigation

The Level 1 analysis consisted of dividing the transverse cracking data into two slab thickness categories (< 250 mm and ≥ 250 mm). The LTPP JPCP data were then evaluated to determine the effect of slab thickness on transverse cracking.

Influence of Slab Thickness on JPCP Transverse Fatigue Cracking

Figure 38 shows a plot of number of cracks per mile versus cumulative ESAL's for all JPCP sections in the LTPP database. Lines were fit through the data to more clearly observe the trends. The available LTPP data indicate that thinner JPCP sections (< 250 mm) experience more fatigue cracking than thicker JPCP sections (≥ 250 mm). Thicker pavements showing a high number of cracks at an early age may be due to inadequate construction practices.

The data were analyzed further to determine the effect of both slab thickness and climate on transverse cracking. The linear trends showed that thinner JPCP sections (< 250 mm) in dry-freeze and wet-freeze regions developed much more transverse fatigue cracking than thicker JPCP sections (≥ 250 mm). The opposite trends were visible in the wet-nofreeze region, where the thicker JPCP sections appeared to exhibit more cracking. Finally, slab thickness showed no effect on the development of transverse cracking for those JPCP sections in the dry-nofreeze region.

Transverse cracking, as discussed in appendix B, occurs for different reasons, including traffic loading, temperature and other climate-related loads, and early age cracking. There is the need therefore to investigate further the opposing trends observed. Figure 39 contains plots showing the influence of slab thickness and climatic region on the transverse fatigue cracking of JPCP sections.

Transverse Cracking Level 2 Investigation

Level 2 investigations of the transverse cracking data consisted of dividing the Level 1 subsets into smaller data sets based on many of the possible influential site and design features identified in table 8. A summary of the Level 1 and 2 variables chosen for the transverse cracking investigation is presented in table 9. Each Level 2 variable is investigated by plotting the observed joint cracking data (expressed as the combined total number of low-, medium-, and high-severity cracks per kilometer for the section) versus the cumulative ESAL's as determined from regression equations of the LTPP annual traffic data. The preliminary analysis consisted of creating plots showing the influence of each Level 2 variable at each Level 1 definition for all of the data observations, regardless of climatic region. Linear trend lines were again fit through the data. The different groups of plots were first created for each pavement type. To

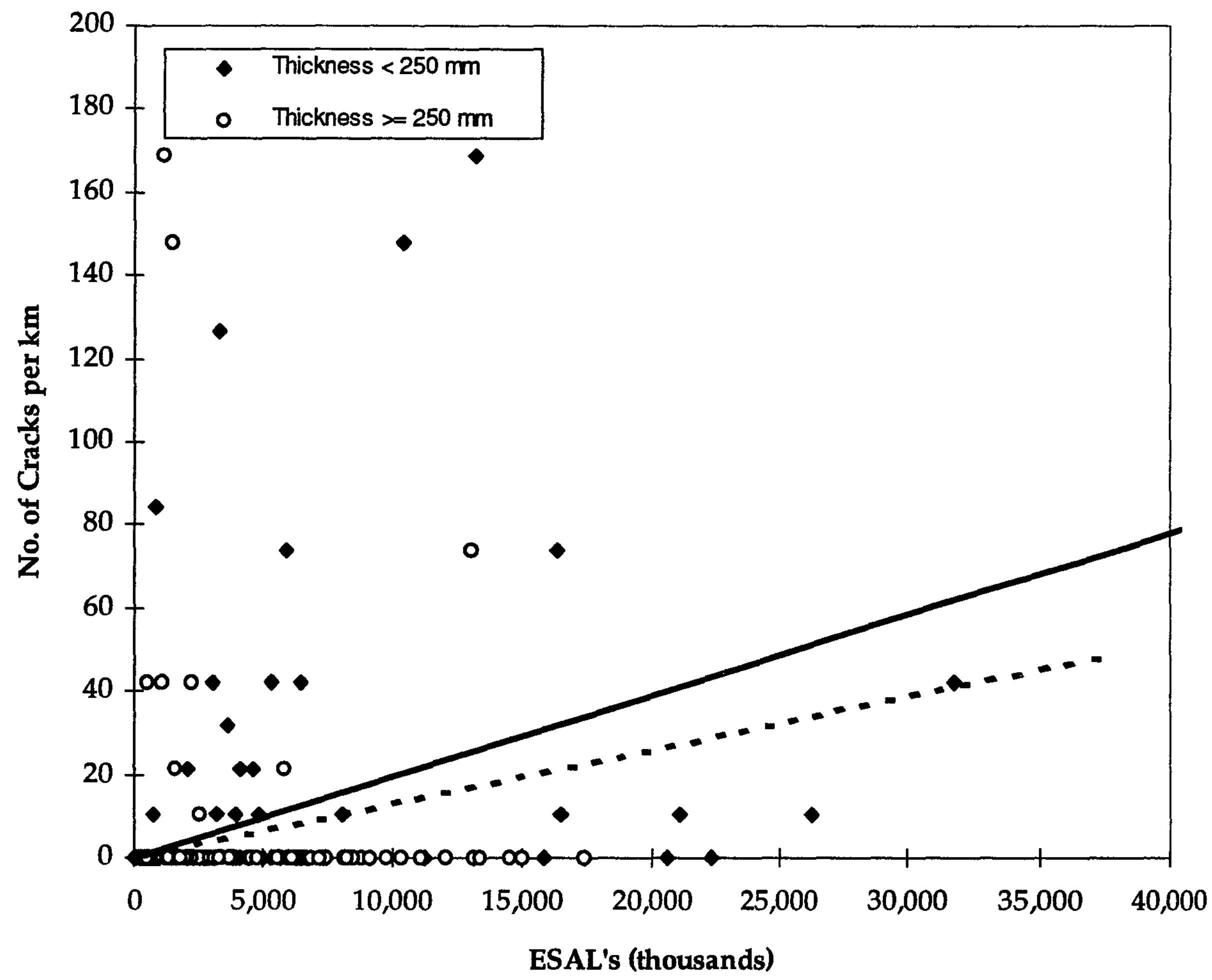


Figure 38. Plot showing the influence of slab thickness on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included).

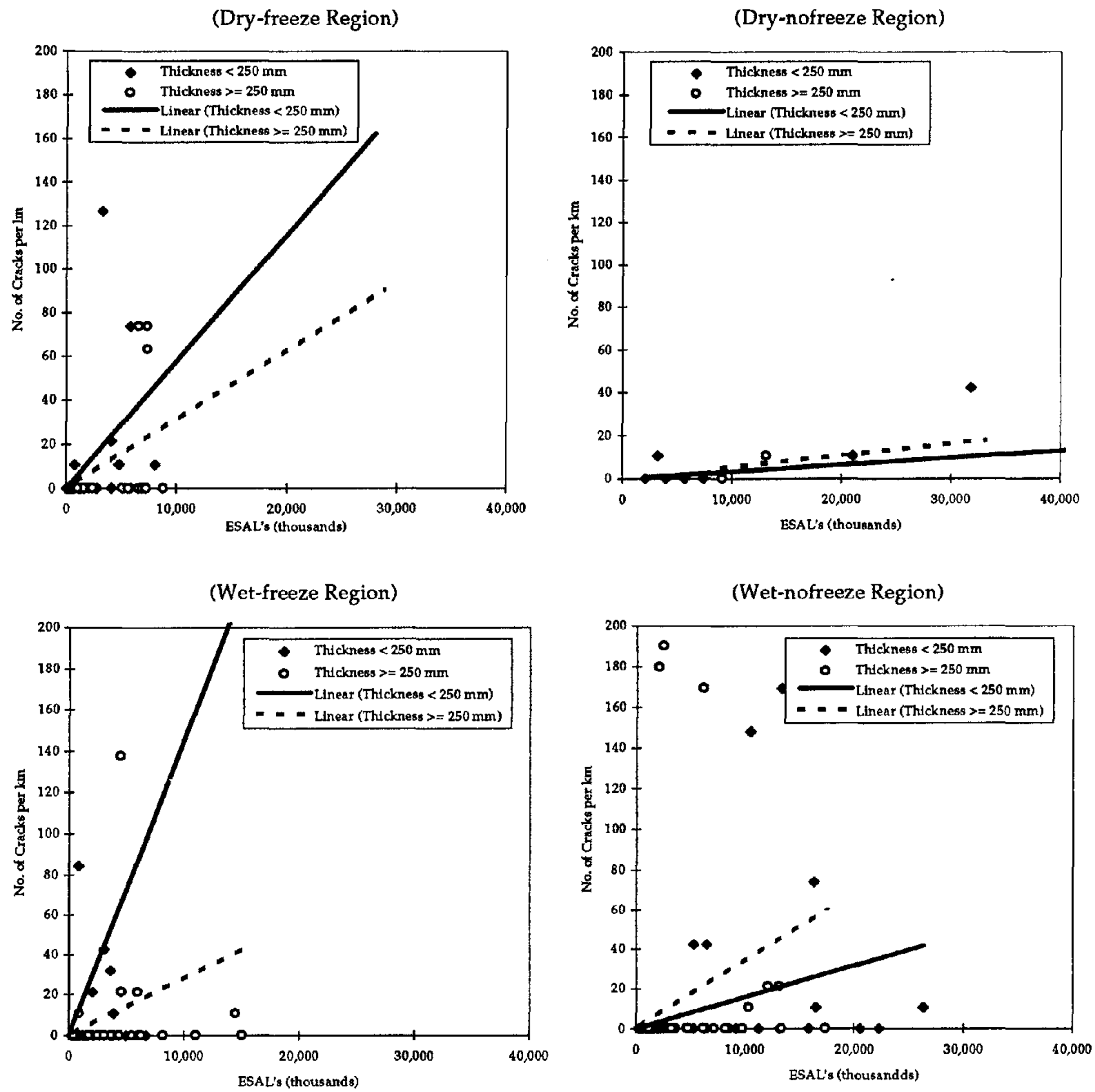


Figure 39. Plots showing the influence of slab thickness and climatic region on the transverse fatigue cracking of JPCP sections.

Table 9. Level 1 and Level 2 data elements used in the evaluation of transverse cracking.

Pavement Types	Level 1 Variables	Level 2 Variables
JPCP	Slab thickness	Freezing index
		Average annual precipitation
		Subgrade type
		Backcalculated static k-value
		Average joint spacing
		Base type
		PCC 28-day modulus of rupture
		Paver type
		Curing method
		Transverse joint forming method

observe any differences in the influence of the Level 2 variables between climatic regions, these plots were then recreated by using only the respective data in each climatic region (when data were available). The results of these analyses are summarized and presented below.

Influence of Site Conditions

The specific effects of the different site conditions on pavement performance were investigated as part of this study. The site-related variables investigated were categorized as follows:

- Freezing index: < 270 and ≥ 270 °C days.
- Average annual precipitation: < 1 m and ≥ 1 m/yr.
- Subgrade type: fine or coarse-grained.
- Modulus of subgrade reaction: < 40.7 and ≥ 40.7 kPa/mm.

Effect of Freezing Index

For JPCP data with thickness < 250 mm, sections with a FI ≥ 277 °C days showed greater cracking than sections with FI <277 °C days. Freezing index did not appear to have any significant effect on the sections with slab thickness ≥ 250 mm. Plots of the

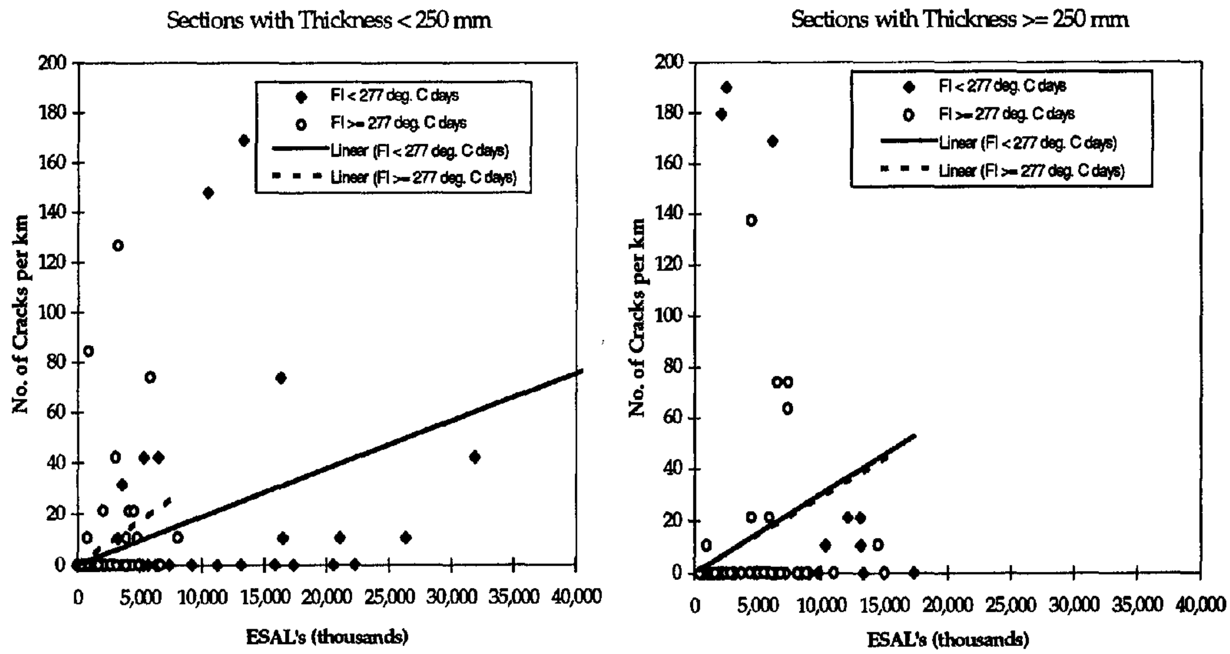


Figure 40. Plots of JPCP fatigue cracking versus traffic as influenced by slab thickness and freezing index (all climatic regions included).

JPCP data as influenced by slab thickness and freezing index are presented in figure 40.

Effect of Annual Precipitation

For JPCP data in both thickness categories (< 250 mm and ≥ 250 mm), sections with more annual precipitation (≥ 1.0 m) showed greater cracking than sections with less annual precipitation (< 1.0 m). It also appeared that the significance of precipitation level was greater for sections with slab thickness < 250 mm. Plots of the JPCP data as influenced by slab thickness and average annual precipitation are presented in figure 41.

Effect of Subgrade Type

An analysis of the sensitivity of JPCP transverse fatigue cracking data to subgrade type showed that, for both levels of slab thickness (< 250 mm and ≥ 250 mm), the sections with coarse-grained subgrade soils appeared to develop more cracking than those built on fine-grained soils. An investigation of the influence of region on these data was not completed due to the lack of sufficient data in each climatic region. Figure 42 contains plots showing the influence of subgrade type on the cracking of JPCP LTPP sections.

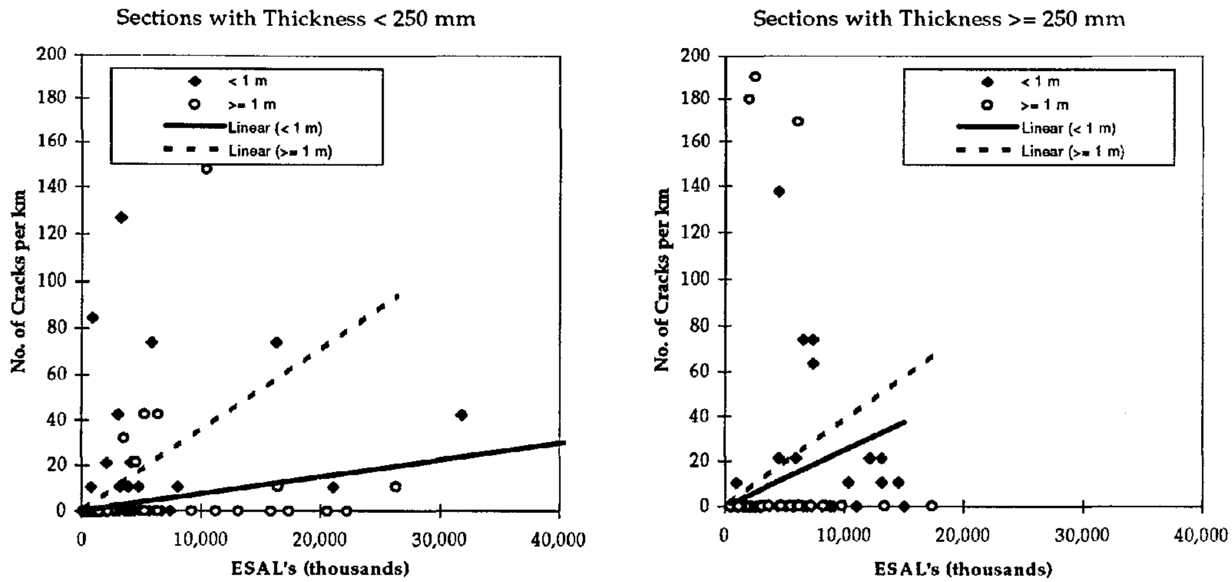


Figure 41. Plots of JPCP fatigue cracking versus traffic as influenced by slab thickness and average annual precipitation (all climatic regions included).

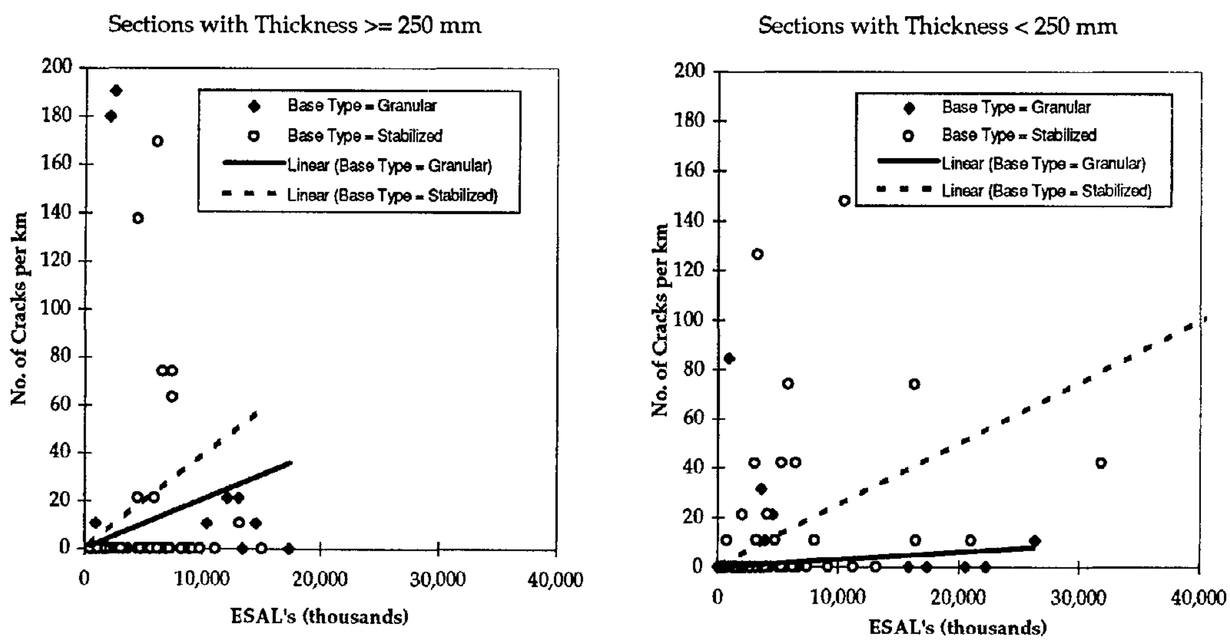


Figure 42. Plots showing the influence of slab thickness and subgrade type on the cracking of JPCP LTPP sections (all climatic regions included).

Effect of Modulus of Subgrade Reaction (Backcalculated Static k-value)

The influence of the two different static k-value levels (k-value < 40.75 kPa/mm and ≥ 40.75 kPa/mm) on JPCP transverse fatigue cracking was investigated for the sections divided into categories of slab thickness (< 250 mm and ≥ 250 mm). The results showed that for both thickness categories, the sections with k-value ≥ 40.75 kPa/mm exhibited more cracking. In fact, the sections with k-values < 40.75 kPa/mm showed minimal cracking in comparison. Figure 43 contains plots showing the influence of slab thickness and k-value on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included). An analysis of the sensitivity of JPCP transverse fatigue cracking data to k-value for different climatic regions was limited by the lack of data in some regions. The available data did, however, show that more JPCP cracking developed for the category of k-value > 40.75 kPa/mm in all climatic regions except the dry-nofreeze. This particular region showed virtually no cracking for those sections where the k-value was ≥ 40.75 kPa/mm. Figures 44 and 45 contain plots showing the influence of k-value category and climatic region on the cracking of JPCP sections in the different thickness categories.

Influence of Design Features

The specific effects of the different design features on pavement performance were investigated as part of this study. The design features investigated were categorized as follows:

- Average joint spacing: ≤ 4.6 m and > 4.6 m
- Base type: stabilized or unstabilized
- PCC 28-day modulus of rupture: < 4.5 MPa and ≥ 4.5 MPa

The effects of these design variables on faulting are presented in the next few sections.

Effect of Average Transverse Joint Spacing

A Level 2 analysis of the effects of average transverse joint spacing on JPCP transverse fatigue cracking involved further separating the sections already divided by slab thickness into the two different average joint spacing categories (≤ 4.6 m and > 4.6 m). The results showed that for the thinner sections (< 250 mm), more cracking developed in the sections with longer joint spacing. For the thicker sections, the trends showed that average joint spacing had little or no effect on the development of transverse fatigue cracking. Figure 46 contains plots showing the influence of slab thickness and average joint spacing on the transverse fatigue cracking of JPCP LTPP sections (data from all climatic regions were included).

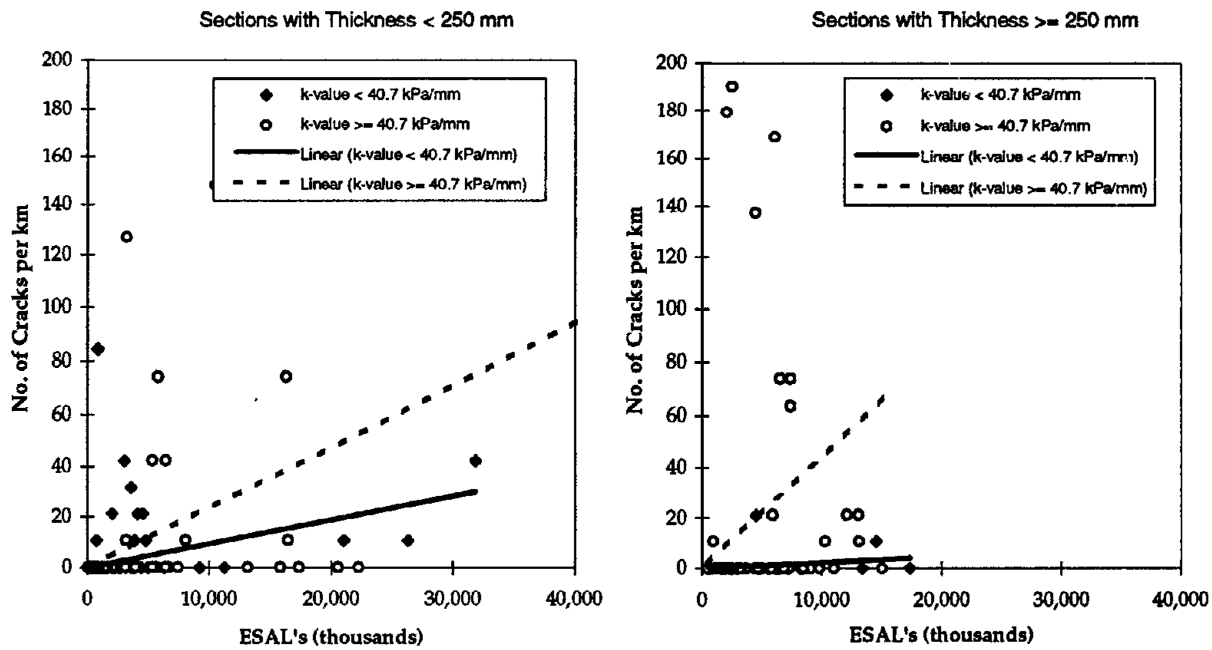


Figure 43. Plots showing the influence of slab thickness and k-value on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included).

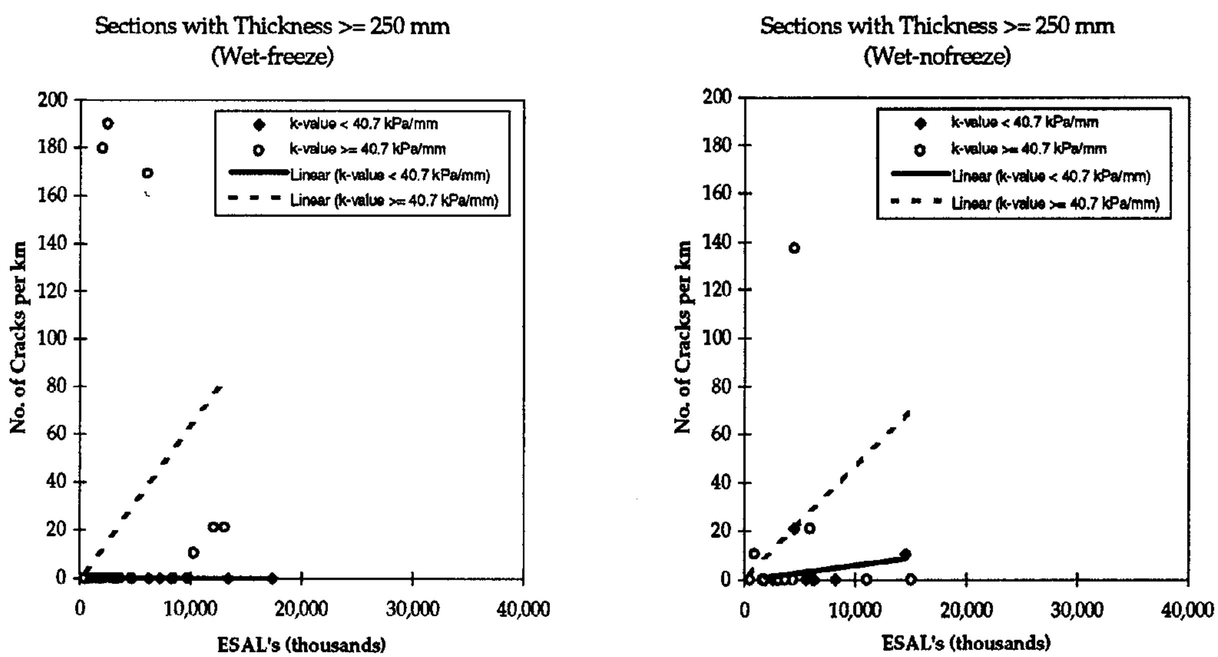


Figure 44. Plots showing the influence of k-value category and climatic region on the transverse fatigue cracking of JPCP sections with thickness $\geq$ 250 mm.

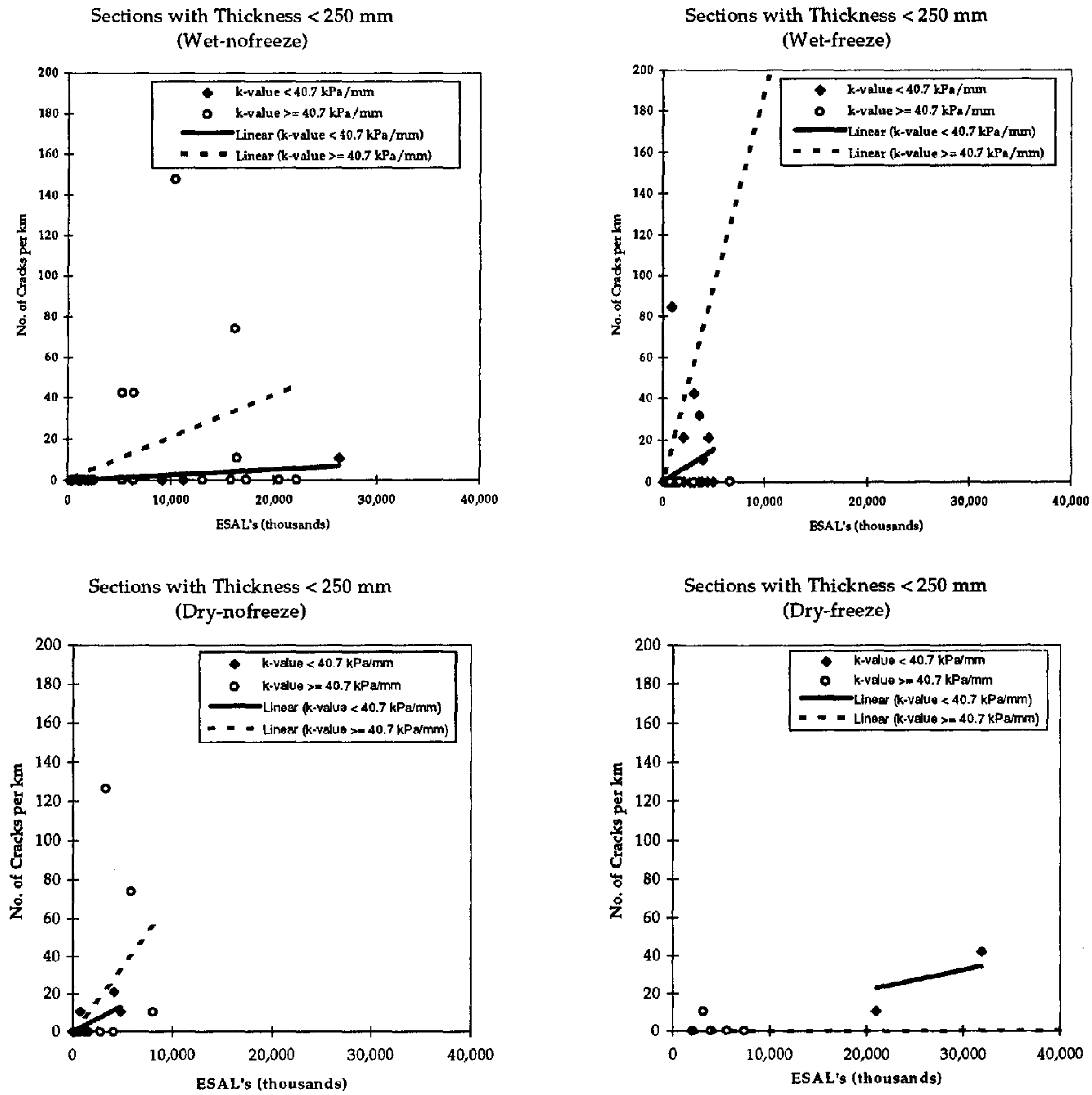


Figure 45. Plots showing the influence of k-value category and climatic region on the transverse fatigue cracking of JPCP LTPP sections with thickness < 250 mm.

Effect of Base Type

The influence of two different base types (granular and stabilized) on JPCP transverse fatigue cracking was investigated for the sections already divided into categories of slab thickness (< 250 mm and ≥ 250 mm). The results showed that for both thickness categories, the sections with stabilized bases exhibited more cracking (on

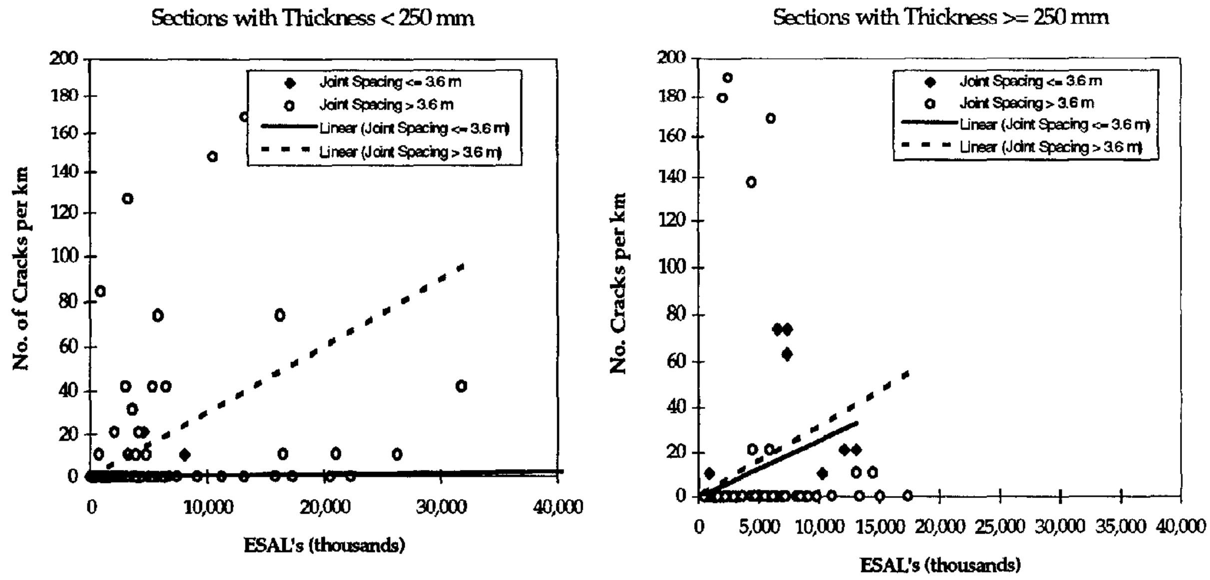


Figure 46. Plots showing the influence of slab thickness and average joint spacing on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included).

average). It is also important to note the linear trend developed for the thinner sections (thickness < 250 mm), with granular bases showing virtually no transverse fatigue cracking. Figure 47 contains plots showing the influence of slab thickness and base type on the transverse fatigue cracking of JPCP LTPP sections (data from all climatic regions were included).

Effect of PCC Strength (28-day Modulus of Rupture)

The influence of two different modulus of rupture categories (M_r < 4.5 MPa and $M_r \geq$ 4.5 MPa) on JPCP transverse fatigue cracking was investigated for the sections already divided into categories of slab thickness (< 250 mm and $\geq$ 250 mm). The results showed that for thinner pavements, JPCP sections with modulus of rupture < 4.5 MPa exhibited more cracking (on average). However, for thicker pavements, JPCP sections with $M_r \geq$ 4.5 MPa showed the most cracking, while the sections with M_r < 4.5 MPa showed virtually no cracking. PCC slabs with very high modulus of rupture tend to have higher stress intensity factors, increasing the likelihood of crack propagation. This trend will, however, require further investigation. Figure 48 contains plots showing the influence of slab thickness and modulus of rupture on the transverse fatigue cracking of JPCP LTPP sections (data from all climatic regions were included).

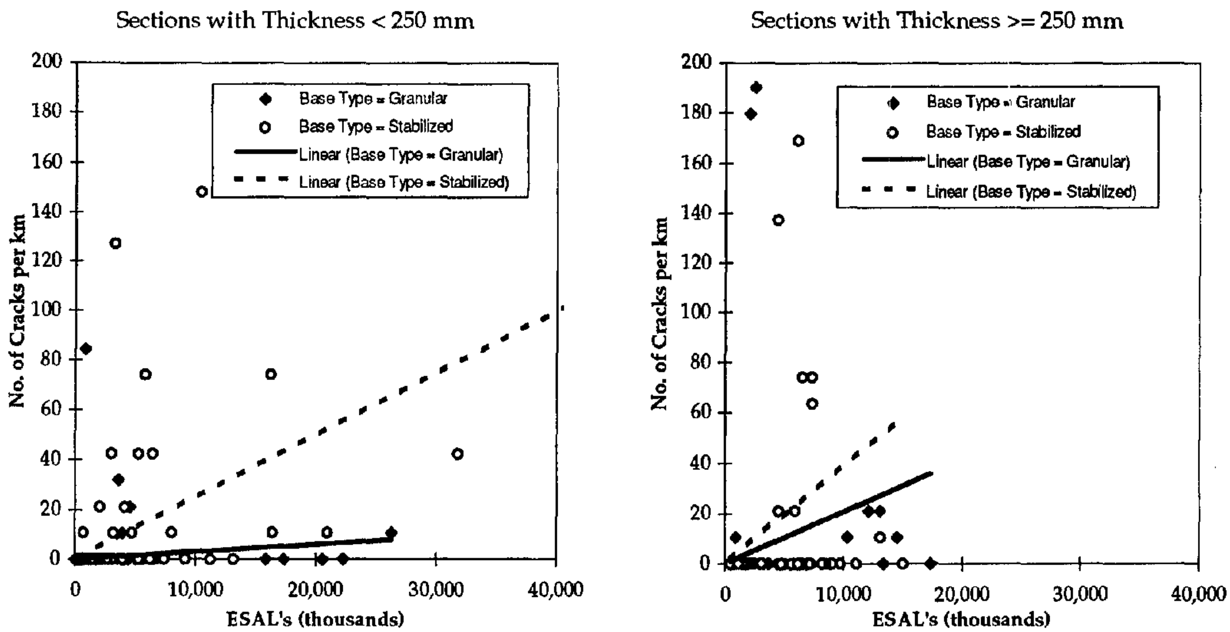


Figure 47. Plots showing the influence of slab thickness and base type on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included).

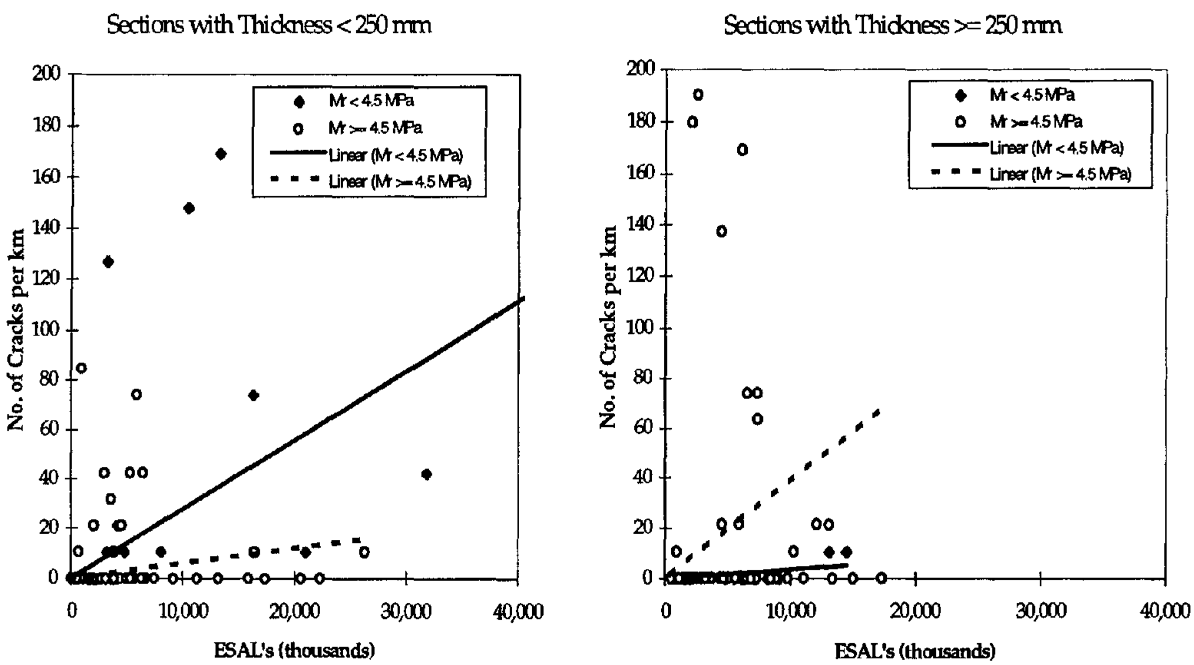


Figure 48. Plots showing the influence of slab thickness and modulus of rupture on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included).

Influence of Construction Practices

The specific effects of construction practices on pavement performance were investigated as part of this study. The construction practices investigated are as follows:

- Paver type.
- Curing method.
- Transverse joint forming method.

The effects of these construction practices on transverse cracking are presented in the next few sections.

Effect of Paver Type

The JPCP fatigue cracking data (already divided into categories based on slab thickness) were further divided into data sets based on paver type. An analysis of these data sets showed that sections constructed with a slip form paver exhibited more transverse fatigue cracking (on average) than those constructed with a side form paver. These trends held true for both slab thickness categories (< 250 mm and ≥ 250 mm). It is important to note that the majority of the sections in both data sets were constructed using a slip form paver. A secondary analysis of the effects of climatic region on the data sets was not completed because of the lack of sufficient data. Figure 49 contains plots showing the influence of paver type and slab thickness on the transverse fatigue cracking of JPCP LTPP sections (data from all climatic regions is included).

Effect of Curing Method

The influence of curing method on the development of transverse fatigue cracking in JPCP sections was investigated as part of this study. The use of burlap polyethylene was compared with the use of a curing compound, and the results showed that the thinner JPCP sections (< 250 mm) exhibited more fatigue cracking (on average) when the burlap polyethylene was used. The opposite trend was observed for the thicker JPCP sections (≥ 250 mm), where those sections cured with burlap polyethylene exhibited virtually no cracking. It is important to note, however, that very few sections in the database were cured using the burlap polyethylene. Figure 50 contains plots showing the influence of curing method and slab thickness on the transverse fatigue cracking of JPCP LTPP sections (data from all climatic regions is included).

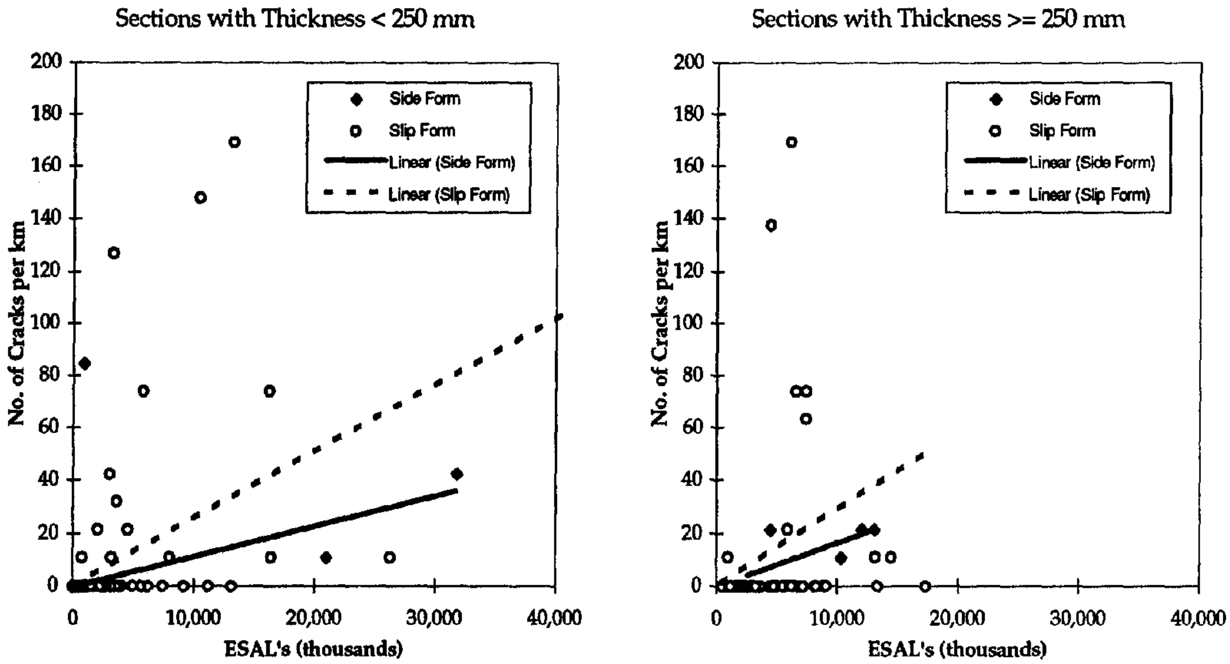


Figure 49. Plots showing the influence of paver type and slab thickness on the transverse fatigue cracking of JPCP LTPP sections.

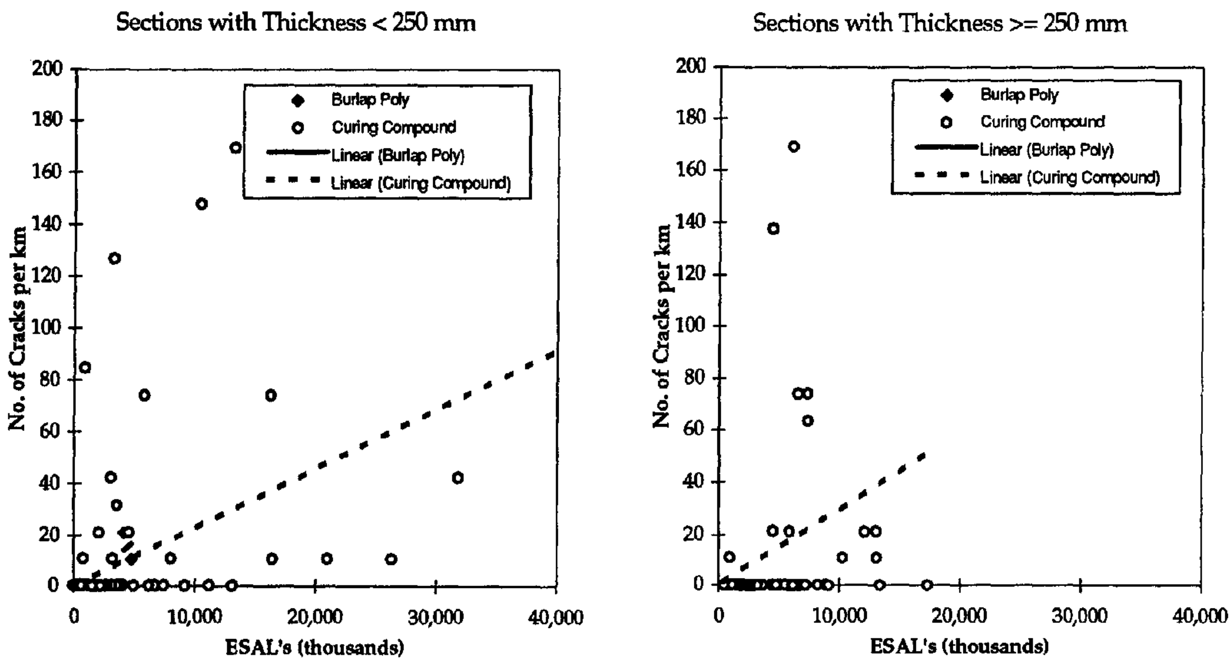


Figure 50. Plots showing the influence of curing method and slab thickness on the transverse fatigue cracking of JPCP LTPP sections (all climatic regions included).

Effect of Transverse Joint Forming Method

Three different joint forming methods were observed for the available LTPP data—plastic insert, metal insert, and sawed. For the JPCP sections, the sections with sawed joints consistently showed more transverse fatigue cracking than those sections with joints formed with plastic inserts. This trend held true for both thickness categories (< 250 mm and ≥ 250 mm). The highest observed fatigue cracking values for the thicker sections came from those constructed using metal inserts. A secondary investigation looking at the influence of climatic region was not completed due to insufficient data. Figure 51 contains plots showing the influence of transverse joint forming method and slab thickness on the transverse fatigue cracking of JPCP LTPP sections (data from all climatic regions were included).

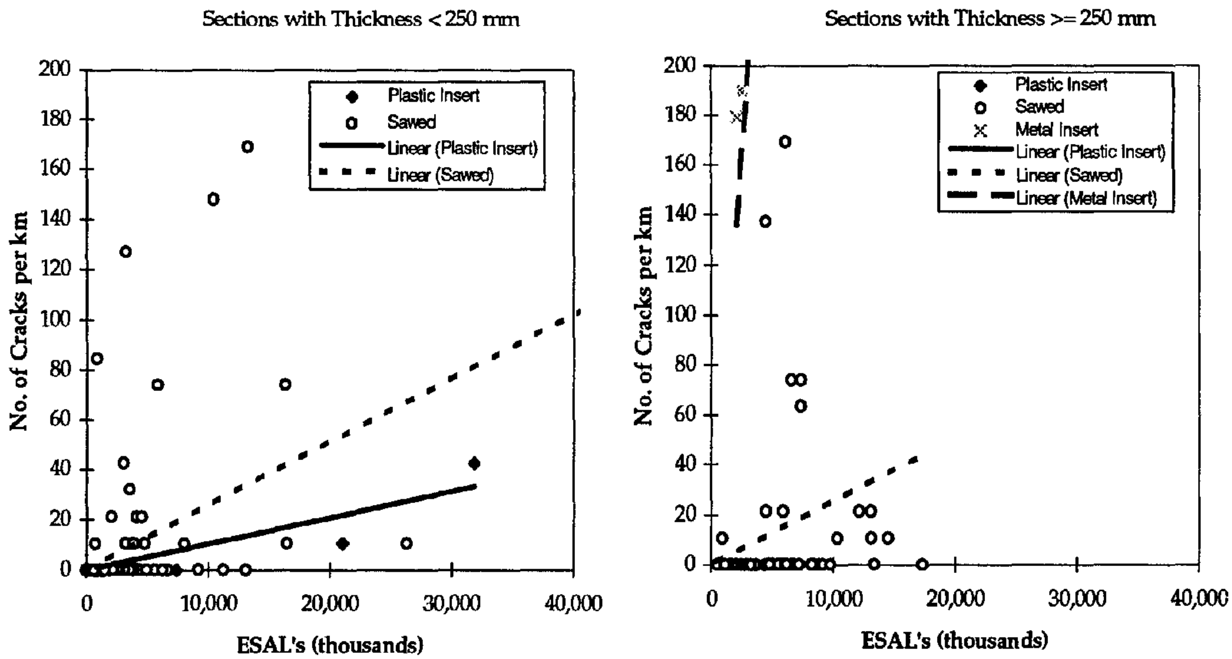


Figure 51. Plots showing the influence of transverse joint forming method and slab thickness on the transverse fatigue cracking of JPCP (all climatic regions included).

Canonical Discriminant Analysis for JPCP Transverse Cracking

The LTPP database for JPCP transverse cracking had very few failed sections or sections with extremely high numbers of transverse cracks. Therefore, the pavement sections were classified as "above" expectation or "other." Because there were only two performance classifications, a single canonical variable, CANTC1, was sufficient for discriminating between the two performance classes. The final form of the canonical discriminant function CANTC1 is as follows:

$$\begin{aligned} CANTC1 = {} & -0.0025h_{PCC} + 3.0\,ST + 8.25C_d - 2.17DRAIN - 0.0063h_b \\ & + 1.963WET + 0.00629DAYST - 0.82RJTSP + 0.132SKEW \end{aligned} \tag{3}$$

where

h_{PCC}	=	PCC slab thickness, mm
ST	=	sealant type, 1 = preformed, 0 = other
C_d	=	drainage coefficient
DRAIN	=	presence of drain, present =1, 0 = other
h_b	=	base thickness, mm
WET	=	wet region, wet = 1, 0 = other
DAYST	=	annual number of days with temperature below 0 °C
RJTSP	=	1 = random joint spacing, 0 = uniform joint spacing
SKEW	=	skew joint, presence = 1, 0 = other

The mean values of CANTC1 are given in table 10. A plot of CANTC1 versus CANTC1 for each observation of the data used in the analysis is shown in figure 52. The plot clearly shows the areas where the pavements in the different performance categories are located. Pavements with a negative CANTC1 value perform above expectation, and the others had CANTC1 values greater than zero. This is in agreement with the mean values of the canonical variables for the different categories. The locations of the different pavement performance categories are summarized as follows:

- Pavement sections performing above expectation were generally located in the area where CANTC1 is less than -0.5. These are the sections of interest.
- Pavement sections performing as expected or below expectation were located in the area where CANTC1 is greater than -0.5.

Summary of Canonical Discriminant Analysis

The model for predicting the canonical variable CANTC1 shows that contrasting PCC slab thickness, drainage type, base thickness, and use of random joint spacing against sealant type, drainage coefficient, wet climates, annual number of days below

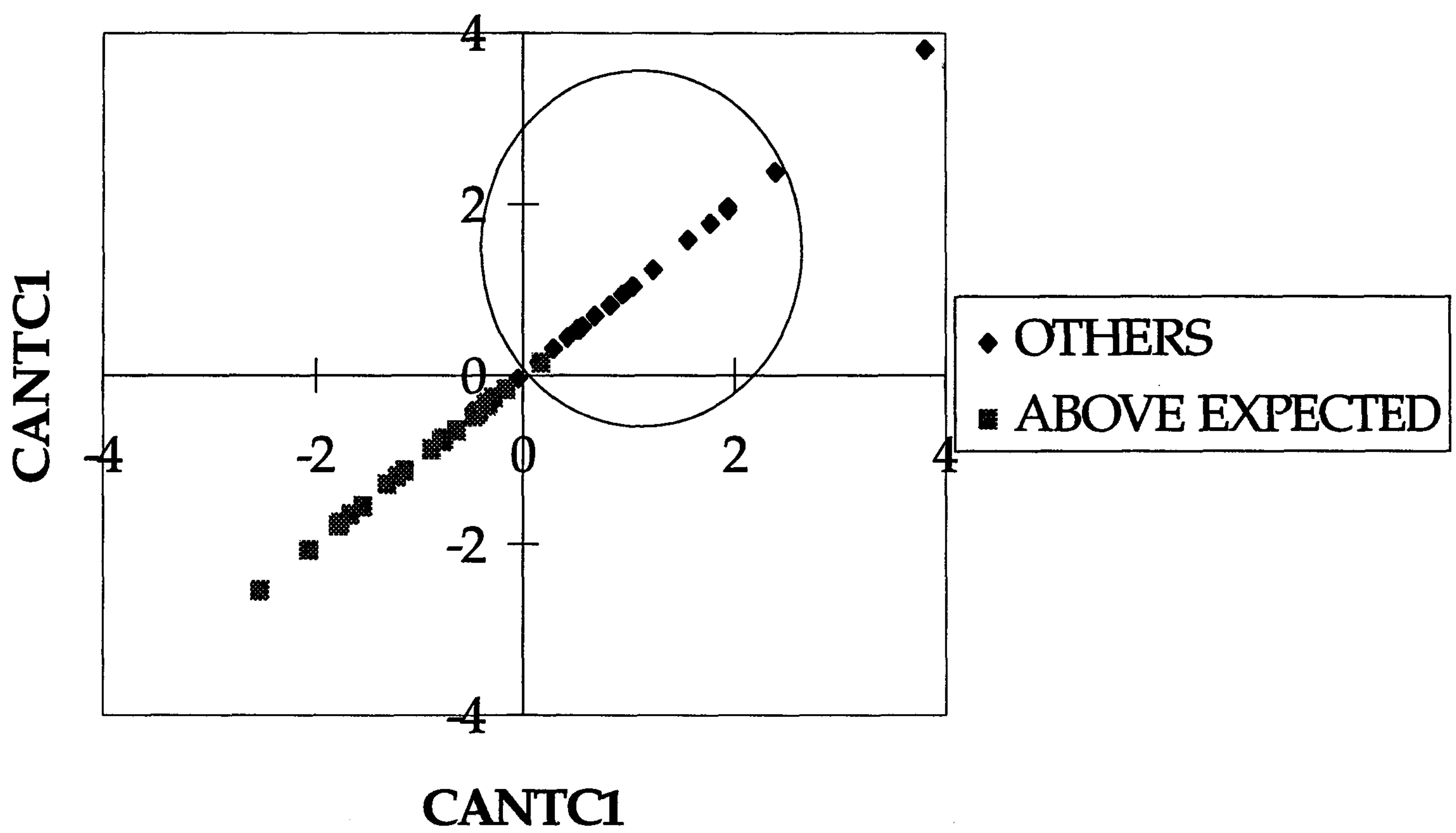


Figure 52. A plot of CANTC1 versus CANTC1 for each observation of the data.

Table 10. Class means for canonical variable CANTC1.

Category	CANTC1
Above Expectation	-0.80
Others	0.74

0 °C, and the presence of skewed joints separates pavements according to performance classification. An increase in PCC slab and base thickness strengthens the pavement structure and results in better transverse cracking performance according to the model, and this is in agreement with results from past studies.

Pavements located in extreme climates tend to perform worse than those in milder climatic areas, as shown by the influence of number of days below 0 °C and wet regions. One interesting trend is that the provision of drains generally improves performance by making CANTC1 more positive; however, providing a more open base by increasing the value of the drainage coefficient results in worse transverse cracking performance. It must be noted, however, that the canonical variables are independent uncorrelated variables developed from basic pavement characteristics and do not always agree with known engineering trends.

Analysis of Variance for JPCP Transverse Cracking

A comprehensive ANOVA was performed to determine the significance of each site condition, design feature, and construction practice that affects transverse cracking. Also, the ANOVA procedure was used to compute the mean transverse cracking for each design feature and site condition used in the ANOVA analysis. Multiple comparison test of the means (Duncan's Test) was then used to determine if there were significant differences between the mean transverse cracking distress levels for the different classes of a given design feature or site condition variable.

Table 11 shows clearly the variables that have a significant effect on faulting. Table 12 is a summary of variables that, though not significant, show quite a difference in mean transverse cracking values for different class levels. These variables could be significant in better designed experiments. The effect of the variables is discussed in the next few sections.

Table 11. Summary of analysis of variance results for JPCP transverse cracking.

Variable	Classification	Percent Slabs with Transverse Cracking	Duncan Class*	Significant Difference
Annual number of wet days	less than 100	6.76	A	Yes
	100 to 140	0.07	B	
	greater than 140	2.04	C	
PCC slab thickness, mm	less than 228	8.52	A	Yes
	228 to 250	1.00	B	
	greater than 250	1.22	B	
Modulus of rupture, MPa	less than 4.5	4.104	A	Yes
	4.5 to 4.8	0.000	B	
	greater than 4.8	2.333	C	
Dowel diameter	no dowels	4.35	A	Yes
	dowels	0.70	B	
Modulus of subgrade reaction, kPa/mm	less than 30	1.533	A	Yes
	30 to 54	1.700	A	
	greater than 54	5.324	B	
Base elastic modulus, MPa	less than 690	1.22	A	Yes
	690 to 6900	0.62	A	
	greater than 6900	6.63	B	
Drainage coefficient, C_d	less than 1.0	1.416	A	Yes
	greater than 1.0	4.368	B	

* Duncan's multiple range test; those with the same letter are not significantly different.

Table 12. Summary of analysis of variance results for variables that potentially influence transverse cracking.

Variable	Classification	Percent Slabs with Transverse Cracking	Duncan Class*	Significant Difference
Number of freeze-thaw cycles	less than 60	3.36	A	No
	60 to 110	1.86	A	
	greater than 110	4.49	A	
Annual mean temperature, °C	less than 7	0.51	A	No
	7 to 15.5	3.97	A	
	greater than 15.5	3.14	A	
Random joint spacing	Yes	2.582	A	No
	No	3.225	A	
Base type	not stabilized	1.191	A	No
	stabilized	4.341	A	
Subgrade type	fine	1.665	A	No
	coarse	4.895	A	
Underlying PCC material type	untreated	53	A	Yes
	treated subgrade	37	A	
	non-asphalt treated	6.2	B	
	unbound material	0.15	C	
	AC-treated	0	C	
Number of layers	3	12	A	Yes
	4	10	A	
	5	0	B	
Coarse agg. content, kg/m^3	less than 1800	19	A	Yes
	greater than 1800	4.5	B	
Fine agg. content, kg/m^3	less than 1300	4.5	A	Yes
	greater than 1300	19	B	

* Duncan's multiple range test; those with the same letter are not significantly different.

Influence of Site Conditions

Effect of Annual Number of Wet Days

The results presented in table 11 show that pavements located in areas with a low number of wet days (less than 100 days per annum) are the most likely to experience transverse cracking. This is followed by pavements in areas with more than 140 wet days per annum. This may be due to the fact that pavements in dry areas experience more shrinkage and warping stresses and, hence, more transverse cracking. Also, the dry regions generally tend to be hotter than the wet areas, increasing the potential of temperature gradient stresses and curling. Pavements in areas with moderate climates (100 to 140 wet days per annum) performed best and had the lowest amount of transverse cracking.

Effect of Wet and Freeze Climates

The mean transverse cracking values for pavements located in extreme climates were higher than those located in the milder climatic regions (moderate number of wet days and freezing). This is a reasonable result, since an increase in precipitation generally corresponds to lower pavement foundation strength, extreme temperatures result in either curling or shrinkage, and both result in higher levels of transverse cracking. The ANOVA test also shows that pavements in areas with precipitation of more than 1.0 m experience more transverse cracking than those in areas with precipitation less than 1.0 m.

Effect of Mean Temperature

Pavements in locations with higher mean temperatures are more likely to be subjected to curling stresses and, therefore, cracking. The ANOVA results show that pavements located in areas with mean temperatures less than 7.2 °C experienced approximately 7 to 8 times less transverse cracking than those in regions with higher mean temperatures.

Effect of Subgrade Type

The ANOVA results showed that, even though the difference in measured percent slabs with transverse cracking for pavements with or without stabilized bases was not significant, pavements with stabilized bases experienced more transverse cracking than pavements with unstabilized bases. Pavements with coarse subgrade types also experienced more transverse cracking. This trend is in agreement for pavements with higher modulus values for both base and subgrade. The explanation for this must be similar to that for higher modulus values explained in the previous section.

Effect of Modulus of Subgrade Reaction

The ANOVA results showed clearly that JPCP with very strong foundations (high subgrade modulus and a high base modulus) experienced more transverse cracking. This is unusual and is contrary to expectation unless temperature gradients are considered. JPCP with high effective modulus of subgrade reaction values, or high base and subbase values, have high curling stresses and, therefore, more transverse cracking.

Influence of Design Features

Effect of PCC Slab Thickness

The ANOVA results clearly show that pavements with thicker slabs experience less cracking. Thicker slabs in general are able to withstand wheel loads and temperature stresses better than thinner ones, resulting in less bending moments, stresses, and deflections. Also, a microcrack initiated at the bottom of the PCC slab will take more load cycles to propagate through the slab to fracture and crack.

Effect of Base Modulus

Results for the effect of base modulus on transverse cracking show that there was a significant amount of cracking for pavements with cement-treated or lean concrete bases (base modulus > 6900 MPa). This may be due to the fact that very stiff bases and foundations provide less support when the PCC slab is curled up or warped, and this increases the likelihood of cracking with the application of wheel loads. Bases with a high modulus are also likely to crack by themselves, with the cracks propagating through the PCC slab.

The group with the second highest mean transverse cracking value was pavements with base modulus less than 690 MPa (unstabilized base material). This is due to the fact that such pavements generally have a weak base and provide less support to the PCC slab. The group with the least amount of cracking was pavements with base modulus values close to 4485 MPa (AC-treated base). This type of base provides uniform support to the PCC slab and is flexible enough to bend with or accommodate movements of the slab when curled or warped.

Effect of Modulus of Rupture

The effect of modulus of rupture on transverse cracking is interesting. Pavements with modulus of rupture values less than 4.5 MPa and greater than 4.8 MPa experienced more transverse cracking than pavements with values between 4.5 and 4.8 MPa. It is obvious from engineering principles that pavements with lower modulus of rupture values are less likely to withstand the stresses imposed by wheel loads and, therefore, are more likely to fracture and crack. However, fracture mechanics principles show that higher elastic modulus and modulus of rupture values tend to increase the stresses that propagate cracks through most materials, including pavement surface layer material, resulting in a faster crack growth rate.

Effect of Dowel Diameter

The ANOVA result shows clearly that pavements with dowels perform better than those without. Dowels provide load transfer across the joints of adjacent slabs. Load transfer reduces deflections and stresses throughout the PCC slab, particularly at the top of the mid-section of the PCC slab. The reduction of stresses and deflections at this location lowers the possibility of top-down mid-section transverse cracking.

Effect of Base Type

Pavements with flexible foundations such as asphalt-treated base generally perform better with less cracking than those with rigid foundations (lean concrete bases). This is because during hot or cold seasons the PCC slab curls or warps. Flexible pavements are better suited to accommodate the changes and movements of the slab and provide a uniform base or foundation during these periods of slab movements. Rigid pavements, on the other hand, cannot provide such support, resulting in voids beneath the slab and a higher potential for cracking.

Effect of Underlying PCC Material Type and Number of Layers

The pavement types with slab directly overlaid on subgrade material showed the highest amount of faulting. This is because subgrade materials tend to be weaker than base and other pavement material so the pavement will likely experience more deflections. The ANOVA results also showed that pavements with more layers had less transverse cracking. Such pavements have stronger foundations, which provides better support to the PCC slab and reduces the potential for excessive deflections. Also, pavements with more layers generally have a more flexible foundation that provides adequate and uniform support at all times and reduces cracking.

Influence of Construction Practices

Effect of Coarse and Fine Aggregate Content

The pavements with more coarse aggregates (greater than 1,800 kg/m^3) and less fines (less than 1,300 kg/m^3) experienced less transverse cracking than those with less coarse aggregates and more fine aggregates. This is expected because concrete materials with a high content of coarse material generally are stronger. They can withstand higher compression, higher stresses, and have a higher resistance to fracture and cracking. Such concrete slabs also tend to be less susceptible to disintegration from moisture and therefore are more likely to resist cracking and experience fewer transverse cracks.

Summary

Using univariate analysis, frequency plots, canonical discriminant analysis, and ANOVA, the variables that influence the occurrence and severity of transverse cracking in JPCP have been analyzed.

According to the results of the analysis, pavements with thicker PCC slabs tend to perform above expectation. Also, pavements with higher modulus of rupture values performed better, and the presence of dowels resulted in better performance because they provide enhanced load transfer and decreased deflections and stresses.

Pavements with stronger foundations (stabilized bases and higher modulus of subgrade reaction values) were more likely to experience transverse cracking. The analysis also showed that pavements located in extreme climates (higher freezing or high temperatures) performed worse than those in milder climates. These observations are reasonable and could serve as basic guidelines for pavement design and evaluation. Also, the canonical function CANTC1 was used to determine if pavements performed better than expected or otherwise. This can be a useful tool in classifying newly designed pavements and to check preliminarily for adequate performance through the pavement's design life.

The construction factors that influence transverse cracking are all related to pavement strength and mix design. These factors included using more dense concrete with a higher percentage of coarse aggregate, using more layers to strengthen the pavement foundation and structure, and placing the PCC slab over a firm, strong stabilized base. Past studies also have shown that stronger pavements have reduced transverse cracking; however, the use of rigid bases such as lean concrete often results in more cracking because of the lack of flexibility and the base itself being prone to cracking. Therefore, using very stiff bases must be avoided when possible.

5. EVALUATION OF SITE CONDITIONS AND PCC PAVEMENT DESIGN FEATURES THAT INFLUENCE ROUGHNESS

Introduction

Many of the primary design features, site conditions, and construction practices that influence PCC pavement performance were identified in appendix B. They include the site conditions of traffic, climate, and subgrade support, as well as the specific design features that are incorporated into pavements to improve performance, such as PCC slab thickness, the presence of dowels, and drainage facilities.

A prioritized list of the features and practices (relevant to each distress type) proposed for investigation with LTPP data was presented in table 1 of chapter 2 of this report. Some of the data elements identified during a literature review are not available in the LTPP database. The list of data elements available in the LTPP database for roughness is presented in table 13. This list was not meant to be exhaustive, and any other variables that were found to significantly influence roughness were investigated thoroughly. The first step in the performance evaluation analysis was a comprehensive univariate analysis, which is presented in appendix A. This chapter presents the results of a preliminary bivariate analysis and a more detailed canonical discriminant analysis and ANOVA to identify the data elements that influence pavement performance.

For the bivariate analysis, the effects of individual design features were investigated separately for each pavement type. The data were further divided based on the four climatic regions to observe any regional differences. Because there are relatively few data sections in the LTPP database, engineering judgment was used to make some intelligent divisions of the sections in order to keep the individual evaluation data sets a minimum size. Each of these divisions is specific to the distress data type being investigated and is described in greater detail in later sections of this chapter.

Preliminary Investigation of Roughness

Roughness is a distress that develops on all three rigid pavement types (JPCP, JRCP, and continuously reinforced concrete pavement [CRCP]). The development of roughness in each of these pavement types is generally influenced by the same primary design variables and construction practices. Each pavement type was analyzed separately using slab thickness as the Level 1 analysis variable. The conclusions and inferences drawn at the bivariate analysis stage are preliminary. There is a great possibility at this stage of the analysis for some of the results to be misleading because of confounding effects and interactions between the data elements. The results of these analyses are summarized and presented as follows.

Table 13. Key design features, site conditions, and construction practices available in LTPP database for roughness.

Data Element	Roughness, IRI
Pavement age	✓
Slab thickness	✓
Joint spacing	✓
Drainage	✓
Base type	✓
Cumulative ESAL's	✓
Freezing index	✓
Edge support	✓
Subgrade type	✓
Annual precipitation	✓
Dowel diameter	✓
Slab stress	✓
PCC modulus of rupture	✓
PCC elastic modulus	✓
PCC compressive strength	✓
Average monthly temperature range	✓
Static k-value	✓
Steel percentage	✓
Joint sealant type	✓
Load transfer type	✓
Freeze-thaw cycles	✓

IRI = International Roughness Index

Roughness Level 1 Analysis

The Level 1 analysis of the roughness data consisted of dividing the roughness data into two slab thickness categories (< 250 mm and ≥ 250 mm). The next step was to analyze the effect of slab thickness on roughness for JPCP, JRCP, and CRCP.

Influence of Slab Thickness

The JPCP and JRCP data showed that sections with greater slab thicknesses (> 250 mm) generally exhibited higher IRI values than thinner slabs. The opposite trend was observed for the CRCP data, as the linear trend representing the thicker sections decreased as cumulative ESAL's increased. Figure 53 contains plots illustrating the influence of slab thickness on the IRI of JPCP, JRCP, and CRCP sections in all climatic regions.

Roughness Level 2 Analysis

Level 2 investigations of the IRI data consisted of dividing the Level 1 subsets into smaller data sets based on the possible influential site conditions, design features, and construction practices identified in table 14. The LTPP data were used to investigate as many of these design features and site conditions as possible. Each Level 2 variable was investigated by plotting the observed roughness, expressed as IRI versus cumulative ESAL's. The preliminary analysis consisted of creating plots showing the influence of each Level 2 variable at each Level 1 definition for all of the data observations, regardless of climatic region. Linear trend lines were fit through the data in order to more easily identify trends in the data. To observe any differences in the influence of the Level 2 variables between climatic regions where necessary, the plots were recreated (for each pavement type) by using only the respective data in each climatic region. The results of the analyses on the influence of site conditions and design features on roughness are summarized and presented in the next few sections.

Influence of Site Conditions

The specific Level 2 climatic investigations looked at the effects of freezing index, freeze-thaw cycles, average annual precipitation, average annual temperature range, and the average annual number of wet days on the measured IRI of JPCP, JRCP, and CRCP sections at different slab thickness levels (< 250 mm and ≥ 250 mm). For these cases, each variable was divided into the following categories for investigation:

- Freezing index: < 270 and ≥ 270 °C days.
- Annual freeze-thaw cycles: < 70 and ≥ 70.
- Average annual precipitation: < 1.0 and ≥ 1.0 m/yr.
- Average annual temperature range: < 11 and ≥ 11 °C.
- Average annual number of wet days: < 125 and ≥ 125 days.
- Subgrade type: fine- or coarse-grained.
- Modulus of subgrade reaction: < 40.7 and ≥ 40.7 kPa/mm.

The effects of the site conditions investigated are presented as follows.

Table 14. Level 1 and 2 data elements used in the evaluation of roughness (IRI) data.

Pavement Types	Level 1 Variables	Level 2 Variables
JPCP JRCP CRCP	Slab thickness	Freezing index
		Freeze-thaw cycles
		Average annual precipitation
		Average annual temperature range
		Average annual number of wet days
		Subgrade type
		Backcalculated static k-value
		Average joint spacing
		Base type
		Base elastic modulus
		PCC 28-day modulus of rupture
		PCC elastic modulus
		Outside shoulder type
		Steel percentage (JRCP & CRCP only)
		Surface texturing method

Effect of Climatic Region

An analysis of the JPCP IRI data by climatic region showed the highest IRI values in the wet-freeze region and the lowest in the dry-nofreeze region. For all four climatic regions, the thicker JPCP sections (thickness $\geq$ 250 mm) generally exhibited higher IRI values than the thinner JPCP sections. Figure 54 contains plots showing the influence of slab thickness and climatic region on the IRI of JPCP LTPP sections. Only a few JRCP data points were available in the regions with dry conditions; therefore, making an analysis across all climatic regions is difficult. The JRCP sections in the wet-freeze and wet-nofreeze regions showed that thicker pavements had higher IRI values than thinner JRCP sections. Figure 55 contains plots showing the influence of slab thickness on the IRI of JRCP LTPP sections in the wet-freeze and wet-nofreeze climatic regions.

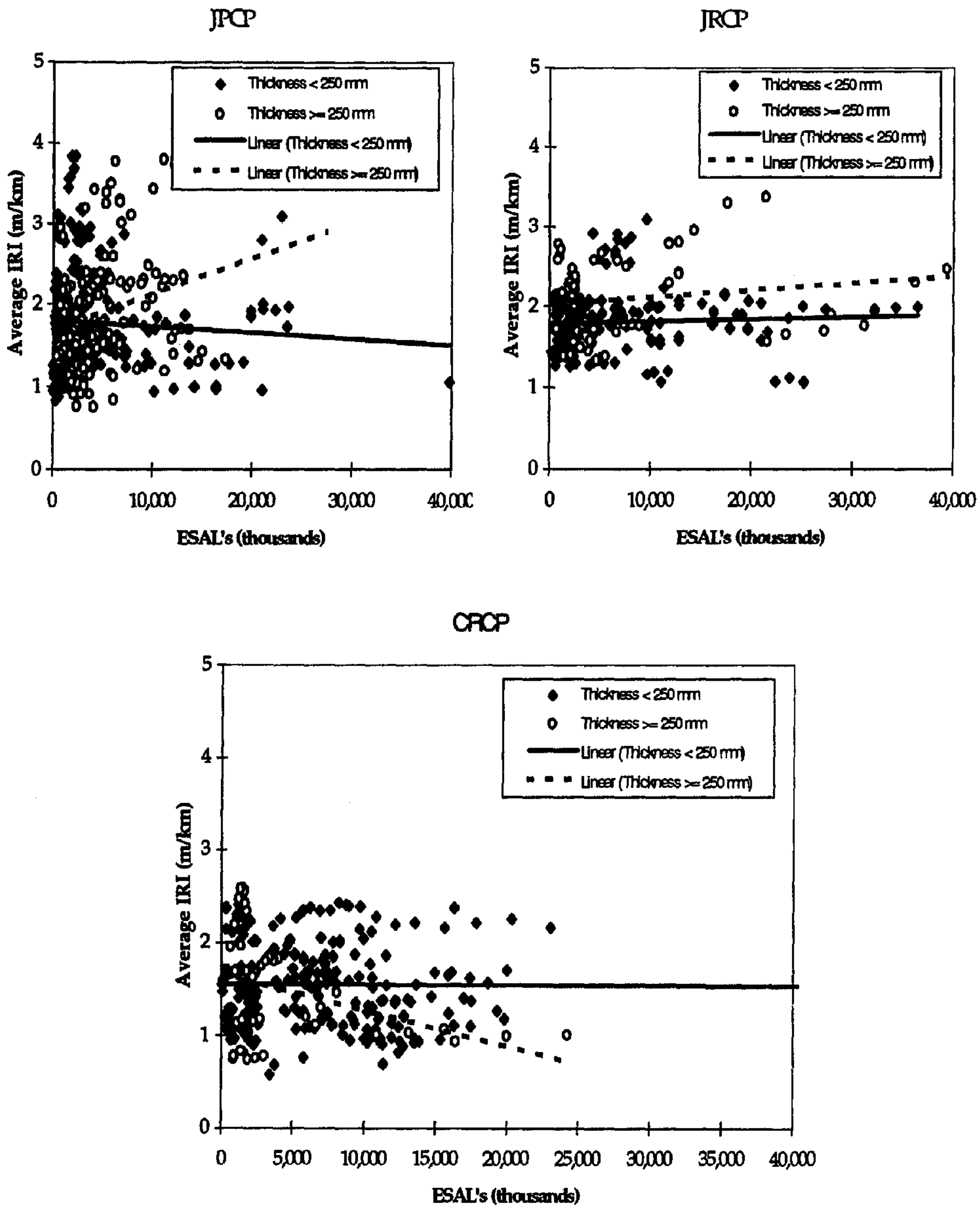


Figure 53. Plots showing the influence of slab thickness on the IRI of JPCP, JRCP, and CRCP sections (all climatic regions included).

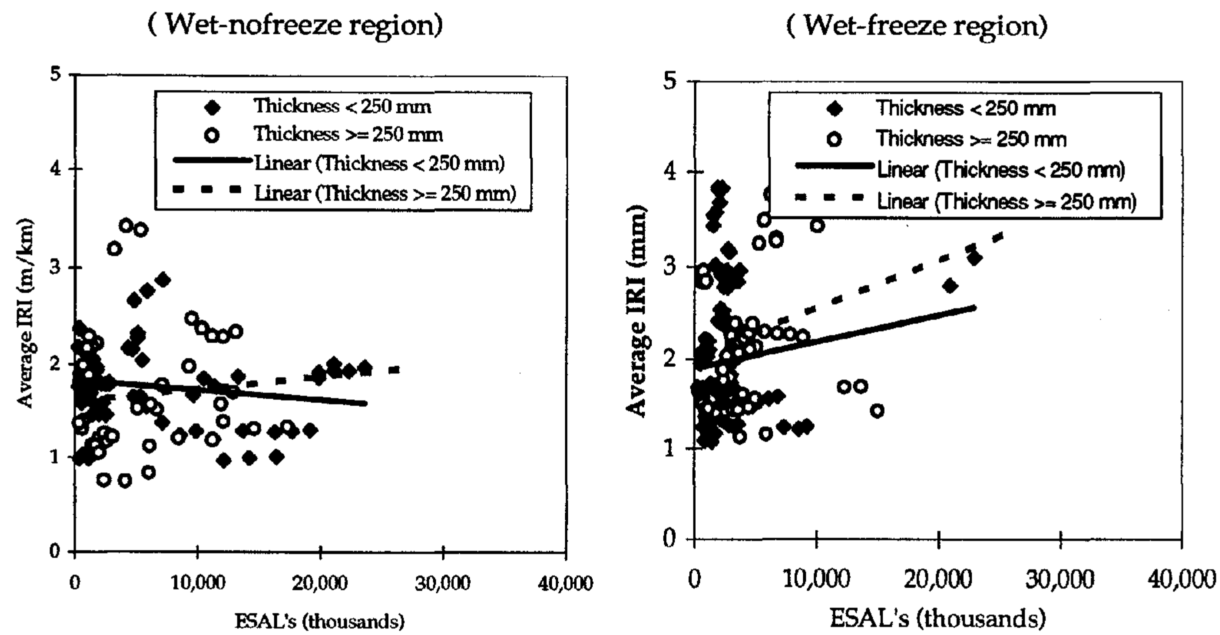


Figure 54. Plots showing the influence of slab thickness and climatic region on the IRI of JPCP LTPP sections.

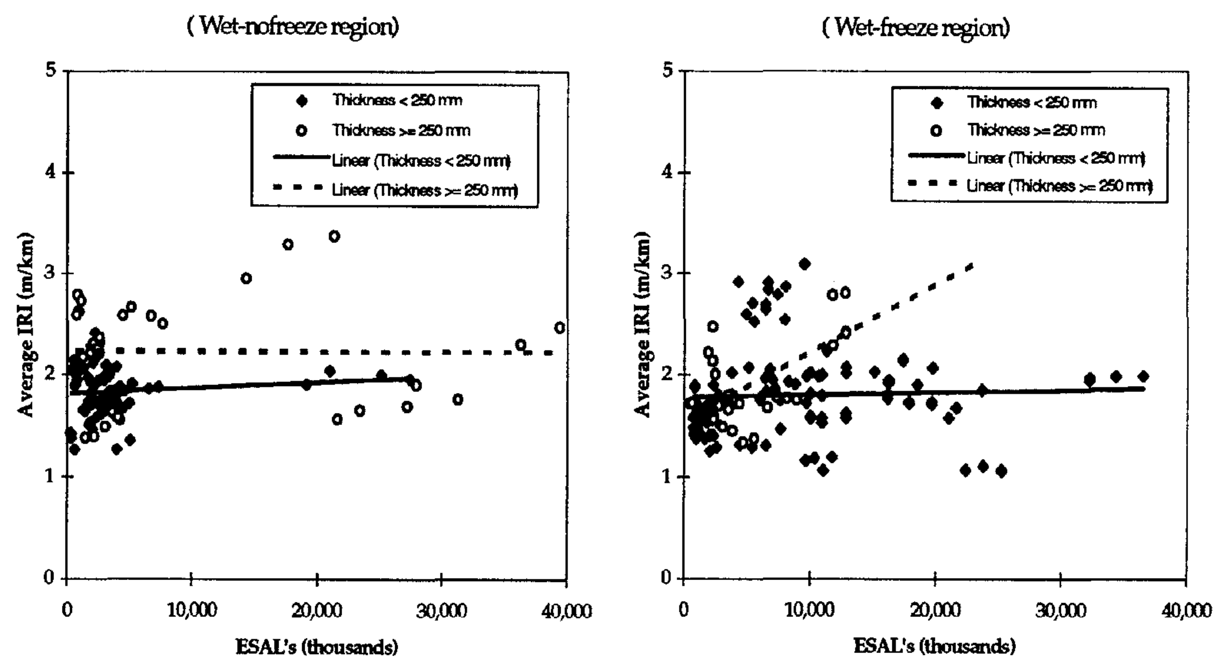


Figure 55. Plots showing the influence of slab thickness and climatic region on the IRI of JRCP LTPP sections.

An analysis of the CRCP IRI data by climatic region showed consistent trends for three of the four climatic regions. No conclusions could be made about the influence of slab thickness in the dry-nofreeze region because of insufficient data. The other three climatic regions showed that thinner CRCP sections exhibited higher IRI values than the thicker CRCP sections. Figure 56 contains plots showing the influence of slab thickness and climatic region on the IRI of CRCP LTPP sections.

Effect of Freezing Index

The JPCP and CRCP data at both levels of slab thickness showed that sections subjected to a freezing index ≥ 270 °C days were generally rougher than those sections subjected to the lower level of freezing index. The JRCP data appeared to show an opposite trend at both levels of slab thickness. The thinner JRCP sections with freezing index < 270 °C days were clearly rougher than those sections experiencing the higher level of freezing index. Overall, the JPCP sections appeared to have the highest IRI values, followed by the JRCP sections, with the CRCP sections being the smoothest of the three pavement types. Plots of the JPCP, JRCP, and CRCP IRI data as influenced by slab thickness and freezing index are presented in figures 57 through 59, respectively.

Effect of Annual Freeze-Thaw Cycles

The JPCP data at both levels of slab thickness showed that sections subjected to freeze-thaw cycles ≥ 70 were generally rougher than those sections subjected to the lower level of freeze-thaw cycles. The JRCP and CRCP data did not show any significant trends, as the linear regressions fit through the data were generally very close together, or in most cases, crossing. Plots of the JPCP data as influenced by slab thickness and freeze-thaw cycles are presented in figure 60.

Effect of Average Annual Precipitation

The JPCP data for sections with slab thickness < 250 mm showed that sections subjected to an average annual precipitation ≥ 1.0 m were generally rougher than those sections receiving less precipitation. The trend appeared to be the opposite for JPCP sections. For both thickness levels, the largest IRI values came from sections receiving < 1.0 m of precipitation. Plots of the JPCP data as influenced by slab thickness and average annual precipitation are presented in figure 61.

The JRCP data for sections with slab thickness < 250 mm showed that those sections subjected to an average annual precipitation ≥ 1.0 m were generally rougher than those sections receiving less precipitation. Plots of the JRCP data as influenced by slab thickness and average annual precipitation are presented in figure 62. The amount of annual precipitation appeared to have no significant effect on the IRI of CRCP sections,

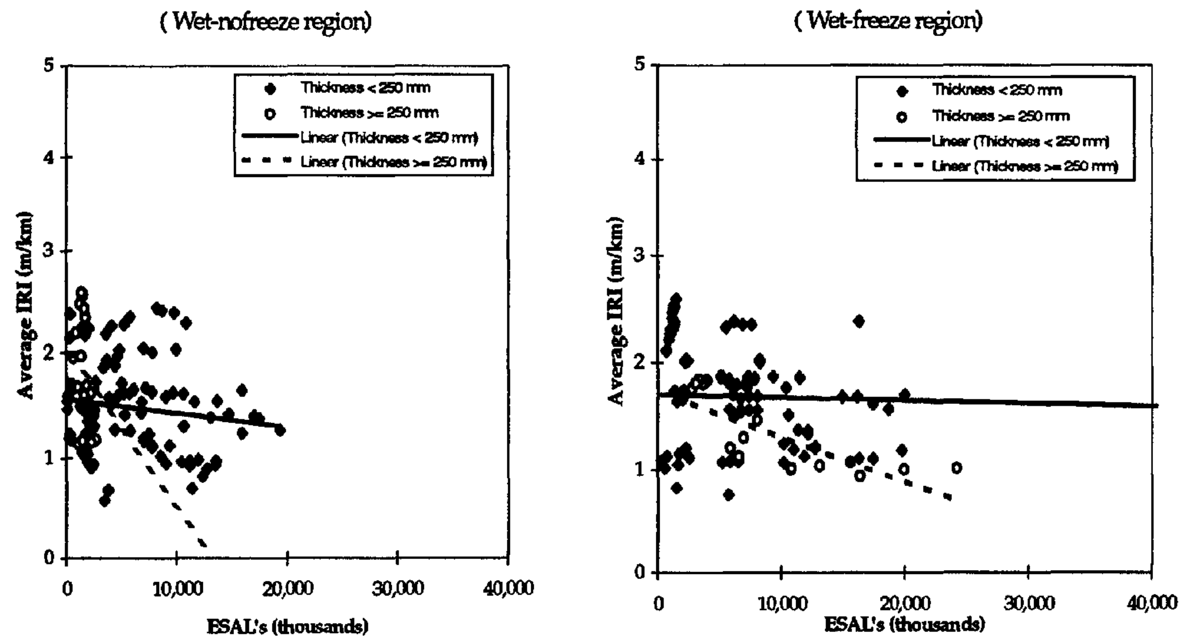


Figure 56. Plots showing the influence of slab thickness and climatic region on the IRI of CRCP LTPP sections.

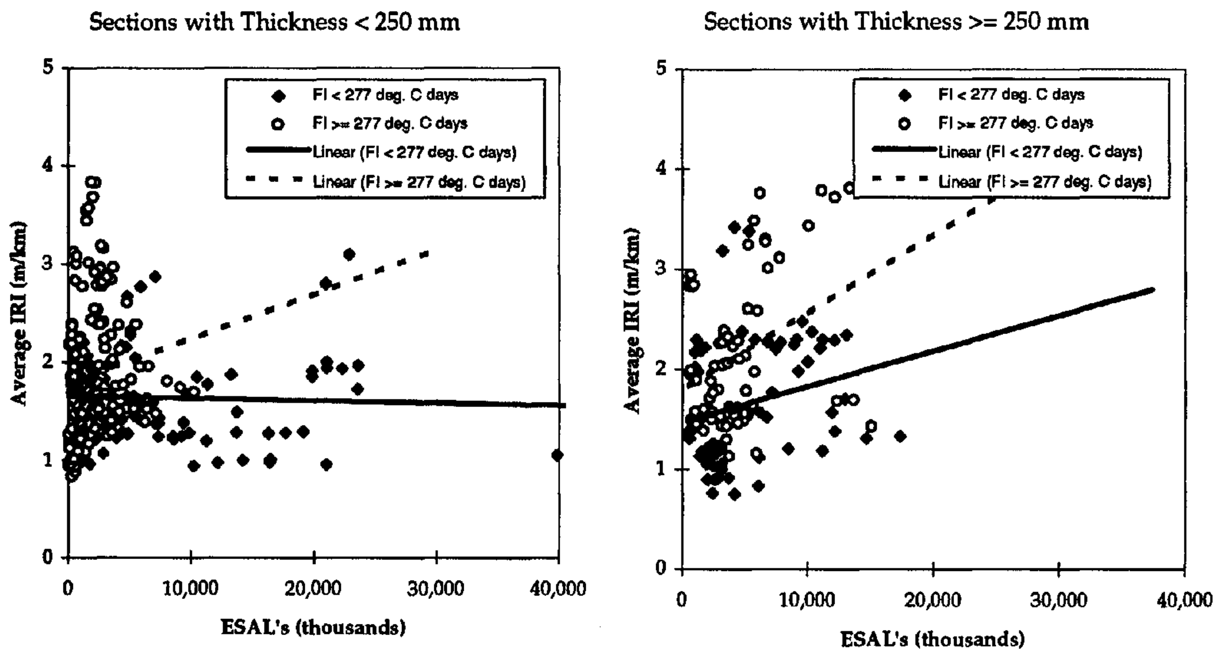


Figure 57. Plots of JPCP IRI versus traffic as influenced by slab thickness and freezing index (all climatic regions included).

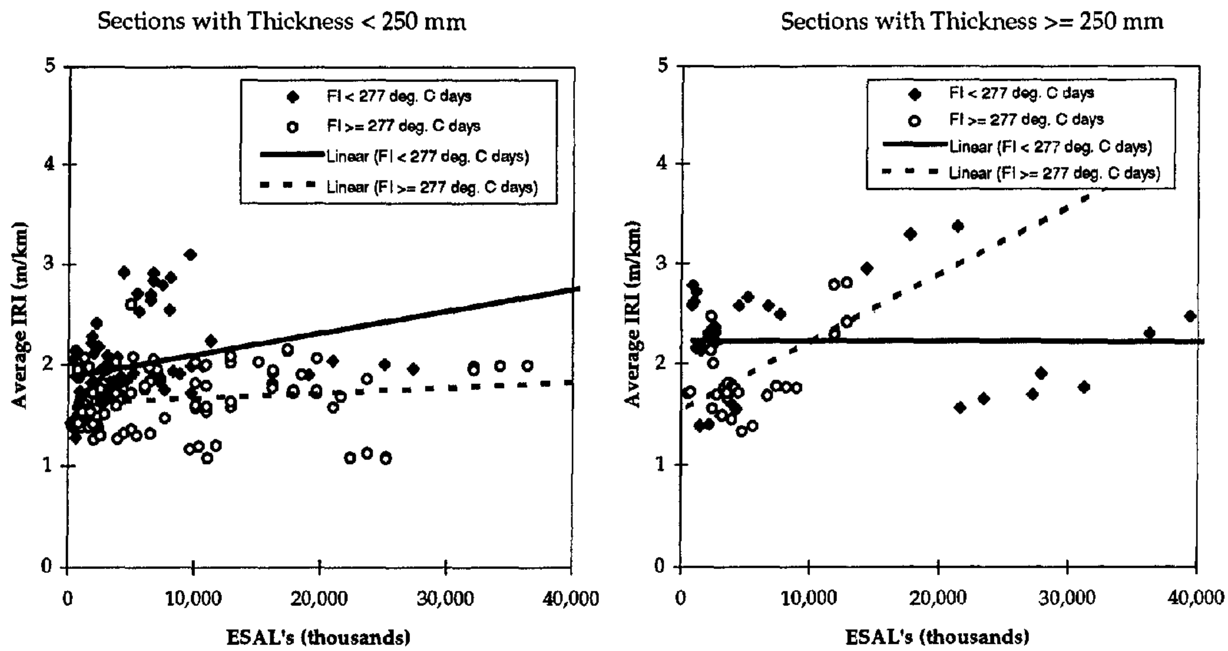


Figure 58. Plots of JRCP IRI versus traffic as influenced by slab thickness and freezing index (all climatic regions included).

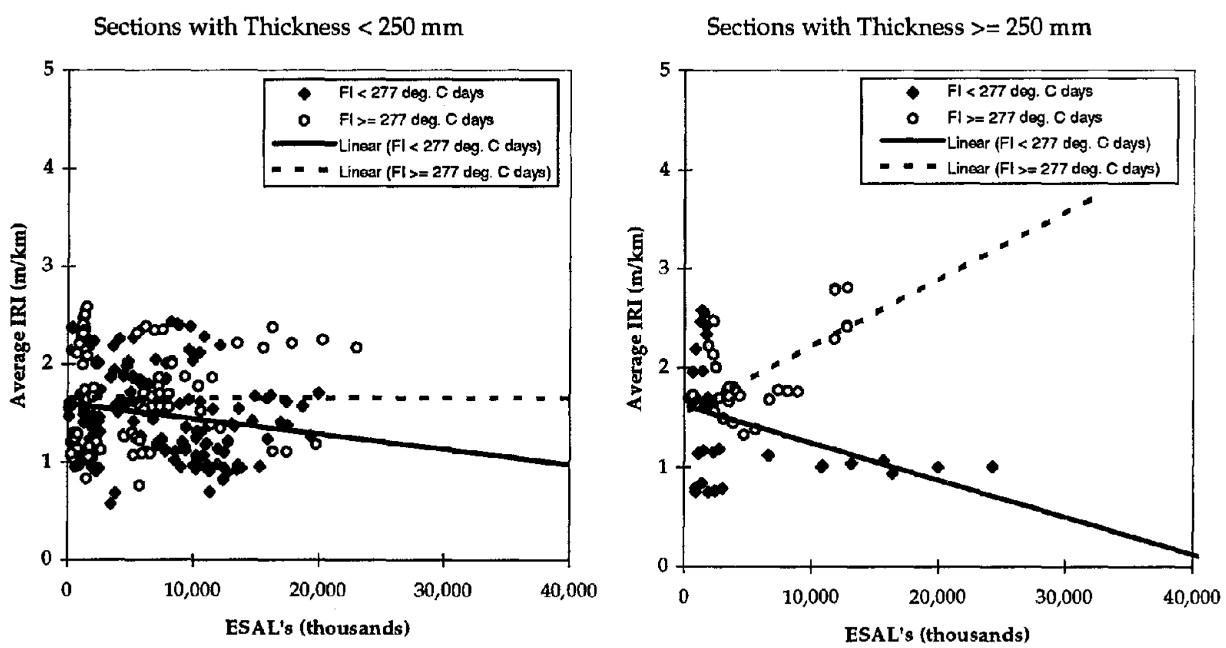


Figure 59. Plots of CRCP IRI versus traffic as influenced by slab thickness and freezing index (all climatic regions included).

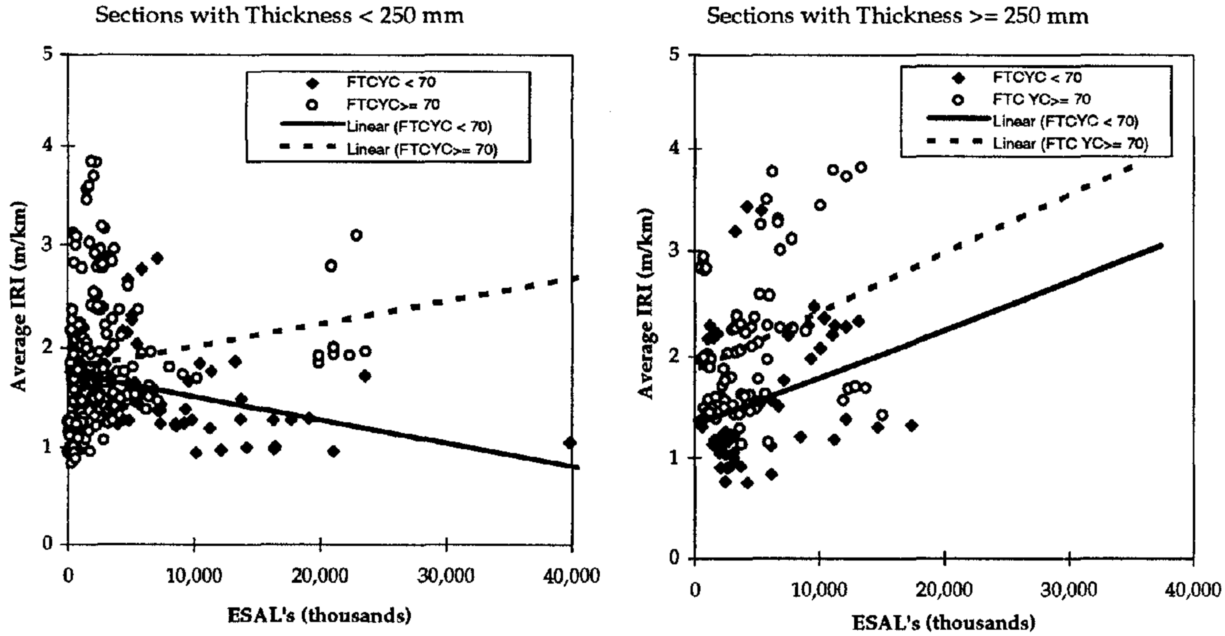


Figure 60. Plots of JPCP IRI versus traffic as influenced by slab thickness and freeze-thaw cycles (all climatic regions included).

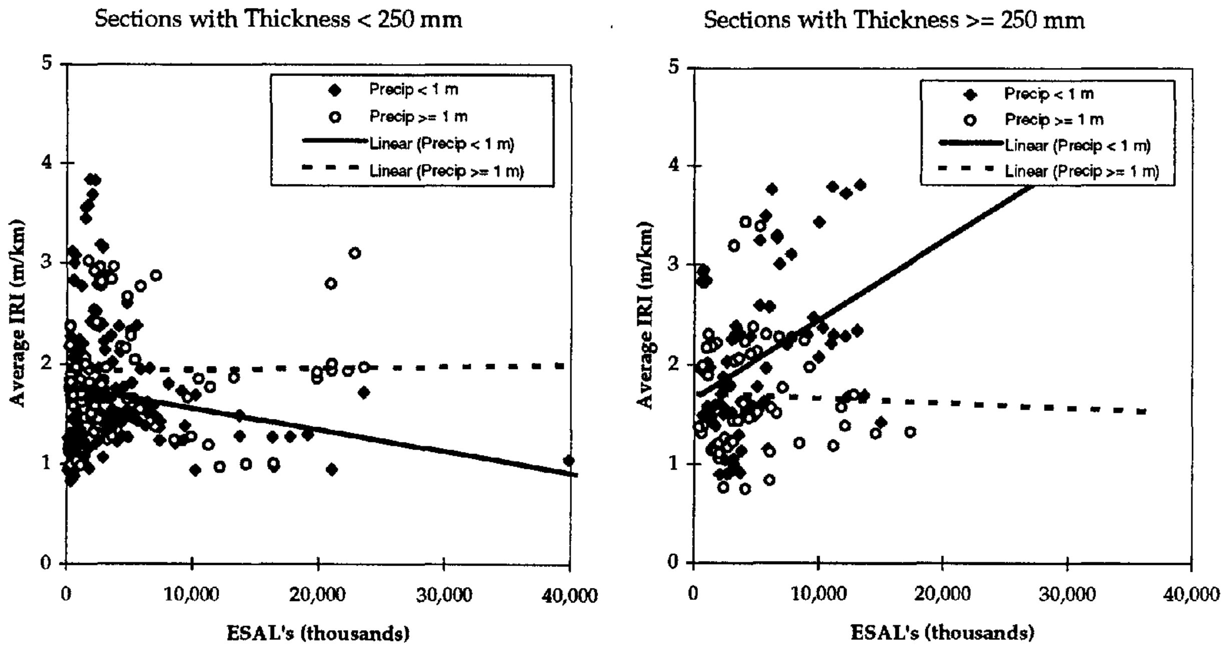


Figure 61. Plots of JPCP IRI versus traffic as influenced by slab thickness and average annual precipitation (all climatic regions included).

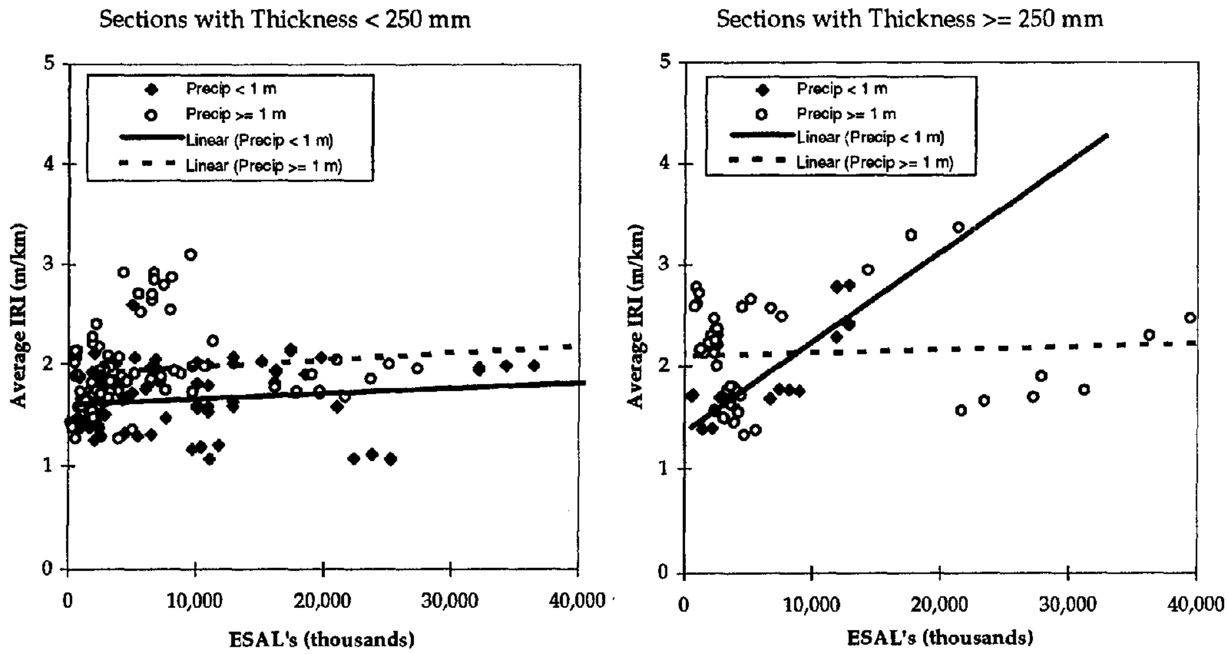


Figure 62. Plots of JRCP IRI versus traffic as influenced by slab thickness and average annual precipitation (all climatic regions included).

as the linear trends were virtually the same within each thickness category. Plots of the CRCP data as influenced by slab thickness and average annual precipitation are presented in figure 63.

Effect of Average Annual Temperature Range

The JPCP data for sections with slab thickness ≥ 250 mm showed that sections subjected to a smaller average annual temperature range (< 11 °C) generally exhibited higher IRI values than those sections subjected to a larger temperature range (≥ 11 °C). No clear trends could be determined for the JPCP thinner sections (thickness < 250 mm).

The JRCP sections showed the complete opposite trends. The thicker JRCP sections subjected to the larger temperature range developed higher IRI values than those sections subjected to the smaller temperature range. The CRCP plots showed that average annual temperature range had little or no significant influence on the IRI within either slab thickness category. Plots of the JPCP, JRCP, and CRCP IRI data as influenced by slab thickness and average annual temperature range are presented in figures 64, 65, and 66.

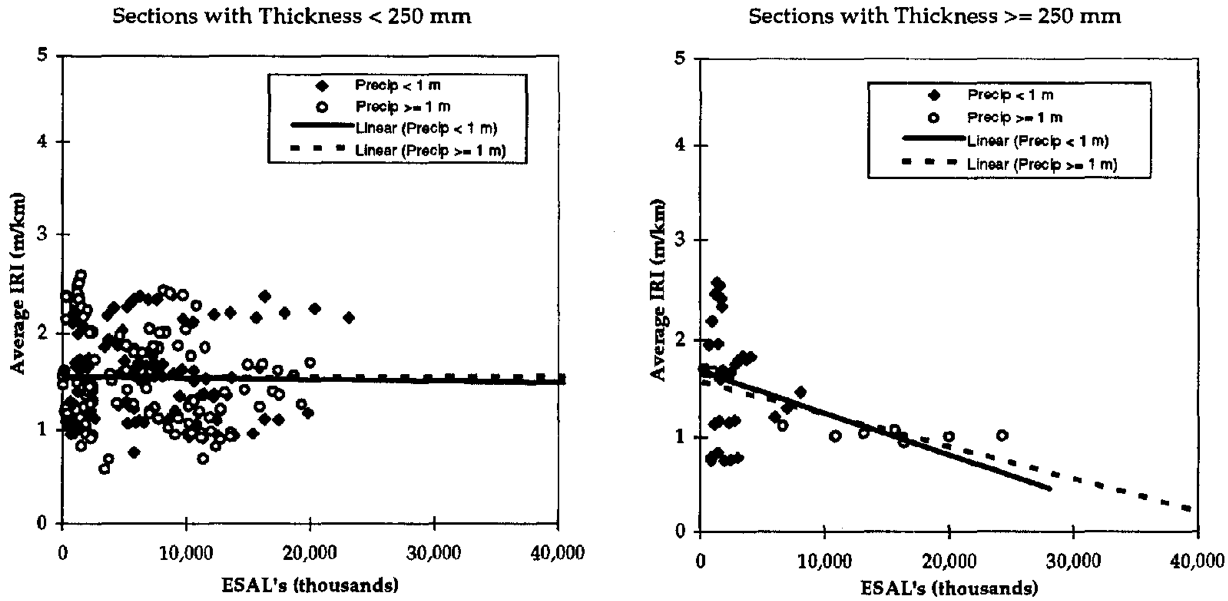


Figure 63. Plots of CRCP IRI versus traffic as influenced by slab thickness and average annual precipitation (all climatic regions included).

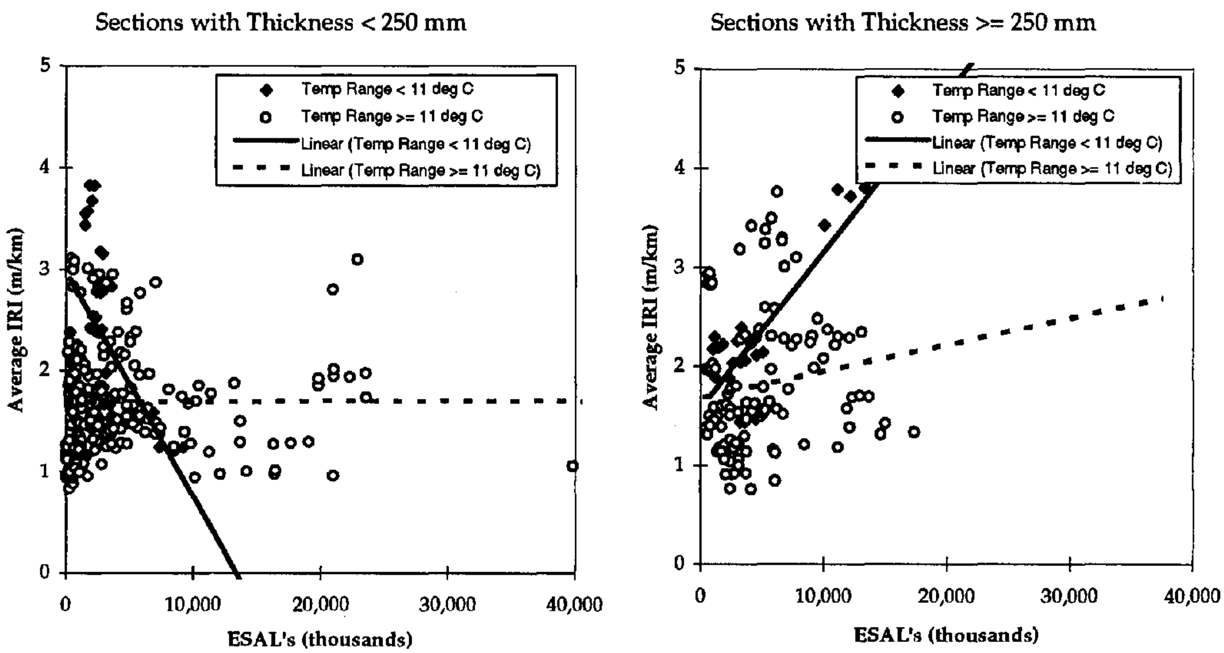


Figure 64. Plots of JPCP IRI versus traffic as influenced by slab thickness and average annual temperature range (all climatic regions included).

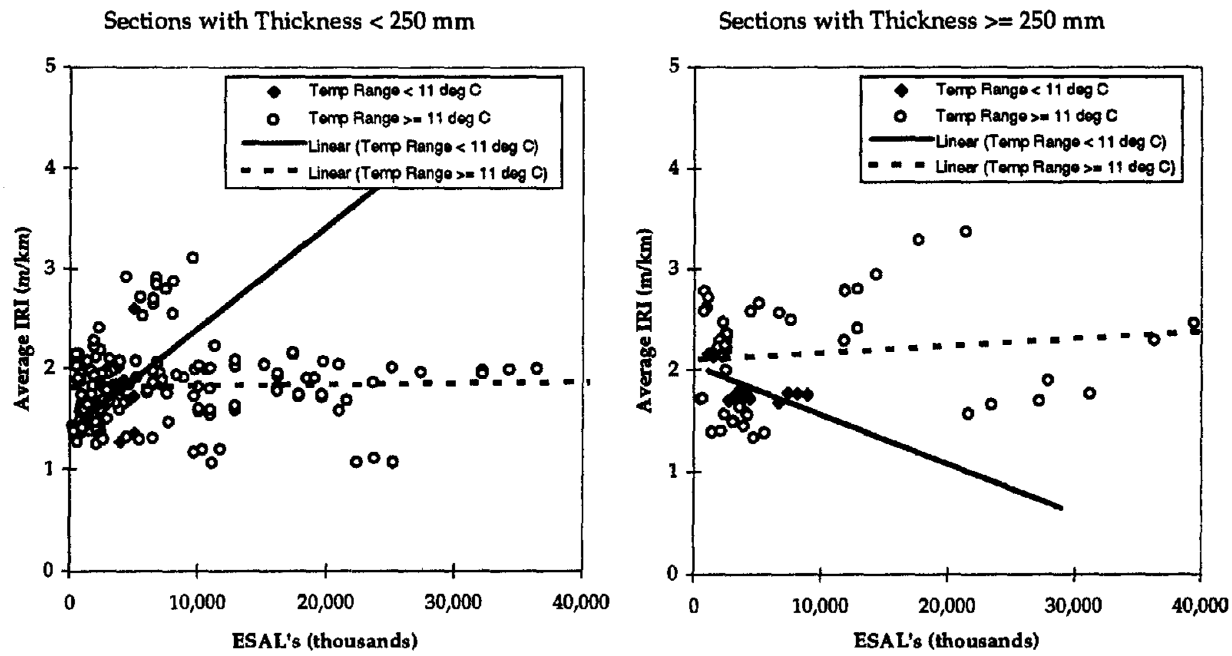


Figure 65. Plots of JRCP IRI versus traffic as influenced by slab thickness and average annual temperature range (all climatic regions included).

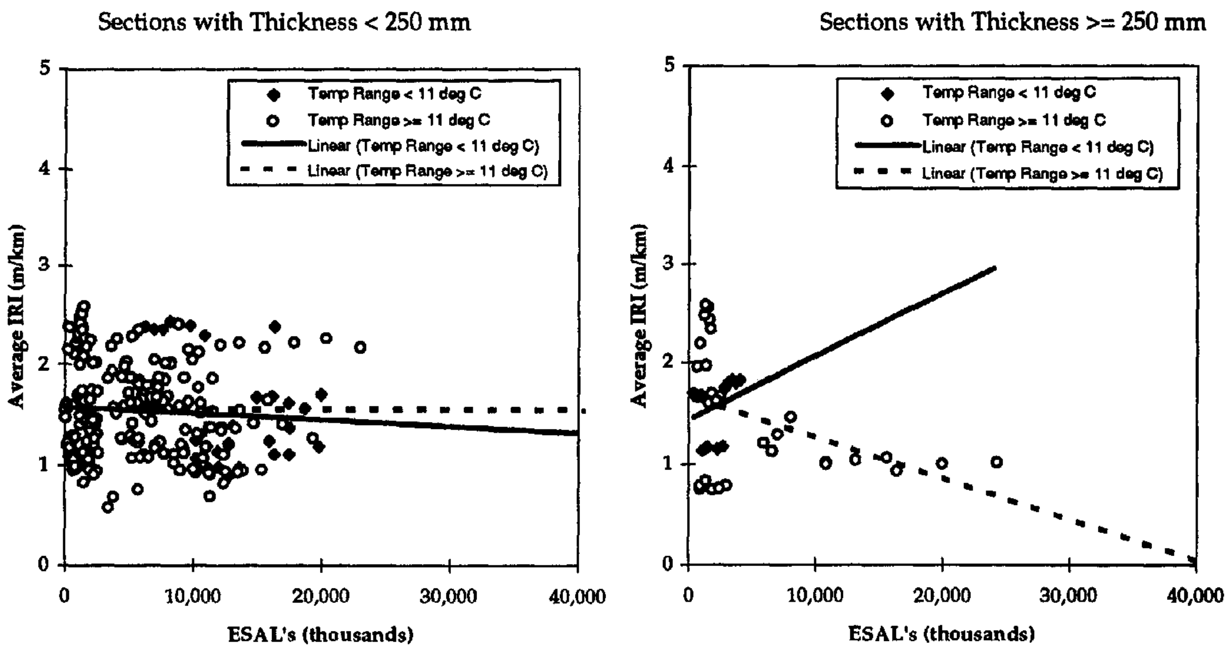


Figure 66. Plots of CRCP IRI versus traffic as influenced by slab thickness and average annual temperature range (all climatic regions included).

Effect of Average Annual Number of Wet Days

The JPCP data for sections with slab thickness $\geq$ 250 mm showed that sections subjected to an average annual number of wet days < 125 were more likely to develop higher IRI values than those sections subjected to $\geq$ 125 wet days. The data representing the thinner JPCP sections showed that the average annual number of wet days had no significant influence on those sections. Plots of the JPCP data as influenced by slab thickness and average annual number of wet days are presented in figure 67. The JRCP data showed that sections subjected to more average annual number of wet days ($\geq$ 125) developed higher IRI values (on average) regardless of slab thickness category. Plots of the JRCP and CRCP data as influenced by slab thickness and average annual number of wet days are presented in figures 68 and 69.

Effect of Subgrade Type

An analysis of the sensitivity of IRI to subgrade type for JPCP sections revealed no consistent linear trends (regardless of thickness category). The JRCP sections in both thickness categories exhibited higher IRI values for those sections with fine-grained subgrades. The linear trends for the thinner CRCP sections also showed that those sections with fine-grained subgrade types exhibited higher IRI values than those with coarse-grained subgrade types. No conclusions could be made for the CRCP sections with slab thickness $\geq$ 250 mm. A more general visual inspection of the data for all three pavement types appeared to show the highest IRI values coming from sections constructed on fine-grained soils. An analysis of the influence of slab thickness and subgrade type within each climatic region was not possible because of insufficient data. Figures 70 through 72 contain plots showing the influence of slab thickness and subgrade type on the IRI of JPCP, JRCP, and CRCP in all climatic regions.

Effect of Modulus of Subgrade Reaction (k-value)

An analysis of the sensitivity of IRI to k-value for JPCP pavements revealed that sections with k-values < 40.7 kPa/mm generally exhibited higher IRI values than those sections with k-values $\geq$ 40.7 kPa/mm (regardless of slab thickness category). The opposite was observed for the thicker sections (thickness $\geq$ 250 mm), where the sections with k-values $\geq$ 40.7 kPa/mm showed higher IRI values. Figure 73 contains plots showing the influence of slab thickness and static k-value on the IRI of JPCP LTPP sections. The LTPP data collected for JRCP sections showed that k-value had no significant influence on IRI for thinner JRCP sections (thickness < 250 mm). The thicker JRCP sections (thickness $\geq$ 250 mm) tended to exhibit higher IRI values for sections with larger k-values (k-value $\geq$ 40.7 kPa/mm). Figure 74 contains plots showing the influence of slab thickness and static k-value on the IRI of JRCP LTPP. Backcalculated static k-value did not appear to have any significant influence on the IRI of CRCP.

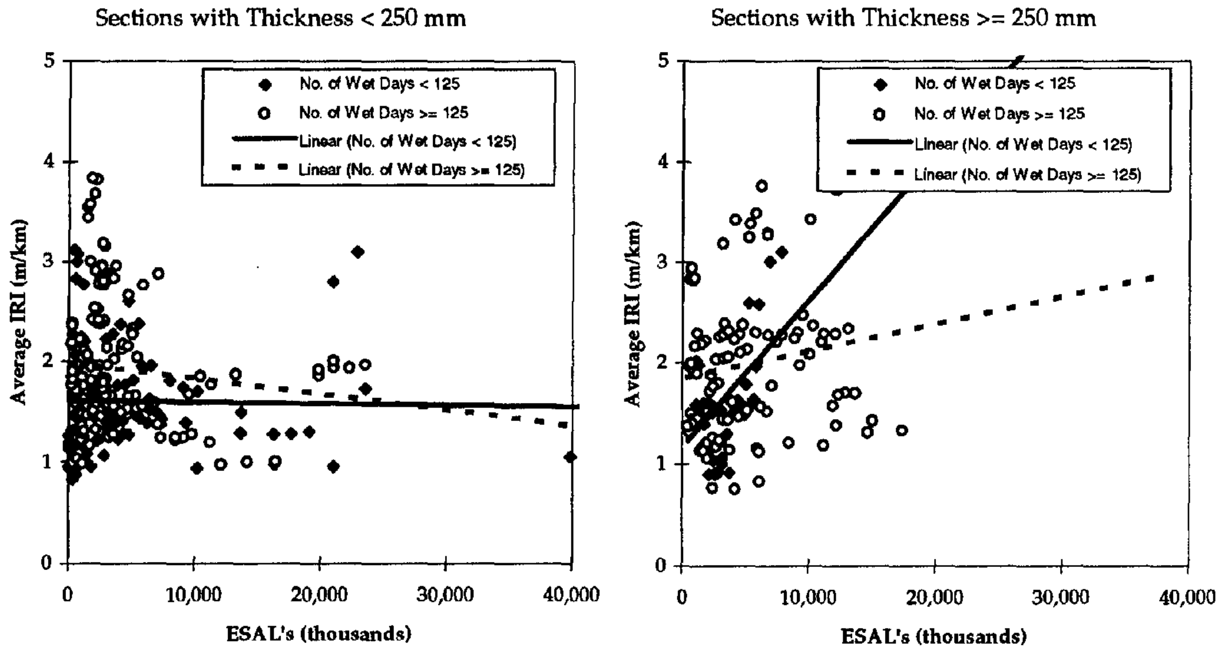


Figure 67. Plots of JPCP IRI versus traffic as influenced by slab thickness and average annual number of wet days (all climatic regions included).

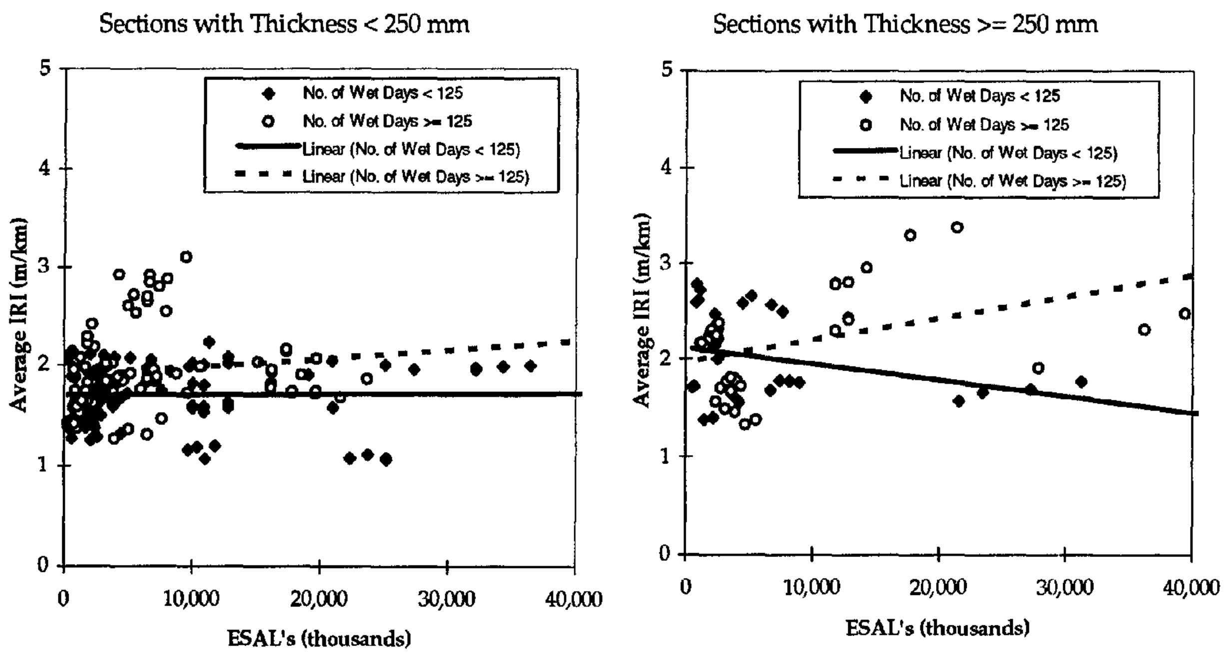


Figure 68. Plots of JRCP IRI versus traffic as influenced by slab thickness and average annual number of wet days (all climatic regions included).

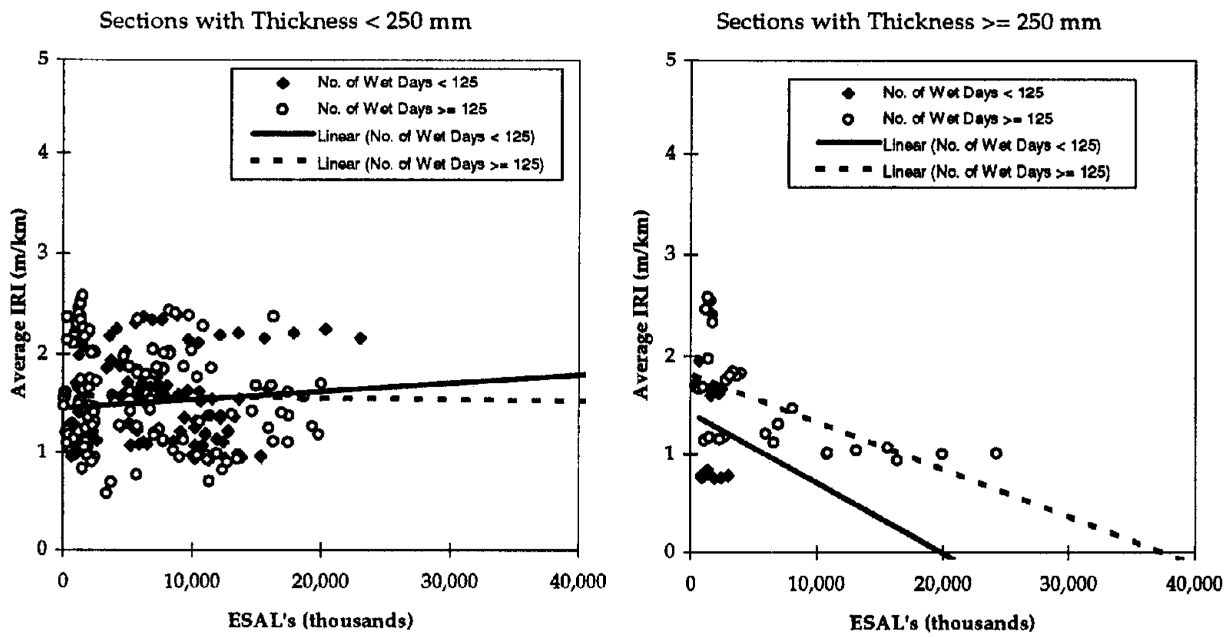


Figure 69. Plots of CRCP IRI versus traffic as influenced by slab thickness and average annual number of wet days (all climatic regions included).

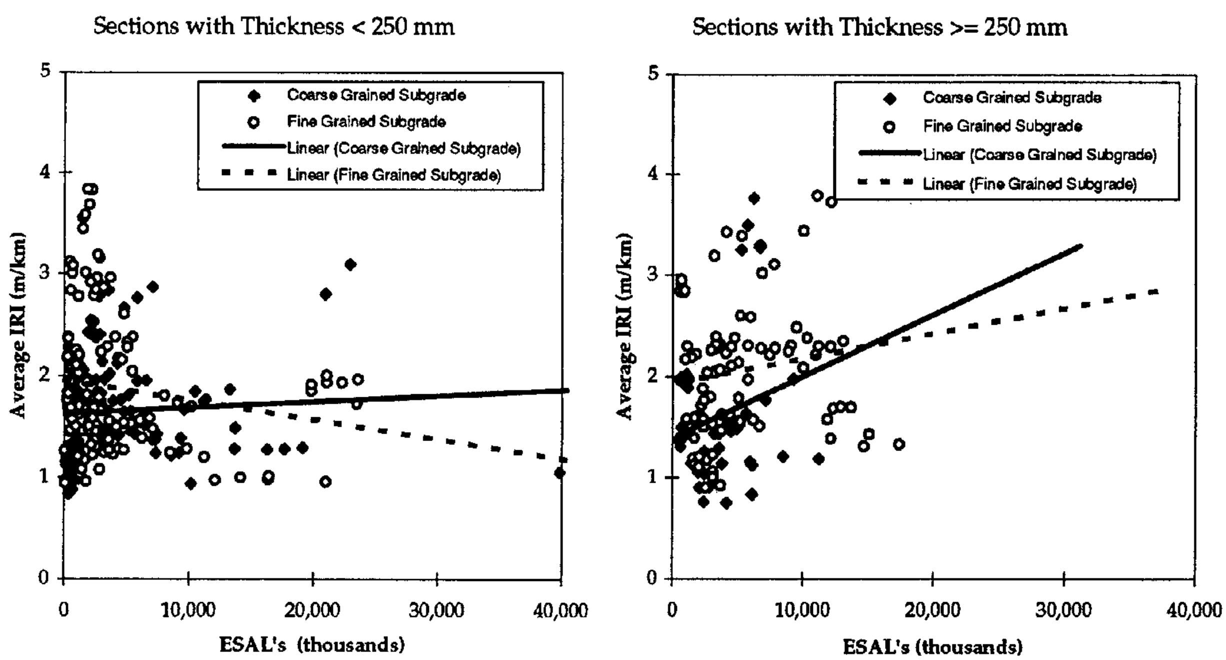


Figure 70. Plots showing the influence of slab thickness and subgrade type on the IRI of JPCP sections (all climatic regions included).

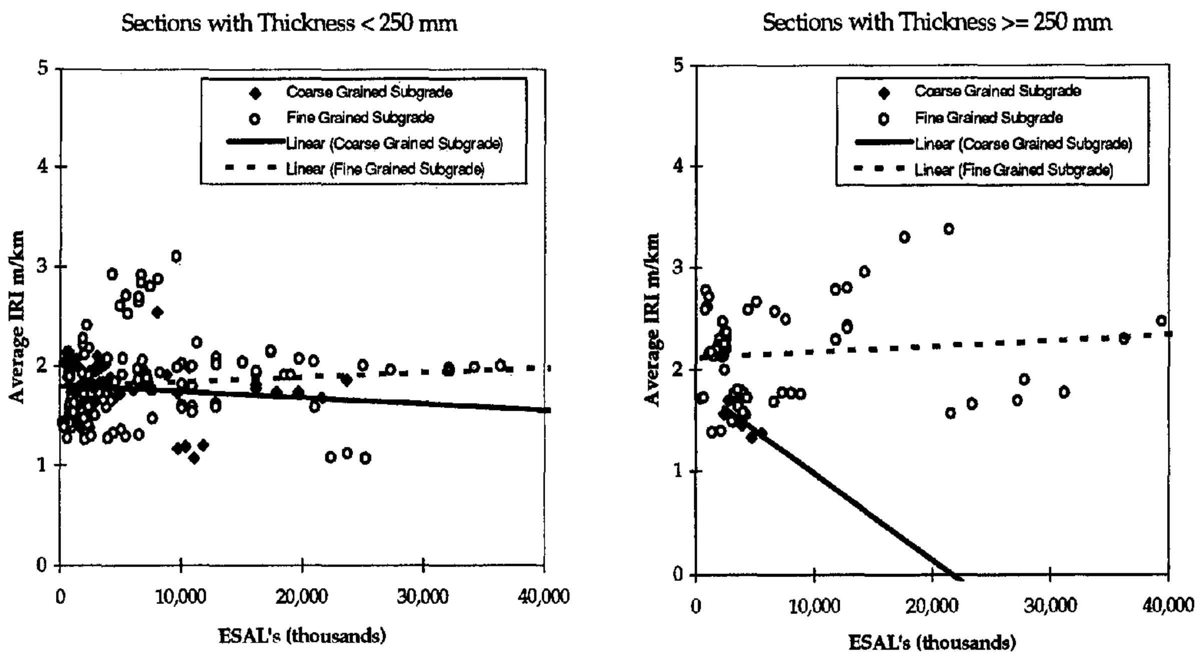


Figure 71. Plots showing the influence of slab thickness and subgrade type on the IRI of JRCP sections (all climatic regions included).

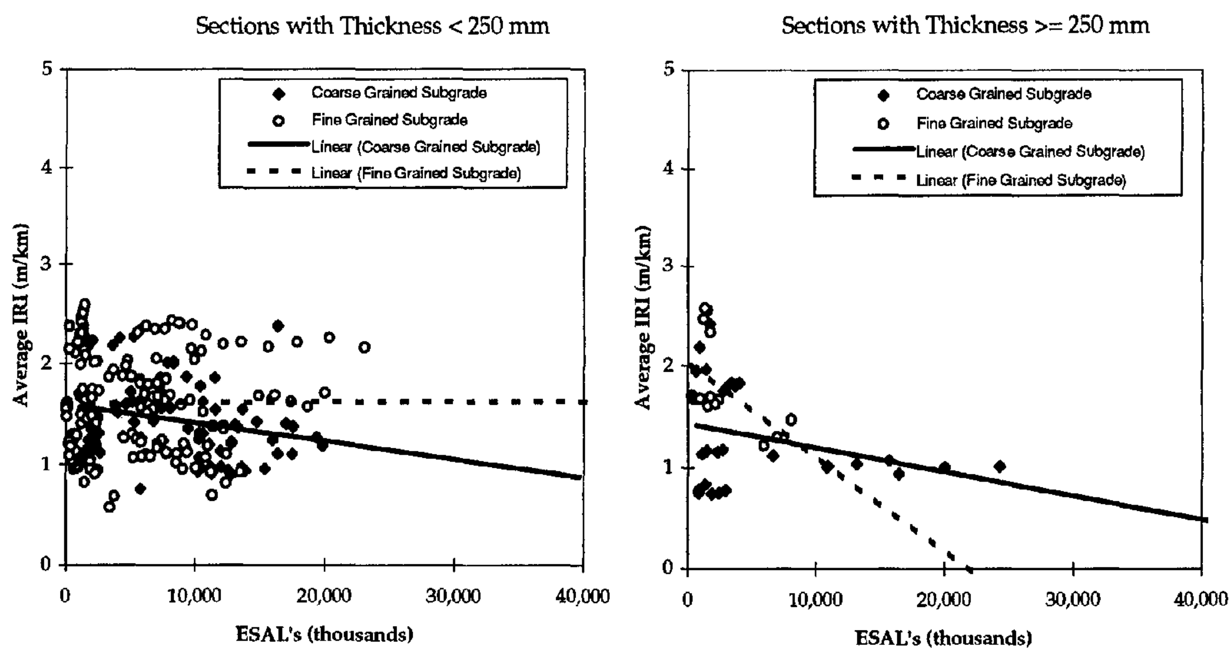


Figure 72. Plots showing the influence of slab thickness and subgrade type on the IRI of CRCP sections (all climatic regions included).

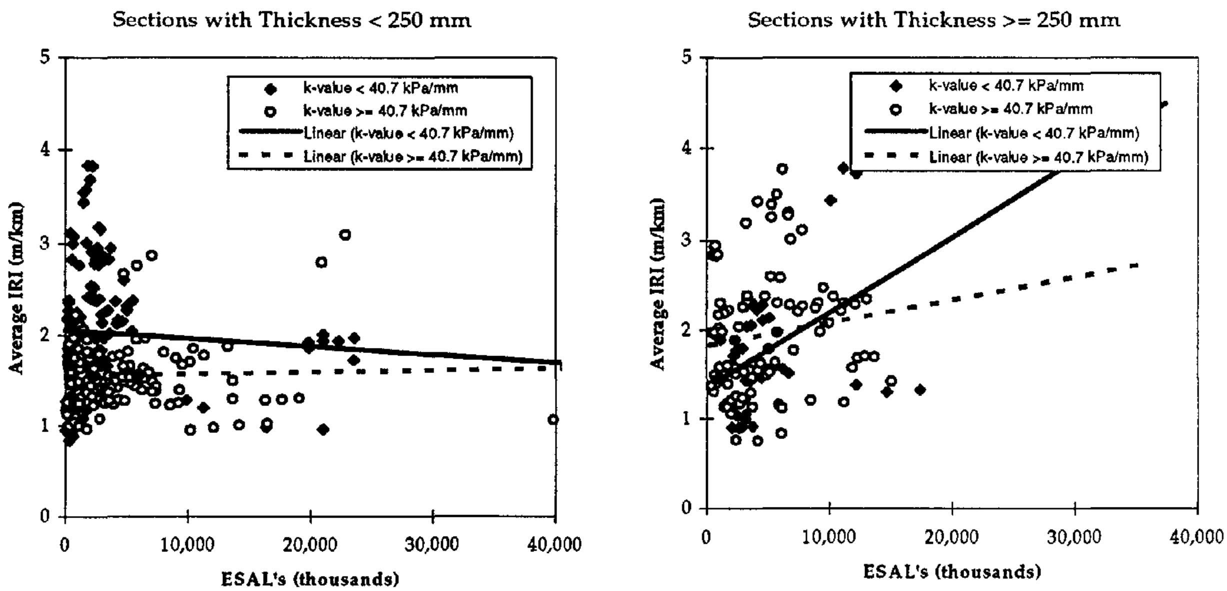


Figure 73. Plots showing the influence of slab thickness and backcalculated static k-value on the IRI of JPCP sections (all climatic regions included).

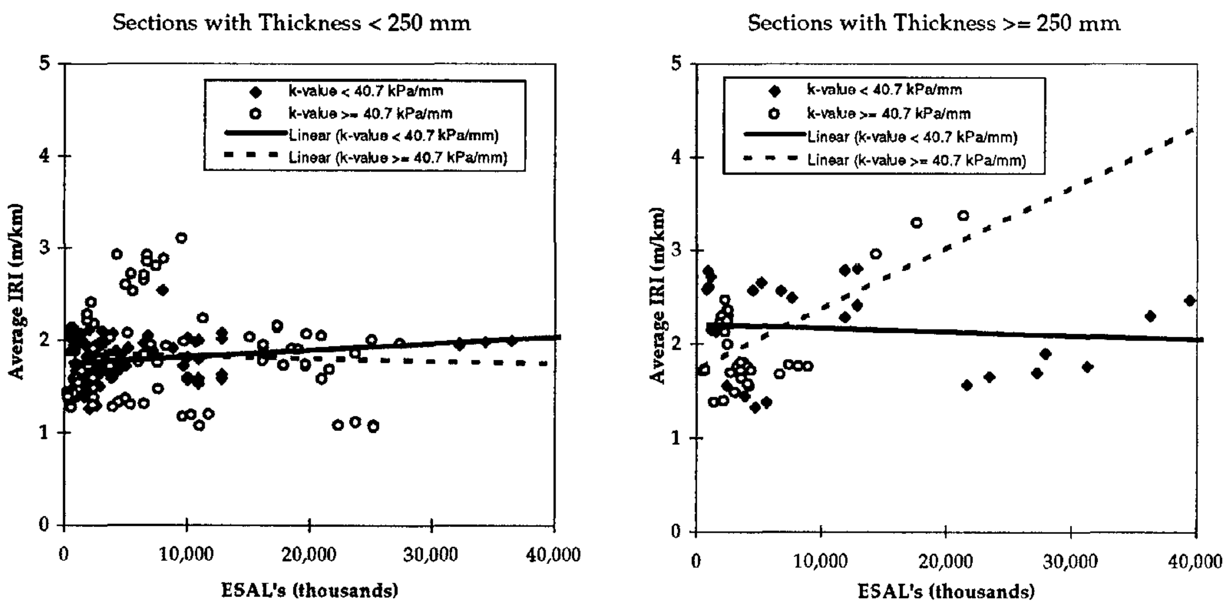


Figure 74. Plots showing the influence of slab thickness and backcalculated static k-value on the IRI of JRCP sections (all climatic regions included).

Influence of Design Features

The specific Level 2 design features investigated as part of this study were joint spacing, base type, base elastic modulus, modulus of rupture, shoulder type, and percentage steel content. For these cases, each variable was divided into the following categories for investigation:

- Joint spacing.
- Base type.
- Base elastic modulus.
- Modulus of rupture.
- Shoulder type.
- Percentage steel content (JRCP and CRCP).

The results of the analysis is presented as follows.

Effect of Average Joint Spacing

An analysis of the sensitivity of IRI to average transverse joint spacing (for JPCP and JRCP) revealed that joint spacing generally had very little or no influence on IRI. These conclusions are based on the virtually identical linear trends developed for the different average joint spacing categories within each of the four data sets representing each combination of pavement type and slab thickness. Figures 75 and 76 show these respective plots of JPCP and JRCP IRI versus traffic for the different thickness categories.

Effect of Base Type

The influence of the two base type categories (granular and stabilized) on the IRI of JPCP, JRCP, and CRCP was investigated for the sections already divided into categories of slab thickness (< 250 mm and ≥ 250 mm). Linear trends through the JPCP data showed higher IRI values (on average) for those sections with granular bases, regardless of thickness category. No clear trends were observed for the data in each individual climatic region. Figure 77 contains plots showing the influence of slab thickness and base type on the IRI of JPCP sections (data from all climatic regions were included).

Linear trends through the data representing the thinner JRCP sections (thickness < 250 mm) showed that base type had very little or no influence on the IRI of those sections. The conclusions were not the same, however, for thicker JRCP sections (≥ 250 mm). Thicker JRCP sections with granular bases were found to exhibit higher IRI values (on average) than those sections with stabilized bases. Like the JPCP data,

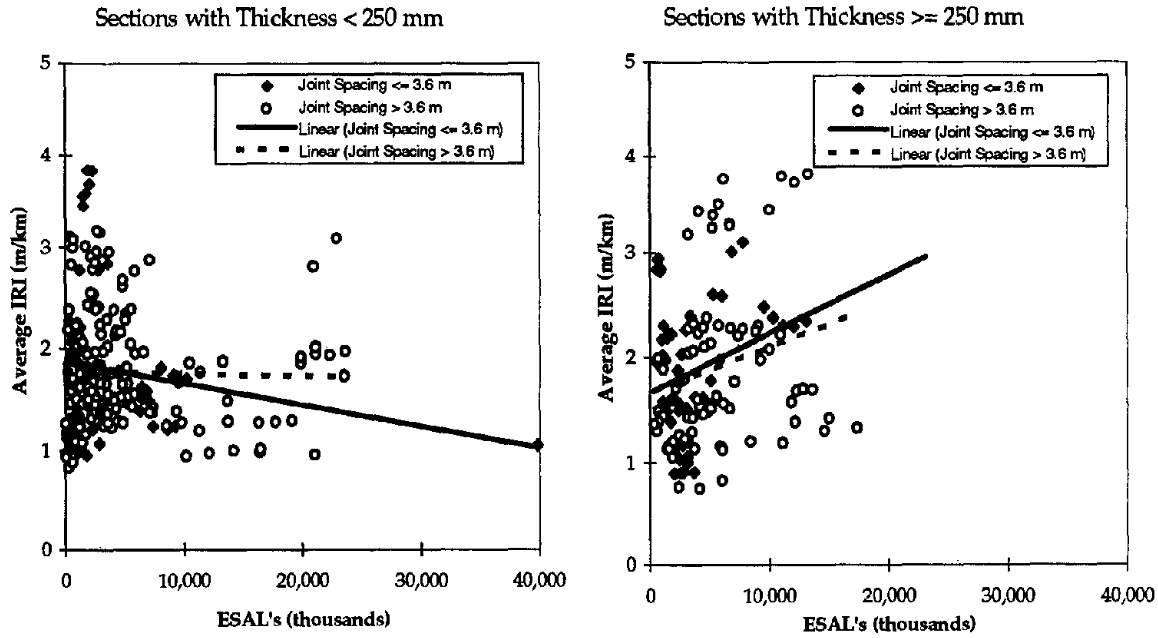


Figure 75. Plots showing the influence of slab thickness and average joint spacing on the IRI of JPCP sections (all climatic regions included).

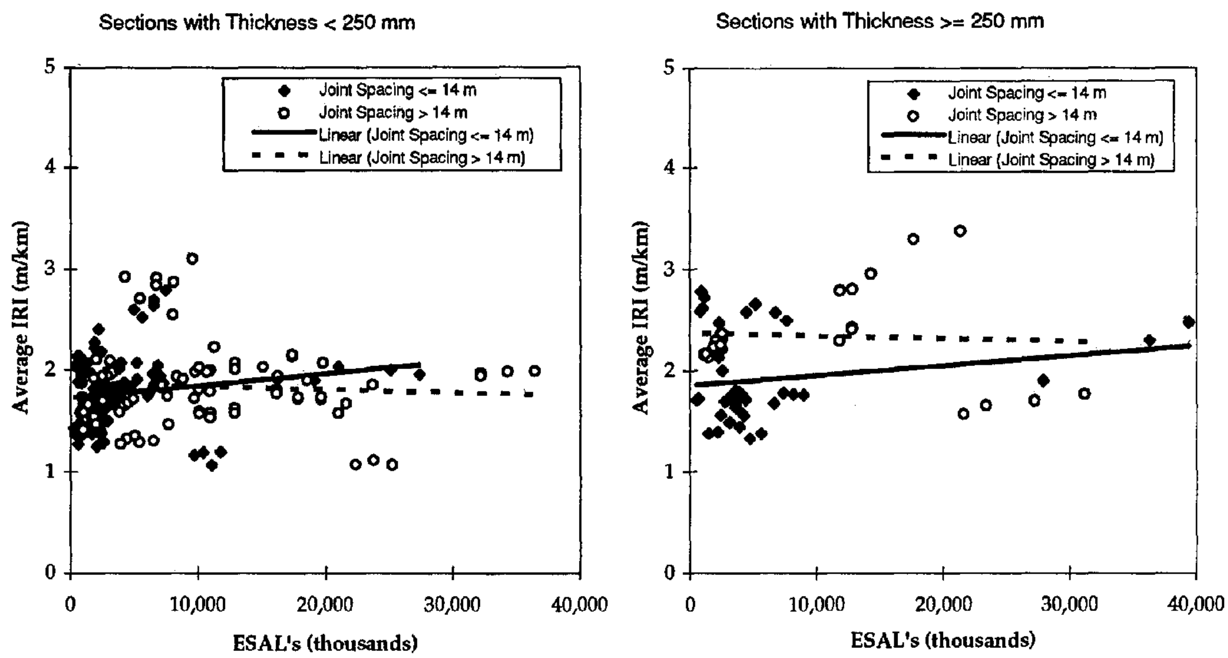


Figure 76. Plots showing the influence of slab thickness and average joint spacing on the IRI of JRCP sections (all climatic regions included).

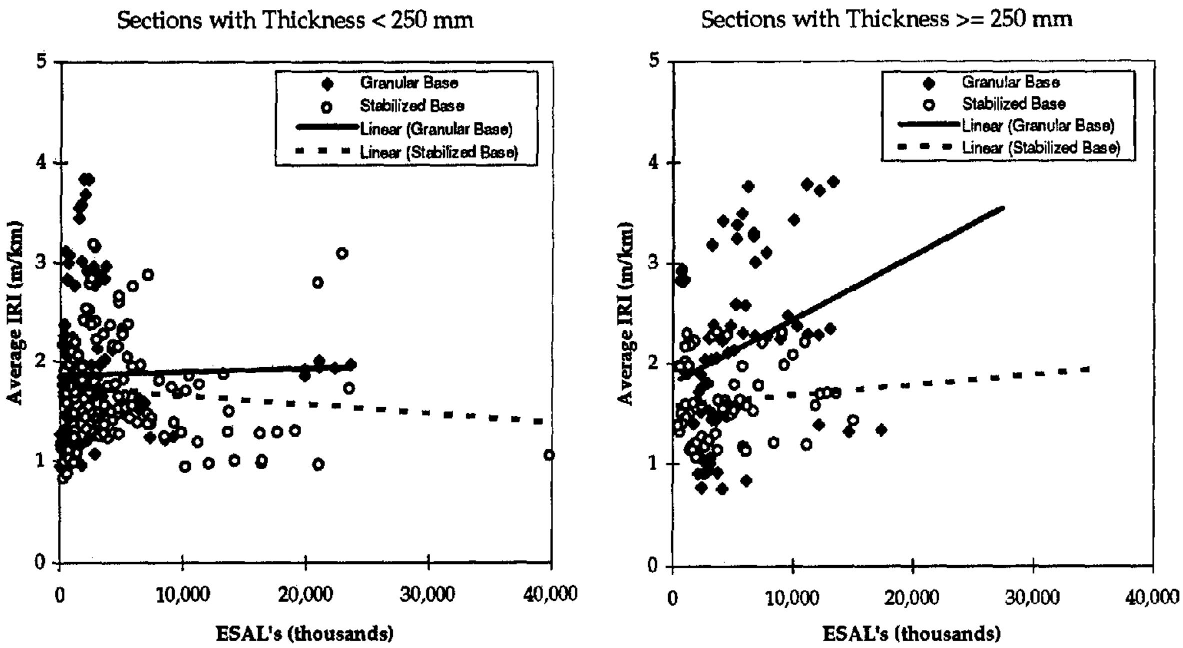


Figure 77. Plots showing the influence of slab thickness and base type on the IRI of JPCP sections (all climatic regions included).

no consistent trends were observed by looking at the data for different individual climatic regions. Figure 78 contains plots showing the influence of slab thickness and base type on the IRI of JRCP sections (data were included from all climatic regions).

An analysis of the CRCP IRI data showed that base type had no influence on the IRI of thinner sections (< 250 mm) and very little influence on the IRI of thicker sections (≥ 250 mm). Insufficient data made it difficult to look at these trends within each climatic region. Figure 79 contains plots showing the influence of slab thickness and base type on the IRI of CRCP sections (data were included from all climatic regions).

Effect of Base Elastic Modulus

The influence of base elastic modulus (≤ 690 MPa and >690 MPa) was investigated for the JPCP, JRCP, and CRCP data sets already divided by slab thickness (< 250 mm and ≥ 250 mm). The investigation revealed that base elastic modulus only had a significant influence on the IRI of JPCP sections. The JPCP sections in both thickness categories were found to exhibit higher IRI values (on average) when the base elastic modulus was ≤ 690 MPa. This trend was particularly clear for the thicker JPCP sections in the wet-freeze region and all of the sections in the wet-nofreeze regions (both

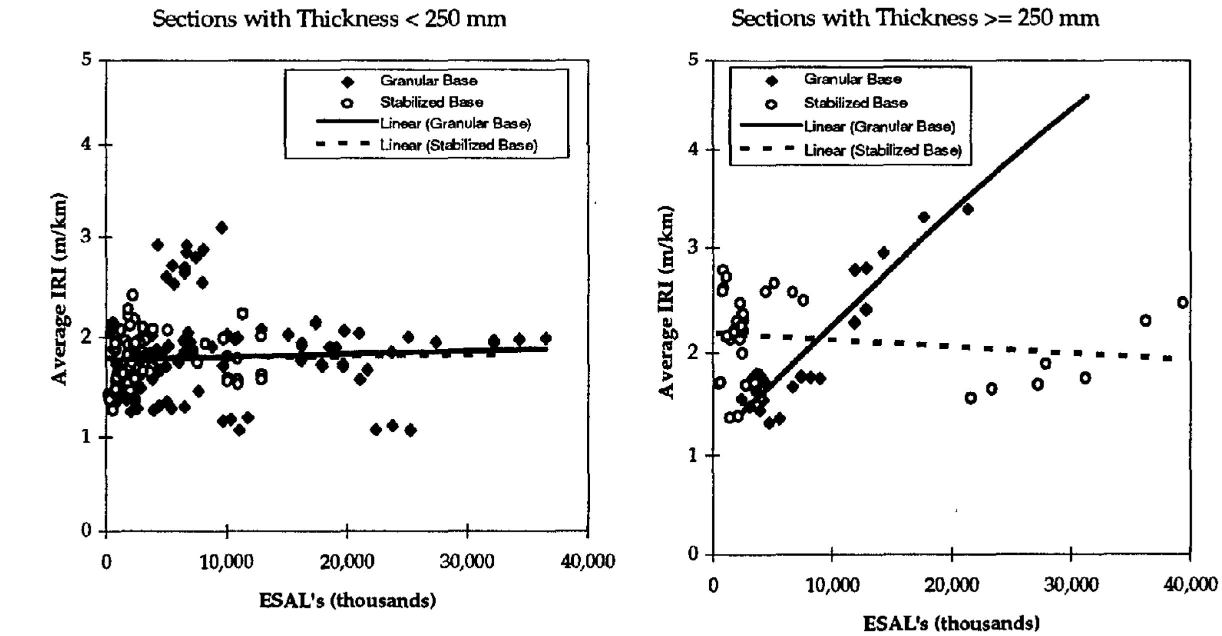


Figure 78. Plots showing the influence of slab thickness and base type on the IRI of JRCP sections (all climatic regions included).

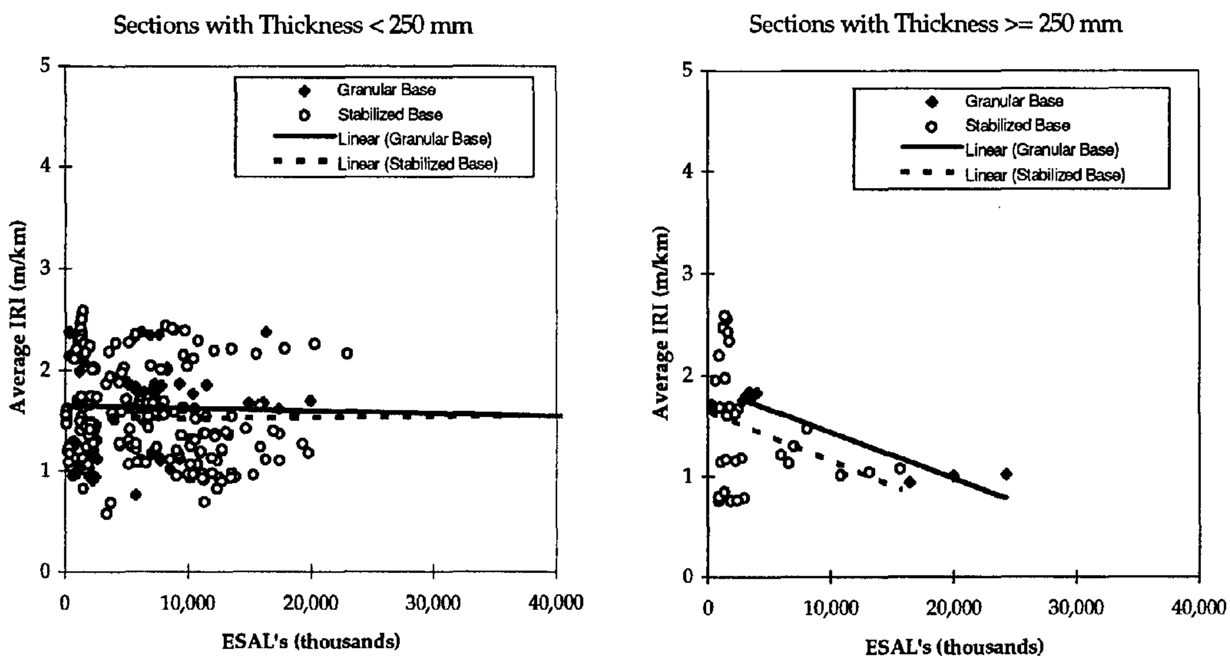


Figure 79. Plots showing the influence of slab thickness and base type on the IRI of CRCP sections (all climatic regions included).

thickness categories included). It was difficult to determine clear trends in any of the other data sets (combinations of climatic region and slab thickness) because of a lack of sufficient data. Figure 80 contains plots showing the influence of slab thickness and base elastic modulus on the IRI of JPCP sections (data were included from all climatic regions).

Effect of PCC 28-day Modulus of Rupture

An investigation of the influence of PCC 28-day modulus of rupture on IRI was conducted for the JPCP, JRCP, and CRCP LTPP sections. The analysis revealed that PCC 28-day modulus of rupture had little or no significant influence on the IRI of JPCP, JRCP, and CRCP sections when data from all climatic regions were grouped together. An analysis of the data in the individual climatic regions did, however, show some clear trends. The investigation of the JPCP sections in the regions with wet conditions showed that higher IRI values were exhibited by sections with a PCC 28-day modulus of rupture $\geq$ 4.5 MPa (regardless of thickness category). No clear trends were observed for the JPCP in the other climatic regions because of insufficient data.

Effect of PCC Elastic Modulus

The influence of two different PCC elastic modulus levels (E_{PCC} < 27,000 MPa and $\geq$ 27,000 MPa) on IRI was investigated for JPCP, JRCP, and CRCP sections already divided by thickness category (< 250 mm and $\geq$ 250 mm). Only the JPCP data showed that PCC elastic modulus had a significant influence on IRI. The thicker JPCP sections showed higher IRI values (on average) when PCC elastic modulus was $\leq$ 27,000 MPa.

The thinner JPCP sections showed an opposite trend. Slightly higher IRI values (on average) were exhibited by those sections with PCC elastic modulus $\geq$ 27,000 MPa. A secondary investigation of the JPCP data in the four individual climatic regions revealed trends for the sections in the wet-freeze region only. The trends in this region followed the trends described above for the data in all climatic regions. The thinner JPCP sections with PCC elastic modulus $\geq$ 27,000 MPa and the thicker JPCP sections with PCC elastic modulus < 27,000 MPa showed higher IRI values (on average). Figure 81 contains plots showing the influence of slab thickness and PCC elastic modulus on the IRI of JPCP LTPP sections (all climatic regions are included).

Effect of Outside Shoulder Type

The influence of two outside shoulder types (PCC and non-PCC) on the IRI of JPCP, JRCP, and CRCP was investigated for the sections already divided into categories of slab thickness (< 250 mm and $\geq$ 250 mm). Linear trends through the JPCP data showed higher IRI values for thicker sections ($\geq$ 250 mm) with non-PCC shoulders, whereas

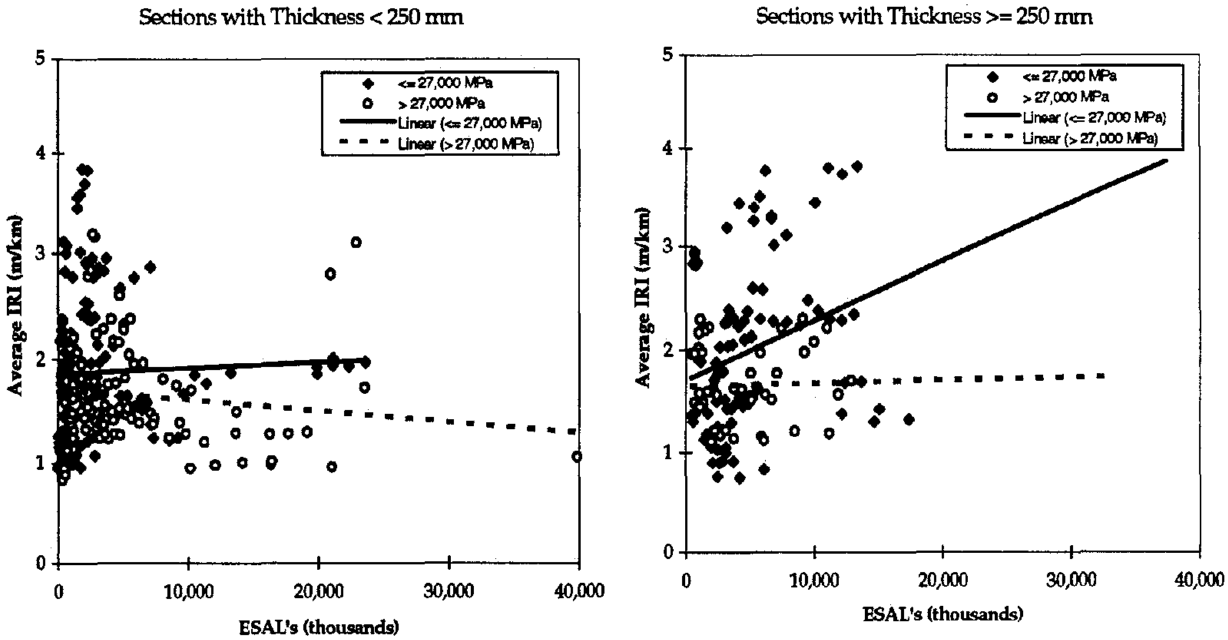


Figure 80. Plots showing the influence of slab thickness and base elastic modulus on the IRI of JPCP sections (all climatic regions included).

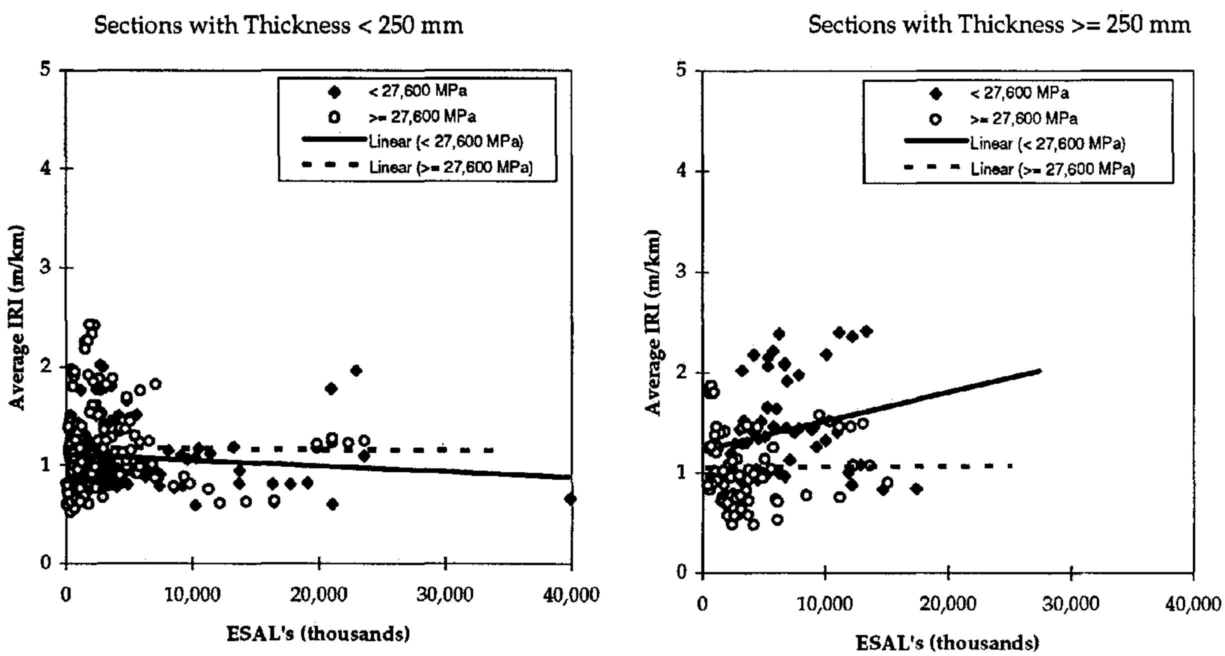


Figure 81. Plots showing the influence of slab thickness and PCC elastic modulus on the IRI of JPCP LTPP sections (all climatic regions are included).

there appeared to be little or no influence of shoulder type on the IRI of thinner JPCP sections (< 250 mm). No clear trends were observed for the data within each individual climatic region. Figure 82 contains plots showing the influence of slab thickness and outer shoulder type on the IRI of JPCP sections (data from all climatic regions were included).

Linear trends through the JRCP data representing the thinner sections (< 250 mm) showed the highest IRI values for sections with PCC shoulders. Linear trends through the JRCP data representing the thicker sections (≥ 250 mm) showed the opposite trend, with the highest IRI values coming from sections with non-PCC shoulders. However, it is important to note that very few JRCP sections with thickness > 250 mm had PCC shoulders. Again, no clear trends were observed for the data within each individual climatic region because of the lack of sufficient data. Figure 83 contain plots showing the influence of slab thickness and outer shoulder type on the IRI of JRCP sections (data from all climatic regions were included).

Linear trends through the CRCP data representing the thinner sections (< 250 mm) showed a general trend of the highest IRI values coming from sections with non-PCC shoulders. No clear trends were developed for the data representing the thicker CRCP sections; however, a visual inspection of the CRCP data showed that the highest IRI values were from sections with PCC shoulders. Insufficient data were available to identify trends for the CRCP sections in the individual climatic regions. Figure 84 contains plots showing the influence of slab thickness and outer shoulder type on the IRI of CRCP sections (data were included from all climatic regions).

Effect of Percentage Steel Content

An investigation of the influence of steel percentage on IRI was conducted for the JRCP and CRCP LTPP sections. The analysis revealed that steel percentage had little or no significant influence on IRI when data from all climatic regions were grouped together.

Influence of Construction Practices on Roughness

The main Level 2 construction practice that influences roughness directly is surface texturing; however, other construction practices that could potentially influence roughness, such as paver type, curing method, joint forming method, steel placement method, and dowel placement method were investigated at the preliminary stage.

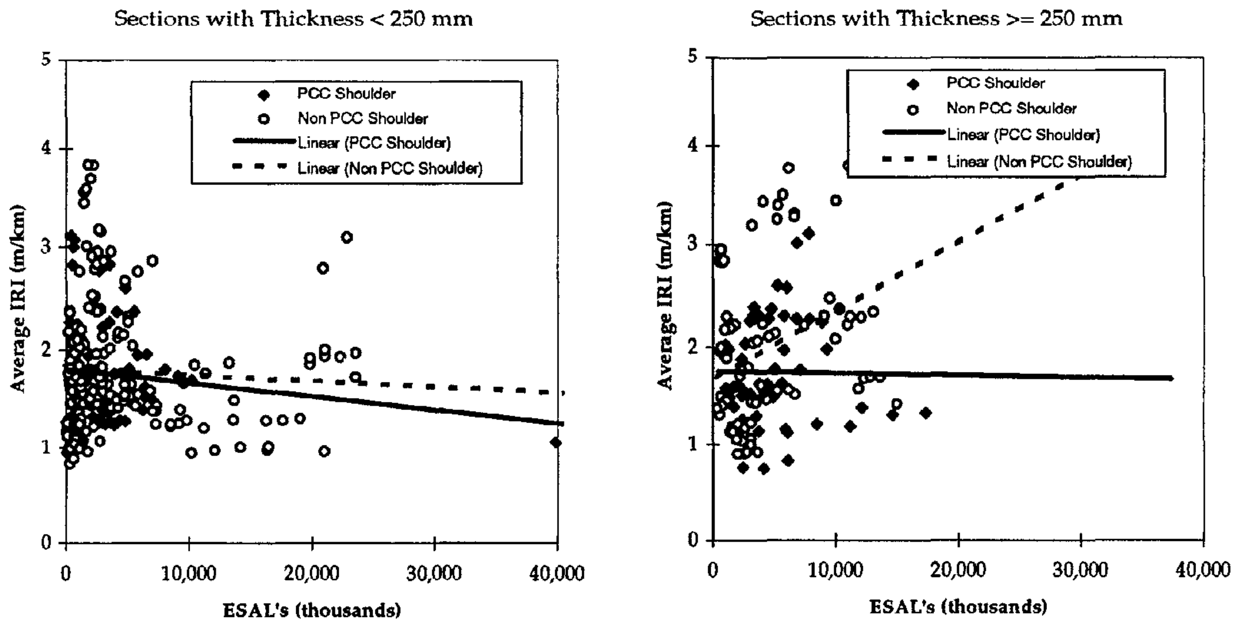


Figure 82. Plots showing the influence of slab thickness and outer shoulder type on the IRI of JPCP sections (all climatic regions included).

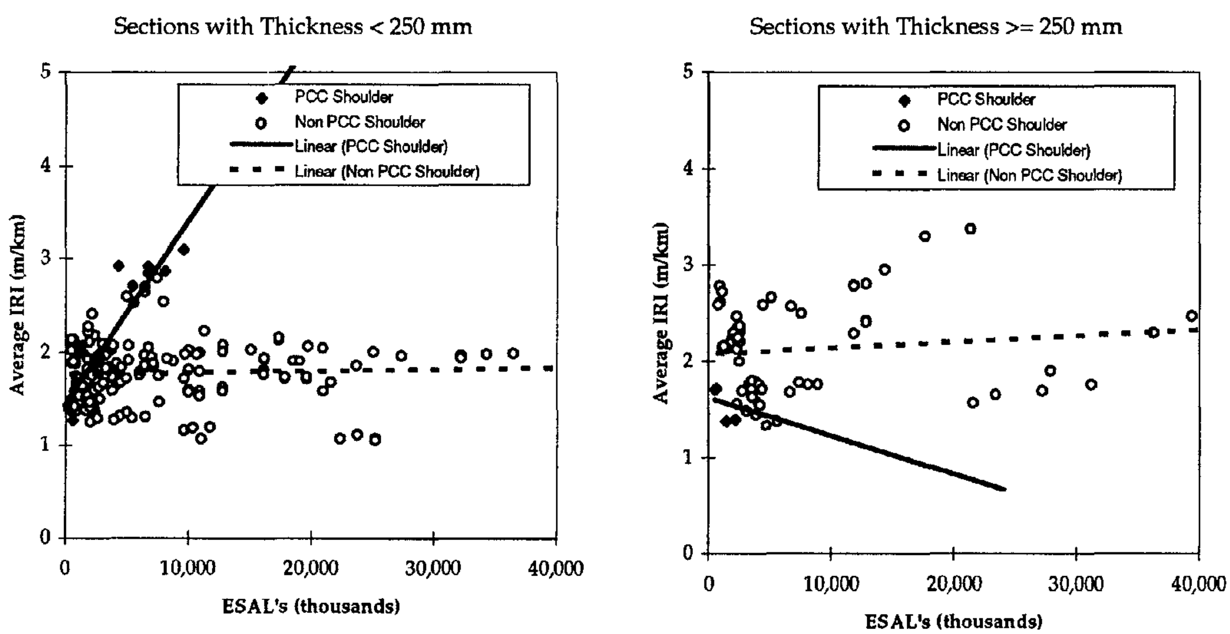


Figure 83. Plots showing the influence of slab thickness and outer shoulder type on the IRI of JRCP sections (all climatic regions included).

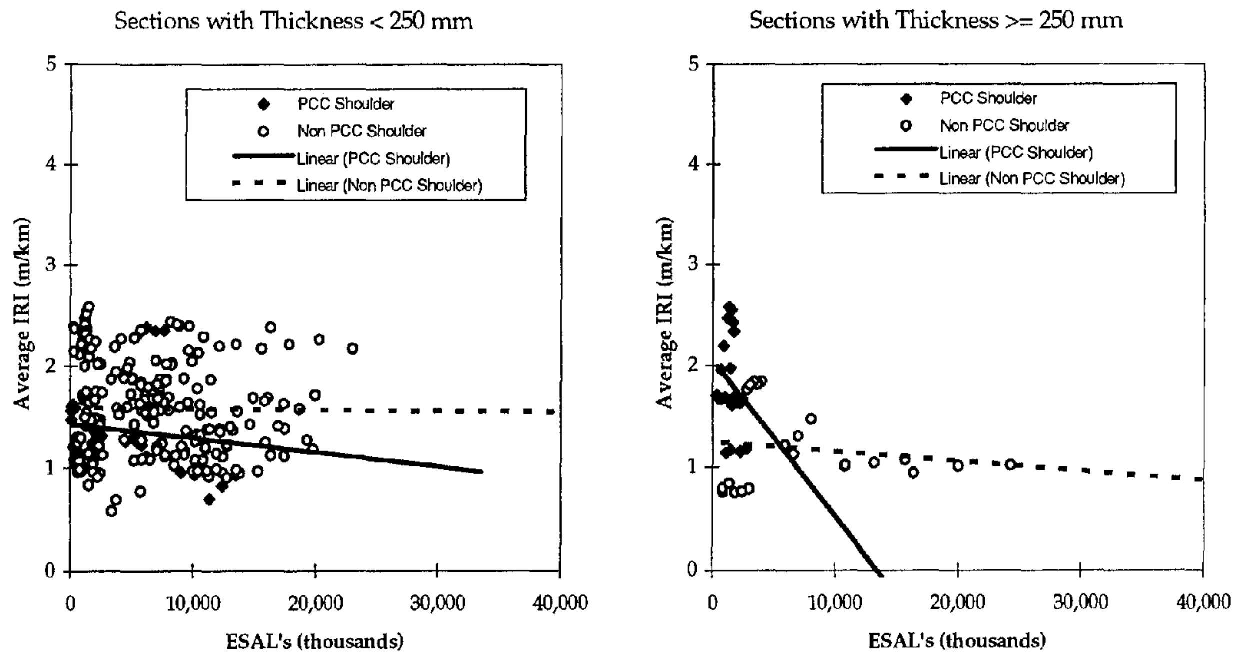


Figure 84. Plots showing the influence of slab thickness and outer shoulder type on the IRI of CRCP sections (all climatic regions included).

Effect of Paver Type

The influence of paver type on the IRI of JPCP, JRCP, and CRCP sections was investigated for the data sets already divided by slab thickness category (< 250 mm and ≥ 250 mm). For all three pavement types, two different paver types were compared—slip form and side form.

Paver type appeared to have a significant effect on the IRI of JPCP sections, with higher values appearing for those sections constructed with a slip form paver. This trend held true for JPCP sections in both slab thickness categories. The influence on the JRCP data was not as clear. Paver type appeared to have no significant influence on the JRCP data with slab thickness < 250 mm; however, for the thicker sections (≥ 250 mm) those constructed using a side form paver exhibited higher IRI values on average (note: this trend is based on very few data points). Finally, no clear trends were observed for the CRCP data in either thickness category. Insufficient data made it impossible to investigate the specific effects of climatic region on these data sets. Figure 85 contains plots showing the influence of paver type and slab thickness on the IRI of JPCP, JRCP, and CRCP LTPP sections, respectively (data from all climatic regions are included).

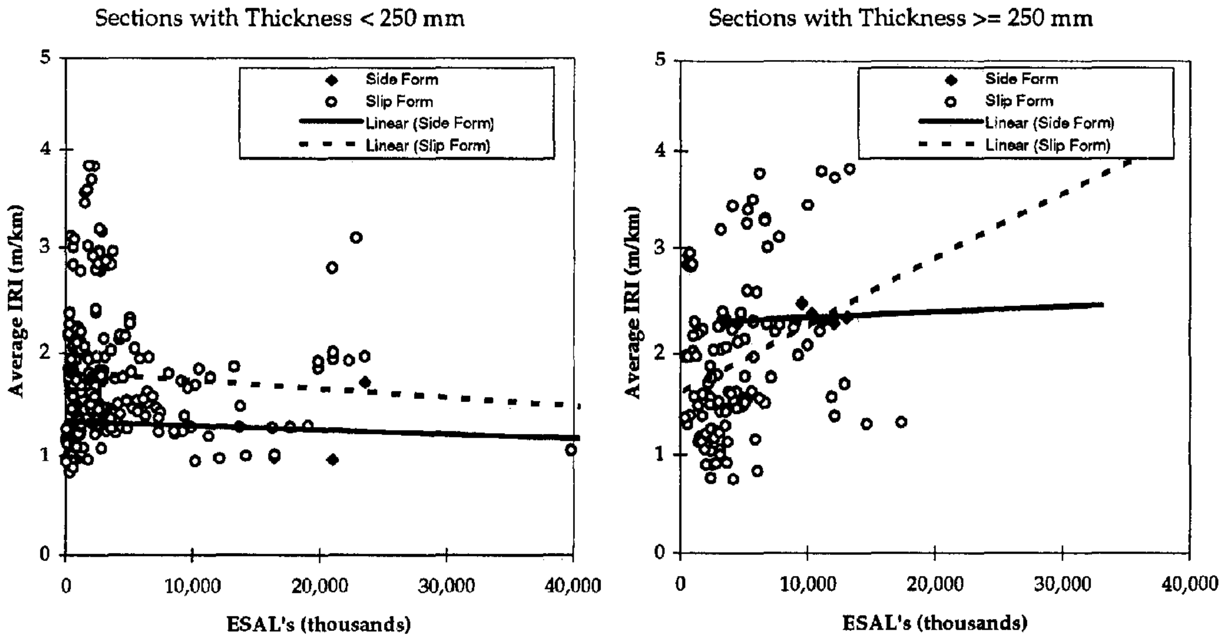


Figure 85. Plots showing the influence of paver type and slab thickness on the IRI of JPCP LTPP sections (all climatic regions included).

Effect of Curing Method

The influence of curing method on the IRI of JPCP, JRCP, and CRCP sections was investigated separately for each pavement type. Four different curing methods were observed for the different pavement types—burlap poly, curing compound, burlap blanket, and white poly sheeting. The JPCP sections with slab thickness < 250 mm showed that higher IRI values (on average) developed for those sections cured with burlap poly when compared with sections cured with a curing compound or white poly sheeting. The influence of curing compound on the IRI of thicker JPCP sections (≥ 250 mm) was not as clear. An evaluation of the linear trends showed that those sections cured with white poly sheeting exhibited higher IRI values (on average) than those cured with a curing compound. Figure 86 contains plots showing the influence of curing method and slab thickness on the IRI of JPCP LTPP sections.

For JRCP pavements, comparisons could only be made for those sections with slab thickness < 250 mm (all JRCP sections with slab thickness ≥ 250 mm were cured with curing compound only). No clear trends identifying the influence of curing method on IRI were determined. All of the CRCP sections were cured using a curing compound; therefore, no comparisons could be made for those data sets. Also, due to insufficient data, no conclusions could be drawn regarding the effects of climatic region.

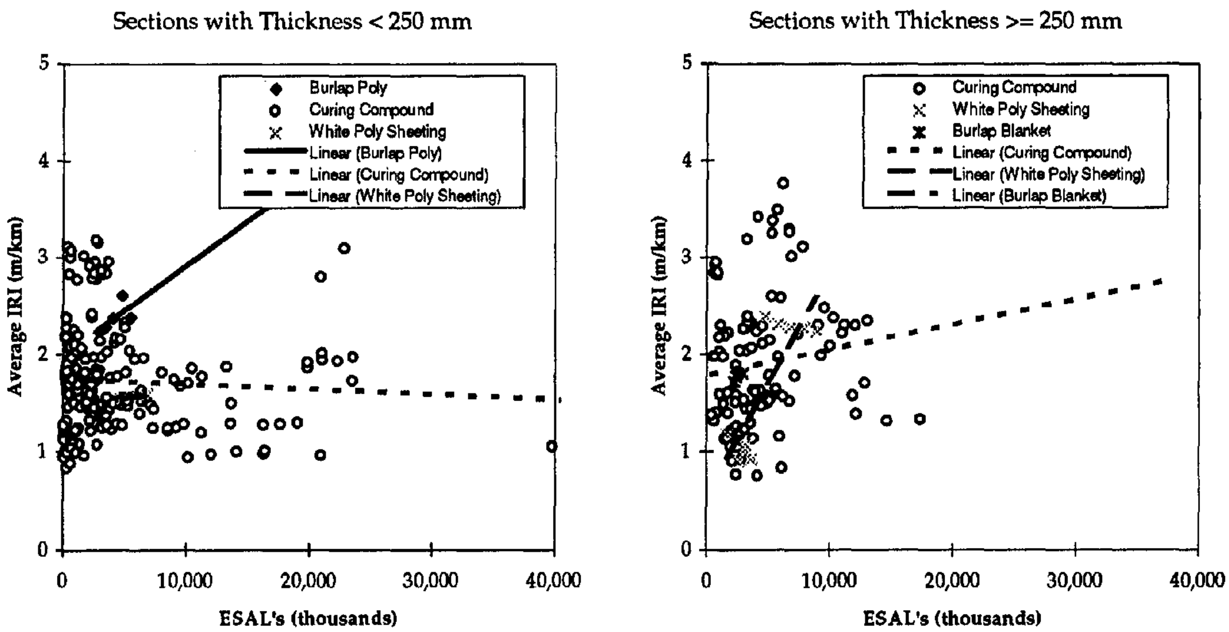


Figure 86. Plots showing the influence of curing method and slab thickness on the IRI of JPCP LTPP sections (all climatic regions included).

Effect of Texture Method

The influence of texture method on the IRI of JPCP, JRCP, and CRCP was investigated for the LTPP data already divided by slab thickness. Six different texture methods were observed for the available LTPP data—astro turf, broom, burlap drag, tine, tine and astro turf, and grooved float. For the JPCP data in both slab thickness categories, the highest IRI values appeared to come from those sections textured with astro turf, and tine and astro turf.

Those sections textured with tines, a broom, or a burlap drag consistently showed lower IRI values for JPCP pavements (on average). Figure 87 contains plots showing the influence of texture method and slab thickness on the IRI of JPCP LTPP sections (data from all climatic regions are included). For the JRCP sections with slab thickness < 250 mm, the sections textured using astro turf and tines and astro turf again showed the highest IRI values (on average).

There did not appear to be much significant difference between the other methods, although those sections textured with a grooved float showed a linear trend with a large decreasing slope. It was difficult to determine any trends for the JRCP data with slab thickness $\geq$ 250 mm. The sections textured with a burlap drag appeared to show the largest IRI values (on average), and there appeared to be no significant difference

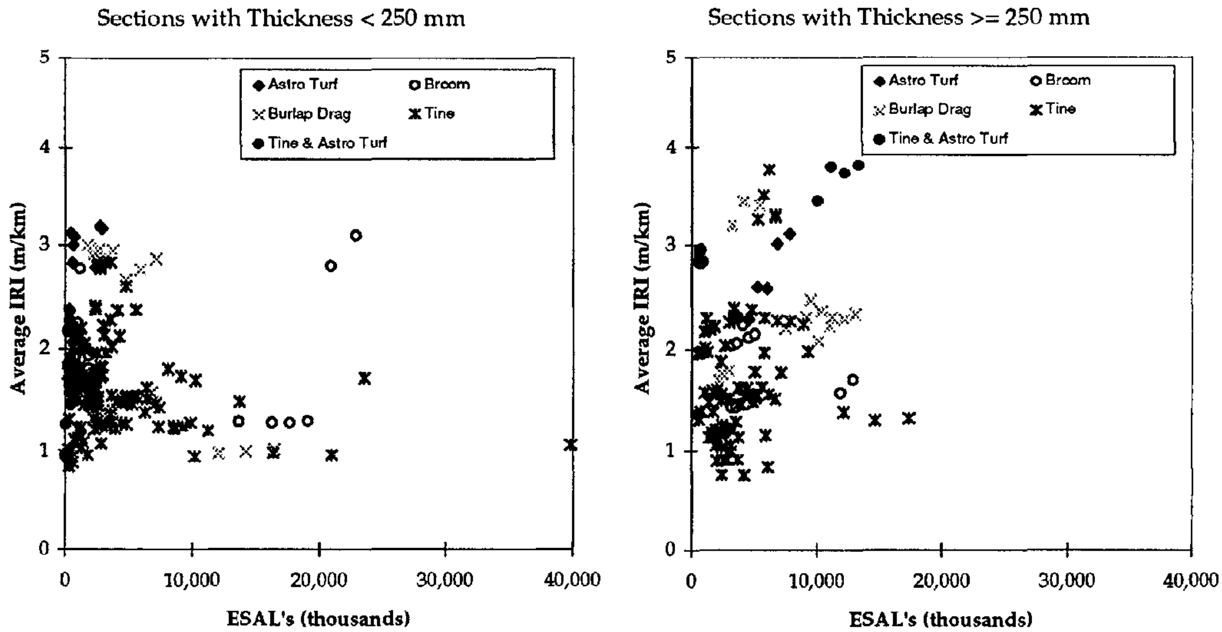


Figure 87. Plots showing the influence of texture method and slab thickness on the IRI of JPCP LTPP sections (all climatic regions included).

between those sections textured with tines or astro turf. Figure 88 contains plots showing the influence of texture method and slab thickness on the IRI of JRCP LTPP sections (data from all climatic regions are included). For the CRCP sections with slab thickness < 250 mm, the sections textured with astro turf and tines and astro turf again showed the greatest linear trends in the IRI values (on average). There did not appear to be much significant difference between the other methods, although those sections textured with a burlap drag showed the lowest IRI values (on average). For those JRCP sections with slab thickness $\geq$ 250 mm, those textured using the burlap drag showed the greatest linear trend slope. The lowest observed IRI values came from those sections textured with a broom. Figure 89 contains plots showing the influence of texture method and slab thickness on the IRI of CRCP LTPP sections (data from all climatic regions are included). The influence of climatic region was not investigated because of a lack of data in most of the data sets.

Effect of Transverse Joint Forming Method

The influence of transverse joint forming method on IRI was investigated for the JPCP and JRCP data already divided by slab thickness. Three different joint forming methods were observed for the available LTPP data—plastic insert, metal insert, and sawed. For the JPCP sections in both thickness categories, a comparison of plastic inserts to sawed joints showed that higher IRI values developed (on average) for those

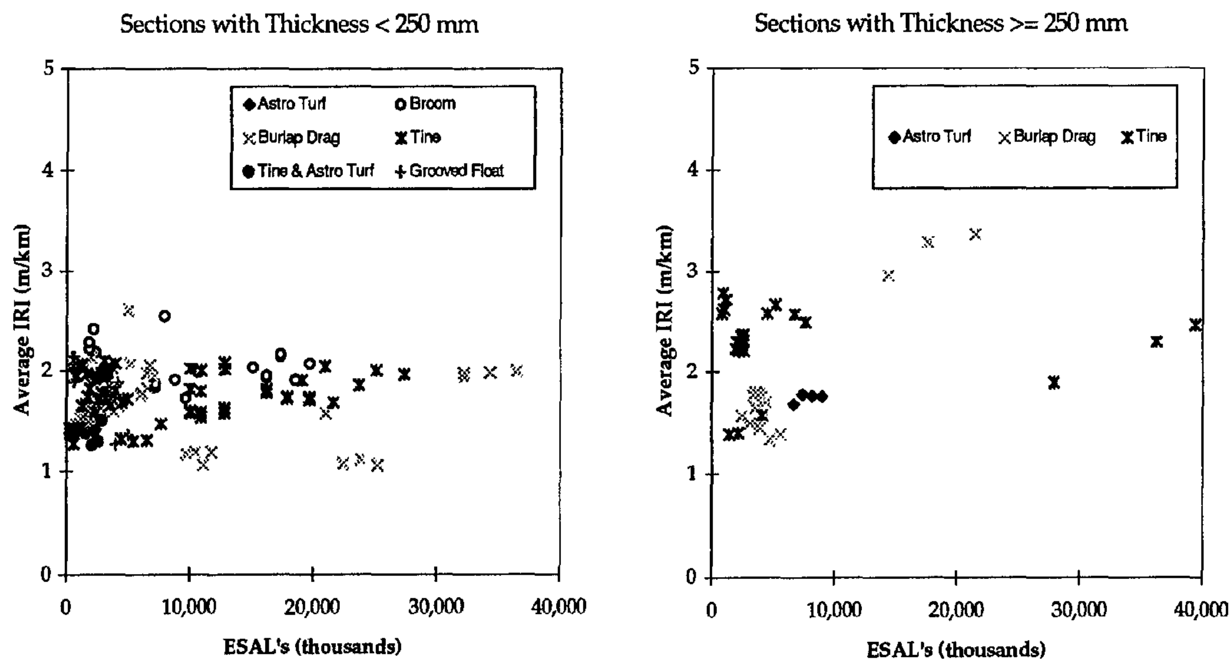


Figure 88. Plots showing the influence of texture method and slab thickness on the IRI of JRCP LTPP sections (all climatic regions included).

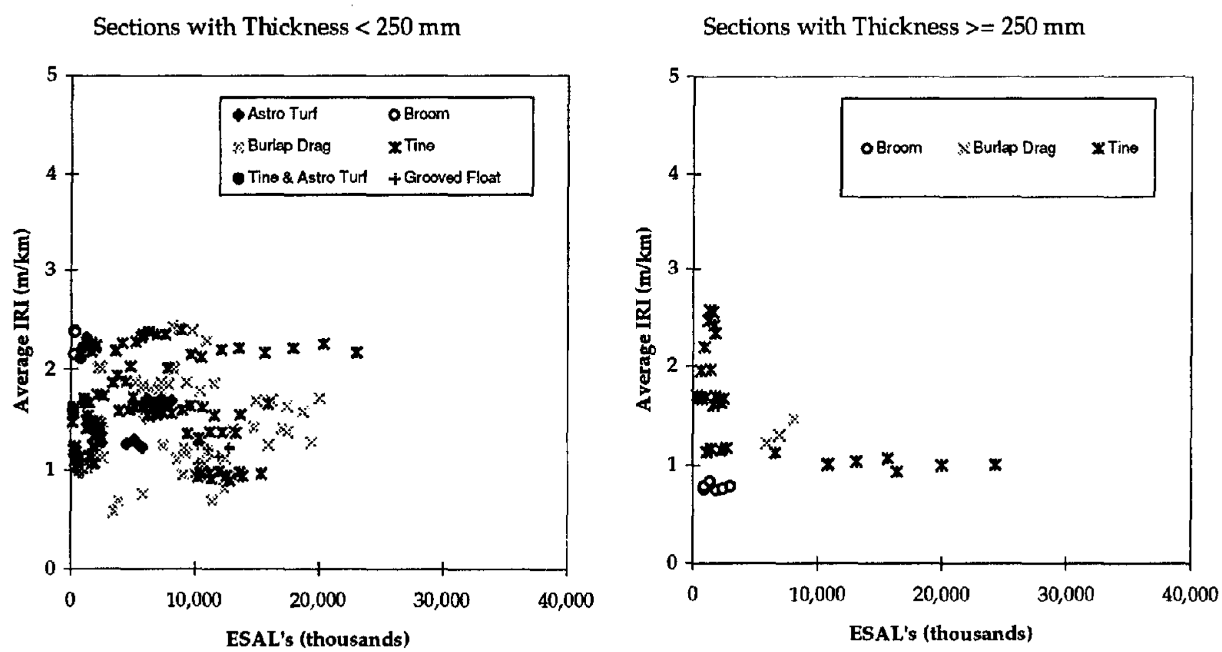


Figure 89. Plots showing the influence of texture method and slab thickness on the IRI of CRCP LTPP sections (all climatic regions included).

sections constructed with sawed joints. Figure 90 contains plots showing the influence of transverse joint forming method and slab thickness on the IRI of JPCP LTPP sections.

Comparisons could only be made for the thinner JRCP sections (< 250 mm) because of insufficient data. The observed linear trends showed that those JRCP sections constructed with plastic inserts developed slightly higher IRI values (on average) than those sections with sawed joints. Figure 91 contains plots showing the influence of transverse joint forming method and slab thickness on the IRI of JRCP LTPP sections (data from all climatic regions were included). Secondary analyses investigating the influence of different climatic regions did not show any clear trends because of a lack of sufficient data.

Effect of Steel Placement Method

The influence of steel placement method on IRI was investigated for the JRCP and CRCP data already divided by slab thickness. Three different steel placement methods were observed for the available LTPP data—between layers, chairs, and mechanically inserted. Consistent trends were observed for the JRCP sections in both thickness categories. Those JRCP sections constructed using chairs exhibited the highest IRI values (on average), followed by those sections using mechanically inserted steel, with the sections constructed by placing the steel between layers showing the lowest values of IRI (on average). Figure 92 contains plots showing the influence of steel placement method and slab thickness on the IRI of JRCP LTPP sections.

The CRCP data did not show any clear trends identifying the influence of steel placement method on IRI. For both thickness categories, their appeared to be no significant difference between the IRI of those sections constructed with chairs and mechanical inserters. Even though the linear trend representing the thinner CRCP sections with a steel placement method of *between layers* shows a steep slope, it is important to note that this line is based on very few data points. Figure 93 contains plots showing the influence of steel placement method and slab thickness on the IRI of CRCP LTPP sections (data from all climatic regions were included). Secondary analyses investigating the influence of different climatic regions did not show any clear trends because of a lack of sufficient data.

Effect of Dowel Placement Method

The influence of dowel placement method on the development of IRI for JPCP and JRCP pavements was investigated for the data sets already divided by slab thickness. Two different dowel placement methods were observed for the available LTPP data—baskets and inserted using a mechanical dowel bar inserter.

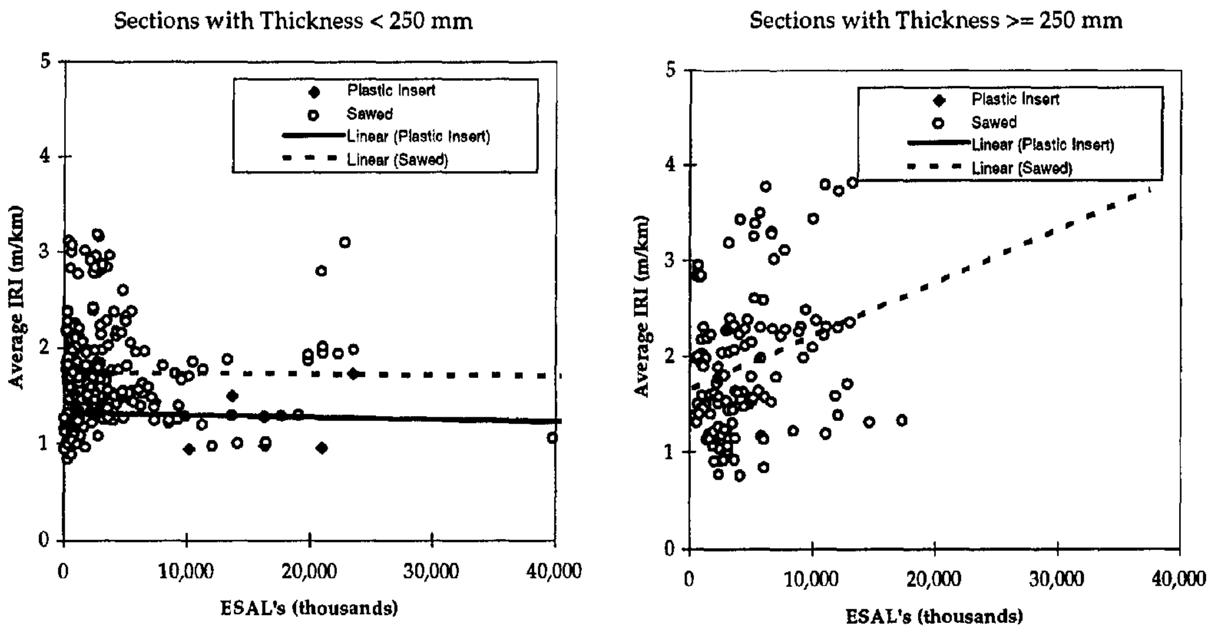


Figure 90. Plots showing the influence of transverse joint forming method and slab thickness on the IRI of JPCP LTPP sections (all climatic regions included).

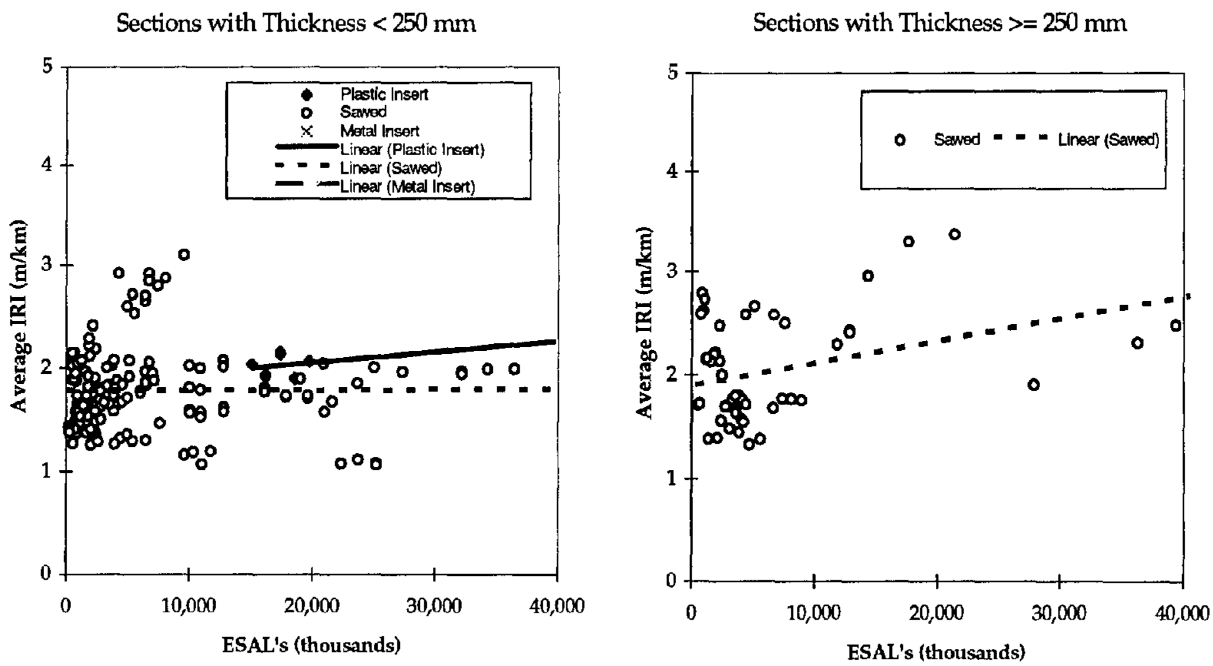


Figure 91. Plots showing the influence of transverse joint forming method and slab thickness on the IRI of JRCP LTPP sections (all climatic regions included).

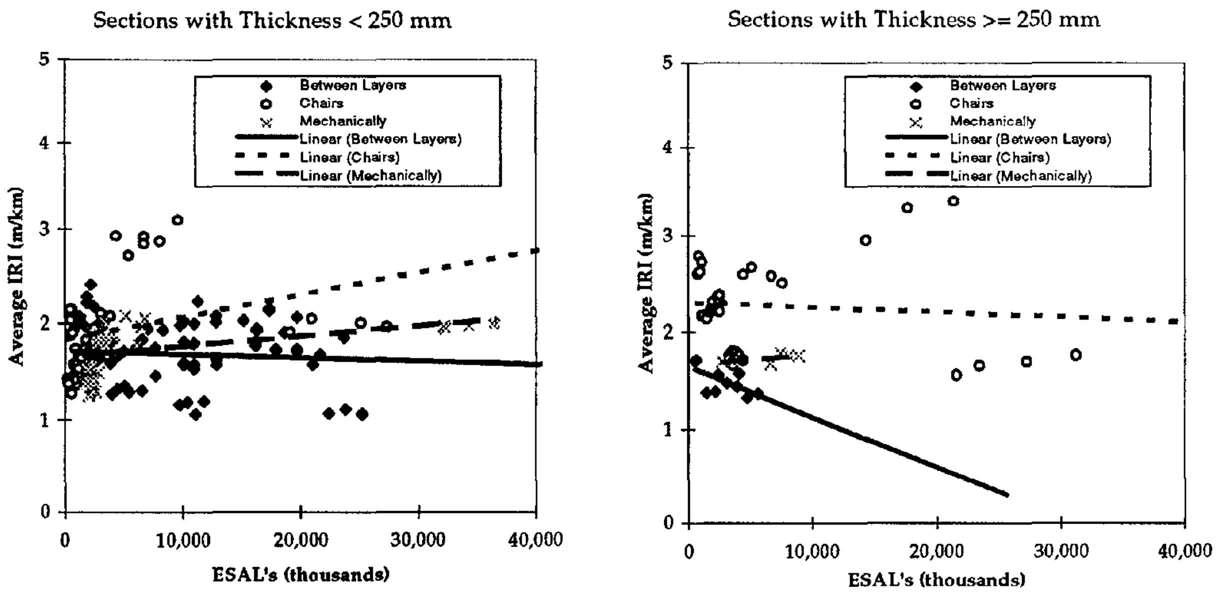


Figure 92. Plots showing the influence of steel placement method and slab thickness on the IRI of JRCP LTPP sections (all climatic regions included).

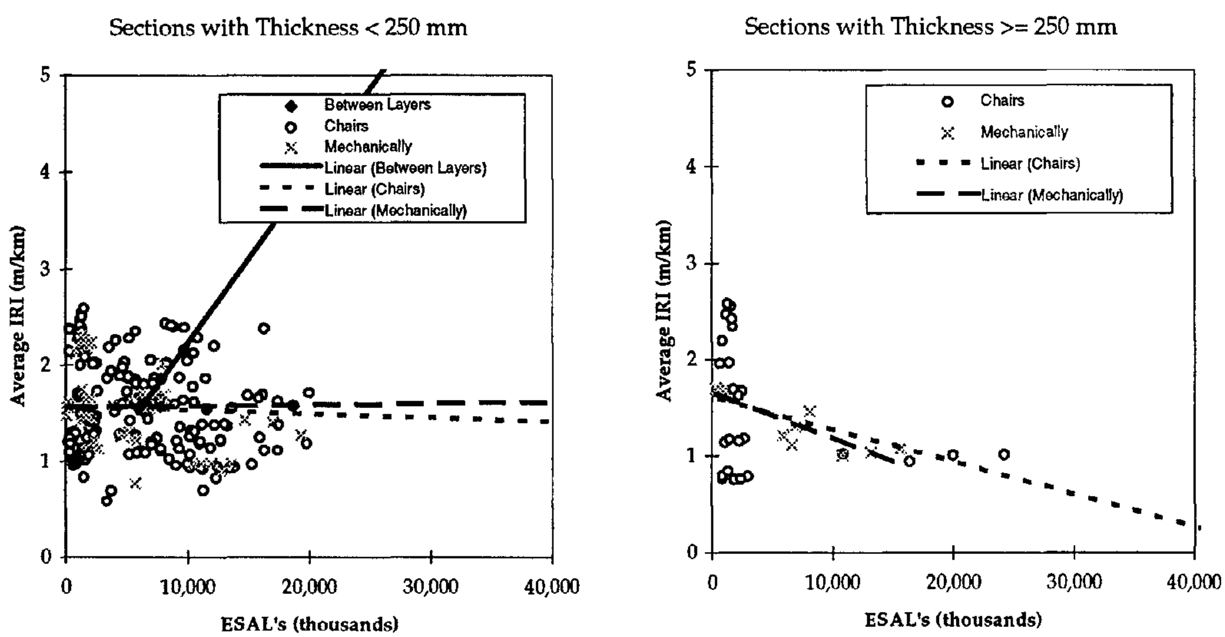


Figure 93. Plots showing the influence of steel placement method and slab thickness on the IRI of CRCP LTPP sections (all climatic regions included).

For the JPCP data, comparisons could only be made for the thicker sections (≥ 250 mm), since only baskets were used for the thinner sections. The data representing the thicker JPCP sections showed that higher IRI values were exhibited (on average) by those sections constructed using dowel baskets.

Figure 94 contains plots showing the influence of dowel placement method on the IRI of JPCP LTPP sections (data from all climatic regions were included). An analysis of the JRCP data showed that the thinner sections constructed using a dowel bar inserter exhibited higher IRI values when compared with those sections constructed using dowel baskets. The data representing the thicker JRCP sections did not appear to show any significant trends. Figure 95 contains plots showing the influence of dowel placement method on the IRI of JRCP LTPP sections (data from all climatic regions were included).

Canonical Discriminant Analysis for JPCP Roughness

The LTPP database for JPCP was categorized into pavements performing above expectation and others (expected and below expected) using the performance classification procedure outlined in chapter 3 of this report. A single canonical variable, CANJPC1, was adequate for separating the JPCP according to roughness. The final form of the canonical function for estimating the value of CANJPC1 was as follows:[5, 6, 7, 8]

$$\begin{aligned} CANJPC1 = {} & 0.027WTDYS + 0.216MEANT + 0.047D32 + 0.024D0 + 0.915TEXT \\ & - 0.08STYPE + 0.005h_{PCC} - 1.18*10\text{-}7E_{PCC} + 0.0163h_b + 0.982J \\ & - 0.92BASTYP - 1.46DRAIN - 0.59SUBTYP + 3.84 \end{aligned} \tag{4}$$

where

WTDYS	=	annual number of wet days
MEANT	=	annual mean temperature, °C
D32	=	annual number of days with temperature above 32 °C
D0	=	annual number of days with temperature below 0 °C
TEXT	=	concrete texture method, 1 = tine, 0 = others
STYPE	=	shoulder type, 1 = rigid, 0 = other
h_{PCC}	=	PCC slab thickness, mm
E_{PCC}	=	PCC elastic modulus, kPa
h_b	=	base thickness, mm
J	=	load transfer coefficient
BASTYP	=	base type, 1= stabilized, 0 = unstabilized
DRAIN	=	1 = presence of drain

SUBTYP = subgrade type, 1 = coarse, 0 = fine material

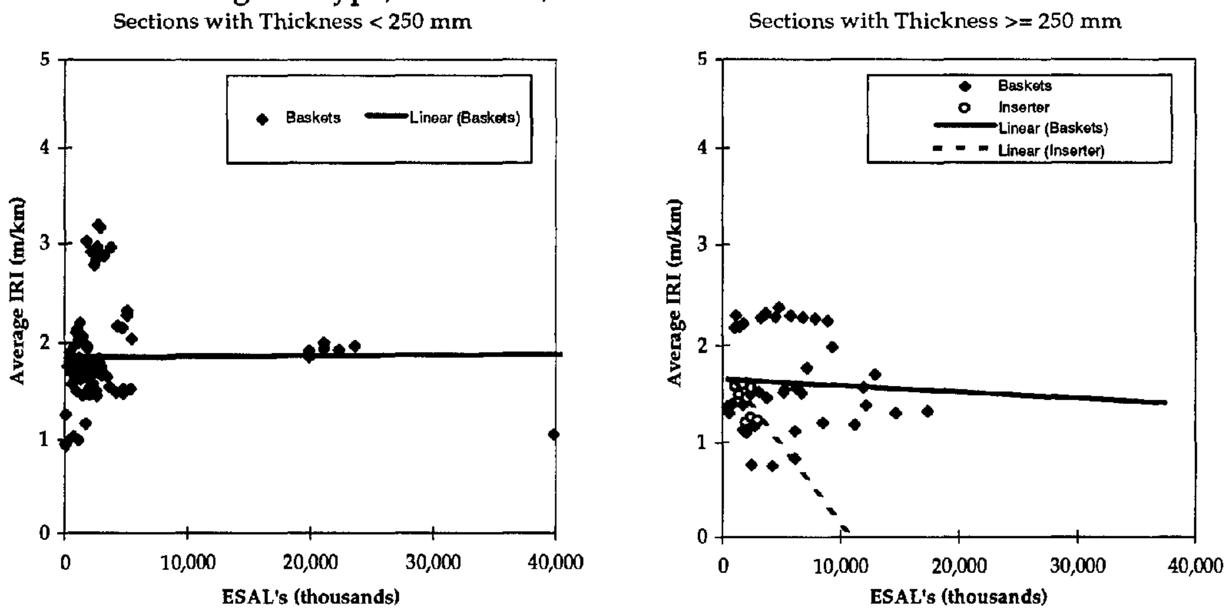


Figure 94. Plots showing the influence of dowel placement method on the IRI of JPCP LTPP sections (all climatic regions included).

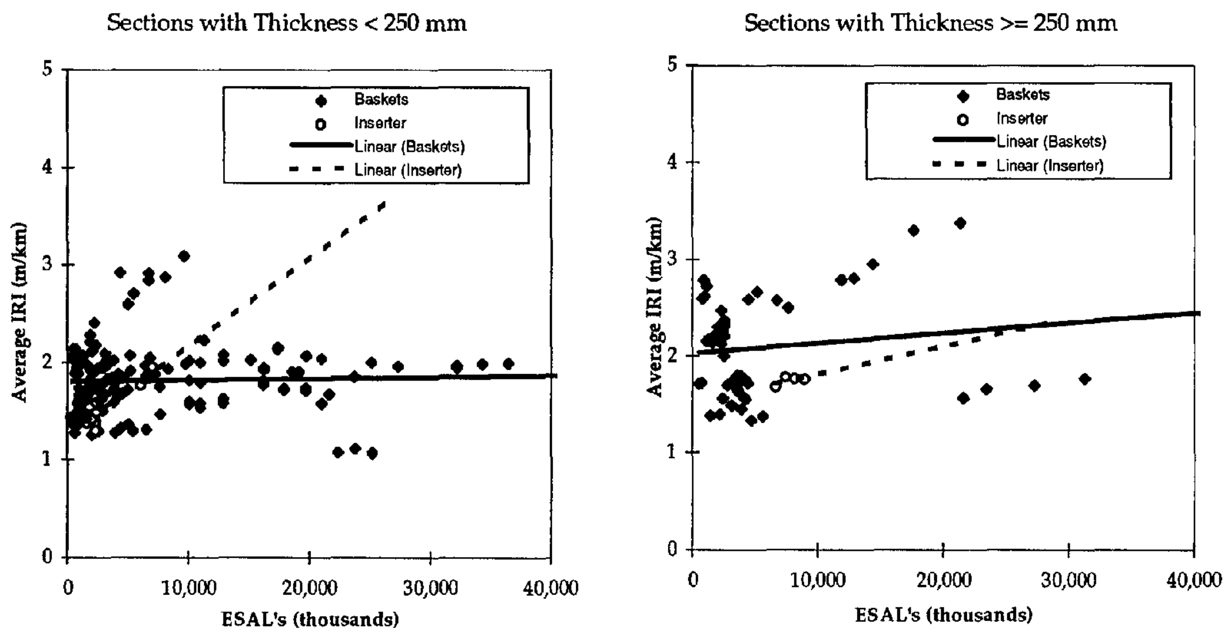


Figure 95. Plots showing the influence of dowel placement method on the IRI of JRCP LTPP sections (all climatic regions included).

The mean values of CANJPC1 for pavements performing above expectation and others are given in table 15. A plot of CANJPC1 versus CANJPC1 for each observation of the data used in the analysis is shown in figure 96.

The plot shows that pavements performing above expectation are located in the negative region of the plot (CANJPC1 < 0), while the pavements in the others category are in the positive region, (CANJPC1 > 0). This is in agreement with the mean values of the canonical variables for the different categories presented in table 15. Classifying pavement performance according to the canonical variable CANJPC1 is summarized as follows:

- Pavement sections performing above expectation were generally located in the area CANJPC1 is less than -0.5.
- Pavement sections performing below expectation or as expected were located in the area where CANJPC1 is greater than 0.5.

Summary of Canonical Discriminant Analysis for IRI Roughness

The canonical function shows that adverse climatic conditions generally contribute to more roughness and, therefore, worse performance. An increase in the values of the annual number of wet days, mean temperature, annual number of days with temperature above 32 °C, and annual number of days with temperature below 0 °C increases the value of CANJPC1. Positive CANJPC1 values imply expected or below expected performance.

A review of the design variables in the canonical function shows that JPCP designed with a rigid shoulder, a stabilized base, constructed over a coarse subgrade material, and with high PCC modulus reduced the value of CANJPC1 (i.e., showed better performance). Also, providing drainage facilities and reducing the load transfer coefficient, J, enhances performance. The trends are in agreement with mechanistic analysis and results of past studies.

Analysis of Variance for JPCP Roughness

A comprehensive ANOVA was performed to determine the significance of each design feature and site conditions that influence the occurrence of roughness for JPCP. Table 16 is a summary of the significant variables that influence roughness according to the ANOVA results and Duncan's multiple range test for comparison of means. Table 17 also summarizes the variables that, though not significant, show an effect on roughness that could be significant. The effect of the design features and site conditions influencing performance are discussed in the next few sections.

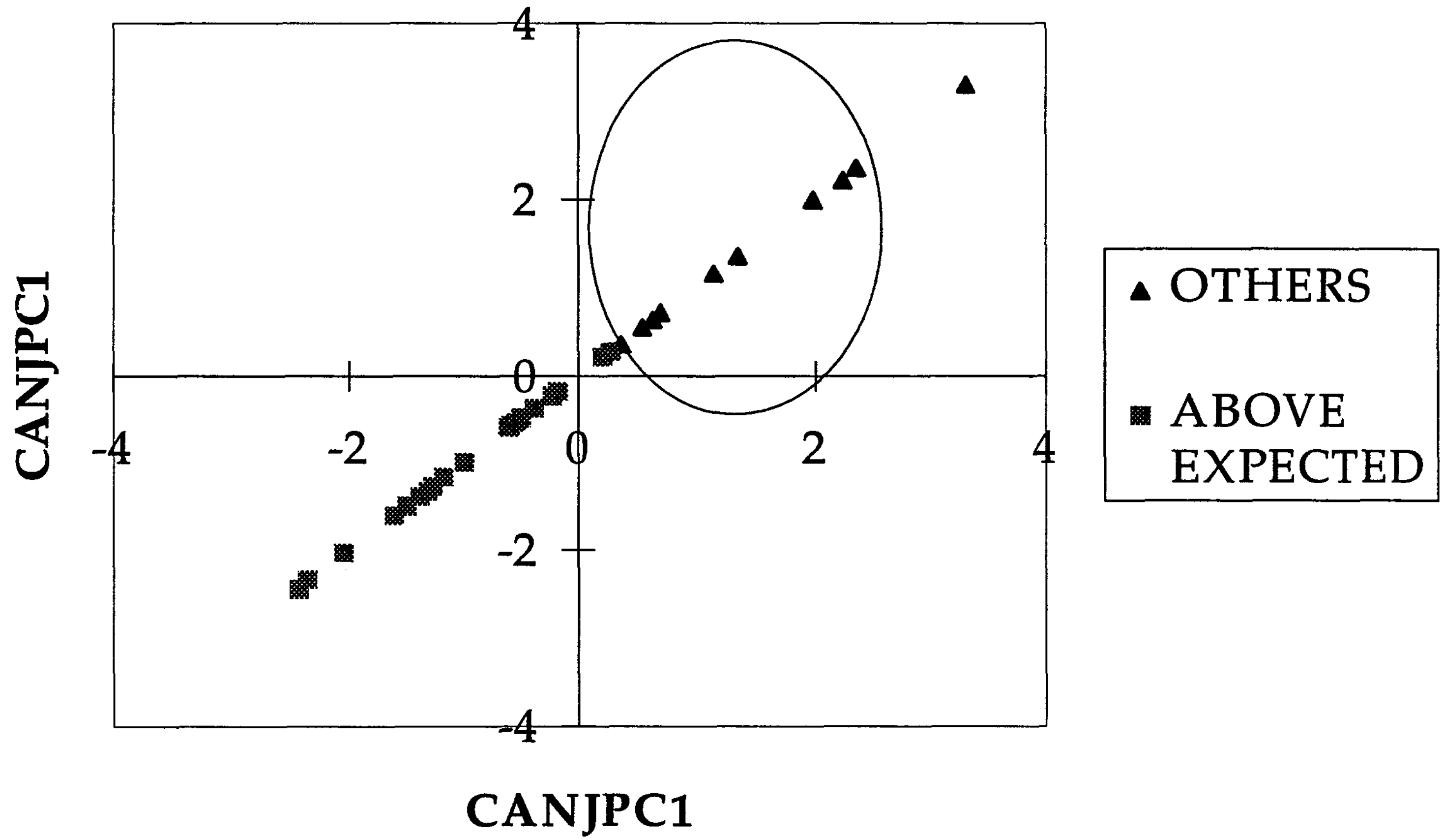


Figure 96. A plot of CANJPC1 versus CANJPC1 for each observation of the data.

Table 15. Class means for canonical variable CANJPC1.

Category	CANJPC1
Others	1.32
Above Expectation	-0.68

Table 16. Summary of analysis of variance results for roughness.

Variable	Classification	Mean IRI m/km	Duncan Class*	Significant Difference
Precipitation, m	less than 0.6	1.56	A	Yes
	0.6 to 1.0	2.07	B	
	greater than 1.0	1.81	C	
Base elastic modulus, MPa	less than 207	1.94	A	Yes
	690 to 6900	1.58	B	
	greater than 6900	1.78	C	
Joint coefficient, J	less than 3.5	1.73	A	No
	greater than 3.5	1.86	A	
Dowel diameter	no dowels	1.87	A	No
	dowels	1.70	A	
Concrete texture	tine	1.72	A	Yes
	others	1.95	B	
Shoulder type	rigid	1.70	A	No
	others	1.86	A	
PCC slab thickness, mm	less than 250	1.75	A	No
	greater than 250	1.89	A	
Annual mean temperature, °C	less than 10	2.05	A	Yes
	10 to 15.5	1.62	B	
	greater than 15.5	1.70	B	

* Duncan's multiple range test; those with the same letter are not significantly different.

Table 16. Summary of analysis of variance results for roughness (continued).

Variable	Classification	Mean IRI m/km	Duncan Class*	Significant Difference
Drain	no drains	1.81	A	No
	drains	1.76	A	
Drainage coefficient	less than 1	1.97	A	Yes
	greater than 1	1.64	B	
Dry	wet areas	1.92	A	Yes
	dry areas	1.56	B	
PCC modulus, MPa	less than 27,600	1.54	A	Yes
	greater than 27,600	1.69	B	
Modulus of subgrade reaction, kPa/mm	less than 40	1.90	A	Yes
	40 to 55	1.84	B	
	greater than 55	1.64	B	
Base thickness, mm	less than 150	1.65	A	Yes
	greater than 150	1.99	B	
Freeze	freeze areas	2.0	A	No
	nofreeze areas	1.75	A	
Subgrade type	fine	1.94	A	Yes
	coarse	1.60	B	

* Duncan's multiple range test; those with the same letter are not significantly different.

Influence of Site Conditions

Effect of Precipitation

The results presented in table 11 show that pavements located in areas with an annual precipitation of less than 0.635 mm had the least amount of roughness (1.56 m/km), whereas pavements located in regions with precipitation greater than 0.635 experienced a roughness level of greater than 1.81 m/km. This shows that precipitation has a significant effect on roughness, and pavement designers should take the effect of excess precipitation into consideration by providing adequate drainage facilities. The variable Dry, which indicates dry and wet climates according to the LTPP database and definitions, also shows that pavements located in wet areas experience more roughness than those in dry climates. This agrees with the results for precipitation. Precipitation generally increases the potential for moisture-related damage, such as pumping, stripping of AC stabilized layers, and lowering the pavement foundation material modulus. All of these increase the potential for distress and, hence, roughness.

Effect of Mean Temperature

Pavements located in warm climates generally have higher mean temperatures than those located in cold climatic areas and subjected to cooler or freezing temperatures. Both extremes are harmful to the pavement structure and result in increased distresses and roughness. The ANOVA results show that pavements located in cold climates (mean temperature less than 10 °C) experience significantly less roughness than those in warmer climates. Pavements in the above 15.5 °C mean temperature range experience more roughness, even though this was not significantly higher than those in the 10 to 15.5 °C range. The results show that extreme climates and temperature adversely affect performance and should be considered in design.

Influence of Design Features

Effect of Base Modulus

Table 11 shows three levels of roughness for the different base types in the LTPP database. Pavements with unstabilized granular bases (modulus < 345 MPa) experienced the highest level of roughness. This is due to the fact that such bases result in weaker foundations for the pavement and increase pavement deflections and stresses. Pavements with lean concrete bases or cement-stabilized bases were the group with the next most roughness (1.57 m/km).

The reason for this may be similar to that observed for transverse cracking. PCC slabs on a rigid foundation that are subjected to very high temperature gradients curl up, resulting in voids between the slab and the base material and high stresses within the PCC slab. This increases the likelihood of cracking. The bases with modulus values between 690 and 6900 MPa (AC-treated bases) had the least roughness. This is because the AC-stabilized layer provides a uniform base support, even when the PCC slab is curled. The trend is similar to that observed for transverse cracking.

Effect of Dowels and Load Transfer Coefficient

The ANOVA results show clearly that pavements with dowels perform better than those without. Dowels provide load transfer across the joints of adjacent slabs, which reduces deflections and faulting at the joints and results in decreased roughness. The AASHTO equation for pavement design includes the J coefficient, which is an adjustment factor for the load transfer conditions of a joint and also for the drainage conditions of the pavement. An increase in J reduces the number of load cycles to failure of a pavement. Pavements with lower J coefficient values are therefore expected to perform better and last longer. The ANOVA results confirm this trend. Pavements with lower J values experience less roughness (1.73 m/km) than those with higher J values (1.86 m/km).

Effect of Concrete Texture Method

Past studies have shown that the initial roughness of a pavement has an effect on the rate of progression and the final roughness of a pavement. Pavements built rough generally stay rougher. The methods of finishing a pavement's surface after construction ultimately affect the final smoothness of the pavement. The ANOVA results show that JPCP with tined surfaces generally are smoother than those with other kinds of finishing.

Effect of Shoulder Type

Jointed concrete pavements with PCC tied shoulders tend to experience less distress and, hence, roughness. This is because there is some load transfer between the PCC pavement and the shoulder. It reduces the critical bending stresses and deflections at the midsection of the slabs when subjected to wheel loads. The ANOVA results show that pavements with PCC shoulders had an average IRI of 1.7 m/km, whereas pavements with other kinds of shoulders had an average IRI value of 1.86 m/km. Even though the difference between the two groups was not significant statistically, the results show that tied PCC shoulders decrease the amount of roughness a pavement experiences.

Effect of Drains and Drainage Coefficient

The ANOVA analysis shows that the provision of drains to a pavement generally reduces roughness. This can be explained by the fact that adequate drainage reduces the amount of water that infiltrates into the pavement structure, thereby reducing the potential for pumping and faulting and weakening of the underlying pavement materials. Providing a base material that enhances drainage also reduces distresses such as faulting. Accordingly, the LTPP data show that an increase in the pavement base drainage coefficient reduces roughness. Pavements with a drainage coefficient less than 1 had a mean IRI value of 1.97 m/km, whereas those with a drainage coefficient of greater than 1 had a mean IRI value of 1.64 m/km.

Effect of PCC Thickness

The analysis shows that pavements with thicker PCC slabs (> 250 mm) experienced more roughness (1.69 m/km) than those with thinner PCC slabs (1.75 m/km). This is because thicker pavements are generally built rougher than thinner sections (because of constructional difficulties) and they remain rougher throughout the pavement's life.

Effect of Pavement Strength and Foundation Support

The variables that determine the support conditions of PCC pavements and pavement strength in the LTPP database are PCC modulus, modulus of subgrade reaction, base thickness, and subgrade type. Increases in magnitude of all of these variables and construction of pavements on coarse subgrade materials increase pavement strength. The ANOVA results show that strengthening a pavement decreases roughness. This is a reasonable result, even though for some distresses increasing base and subgrade stiffness could have a detrimental effect on the pavement. Generally, stronger pavements experience less distress and, therefore, roughness.

Influence of Construction Practices

Effect of Concrete Texture Method

The ANOVA analysis showed that, generally, pavements finished by a grooved float or astroturf were smoother that those finished by other finishing methods.

Summary of Site Conditions, Design Features, and Construction Practices that Influence JPCP Roughness

Using univariate analysis, frequency plots, canonical discriminant analysis, and ANOVA, the design-, site-, and construction-related variables that influence the occurrence and severity of roughness in JPCP have been analyzed. According to the results of the analysis, pavements with stiffer foundations tend to have less roughness than those constructed over weaker foundations. Also, the presence of dowels resulted in less roughness because of reduced faulting; however, thicker PCC slabs and bases resulted in pavements with more roughness. The analysis also showed that pavements located in climates with high precipitation and with extreme temperatures (hot or cold) performed worse than those located in milder climates. These observations and the canonical function developed can be used in design to enhance pavement performance.

Canonical Discriminant Analysis for JRCP Roughness

The LTPP database for JRCP was categorized into pavements performing above expectation, as expected, and below expectation using the procedures outlined in chapter 3 of this report. Two canonical variables, CANJRC1 and CANJRC2, were developed and used for classifying performance using design and site variables. The final form of the canonical functions for estimating CANJRC1 and CANJRC2 were as follows:[5, 6, 7, 8]

$$\begin{aligned} \text{CANJRC1} &= -0.0005\text{PRECIP} - 0.025\text{D32} - 0.96\text{TEXT} - 4.45\text{STYPE} \\ &\quad + 16.71\text{DSC} + 0.016\text{DTS} - 0.03\text{hb} + 4.64C_d + 0.044\text{KVAL} \end{aligned} \tag{5}$$

$$\begin{aligned} \text{CANJRC2} &= 0.0054\text{PRECIP} - 0.025\text{D32} - 1.11\text{TEXT} + 1.17\text{STYPE} \\ &\quad + 4.39\text{DSC} + 0.01\text{DTS} - 0.019h_b + 2.34C_d - 0.019\text{KVAL} \end{aligned} \tag{6}$$

where

PRECIP = annual precipitation, mm
D32 = annual number of days with temperature above 32 °C
TEXT = concrete texture method, 1 = tine, 0 = other
STYPE = shoulder type, 1 = rigid, 0 = other
DSC = design steel content
DTS = design steel spacing, mm
h_b = base thickness, mm
C_d = drainage coefficient
KVAL = modulus of subgrade reaction, kPa/mm

The mean values of CANJRC1 and CANJRC2 for pavements performing above expectation, as expected, and below expectation are given in table 17. A plot of CANJRC1 versus CANJRC2 for each observation of the LTPP data used in the analysis is shown in figure 97. The plot shows that the canonical variable (CANJRC1) accounted for most of the discrimination between pavements performing above expectation and the other performance categories. Performance classification based on the canonical variables CANJRC1 and CANJRC2 are as follows:

- Pavement sections performing above expectation were generally located in the area where CANJRC1 is greater than 0.
- Pavements with performance classification as expected or below expectation generally had CANJRC1 values less than -1.0.

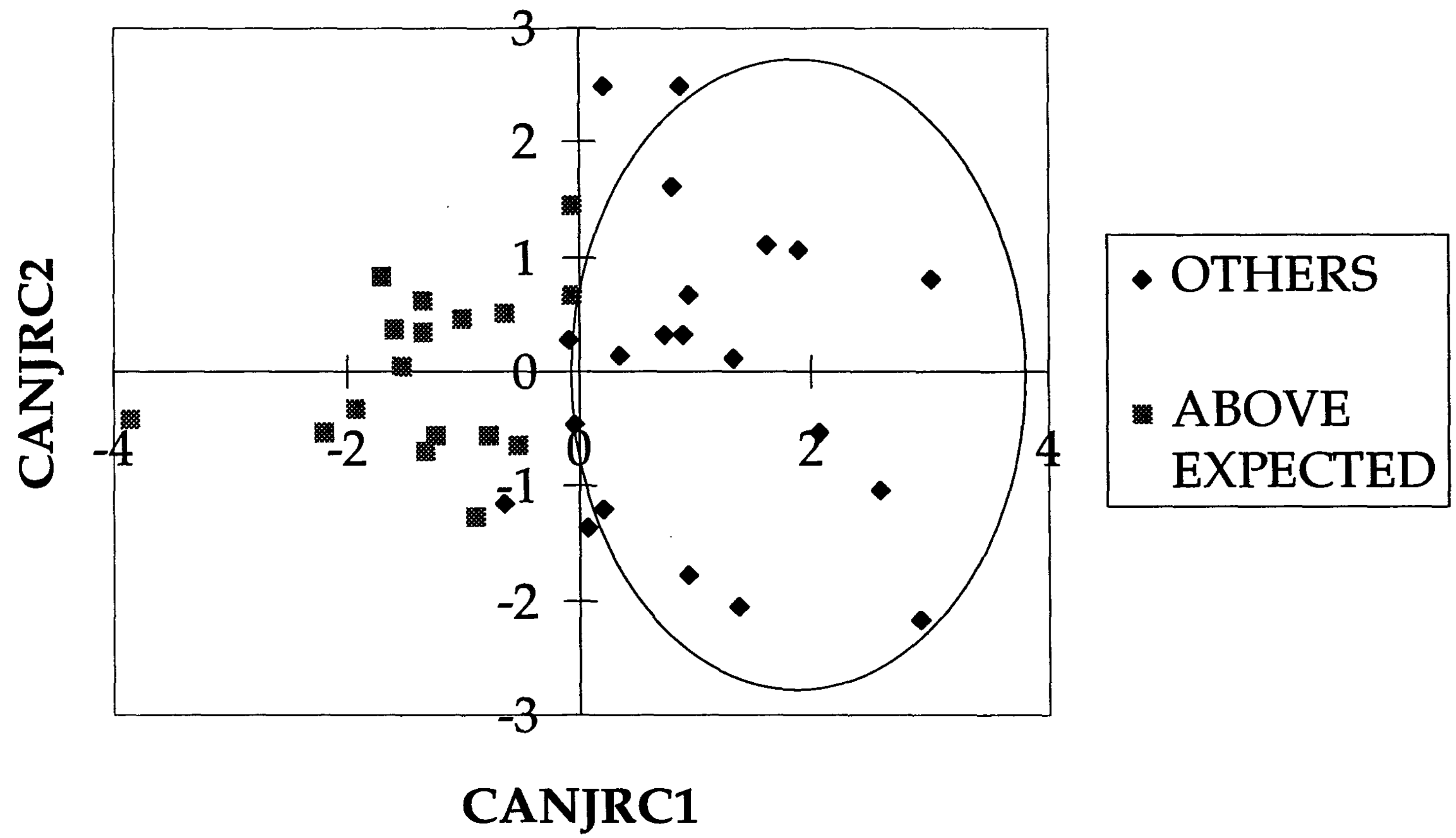


Figure 97. A plot of CANJRC1 versus CANJRC2 for each observation of the data.

Table 17. Class means for canonical variable CANJRC1 and CANJRC2

Category	CANJRC1	CANJRC2
Below expectation	-3.02	-2.67
Expected	-1.21	0.93
Above expectation	1.62	0.26

Summary of Canonical Discriminant Analysis for JRCP Roughness

The plot of the canonical variables shows that the canonical function that accounts for most of the difference between above expected and other pavement performance categories is CANJRC1. Above expected performing pavements generally have positive CANJRC1 values. Increasing the values of precipitation, number of days with temperature above 32 °C, and base thickness decreases the value of CANJRC1 and, therefore, lowers pavement performance. However, increasing the design steel content, design steel spacing, drainage coefficient, and modulus of subgrade reaction increases the value of CANJRC1 and improves performance.

Analysis of Variance for JRCP Roughness

A comprehensive ANOVA was performed to determine the significance of each design feature and site condition that could have an effect on roughness for JRCP. Table 18 is a summary of the significant variables that influence roughness according to the ANOVA and Duncan's multiple range test for the comparison of means. Some variables that do not have a significant effect on roughness but show quite a difference in roughness for different classification levels of those variables are also presented. The effects of the variables are discussed in the next few sections.

Influence of Site Conditions

Effect of Precipitation

The results presented in table 18 show that pavements located in areas with an annual precipitation of less than 1 m had the least amount of roughness (1.6 m/km), and pavements located in regions with precipitation greater than 1 m experienced a roughness level of greater than 2.2 m/km. This trend is similar to that of the effect of precipitation on roughness for JPCP.

Table 18. Summary of analysis of variance results for JRCP roughness.

Variable	Classification	Mean IRI m/km	Duncan Class*	Significant Difference
Precipitation, m	less than 1	1.59	A	Yes
	greater than 1	2.02	B	
PCC thickness, mm	less than 250	1.73	A	Yes
	greater than 250	2.07	B	
Joint spacing, m	less than 13.7	1.59	A	Yes
	greater than 13.7	1.94	B	
Subgrade type	fine	1.92	A	Yes
	coarse	1.61	B	
Mean temperature, °C	less than 12.7	1.70	A	Yes
	greater than 12.7	2.0	B	
Drain	no drains	1.87	A	Yes
	drains	1.62	B	
Drainage coefficient	less than 1	1.89	A	No
	greater than 1	1.64	B	

* Duncan's multiple range test; those with the same letter are not significantly different.

Effect of Mean Temperature

Mean temperture is an indication of the kind of temperature cycles to which a pavement is subjected. Pavements located in warm climates have higher mean temperatures and experience greater temperature stresses than those located in colder regions. Both extremes are harmful to the pavement structure and result in increased distresses and roughness. The ANOVA results show that pavements located in cold climates (mean temperature less than 10 °C) experience significantly less roughness than those in warmer climates. Pavements in the above 15.5 °C mean temperature range experience more roughness, even though this was not significantly higher that those in the 10 to 15.5 °C range.

Effect of Subgrade Type

The ANOVA results show that pavements located on subgrades made up of coarse materials experienced less roughness than those on finer subgrades. Coarse-graded subgrade material generally strengthens the pavement's foundation, and pavements with stronger foundations generally experience less distress.

Influence of Design Features

Effect of PCC Thickness

Table 18 shows that there is a significant difference in roughness values for pavements with PCC thickness less than 250 mm and greater than 250 mm. The trend is similar to that for JPCP, where the thicker pavements experienced more roughness. This is chiefly due to difficulties with constructing thicker pavement sections.

Effect of Joint Spacing

The ANOVA analysis shows that pavements with joint spacing greater than 13.7 m experienced more roughness than those with shorter joint spacing. This trend was also similar for JPCP pavements, although the difference in roughness was not significant. This may be due to the fact that the problems associated with longer joint spacing may be aggravated with JRCP pavements because they have much longer joint spacing (greater than 12.2 m). Pavements with longer joints for the same level of reinforcement and foundation support will deflect more than pavements with shorter joints. Increased deflections and stresses translate to more cracking and distress.

Effect of Drains and Drainage Coefficient

The ANOVA analysis shows that the provision of drains to a pavement generally reduces distress and roughness. This can be explained by the fact that adequate drainage reduces the amount of water within the pavement structure, thereby reducing the potential for pumping and weakening of the underlying pavement materials. Providing a base material that enhances drainage also reduces distresses such as faulting and, hence, roughness. This is also shown by the fact that an increase in the pavement base drainage coefficient reduces roughness. Pavements with a drainage coefficient less than 1.0 had a mean roughness value of 1.9 m/km, whereas those with a drainage coefficient of greater than 1 had a mean roughness value of 1.64 m/km.

Influence of Construction Practices

Effect of Concrete Texture Method

The ANOVA analysis showed that, generally, pavements finished by a grooved float or astroturf were smoother that those finished by other finishing methods.

Summary of Site Conditions and Design Features that Influence JRCP Roughness

The results of the analysis show that pavements located in areas with precipitation greater than 1.0 m experience more roughness than those at locations with precipitation less than 1.0 m. However, the provision of drainage facilities significantly reduced the severity of roughness. Also, pavements with thicker PCC slabs had significantly more roughness than thinner ones. This may be due to the fact that constructing thicker slabs is difficult and could result in poor workmanship, increasing initial roughness.

The analysis also showed that pavements located hot climates (mean temperature greater than 12.7 °C) performed worse than those in milder climates. These observations are reasonable and could serve as basic guidelines for pavement design and evaluation. Also, the canonical function CANJRC2 was used to determine pavements performing better than expected or otherwise. This can be a useful tool in classifying newly designed pavements or to check preliminarily for adequate performance through a pavement's design life.

Canonical Discriminant Analysis for CRCP Roughness

The LTPP database for CRCP was categorized into pavements performing above expectation, as expected, and below expectation using the procedures outlined in chapter 3 of this report. Two canonical variables, CANCRC1 and CANCRC2, were used to discriminate between the different performance classes. The final forms of the canonical functions for estimating CANCRC1 and CANJRC2 are as follows:[5, 6, 7, 8]

$$\text{CANCRC1} = 0.2\text{MINT} + 0.05\text{D0} + 1.82\text{TEXT} - 0.00054M_R + 0.0027h_b - 1.4\text{BASTYP} - 0.6\text{SUBTYP} - 2.7\text{DSC} + 0.0003\text{WTDYS} - 17.5 \quad (7)$$

$$\text{CANCRC2} = -0.0035\text{MINT} + 0.00097\text{D0} + 0.18\text{TEXT} - 0.00015M_R + 0.0082h_b - 2.06\text{BASTYP} - 0.63\text{SUBTYP} + 1.58\text{DSC} - 0.0196\text{WTDYS} + 0.2 \quad (8)$$

where

MINT	=	annual minimum temperature, °C
D_0	=	annual number of days with temperature below 0 °C
TEXT	=	concrete texture method, 1 = tine, 0 = others
M_R	=	modulus of rupture, kPa
h_b	=	base thickness, mm
BASTYP	=	base type, 1 = stabilized, 0 = unstabilized
SUBTYP	=	subgrade type, 1 = coarse, 0 = fine-grained
DSC	=	design steel content, percent
WTDYS	=	average annual number of wet days

The mean values of CANCRC1 and CANCRC2 for pavements performing above expectation, as expected, and below expectation are shown in table 19. A plot of CANCRC1 versus CANCRC2 for each observation of the LTPP data used in the analysis is shown in figure 98. The plot shows that the canonical variable CANCR1 accounted for most of the differences between the sections performing above expectation and the other performance categories. Pavement performance classification based on CANCRC1 is summarized as follows:

- Pavement sections performing above expectation were generally located in the area where CANCRC1 is less than 0.
- The pavement sections with performance classification expected or below expectations were located in the area where CANCRC1 is greater than 0.5.

Summary of Canonical Discriminant Analysis Results

The plot of the canonical variables shows that the canonical function that accounts for most of the difference or variance between above expected and other pavement performance categories is CANCRC1. Pavements performing better than expected generally have negative CANCRC1 values. Increasing the minimum temperature, the number wet days, and the number of days with temperature below 0 °C increases the value of CANCRC1 and, hence, decreases performance.

Providing stabilized bases, increasing the design steel content, and constructing the pavement over a coarse subgrade enhance performance by decreasing CANCRC1. Pavements with higher modulus of rupture values also perform better. However, increasing base thickness tends to increase roughness.

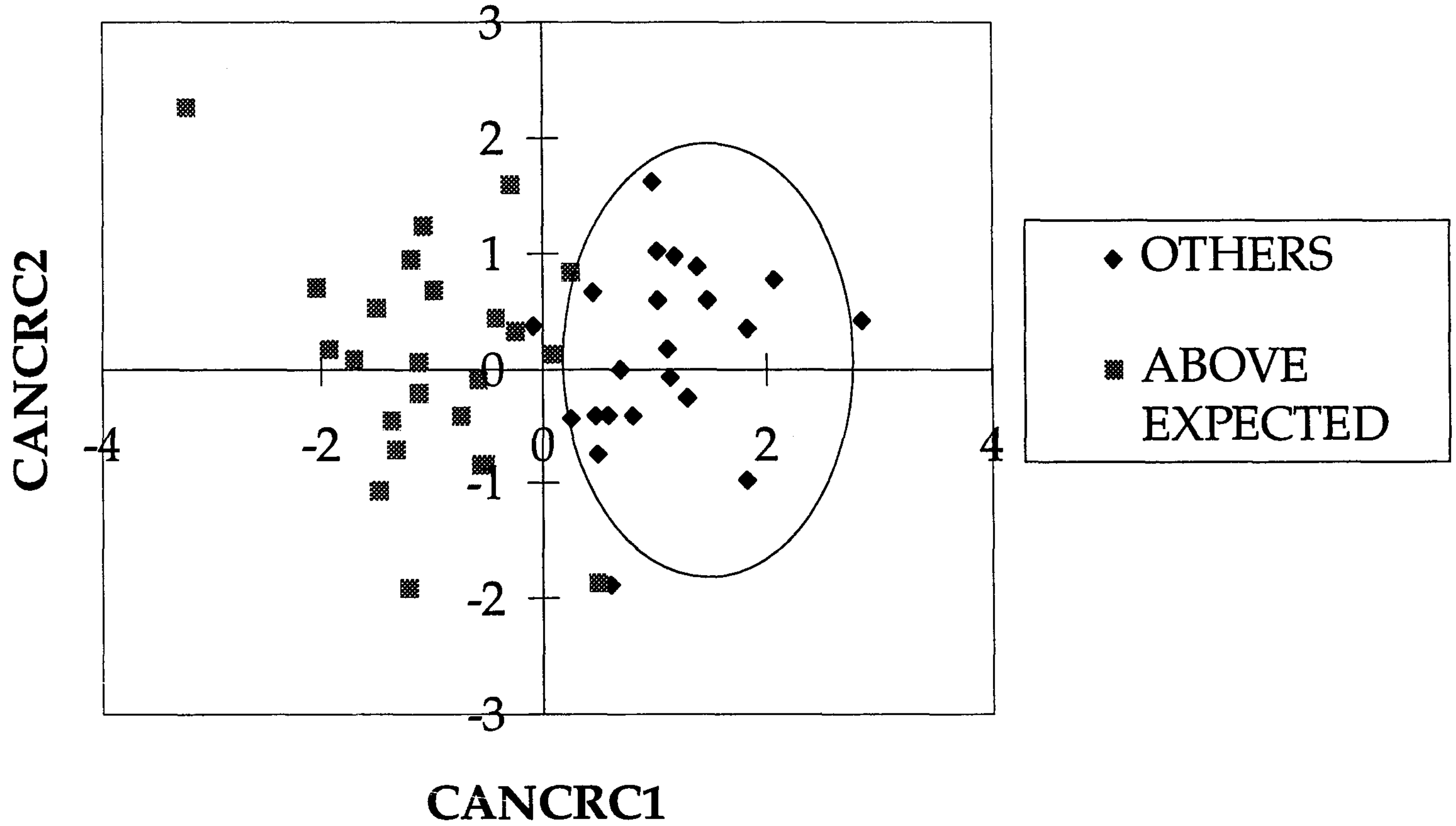


Figure 98. A plot of CANCRC1 versus CANCRC2 for each observation of the data.

Table 19. Class means for canonical variable CANCRC1 and CANCRC2.

Category	CANCRC1	CANCRC2
Below expectation	0.67	-0.95
Expected	0.65	0.07
Above expectation	-0.61	0.001

Analysis of Variance of CRCP Roughness

A comprehensive ANOVA was performed to determine the significance of each design feature and site condition that could have an effect on roughness for CRCP. Table 20 is a summary of the significant variables that influence roughness according to the ANOVA and Duncan's multiple test results. Table 20 also shows a number of variables that, though not significant, have quite an effect on roughness and could potentially have a significant effect on roughness. The effect of the variables is discussed in the next few sections.

Influence of Site Conditions

Effect of Mean Temperature

The ANOVA results show that pavements in hot climates (temperature greater than 18.3 °C) had the most roughness (1.83 m/km). The pavements with the second highest roughness values were located in cold climates (temperature less than 12.7 °C). However, the pavements in moderate climates (temperature between 12.7 to 18.3 °C) had the least amount of roughness. This is in agreement with trends observed for JPCP and JRCP that show that extreme climates have an adverse effect on pavements, increasing distress and lowering performance.

Effect of Pavement Strength and Foundation Support

The variables that influence the support conditions of the PCC pavement and the pavement strength in general are base thickness, base type, and subgrade type. An increase in base thickness, the use of stabilized bases, and the construction of pavements on coarse subgrade materials increase pavement strength. The ANOVA results show that, in all these cases, strengthening a pavement decreases roughness. This is a reasonable result because, generally, stronger pavements experience less distress.

Table 20. Summary of analysis of variance results for roughness.

Variable	Classification	Mean IRI m/km	Duncan Class*	Significant Difference?
Mean temperature, °C	less than 12.7	1.43	A	Yes
	12.7 to 18.3	1.35	A	
	greater than 18.3	1.83	B	
PCC thickness, mm	less than 225	1.43	A	
	greater than 225	1.51	A	
Concrete texture	tine	1.57	A	Yes
	others	1.35	B	
Base thickness, mm	less than 150	1.43	A	Yes
	greater than 150	1.34	B	
Dry	dry climate	1.36	A	No
	wet climate	1.48	A	
Base type	unstabilized	1.56	A	Yes
	stabilized	1.42	B	
Subgrade type	fine	1.48	A	No
	coarse	1.40	A	
Drain	no drains	1.42	A	No
	drains	1.57	A	
Drainage coefficient	less than 1	1.51	A	No
	greater than 1	1.37	A	

* Duncan's multiple range test; those with the same letter are not significantly different.

<u>Influence of Design Features</u>

Effect of PCC Thickness

Table 20 shows that increased PCC thickness results in more roughness. This has been explained in detail for JPCP and JRCP, and the reasons are applicable to CRCP.

Effect of Drains and Drainage Coefficient

The ANOVA analysis shows that the provision of drains to a pavement generally reduces distress and roughness. This can be explained by the fact that adequate drainage reduces the amount of water within the pavement structure, thereby reducing the potential for pumping and weakening of the underlying pavement materials. Providing a base material that enhances drainage also reduces distresses such as pumping and faulting. This is also shown by the fact that an increase in the pavement base drainage coefficient reduces roughness and increases performance. Pavements with a drainage coefficient less than 1 had a mean roughness value of 1.51 m/km, and those with a drainage coefficient of greater than 1 had a mean roughness value of 1.32 m/km.

Influence of Construction Practices

Effect of Concrete Texture Method

Past studies have shown that the initial roughness of a pavement has an effect on the rate of progression and the final roughness of a pavement. Pavements built rough generally stay rougher. The methods of finishing a pavement's surface after construction ultimately affect the final smoothness of the pavement. The ANOVA analysis results show that CRCP with tined surfaces generally are rougher in the long run than those with other finishing methods. An analysis of the effect of concrete texture on performance for all pavement types is presented in the next chapter.

Summary of Site Conditions, Design Features, and Construction Practices that Influence CRCP Roughness

Using univariate analysis, frequency plots, canonical discriminant analysis, and ANOVA, the design and climatic variables that influence the occurrence and severity of faulting in CRCP have been analyzed. According to the results of the analysis, stiffer pavements tend to perform better than pavements with less strength or stiffness. This is shown by the fact that pavements constructed on coarse subgrades with stabilized bases performed better than those on weaker foundations.

The analysis also showed that pavements located in climates with higher annual number of wet days and with extreme climates performed worse than those in milder climates. These observations are reasonable and could serve as basic guidelines for pavement design and evaluation. Also, the canonical function CANCRC1 was used to determine pavements performing better than expected, or otherwise. This can be a useful tool in classifying newly designed pavements or to check preliminarily for adequate performance through a pavement's design life.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study was intended to determine, through the use of statistical and engineering principles, the pavement design features and construction practices that enhance pavement performance. Chapters 3 to 5 discussed in detail the effects of key design features and construction practices on performance. The influence of site conditions on performance is also discussed. The criteria for determining performance were based on the level of three different distresses: faulting for JPCP, transverse cracking for JPCP, and roughness for JPCP, JRCP, and CRCP.

This report presents several canonical functions to be used in discriminating between pavements on the basis of predetermined performance criteria. The results of an ANOVA showing variables that affect performance have also been presented and discussed. The recommendations presented in this chapter are a result of both the canonical discriminant analysis and the ANOVA. Volume I of this report contains a more comprehensive set of recommendations on the design and construction of concrete pavements on the basis of the results in this volume and volume III.

Recommendations - Design Features that Influence Performance

The design features or variables that influence the performance of concrete pavements are summarized in table 21.

PCC Elastic Modulus

The table shows that using a PCC with modulus greater than 27,600 MPa reduces roughness in JPCP. PCC modulus, however, had no significant effect on the other distress types or pavement types.

Base Elastic Modulus

JPCP pavements with AC-stabilized bases had less transverse cracking, whereas those with portland cement-stabilized bases had less faulting. The reduction of both of these distresses resulted in less roughness. It is important, therefore, to determine which kind of distress is more critical during the design process. Pavements located in areas with site conditions conducive to pumping and faulting, such as poor base materials, subgrades with a high percentage of fines, and high precipitation or number of wet days, must use PCC-stabilized bases to reduce the potential for faulting.

Table 21. Design variables that influence pavement performance.

Design Variable	Level	Influence on Distress, ✓ = positive				
		Faulting	Transverse Cracking	Roughness		
				JPCP	JRCP	CRCP
PCC elastic modulus, MPa	greater than 27,600			✓		
	less than 27,600					
Base elastic modulus, MPa	unstabilized (less than 690)					
	AC stabilized (690 to 6900)		✓	✓		
	cement stabilized greater than 6900	✓		✓		
PCC slab thickness, mm	less than 225			✓		✓
	greater than 225	✓	✓		✓	
Base thickness, mm	less than 150					
	greater than 150			✓		✓
Base type	erodible (unstabilized)					
	nonerodible (stabilized)	✓				✓
Drainage coefficient	less than 1		✓			
	greater than 1	✓		✓	✓	✓
Presence of drainage facilities	Yes	✓		✓	✓	
	No					✓

Table 21. Design variables that influence pavement performance (continued).

Design Variable	Level	Influence on Distress, ✓ = positive				
		Faulting	Transverse Cracking	Roughness		
				JPCP	JRCP	CRCP
Joint coefficient	less than 3.2	✓		✓		
	greater than 3.2					
Radius of relative stiffness, mm	less than 890					
	890 to 1150					
	greater than 1150	✓				
Skew joints?	Yes	✓				
	No					
Dowels	Yes	✓	✓	✓		
	No					
Modulus of rupture, MPa	less than 4.5					
	greater than 4.5		✓			
Shoulder type	flexible					
	rigid			✓		
JRCP joint spacing, m	less than 13.7				✓	
	greater than 13.7					

Pavements located in areas with high temperature ranges, with longer joint spacing, and having a potential for transverse cracking must be designed with AC-stabilized bases to reduce this potential.

PCC Slab Thickness

Table 21 shows that JPCP pavements with thicker slabs (> 225 mm) had less faulting and transverse cracking. However, for JPCP and CRCP, the pavements with thicker PCC slabs experienced a higher level of roughness. The trend for faulting and transverse cracking shows that thicker PCC slabs reduce the occurrence of distress. The increased roughness is a result of poor construction. It is therefore recommended that pavements use thicker slabs to reduce the occurrence of distress, but in such circumstances a higher level of quality control should be exhibited during construction to reduce the amount of initial roughness of the pavement.

Base Thickness

Pavement with greater base thicknesses (JPCP and CRCP) experienced less roughness. This is due to the fact that thicker bases provide stronger foundations. The use of thick bases therefore enhances pavement performance.

Base Type

Generally, the two base types used are stabilized and non-stabilized. They also can be categorized as erodible or non-erodible, depending on the level of corrosion that the base material can undergo when saturated with infiltrated water. Table 19 shows that pavements with non-erodible bases experienced less faulting for JPCP and less roughness for CRCP.

Drainage Facilities and Drainage Coefficient

There are two main types of drainage facilities provided for the drainage of pavements: edge drains only or permeable or open bases with edge drains. The design variable drainage coefficient is related to the permeability or openness of the base layer, with the more permeable bases having values closer to 1.3. Dense-graded bases with little or no permeability have values close to 0.7. The data element "presence of drainage facilities" refers to the presence of any or both of the drainage facilities described. Table 21 shows that pavements with drainage coefficients greater than 1 had less faulting for JPCP and roughness for all three pavement types. However, there was increased transverse cracking for JPCP. Once again, more open bases to reduce faulting and other moisture-related distress should be carefully weighed against the potential increase in transverse cracking. Using a stronger stabilized permeable base should provide a stronger foundation and less cracking. The provision of drainage facilities in general reduced distresses and roughness.

Joint Conditions

The joint conditions, use of dowels, skewed joints, and joint load transfer coefficient of JPCP had a significant effect on faulting. Table 21 shows that JPCP with a load transfer coefficient less than 3.2 experience less faulting. JPCP with dowels experienced less faulting, transverse cracking, and roughness, and JPCP with skewed joints also performed better.

Almost all the JRCP sections in the LTPP database had dowels; therefore, the effect of joint conditions was not analyzed. For JRCP, joint spacing had a significant influence on roughness. This may be due to the fact that JRCP tend to have longer joints than other pavement types. JRCP with joint spacing less than 13.7 m performed better than those with longer joint spacing; therefore, limiting joint spacing to below 13.7 m is recommended.

Shoulder Type

The three common types of material used in the construction of PCC pavement shoulders are PCC, AC, and granular surface. Table 21 shows that shoulder type influenced performance for JPCP only. The use of concrete shoulders for JPCP enhances the performance of the pavement because JPCP generally experience greater levels of deflections at the slab midsection than other PCC pavement types, and the use of tied PCC shoulders provides some load transfer at the slab midsection, reducing deflections and the potential for distress and roughness.

Modulus of Rupture

The modulus of rupture of a pavement is a general estimate of the strength of the pavement and its ability to withstand stresses, fracture, and cracking. Table 21 shows that pavements with modulus of rupture values greater than 4.5 MPa experience less transverse cracking. This shows that maximizing the strength of the PCC slab generally enhances performance. It must be noted, however, that PCC slabs with very high modulus of rupture values tend to be brittle and could be susceptible to cracking and fracture.

Recommendations - Construction Practices that Influence Performance

The construction practices that influenced pavement performance are summarized as follows:

- Pavements constructed with AC-treated base perform best. The construction of PCC slabs directly on subgrade material, stabilized or unstabilized, must be avoided.
- Pavements with more layers performed better than those with fewer layers.
- Jointed pavements with dowels performed better than jointed pavements using other kinds of load transfer mechanisms or no load transfer at all.
- The best method for dowel placement, according to the LTPP database, is by preplacing the dowels on baskets.
- The best joint forming procedure is the plastic insert method.
- PCC mix design affects the durability of the PCC slab and, hence, performance. The most durable concrete mixtures had greater than 1,800 kg/m^3 of coarse aggregate and less than 1,300 kg/m^3 of fine aggregate. Cement and water content did not significantly influence performance.
- The two most effective methods for curing PCC slabs after construction, according to the LTPP database, are polythene and burlap.

Recommendations - Site Conditions that Influence Performance

Site conditions (the climate in which a pavement is located and subgrade type a pavement is constructed over) ultimately affect performance. A summary of the climate and subgrade conditions that adversely affect performance are listed below:

• Average annual number of wet days:	greater than 140 days
• Climate:	wet
• Number of air freeze thaw cycles:	greater than 110
• Annual mean temperature:	greater than 15.5 °C
• Annual precipitation:	greater than 1 m
• Subgrade type:	fine

Recommendations for design against these adverse site conditions have been discussed in earlier chapters of this report.

Recommendations for Future Research

The results and recommendations presented in this report are based on a comprehensive study of the LTPP database. The study was in the form of a preliminary data analysis (univariate and bivariate analysis) and a detailed statistical analysis in the form of canonical discriminant analysis and an ANOVA. The study was successful to a large extent, but additional data will make it possible to study in greater detail the effect of design features, site conditions, and construction practices that influence PCC pavement performance.

APPENDIX A

OVERVIEW OF LTPP PCC PAVEMENT SECTIONS

Introduction

The focus of this study was to use the LTPP database to investigate the primary pavement design features and practices that affect pavement performance and provide recommendations for the design and construction of long-lived concrete pavements. As a result, the first task was to evaluate the LTPP database to obtain information on the characteristics of the pavement sections that are included in the database. This appendix not only describes how the data were processed and reduced for this project, but also provides detailed information on the characteristics of the LTPP pavement sections. Many statistics (e.g., mean, standard deviation, minimum value, maximum value, and median) were used to descibe and quantify most of the important design features, site conditions, and construction practice variables for the different pavement types.

Because the LTPP pavement sections are distributed across the United States and Canada, certain regional differences in the characteristics of the pavements are expected. The influence of these regional differences on long-term pavement performance was investigated in this study.

LTPP Database

The data used in this analysis come from the following three LTPP General Pavement Study (GPS) experiments:

- GPS-3 Jointed Plain Concrete Pavements.
- GPS-4 Jointed Reinforced Concrete Pavements.
- GPS-5 Continuously Reinforced Concrete Pavements.

The data were obtained in 1995 from the National Information Management System (NIMS) that houses the database. The data consisted of pavement characteristics for 123 JPCP, 69 JRCP, and 85 CRCP sections located throughout the United States and Canada. These are 150-m pavement sections typically with 3.6-m-wide traffic lanes and either AC or tied PCC shoulders. The data available from the LTPP NIMS for these sections include climatic, material properties, traffic loading, surface profile, distress, and numerous other types of data. For this study, data from the following specific data modules of the LTPP database were downloaded from the NIMS (in ASCII format) for all GPS 3, 4, and 5 pavement sections:

- Inventory data.
- Materials testing data.

- Climatic data.
- Traffic data.
- Pavement monitoring data.

Data Processing and Reduction

The data that were obtained from the LTPP database were placed into a Microsoft Access® database to facilitate quick and easy retrieval of the data for various analyses. The same LTPP nomenclature used in the NIMS was used in preparation for data manipulation and reduction. Because the LTPP data are provided in several different tables, it was necessary to use Microsoft Access for efficient merging and organization of the data.

Microsoft Access® proved to be a valuable tool for this data manipulation. This software allowed tables to be merged and organized by section identification. In addition, the data could easily be subdivided into various categories. For instance, by simply changing the experiment number, the data could be divided into JPCP, JRCP, and CRCP. All of the pertinent data elements were combined for each unique LTPP section within each pavement type.

The following paragraphs describe the types of data associated with each pavement type, as well as interesting quantifiable characteristics of many of the data elements. Comparisons between different climatic regions are also presented where appropriate. A complete summary of the data contained in the LTPP database, and identified as important to pavement performance in the previous chapter, is contained in this appendix.

Jointed Plain Concrete Pavements

The LTPP database contains a variety of data elements for 123 JPCP pavement sections (GPS-3). These sections (from 32 States, Puerto Rico, and 3 Canadian Provinces) are divided among the four climatic regions in the following manner:

- Dry-Freeze: 27 sections
- Dry-Nofreeze: 12 sections
- Wet-Freeze: 43 sections
- Wet-Nofreeze: 41 sections

<u>Pavement Age and Traffic</u>

The JPCP pavement sections range in age from 5.3 to 36.4 years, with a mean of 16.4 and a standard deviation of 6.1 years. A histogram of JPCP section age is provided in figure 99.

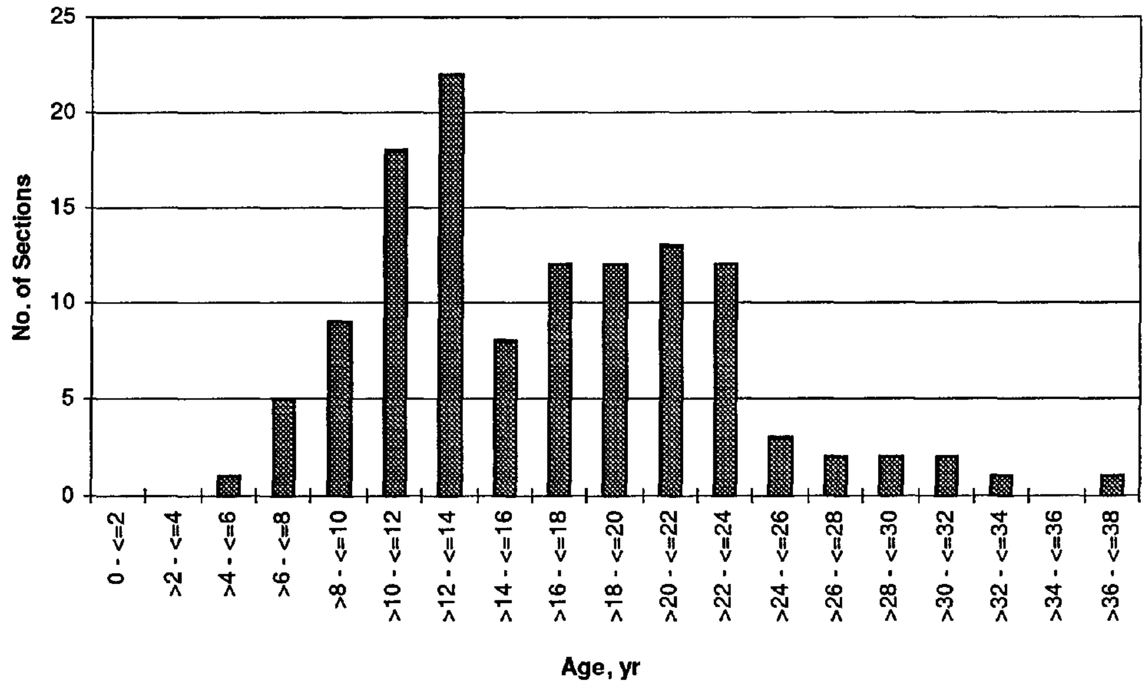


Figure 99. Histogram of age for JPCP (GPS-3) LTPP sections.

Traffic data were available for only 101 of the 123 JPCP sections. These sections showed a wide range of traffic loading, with average traffic ranging from 8 to 3,144 thousand ESAL's (3,144 KESAL's) per year, with a mean value of 305, a median of 197, and a standard deviation of 379 KESAL's/year. The slab thicknesses of these sections range from 150 to 335 mm, with a mean and median of 240 mm, and a standard deviation of 30 mm. Histograms of ESAL's and slab thickness for JPCP sections are contained in figures 100 and 101, respectively. A complete summary of the traffic statistics by climatic region is presented in table 22.

Design Features

Slab Thickness

The wet-nofreeze climatic region contains both the minimum and maximum (150 and 335 mm) JPCP thickness values in the database, as well as having the largest mean (240 mm) and median (250 mm) values of the four climatic regions. A complete summary of statistics by climatic region is presented in table 23.

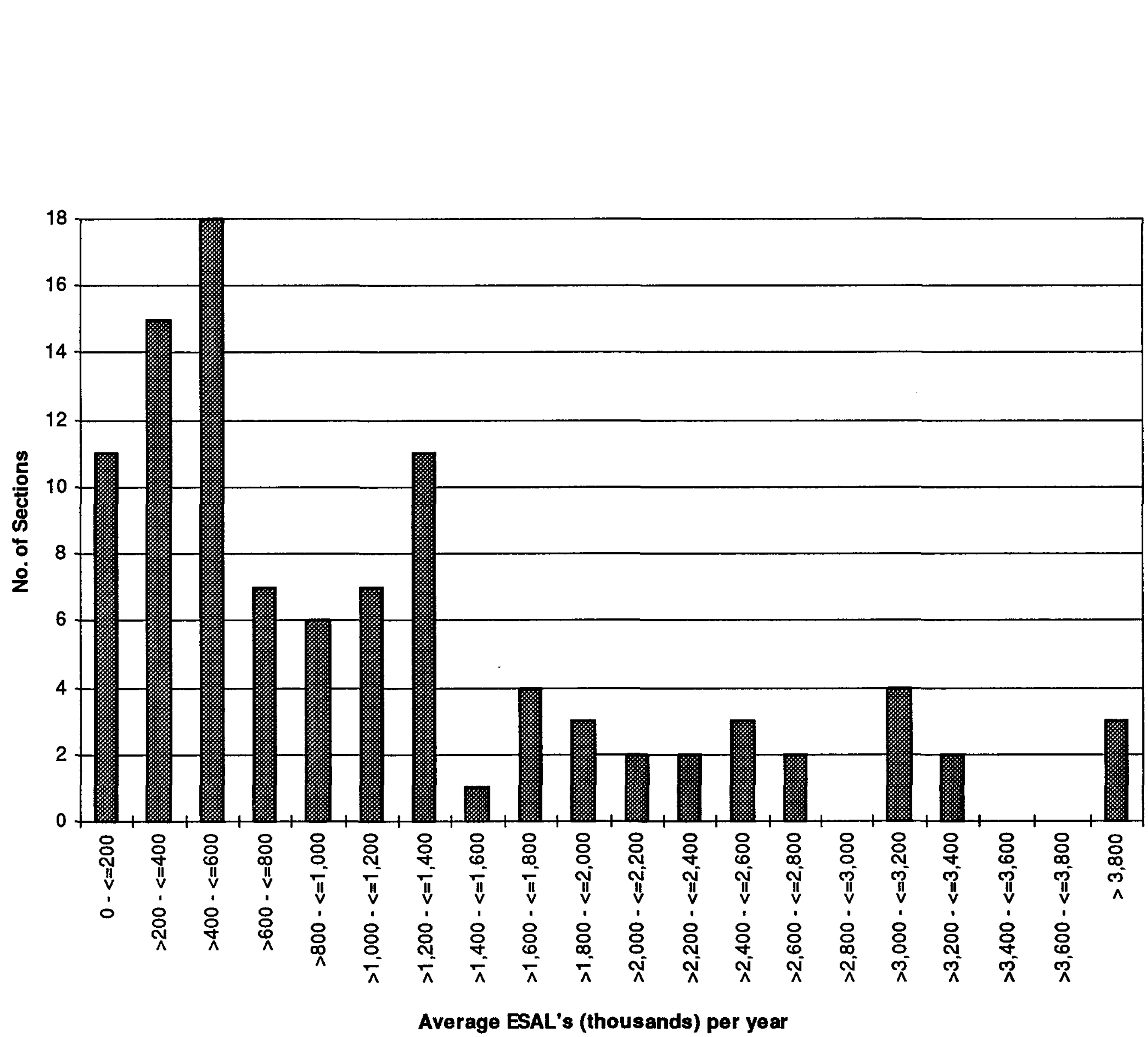


Figure 100. Histogram of ESAL's per year for JPCP (GPS-3) LTPP sections.

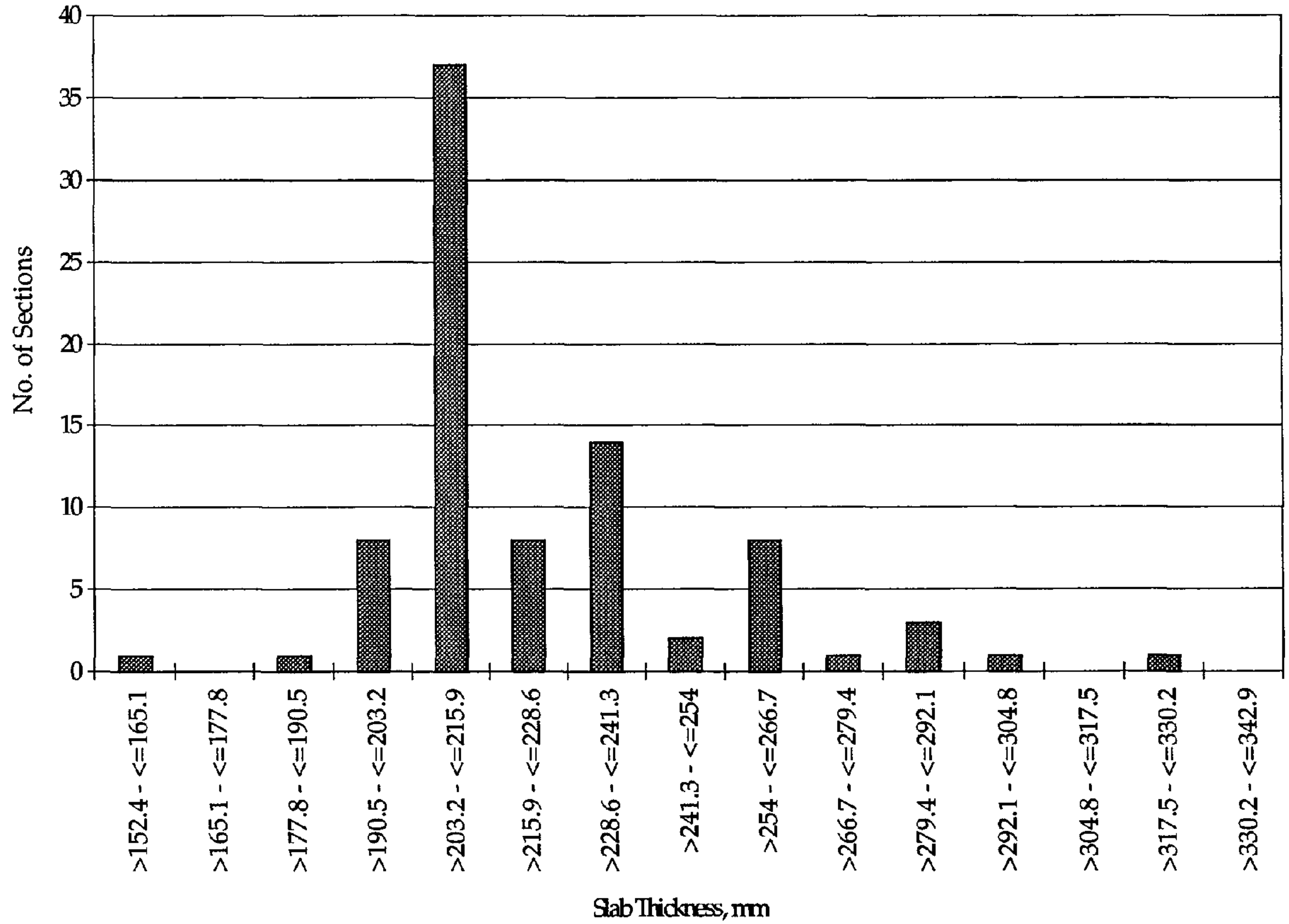


Figure 101. Histogram of slab thickness for JPCP (GPS-3) LTPP sections.

Table 22. JPCP traffic statistics by climatic region (KESAL's/year).

Statistic	Climatic region			
	Dry-freeze	Dry-nofreeze	Wet-freeze	Wet-nofreeze
Mean	233	811	243	289
Std. Deviation	184	954	224	252
Min. value	8	139	21	15
Max. value	555	3,144	988	787
Median	233	431	164	171

Table 23. JPCP thickness statistics by climatic region (mm).

Statistic	Climatic region			
	Dry-freeze	Dry-nofreeze	Wet-freeze	Wet-nofreeze
Mean	241	236	234	245
Std deviation	25.4	28	28	33
Min. value	198	198	180	152
Max. value	302	290	322	337
Median	241	233	233	251

Transverse Joint Spacing and Orientation

The average transverse joint spacing of the 123 JPCP sections ranged from 3.47 to 9.15 m, with a mean of 5.12, a median of 4.72, and a standard deviation of 1.12 m. A histogram of the joint spacing of all JPCP sections is presented in figure 102. The data in the LTPP database showed that the average transverse joint spacing was longer (on average) in the wet climatic regions than in the dry climatic regions. The mean average joint spacings for the wet-freeze and wet-nofreeze climatic regions were 5.12 and 5.76 m, respectively, and the values for the dry-freeze and dry-nofreeze regions were 4.4 and 4.5 m, respectively.

The LTPP data showed that 54 percent (67 of 123) of all of the JPCP sections were constructed with random joint spacing. A total of 19 different random spacing designs were observed in the database, with the most common (32 of 67 sections) being the California design of 3.6-4-5.8-5.5 m. A much higher percentage of the sections in the dry climatic regions were constructed with random joints. Random joints were

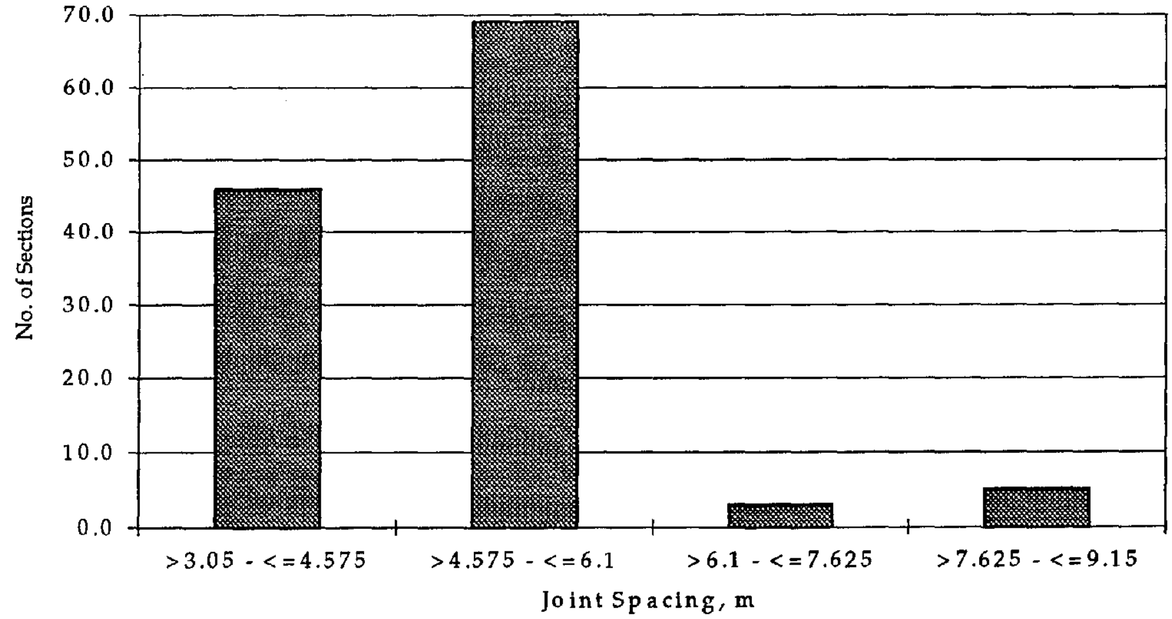


Figure 102. Histogram of joint spacing for JPCP (GPS-3) LTPP sections.

constructed in 74 percent (20 of 27) of the dry-freeze sections, 100 percent (12 of 12) of the dry-nofreeze sections, 49 percent (21 of 43) of the wet-freeze sections, and 34 percent (14 of 41) of the wet-nofreeze sections. The LTPP data showed that 67 percent (83 of 123) of all of the JPCP sections were constructed with skewed transverse joints. The majority of sections within each climatic region, except the wet-nofreeze section, were constructed with skewed joints. Specific numbers for each climatic region show that skewed joints existed in 93 percent (25 of 27) of the sections in the dry-freeze region, 100 percent (12 of 12) of the sections in the dry-nofreeze region, 70 percent (30 of 43) of the sections in the wet-freeze region, and 39 percent (16 of 41) of the sections in the wet-nofreeze region.

PCC Elastic Modulus and 28-day Modulus of Rupture

PCC elastic modulus and 28-day modulus of rupture data were available for only 95 of the 123 JPCP sections. The availability of the data within each climatic region consisted of 26 of 27 sections in the dry-freeze region, 8 of 12 in the dry-nofreeze region, 32 of 43 in the wet-freeze region, and 29 of 41 in the wet-nofreeze region.

The available PCC elastic modulus data for the 95 JPCP sections ranged from 24,205 to 36,052 MPa, with a mean of 27,137 MPa, a median of 26,670 MPa, and a standard deviation of 3,001 MPa. A histogram of the PCC elastic moduli for these available sections is presented in figure 103. In an analysis within each climatic region, the

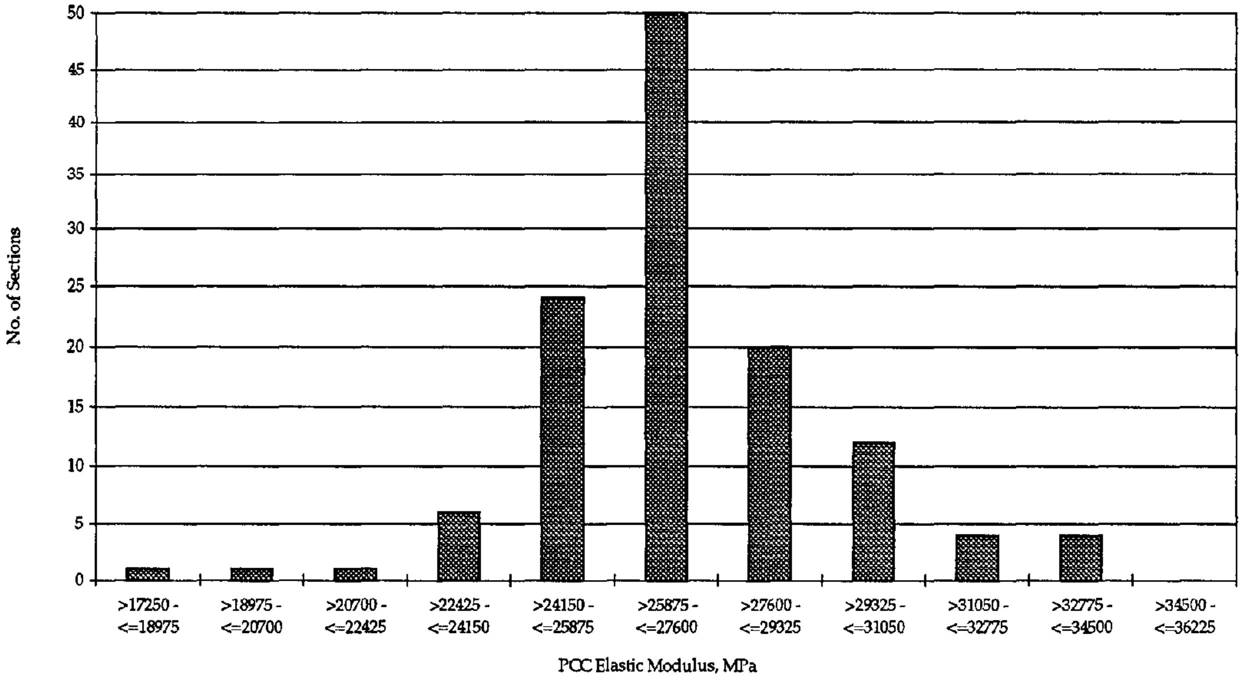


Figure 103. Histogram of available PCC elastic moduli for JPCP (GPS-3) LTPP sections.

largest climatic region elastic modulus mean value was observed in the dry-freeze region (28,726 MPa), and the smallest was the mean of the available sections in the dry-nofreeze region (24,321 MPa).

The available 28-day PCC modulus of rupture data for the 95 JPCP sections ranged from 3 to 6.3 MPa, with a mean of 4.75 MPa, a median of 4.66 MPa, and a standard deviation of 0.56 MPa. A histogram of the 28-day PCC modulus of rupture for these available sections is presented in figure 104. In an analysis within each climatic region, the largest climatic region 28-day PCC modulus of rupture mean value was observed in the dry-freeze region (5 MPa), and the smallest was the mean of the available sections in the dry-nofreeze region (4.3 MPa).

Base Type

Base type information was available for 121 of the 123 JPCP LTPP pavement sections (both missing sections are in the wet-nofreeze region). The database contained 10 different specific base types. Of the 10 observed base types for these sections, 3 were classified as *granular*, and the remaining 7 were classified as *stabilized*. Using these two general classifications, it was observed that 43 percent (53 of 123) of the sections were constructed with a granular base, 55 percent (68 of 123) with a stabilized base, and 2 percent (2 of 123) with unidentified base type codes. Figures 105 and 106 illustrate the number of sections constructed with each base type.

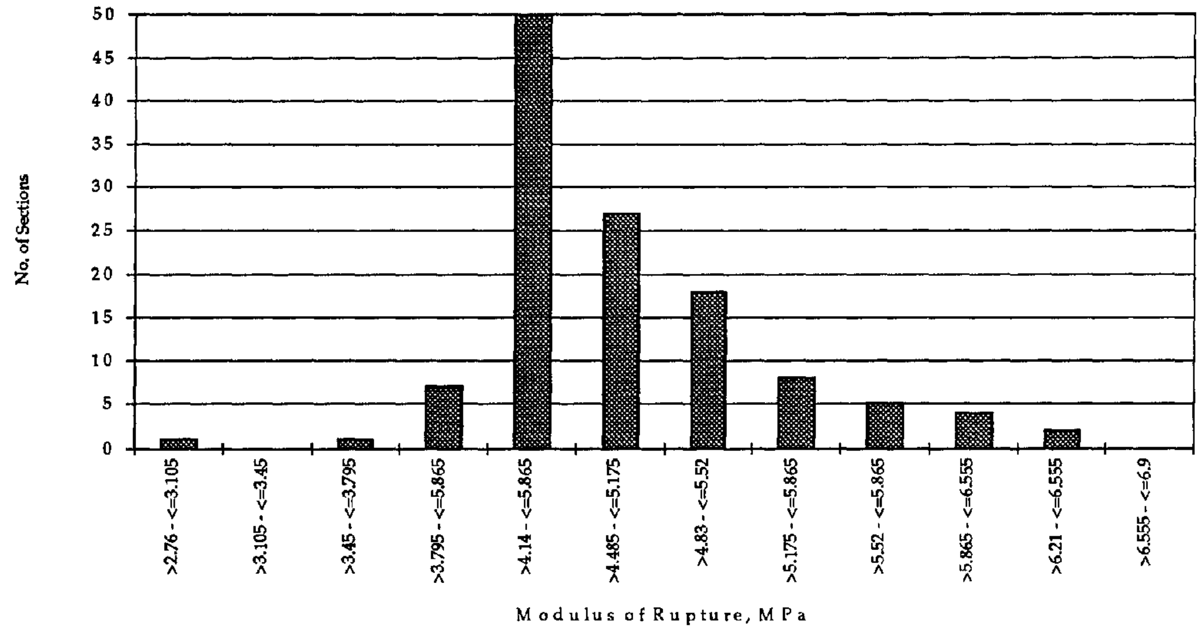


Figure 104. Histogram of available 28-day PCC modulus of rupture for JPCP (GPS-3) LTPP sections.

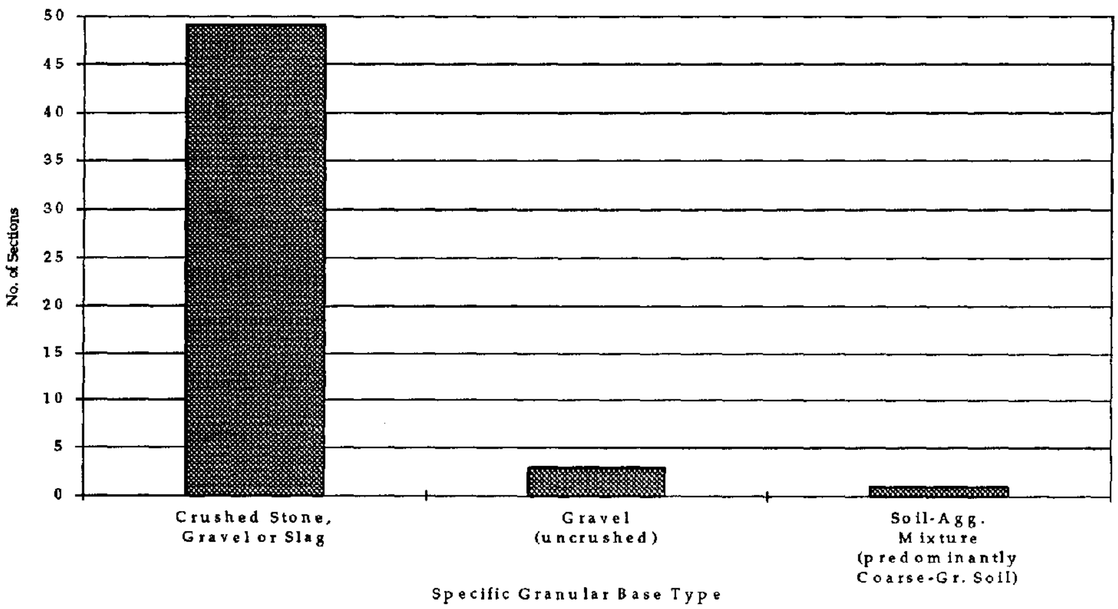


Figure 105. Bar chart of specific granular base types for all JPCP (GPS-3) LTPP sections.

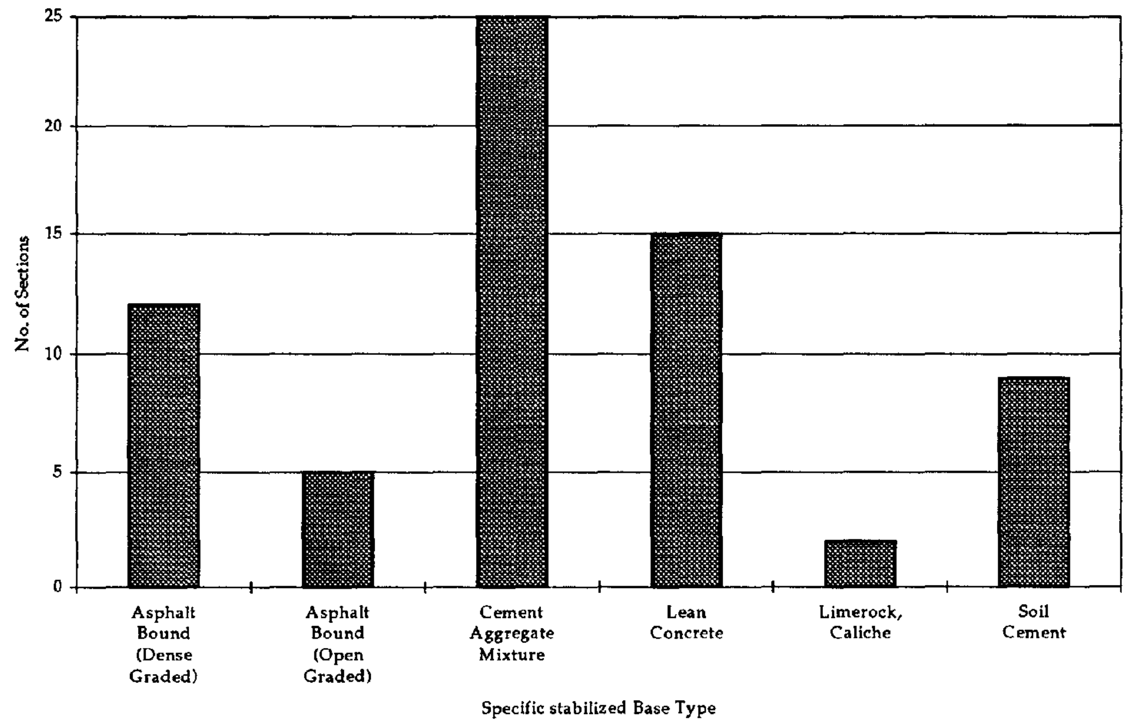


Figure 106. Bar chart of specific stabilized base types for all JPCP (GPS-3) LTPP sections.

An analysis of the base types within and between different climatic regions showed that the majority of sections in the regions with freeze conditions were constructed with granular bases ranging in thickness from 33 to 390 mm. The majority of the sections in the regions with nofreeze conditions were constructed with stabilized bases ranging in thickness from 28 to 300 mm. More specifically, granular bases were constructed for 56 percent (15 of 27) of the sections in the dry-freeze region and 58 percent (25 of 43) in the wet-freeze region, whereas stabilized bases were constructed for 92 percent (11 of 12) of the sections in the dry-nofreeze region and 69 percent (27 of 39) of the sections in the wet-freeze region. Two of the JPCP sections were constructed with no base in this region.

A more detailed look at the specific base types shows that the most frequently observed granular base type in all four climatic regions is *crushed stone, gravel, or slag*. *Cement-aggregate mixtures* were the most frequently observed stabilized base type for 3 of 4 climatic regions (excluding the dry-freeze region). The most frequently used base type in the dry-freeze region is *lean concrete (<3 sacks cement/cy)*. The frequency of granular and stabilized base types summarized by climatic region is presented in tables 24 and 25.

Table 24. JPCP sections with granular base types summarized by climatic region.

Base type	Climatic region			
	Dry-freeze	Dry-nofreeze	Wet-freeze	Wet-nofreeze
Crushed stone, gravel, or slag	13	1	24	11
Gravel (uncrushed)	2	0	1	0
Soil-aggregate mixture	0	0	0	1
Total	15	1	25	12

Table 25. JPCP sections with stabilized base types summarized by climatic region.

Base type	Climatic region			
	Dry-freeze	Dry-nofreeze	Wet-freeze	Wet-nofreeze
Asphalt bound (dense-graded, hot laid, central plant mix)	4	1	2	5
Asphalt bound (open-graded, cold laid, central plant mix)	0	0	2	0
Asphalt bound (open-graded, hot laid, central plant mix)	0	0	3	0
Cement-aggregate mixture	2	8	6	9
Lean concrete	5	2	3	5
Limerock, caliche (soft carbonate rock)	0	0	0	2
Soil cement	1	0	2	6
Total	12	11	18	27

Lane Width

Three different constructed lane widths were observed for the 123 JPCP sections, with the majority being 3.6 m (92 percent—113 of 123). One section was constructed with a 3.35-m width, and 9 sections (7 percent—9 of 123) were widened lane sections constructed with 4.3-m lane widths.

Shoulder Type

Seven different outer shoulder types were used for the 123 JPCP sections in the LTPP database, with the majority being asphalt concrete (46 percent—56 of 123) or portland cement concrete (37 percent—45 of 123). The remaining outer shoulder types consisted of *granular* (8 percent—10 of 123), *surface treatment* (4 percent—5 of 123), *turf* (2 percent—3 of 123), and *other* (3 percent—4 of 123). Figure 107 contains a bar chart showing the number of sections constructed with different outer shoulder types.

Joint Sealant Type

Six different transverse joint sealant types were observed for the 123 JPCP sections in the LTPP database. Of the 123 sections, 28 percent (35 of 123) were unsealed (sealant type was blank in the database), 23 percent (28 of 123) were sealed with *low-modulus silicone*, 18 percent (22 of 123) used *rubberized asphalt*, 14 percent (17 of 123) used a *preformed* seal, 5 percent (6 of 123) used an *asphalt* seal, and 12 percent (15 of 123) used other sealant types. Figure 108 contains a bar chart showing the distribution of the different transverse joint sealant types for the JPCP.

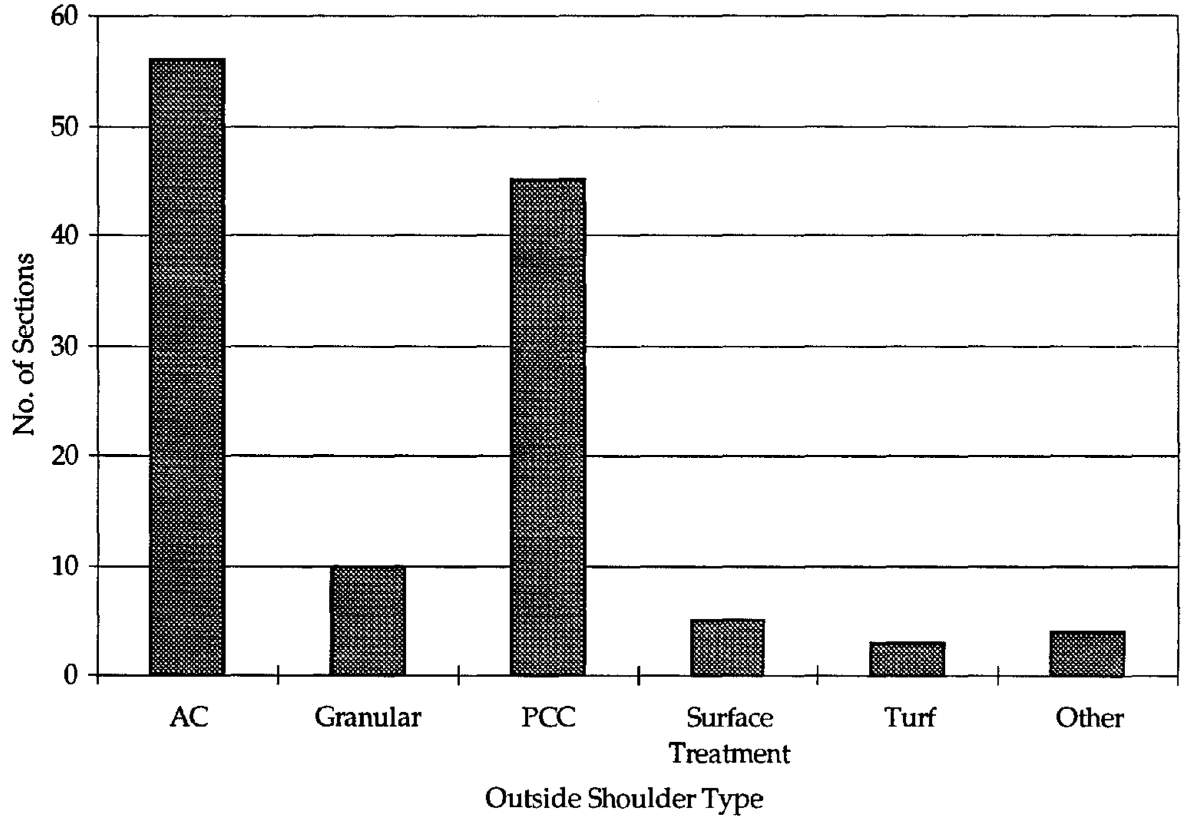


Figure 107. Bar chart of outer shoulder types for all JPCP (GPS-3) LTPP sections.

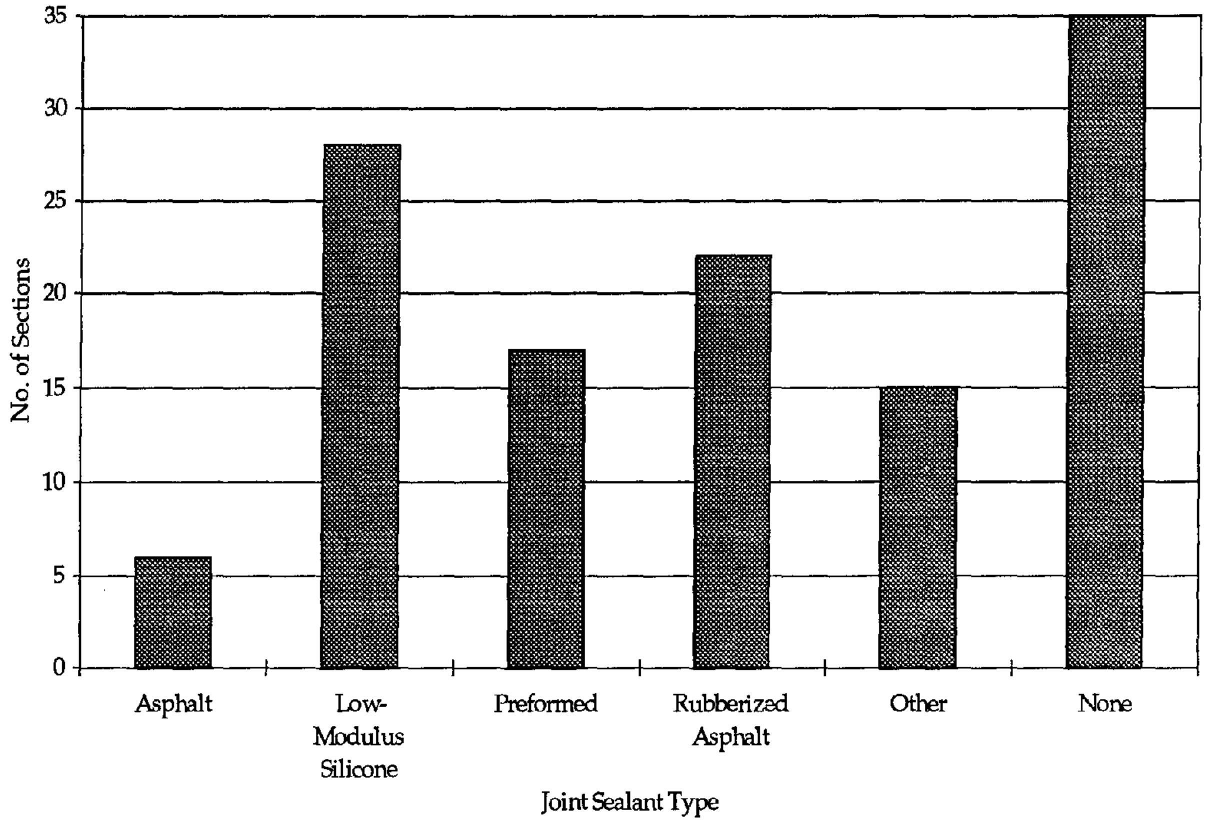


Figure 108. Bar chart of transverse joint sealant types for all JPCP (GPS-3) LTPP sections.

Site Conditions

Freezing Index

Even though the data have already been divided into four climatic regions on the basis of the annual mean daily air temperature and the annual average precipitation, it is also interesting to look at some other specific climatic variables. Freezing index was available for 120 of the 123 JPCP sections, and it varied from 0 to 1,886 degree days (°C-days), with a mean of 365, a median of 262, and a standard deviation of 395 degree days. As expected, an analysis of the mean freezing index within different climatic regions showed much larger values for the regions with freeze conditions.

More specifically, the sections in the dry-freeze and wet-freeze regions had values ranging from 16 to 1,806 degree days, while the sections in the dry-nofreeze and wet-nofreeze regions had values ranging from 0 to 260 degree days. A histogram of the available freezing index data from the 120 JPCP sections is presented in figure 109.

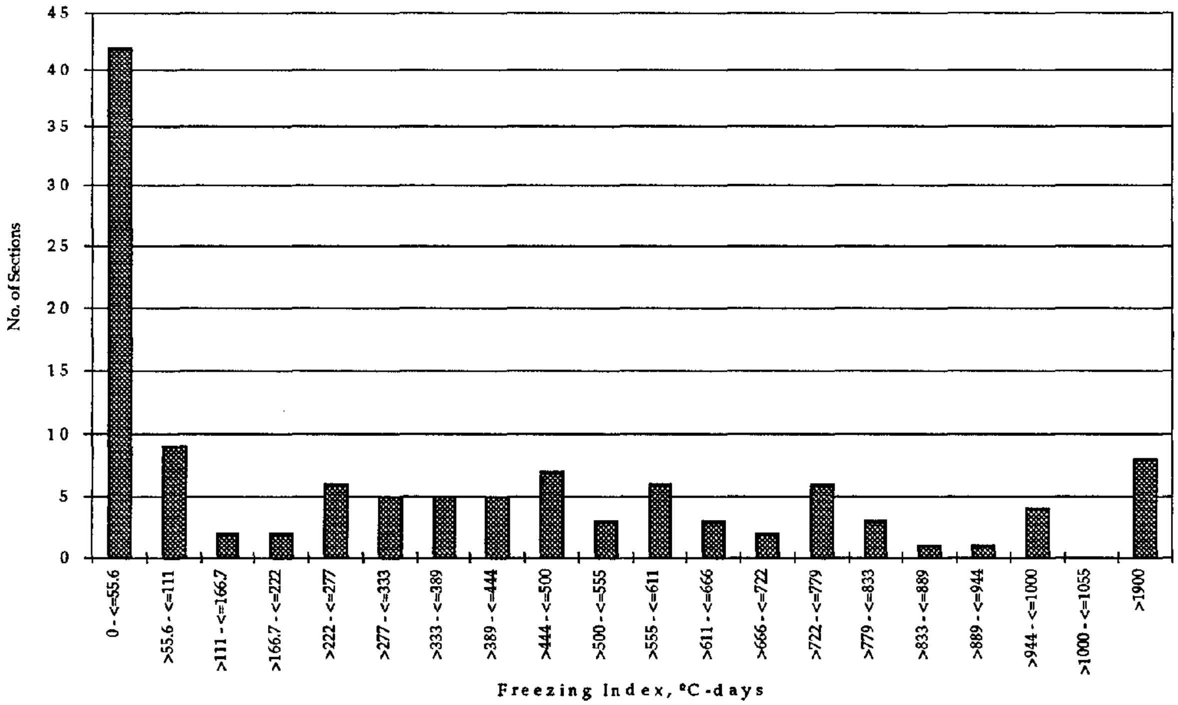


Figure 109. Histogram of available freezing index data for JPCP (GPS-3) LTPP sections.

Freeze-Thaw Cycles

Average annual freeze-thaw cycles were available for 120 of the 123 JPCP sections, and the number of cycles varied from 0.0 to 168.7, with a mean of 76.9, a median of 83.1, and a standard deviation of 40.9. As expected, an analysis of the average annual freeze-thaw cycles within different climatic regions showed larger mean values for the regions with freeze conditions. More specifically, the sections in the dry-freeze and wet-freeze regions had mean values of 117.2 and 92.7, respectively, whereas the sections in the dry-nofreeze and wet-nofreeze regions had mean values of 25.9 and 46.3, respectively. A histogram of the available average annual freeze-thaw cycle data from the 120 JPCP sections is presented in figure 110.

Average Annual Precipitation

The average annual precipitation ranged from 0.1 to 1.37 m, with a mean of 0.82 m, a median of 0.85 m, and a standard deviation of 0.4 m for all 123 sections. As expected, an analysis of the average annual precipitation within different climatic regions showed larger mean values for the regions with wet conditions. More specifically, the sections in the wet-freeze and wet-nofreeze regions had mean values of 0.91 and 1.16 m respectively, and the sections in the dry-freeze and dry-nofreeze regions had mean values of 0.37 and 0.33 m, respectively. A histogram of the average annual precipitation data for the JPCP sections is presented in figure 111.

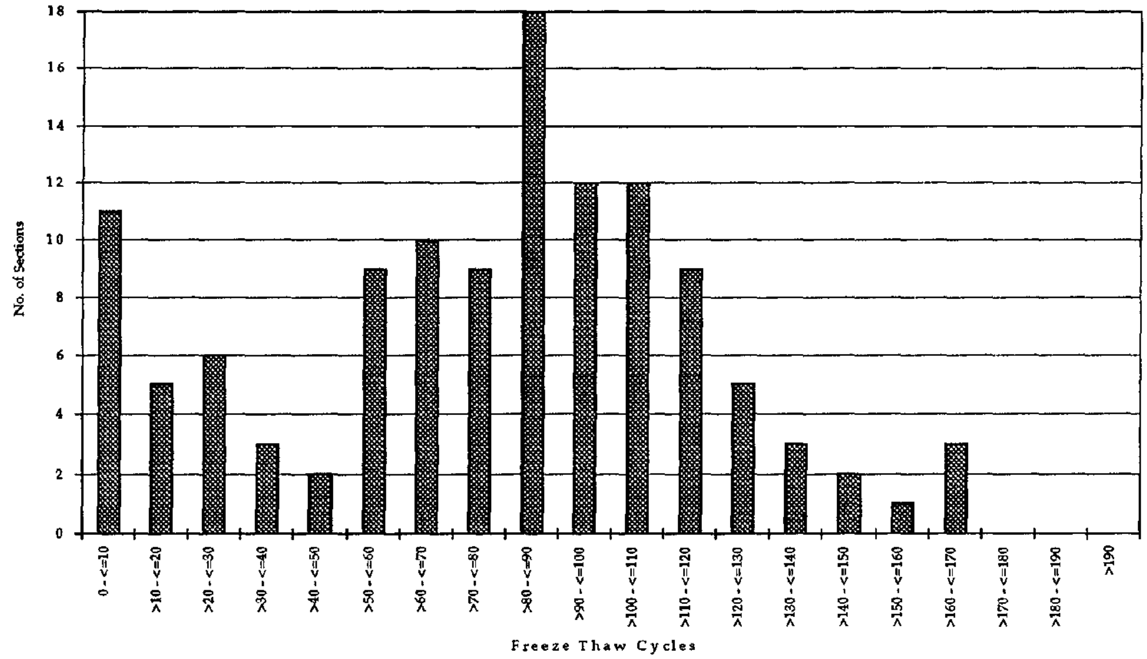


Figure 100. Histogram of available average annual freeze-thaw cycle data for JPCP (GPS-3) LTPP sections.

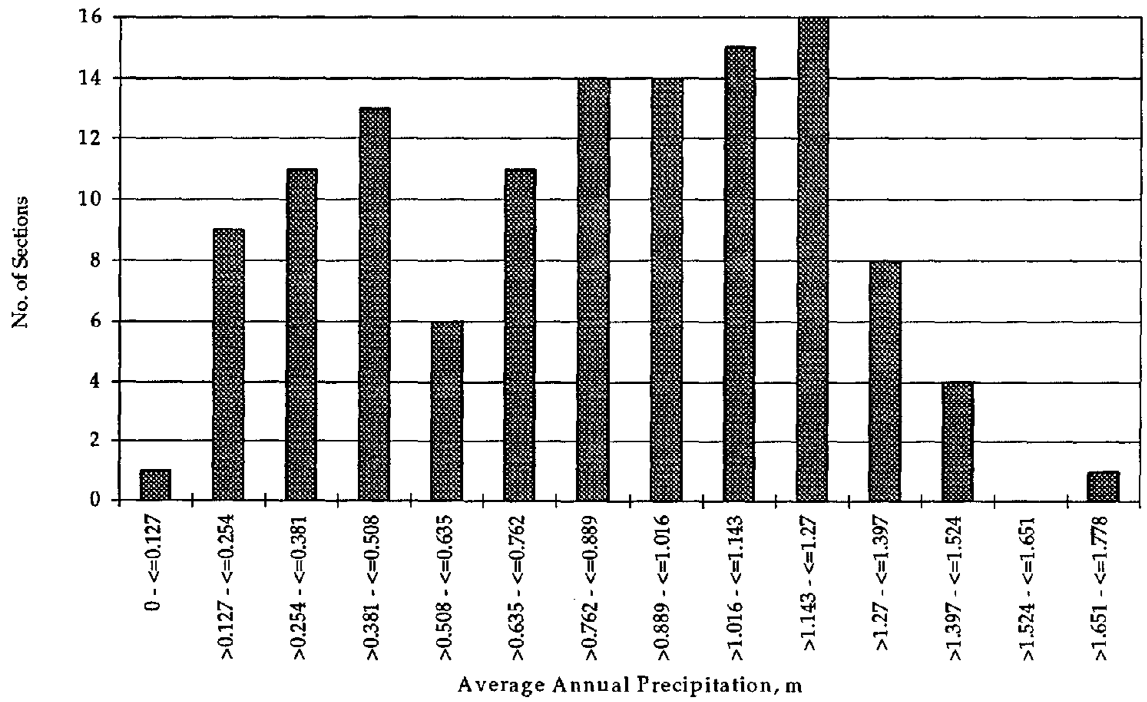


Figure 111. Histogram of average annual precipitation for JPCP (GPS-3) LTPP sections.

Average Annual Temperature Range

The average annual temperature range was available for 120 of the 123 JPCP sections, and it varied from 8 to 19 °C, with a mean of 12.8 °C, a median of 12.6 °C, and a standard deviation of 3.8 °C. An analysis of the average annual temperature range within different climatic regions revealed slightly larger mean values for the regions with dry conditions. More specifically, the sections in the dry-freeze and dry-nofreeze regions had mean temperature range values of 14.3 and 15.4 °C, respectively, whereas the sections in the wet-freeze and wet-nofreeze regions had mean values of 11.4 and 12.6 °C, respectively. A histogram of the average annual temperature range data from the 120 JPCP sections is presented in figure 112.

Subgrade Properties

Two important subgrade properties that had related data available in the LTPP database were subgrade type and backcalculated static k-value. The availability of the data and some important statistics are discussed below.

Subgrade Type

Subgrade type information was available for all 123 JPCP LTPP pavement sections. The subgrade types were classified into *fine-* and *coarse-*grained categories based on subgrade material descriptions in the database. The majority of the JPCP sections in the database (55 percent—68 of 123) have fine-grained subgrade soils. The majority of the observed subgrade soils in the wet regions are fine-grained (61 percent—51 of 84), while the majority in the dry regions are coarse-grained (56 percent—22 of 39). More specifically, 58% (25 of 43) of the sections in the wet-freeze region and 63 percent (26 of 41) of the sections in the wet-nofreeze region have fine-grained subgrade soils, while 52 percent (14 of 27) of the sections in the dry-freeze region and 66 percent (8 of 12) of the sections in the dry-nofreeze region have coarse-grained subgrade soils.

Static k-value

The static k-value was backcalculated from falling weight deflectometer (FWD) data available for 115 of the 123 JPCP sections in the LTPP database. The backcalculated static k-values for the 115 sections ranged from 13.3 to 160 kPa/mm, with a mean of 49 kPa/mm, a median of 43.7 kPa/mm, and a standard deviation of 25.5 kPa/mm. An analysis of the backcalculated static k-value within different climatic regions showed no significant differences between the mean values of the sections in different climatic regions. More specifically, the mean values for the sections in each climatic region were calculated to be 52.45 kPa/mm for the dry-freeze region, 49 for the dry-nofreeze region, 43 for the wet-freeze region, and 53.5 for the wet-nofreeze region. A histogram of the backcalculated static k-value data for all 115 JPCP sections with available FWD data is presented in figure 113.

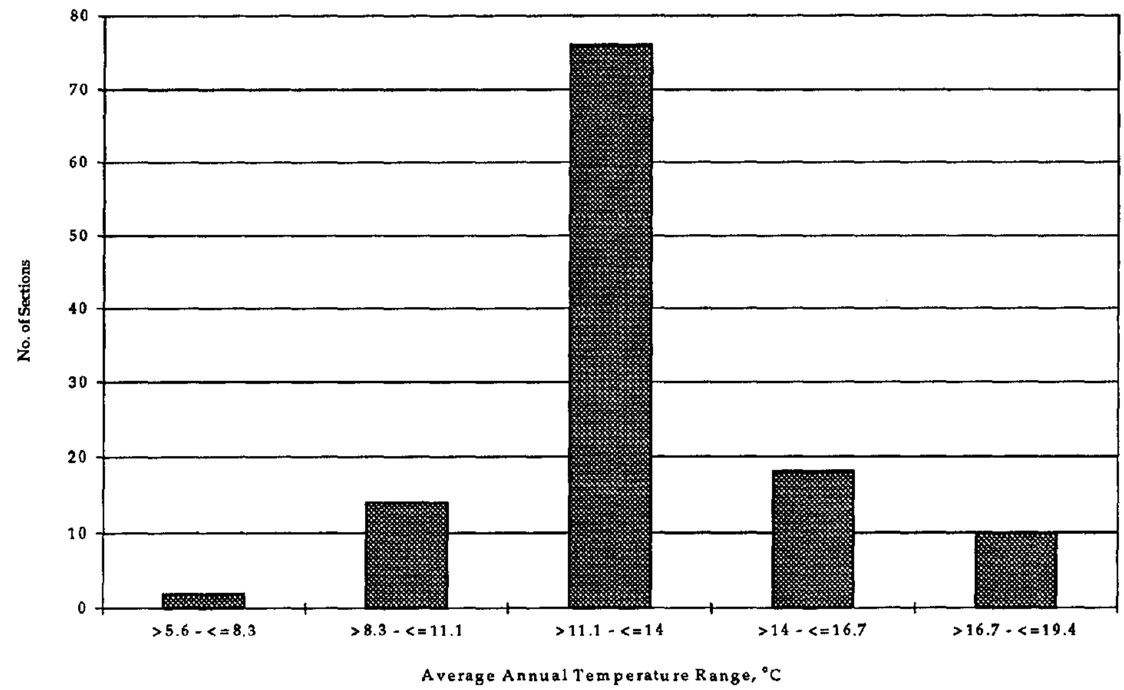


Figure 112. Histogram of available average annual temperature range data for JPCP (GPS-3) LTPP sections.

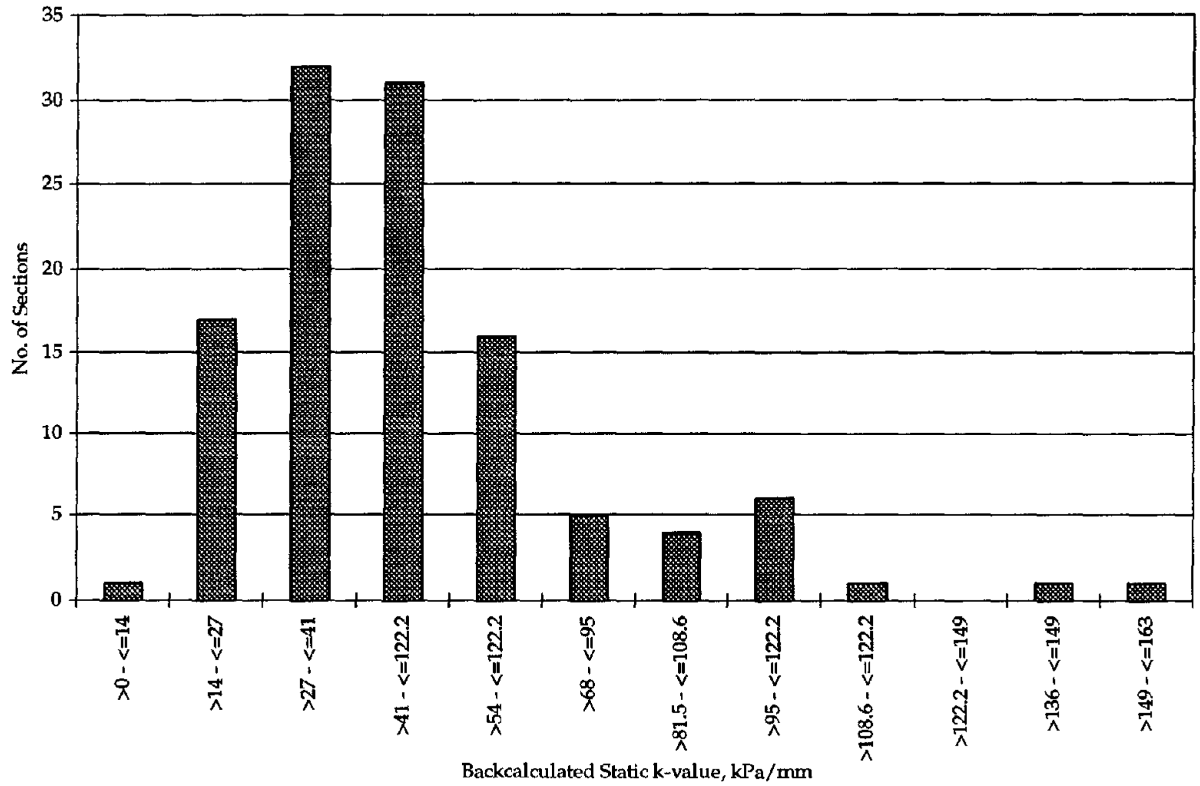


Figure 113. Histogram of available backcalculated static k-value data for JPCP (GPS-3) LTPP sections.

Construction Practices

Paver Type

Data on the type of paver used for construction were available for 104 of 123 JPCP pavement sections in the LTPP database. Of those 104 sections, 92 percent (96 of 104) were constructed using a *slip-form* paver and 7 percent (7 of 104) used a *side-form* paver. No information is available on the type of paver used to construct the remaining sections.

Curing Method

Data on the method of curing used for construction were available for 102 of 123 JPCP pavement sections in the LTPP database. Of those 102 sections, nearly all (96 percent—97 of 102) were cured with a *curing compound*. For the remaining five sections, *burlap blankets* were used on one section, *white polyethylene* on three sections, and a *burlap-polyethylene* combination on one section.

Concrete Texture Method

Data on the method of texture used for construction were available for 101 of 123 JPCP pavement sections in the LTPP database. Of those 101 sections, the majority of the sections (66 percent—67 of 101) were *tined*. For the remaining 34 sections, 7 sections used a *broom*, 9 sections used a *burlap drag*, 7 used *astro-turf*, 6 used a *tine and astro turf* combination, and 5 sections were marked as *other*.

Transverse Joint Forming Method

Data on the transverse joint forming method used during construction were available for 115 of 123 JPCP pavement sections in the LTPP database. Of those 115 sections, the majority of the sections (95 percent—109 of 115) were *sawed*. Of the remaining 6 sections, 5 sections used a *plastic insert* and 1 used a *metal insert*.

Subdrainage

Two important subdrainage characterizing variables related to data available in the LTPP database were subdrainage type and presence of longitudinal drains. Subdrainage type information was available for all 123 JPCP LTPP pavement sections, with the majority of the sections showing no subdrainge (68 percent—84 of 123). Other listed subdrainge types included *blanket* (3 percent—4 of 123), *blanket with longitudinal drains* (2 percent—2 of 123), *longitudinal drains* (20 percent—25 of 123), *transverse drains* (4 percent—5 of 123), and *other* (2 percent—3 of 123). Figure 114 contains a bar chart showing the number of JPCP sections constructed with each subdrainage type. The LTPP data showed that only 23 percent (28 of 123) of all of the JPCP sections were constructed with longitudinal drains. As expected, a higher percentage of the sections

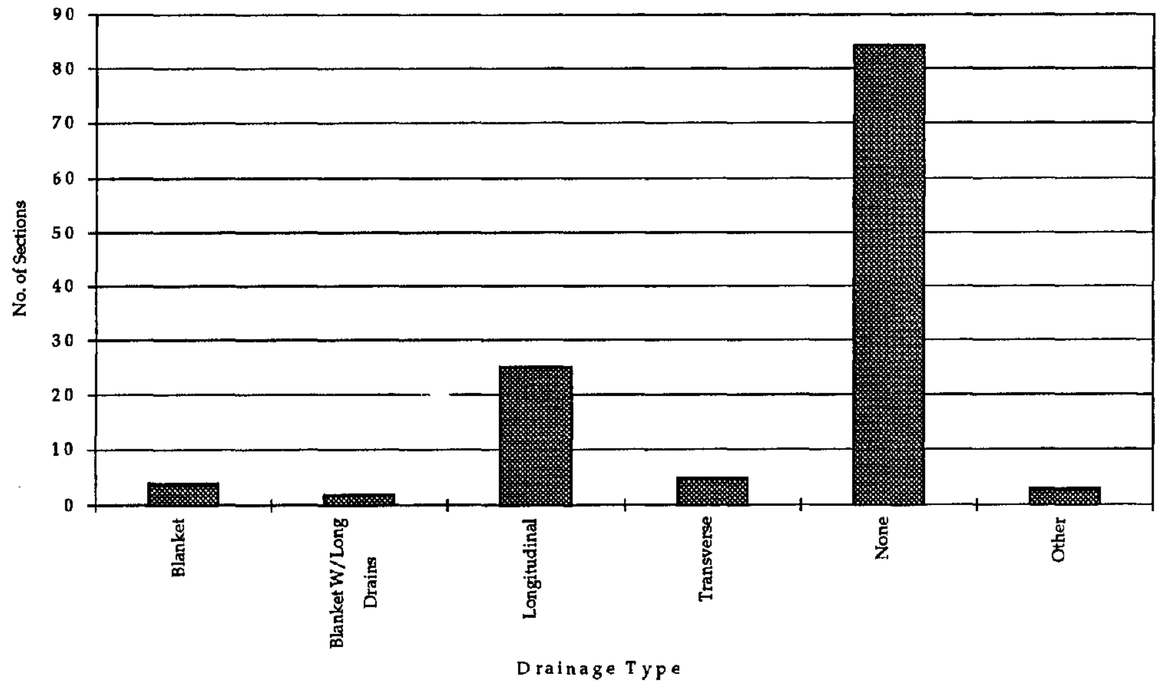


Figure 114. Bar chart of subdrainage types for all JPCP (GPS-3) LTPP sections.

in the wet climatic regions were constructed with longitudinal drains. More specifically, longitudinal drains were used in 33 percent (14 of 43) of the wet-freeze sections, 27 percent (11 of 41) of the wet-nofreeze sections, 0 percent (0 of 27) of the dry-freeze sections, and 25 percent (3 of 12) of the dry-nofreeze sections.

Load Transfer Mechanism

Load transfer type information was available for 101 of the 123 JPCP LTPP pavement sections, with just over half using *aggregate interlock* (52 percent—53 of 101) and the remaining 48 percent (48 of 101) using *round dowels.* An analysis of the load transfer type within different climatic regions revealed that the majority of sections in the regions with wet conditions used round dowels, and the majority of sections in the regions with dry conditions used aggregate interlock. More specifically, for the available data, round dowels were used in 66 percent (21 of 32) of the wet-freeze sections, 60 percent (21 of 35) of the wet-nofreeze sections, 18 percent (4 of 22) of the dry-freeze sections, and 17 percent (2 of 12) of the dry-nofreeze sections. Data for the dowel diameter were available for 46 of the 48 JPCP sections where round dowels were used. The dowel diameter of these 46 sections ranged from 6.4 to 38.1 mm, with a mean of 30, a median of 31.75, and a standard deviation of 5 mm. A histogram of the available dowel diameter data is presented in figure 115. An analysis of the dowel diameter within different climatic regions showed no significant differences between the mean values of the sections in different climatic regions.

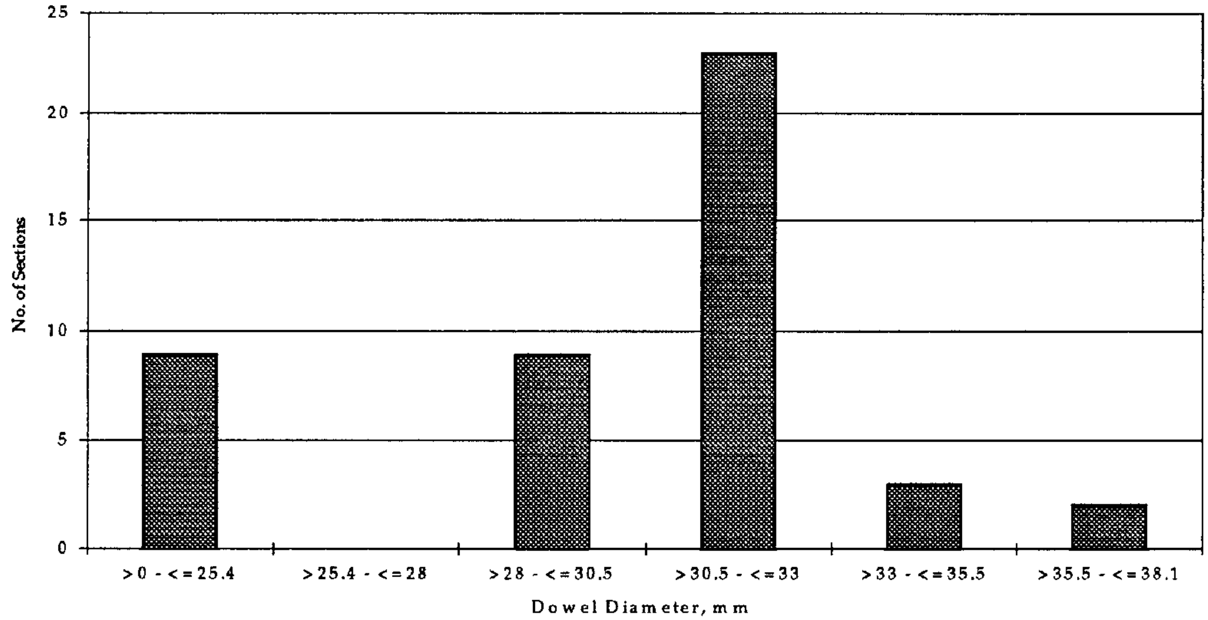


Figure 115. Histogram of available dowel diameter data for JPCP (GPS-3) LTPP sections.

Jointed Reinforced Concrete Pavements

The LTPP database contains a variety of data elements for 69 JRCP pavement sections (GPS-4). The sections (from 21 States and 1 Canadian Province) are divided among the four climatic regions in the following manner:

- Dry-Freeze: 3 sections
- Dry-Nofreeze: 0 sections
- Wet-Freeze: 40 sections
- Wet-Nofreeze: 26 sections

Pavement Age and Traffic

Traffic data were available for 62 of the 69 JRCP sections. These sections show a wide range of load-carrying requirements, with average traffic ranging from 33 to 1,301 KESAL's per year, with a mean value of 342, a median of 230, and a standard deviation of 379 KESAL's per year. The sections range in age from 1.1 to 36.4 years, with a mean of 21.0, a median of 22.0, and a standard deviation of 6.5 years. A histogram of JRCP section age is provided in figure 116. A histogram of KESAL's per year for JRCP sections is contained in figure 117.

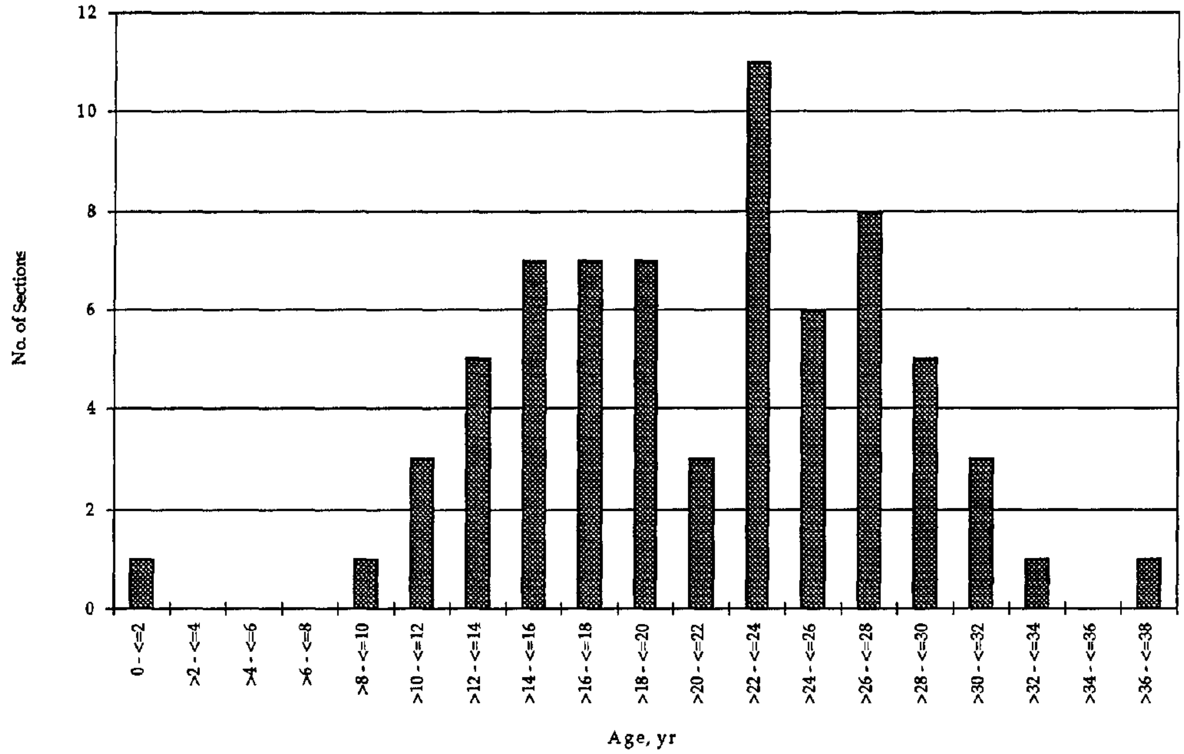


Figure 116. Histogram of age for JRCP (GPS-4) LTPP sections.

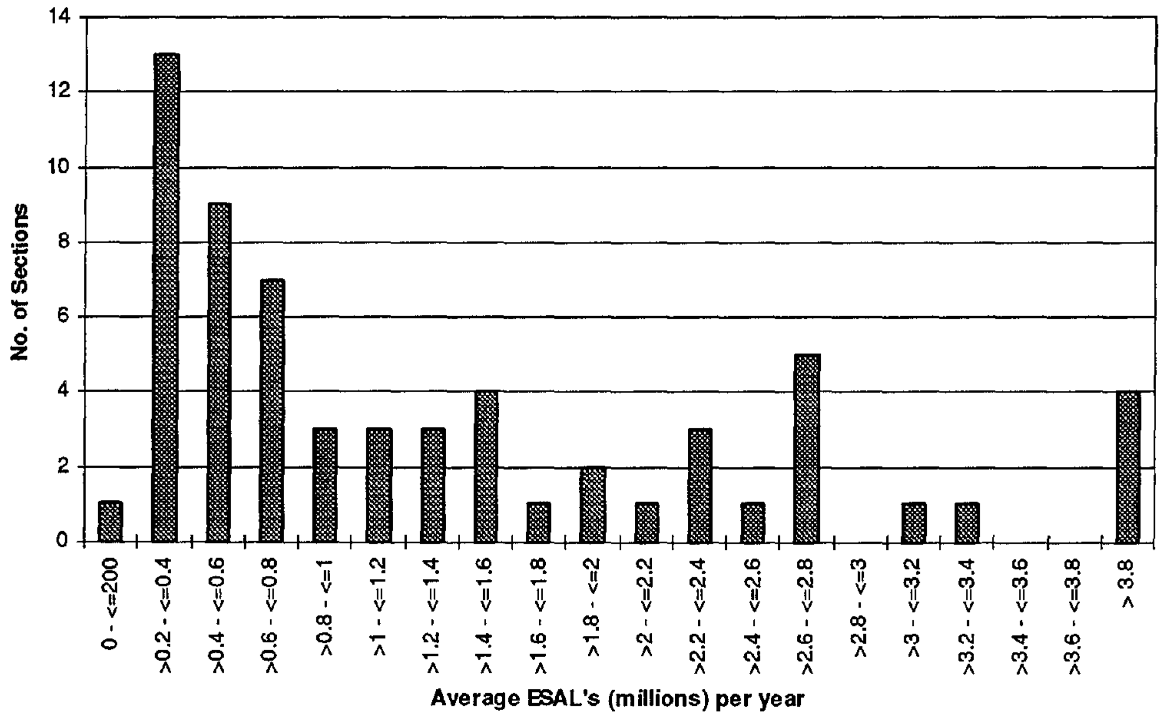


Figure 117. Histogram of ESAL's for JRCP (GPS-4) LTPP sections.

Design Features

Slab Thickness

The slab thicknesses for all 69 JRCP sections range between 190 and 290 mm, with a mean of 241, a median of 238, and a standard deviation of 20.3 mm. A histogram of slab thickness for JRCP sections is contained in figure 118.

Transverse Joint Spacing and Orientation

The average transverse joint spacing of the 69 JRCP sections ranged from 4.6 to 30.5 m, with a mean of 15.03, a median of 13.9, and a standard deviation of 5 m. A histogram of the joint spacing of all JRCP sections is presented in figure 119. The data in the LTPP database showed that the average transverse joint spacing was longer (on average) in the wet climatic regions than in the dry climatic regions. The mean average joint spacing for the wet-freeze and wet-nofreeze climatic regions was 15.6 and 14.8, respectively, and the value for the dry-freeze region was 9.51 m.

The LTPP data showed that 12 percent (8 of 69) of the JRCP sections were constructed with skewed transverse joints. The majority of sections within each climatic region were constructed without skewed joints. Specific numbers for each climatic region show that skewed joints existed in 33 percent (1 of 3) of the sections in the dry-freeze region, 18 percent (7 of 40) of the sections in the wet-freeze region, and 0 percent (0 of 26) of the sections in the wet-nofreeze region.

PCC Elastic Modulus and 28-day Modulus of Rupture

PCC elastic modulus and 28-day modulus of rupture data were obtained for only 41 of the 69 JRCP sections. The availability of the data within each climatic region consisted of 2 of 3 sections in the dry-freeze region, 20 of 40 in the wet-freeze region, and 19 of 26 in the wet-nofreeze region. The available PCC elastic modulus data for the 41 JRCP sections ranged from 22,073 to 34,138 MPa, with a mean of 28,255 MPa, a median of 28,402 MPa, and a standard deviation of 2,580 MPa. A histogram of the PCC elastic moduli for these available sections is presented in figure 120. In an analysis within each climatic region, the largest climatic region elastic modulus mean value was observed in the wet-freeze region (28,376 MPa), and the smallest was the mean of the available sections in the dry-freeze region (26,138 Mpa).

The available 28-day PCC modulus of rupture data for the 41 JRCP sections ranged from 3.8 to 6.65 MPa, with a mean of 4.98 MPa, a median of 4.96 MPa, and a standard deviation of 0.55 MPa. A histogram of the 28-day PCC modulus of rupture for these available sections is presented in figure 121. In an analysis within each climatic region, the largest climatic region 28-day PCC modulus of rupture mean value was observed in the wet-freeze region (5.05 MPa), and the smallest was the mean of the available sections in the dry-freeze region (4.6 MPa).

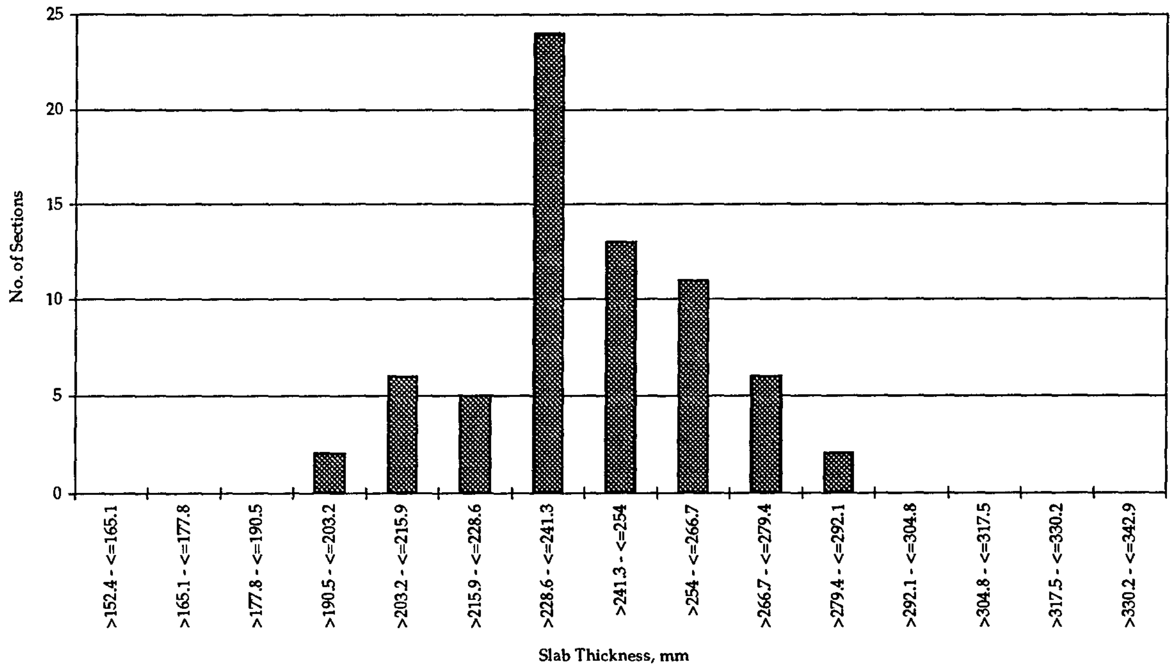


Figure 118. Histogram of slab thickness for JRCP (GPS-4) LTPP sections.

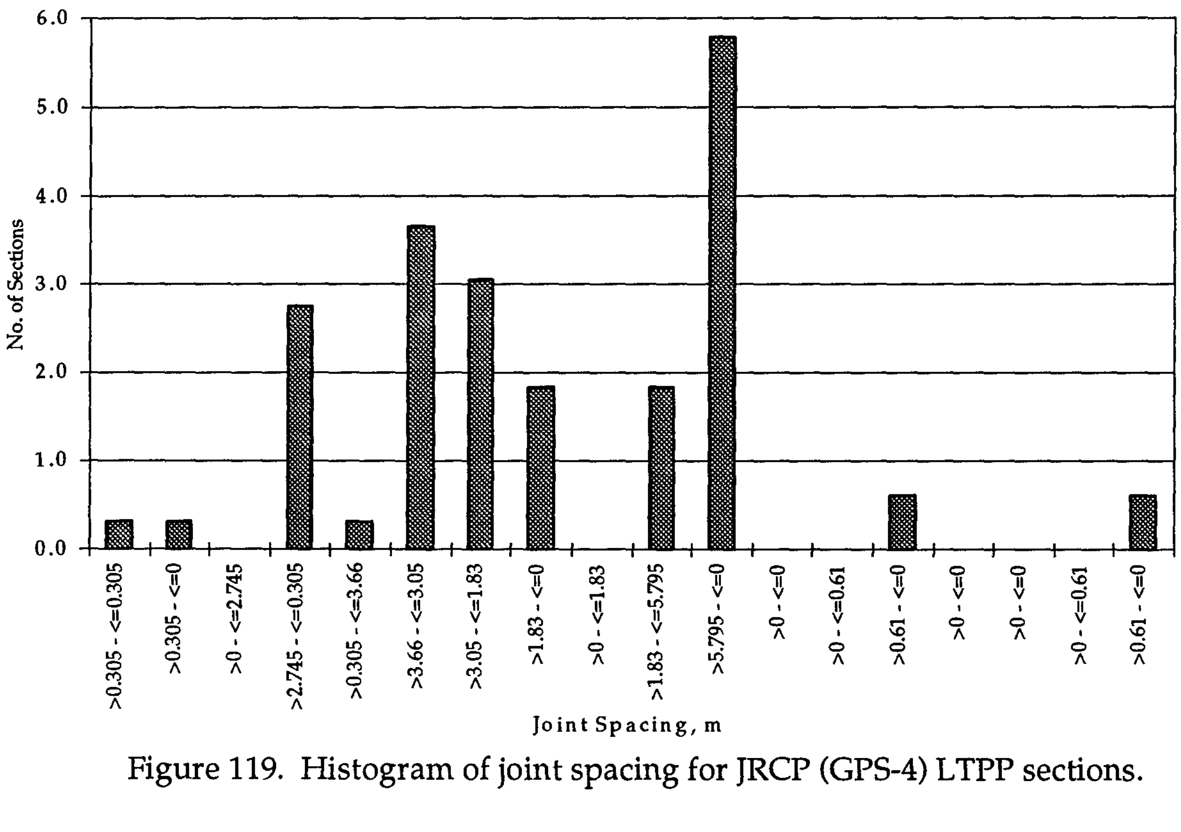


Figure 119. Histogram of joint spacing for JRCP (GPS-4) LTPP sections.

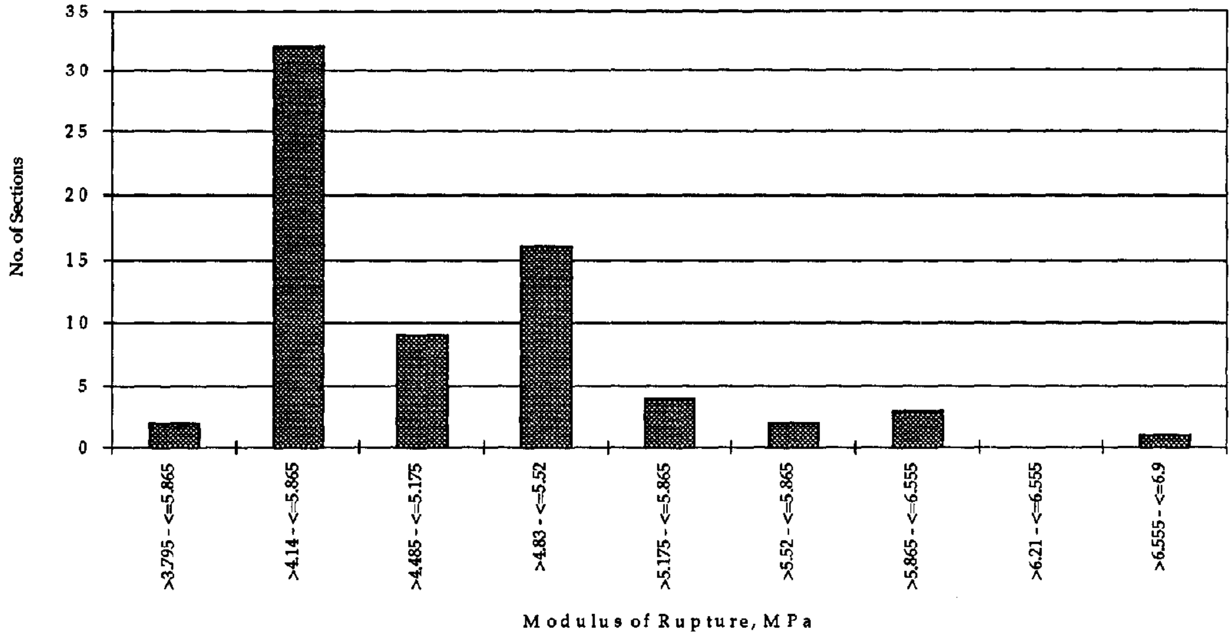


Figure 120. Histogram of available 28-day PCC modulus of rupture for JRCP (GPS-4) LTPP sections.

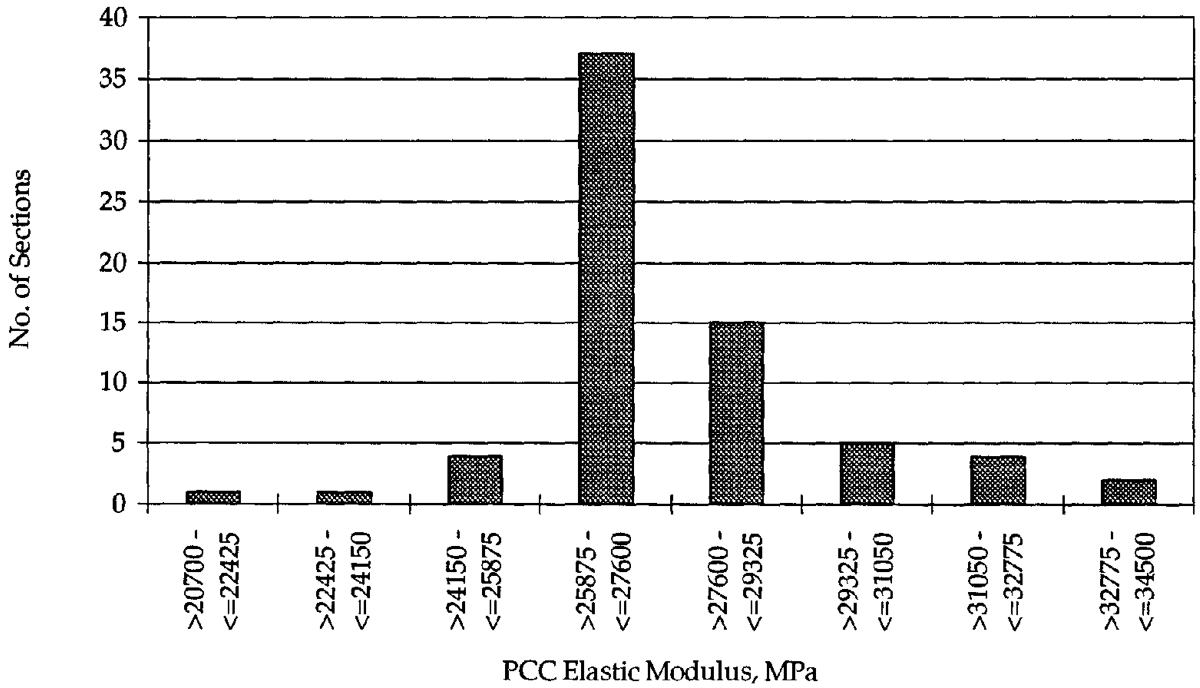


Figure 121. Histogram of available PCC elastic moduli for JRCP (GPS-4) LTPP sections.

Base Type

Base type information was available for 68 of the 69 JRCP LTPP pavement sections (the missing section was in the wet-nofreeze region). The database contained 12 different specific base type definitions for these sections. Of the 12 observed base types for these sections, 5 were classified as *granular*, and the remaining 7 were classified as *stabilized*. Using these two more general classifications, it was observed that 61 percent (42 of 69) of the sections were constructed with a granular base, 38 percent (26 of 69) with a stabilized base, and 1 percent (1 of 69) with an unidentified base type code. Figures 122 and 123 illustrate the number of sections constructed with each base type.

An analysis of the base types within and between different climatic regions showed that the majority of sections in the regions with freeze conditions were constructed with granular bases, whereas the majority of the sections in the regions with nofreeze conditions were constructed with stabilized bases. More specifically, granular bases were constructed for 66 percent (2 of 3) of the sections in the dry-freeze region and 78 percent (31 of 40) in the wet-freeze region, and stabilized bases were constructed for 64 percent (16 of 25; 1 section was missing data) of the sections in the wet-nofreeze region.

A more detailed look at the specific base types shows that the most frequently used granular base type in all four climatic regions is *crushed stone, gravel, and slag*. The most frequently observed stabilized base type in all four climatic regions is titled *cement-agg mixture*. The frequency of granular and stabilized base types summarized by climatic region is presented in tables 26 and 27.

Design Steel Content

Design steel content data were available for 34 of the 69 JRCP sections, and values ranged from 0.03 to 0.57 percent, with a mean of 0.15 percent and a median of 0.11 percent. A histogram of the available design steel content is presented in figure A.26. No significant differences in design steel content were observed between different climatic regions.

Shoulder Type

Five different outer shoulder types were used for the 69 JRCP sections in the LTPP database, with the majority being asphalt concrete (57 percent—39 of 69). The remaining outer shoulder types consisted of *surface treatment* (28 percent—19 of 69), *PCC* (10 percent—7 of 69), *granular* (4 percent—3 of 69), and *other* (1 percent—1 of 69). Figure 125 contains a bar chart showing the distribution of sections among different outer shoulder types.

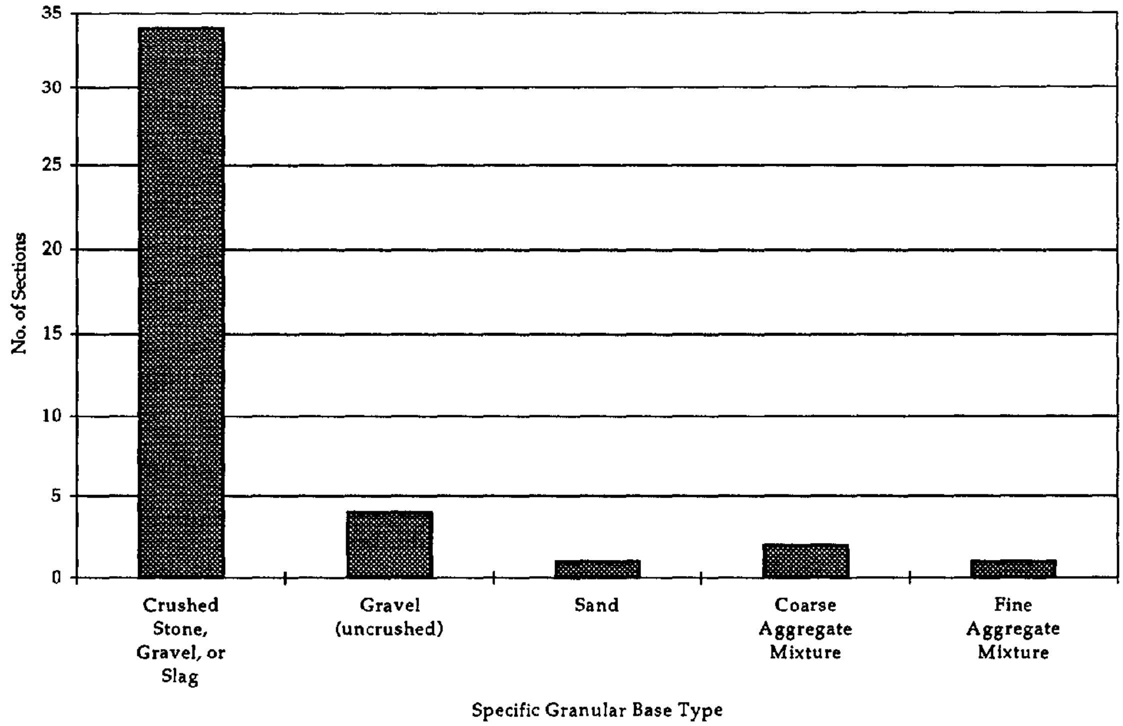


Figure 122. Bar chart of specific granular base types for all JRCP (GPS-4) LTPP sections.

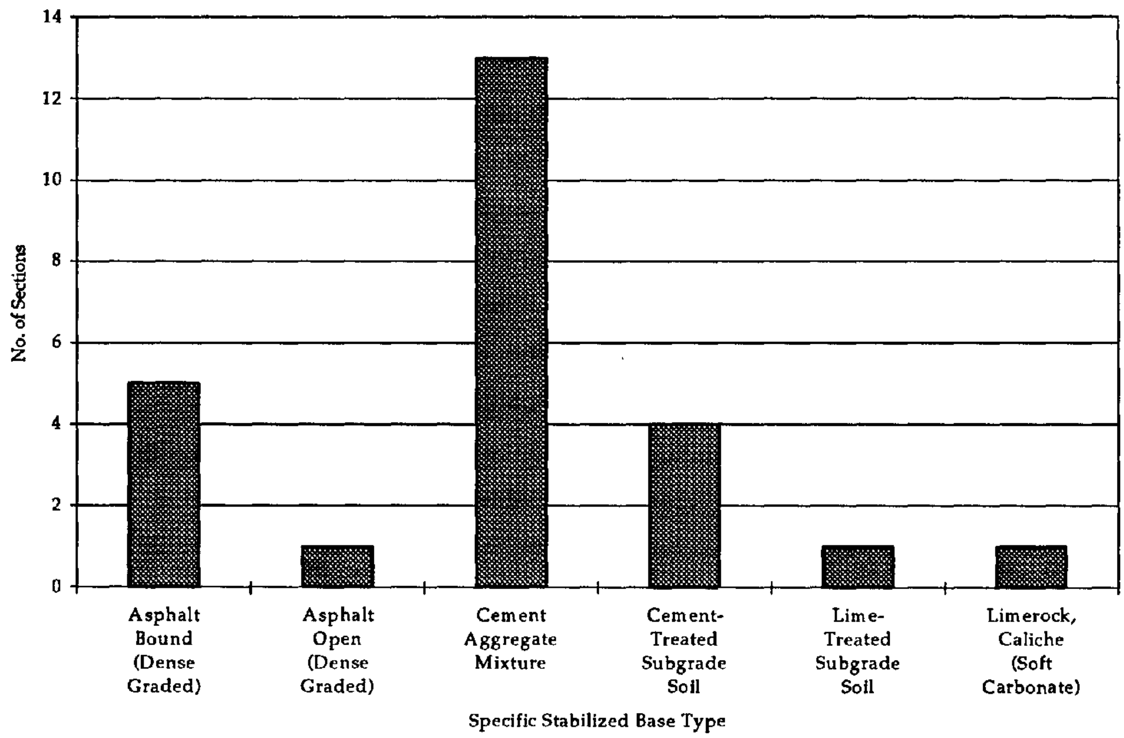


Figure 123. Bar chart of specific stabilized base types for all JRCP (GPS-4) LTPP sections.

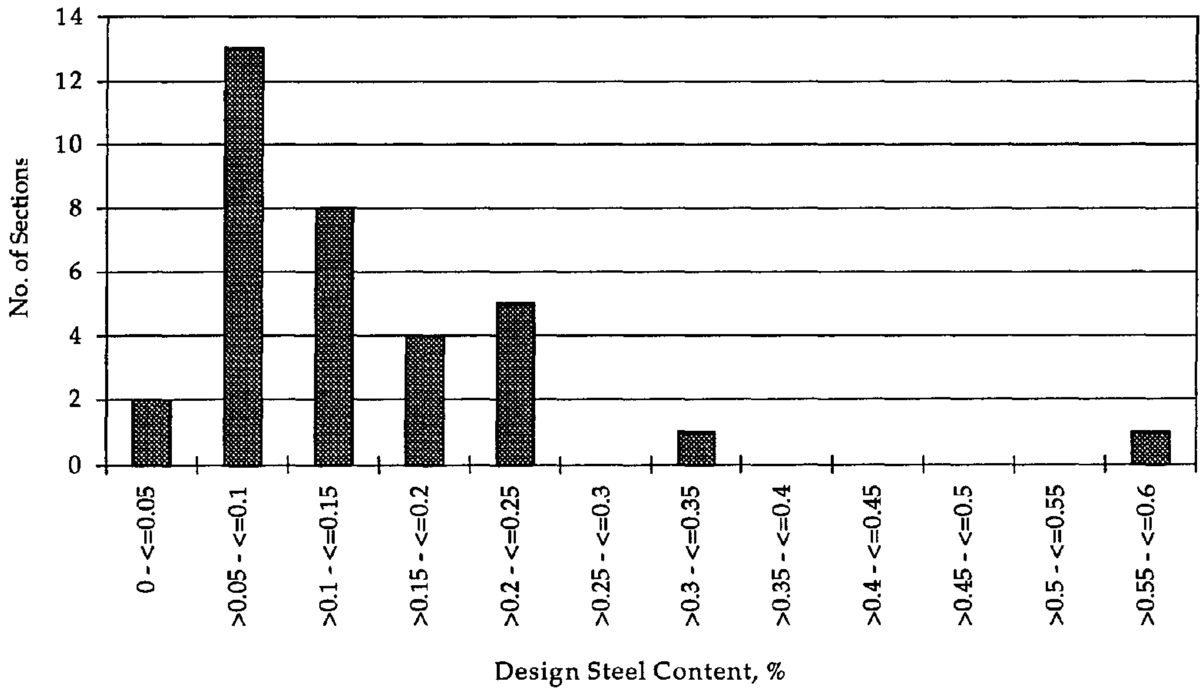


Figure 124. Histogram of available design steel content data for JRCP (GPS-4) LTPP sections.

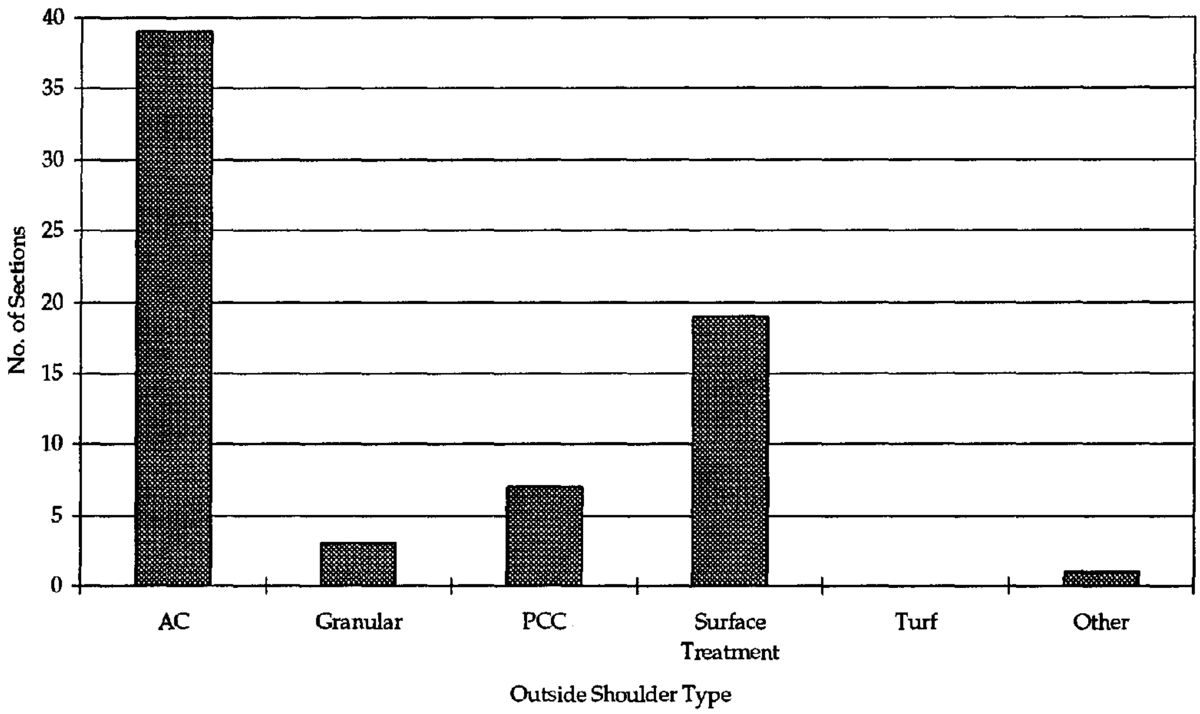


Figure 125. Bar chart of outer shoulder types for all JRCP (GPS-4) LTPP sections.

Table 26. JRCP sections with specific granular base types summarized by climatic region.

Base type	Climatic region			
	Dry-freeze	**Dry-nofreeze**	**Wet-freeze**	**Wet-nofreeze**
Crushed stone, gravel, or slag	2	0	26	6
Gravel (uncrushed)	0	0	4	0
Sand	0	0	1	0
Soil-aggregate mixture (coarse)	0	0	0	2
Soil-aggregate mixture (fine)	0	0	0	1
Total	2	0	31	9

Table 27. JRCP sections with specific stabilized base types summarized by climatic region.

Base type	Climatic region			
	Dry-freeze	**Dry-nofreeze**	**Wet-freeze**	**Wet-nofreeze**
Asphalt bound (dense-graded, cold laid)	0	0	1	0
Asphalt bound (dense-graded, hot laid)	0	0	2	3
Asphalt bound (open-graded, hot laid)	0	0	1	0
Cement-aggregate mixture	1	0	3	9
Cement-treated subgrade	0	0	2	2
Lime-treated subgrade	0	0	0	1
Limerock, caliche, soft carbonate rock	0	0	0	1
Total	1	0	9	16

Reinforcing Steel

Reinforcing steel type information was available for only 66 of the 69 JRCP LTPP pavement sections, with the majority of the sections using *welded wire fabric* (76 percent—50 of 66). Of the remaining 16 sections, 23 percent (15 of 66) used *deformed bars* and 2 percent (1 of 66) fell into the *other* category.

Site Conditions

Freezing Index

Even though the data have already been divided into four climatic regions on the basis of the annual mean daily air temperature and the annual average precipitation, it is also interesting to look at some other specific climatic variables. Freezing index was available for 68 of the 69 JRCP sections, with values ranging from 4.9 to 1,935 degree days (°C-days), with a mean of 391, a median of 313, and a standard deviation of 368 degree days. As expected, an analysis of the mean freezing index within different climatic regions showed much larger mean values for the regions with freeze conditions. More specifically, the sections in the dry-freeze and wet-freeze regions had mean values of 1,305 and 491 degree days, respectively, while the sections in the wet-nofreeze had a mean value of 122 degree days. A histogram of the available freezing index data from the 68 JRCP sections is presented in figure 126.

Average Annual Freeze-Thaw Cycles

Average annual freeze-thaw cycles were available for 68 of the 69 JRCP sections, and the number of cycles varied from 11.7 to 139.8, with a mean of 79.5, a median of 85.3, and a standard deviation of 24.5. As expected, an analysis of the average annual freeze-thaw cycles within different climatic regions showed larger mean values for the regions with freeze conditions. More specifically, the sections in the dry-freeze and wet-freeze regions had mean values of 98.6 and 91.2, respectively, whereas the sections in the wet-nofreeze region had a mean value of 58.4. A histogram of the available average annual freeze-thaw cycle data from the 58 JRCP sections is presented in figure 127.

Average Annual Precipitation

The average annual precipitation ranged from 0.43 to 1.72 m, with a mean of 1.03, a median of 1.0, and a standard deviation of 0.25 m for all 69 sections. As expected, an analysis of the average annual precipitation within different climatic regions showed larger mean values for the regions with wet conditions. More specifically, the sections in the wet-freeze and wet-nofreeze regions had mean values of 0.965 and 1.2 m, respectively, and the sections in the dry-freeze region had a mean value of 0.497 m. A histogram of the average annual precipitation data for the JRCP sections is presented in figure 128.

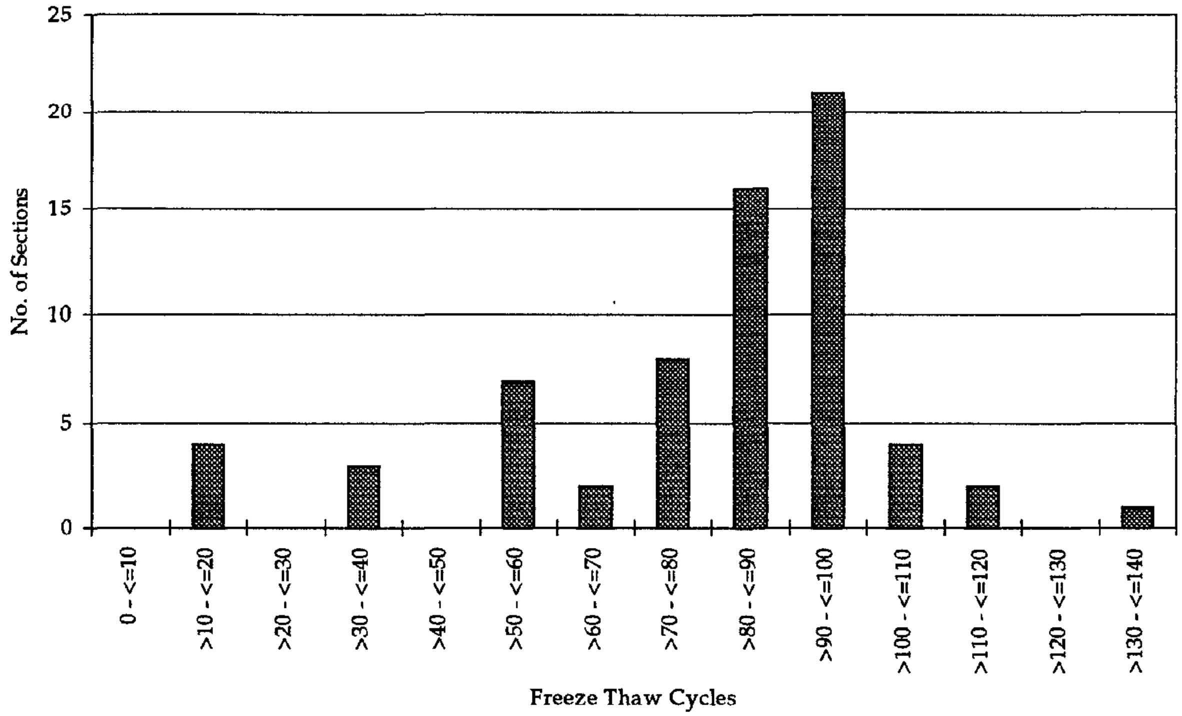


Figure 126. Histogram of available average annual freeze-thaw cycle data for JRCP (GPS-4) LTPP sections.

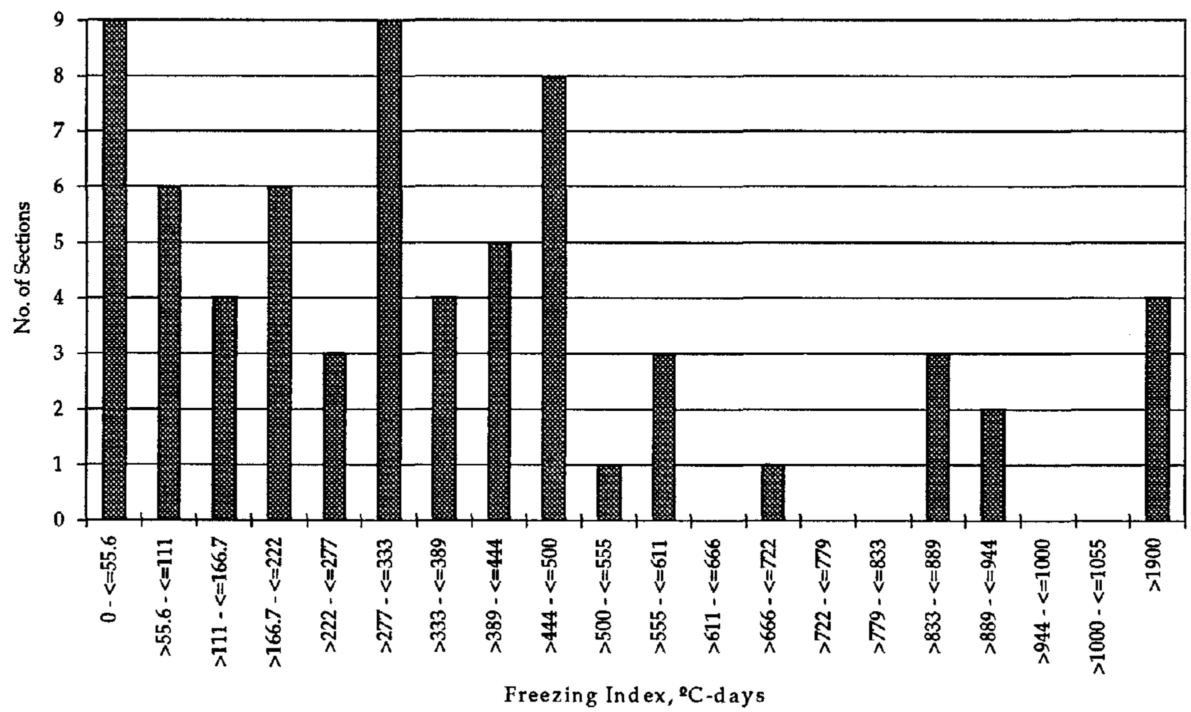


Figure 127. Histogram of available freezing index data for JRCP (GPS-4) LTPP sections.

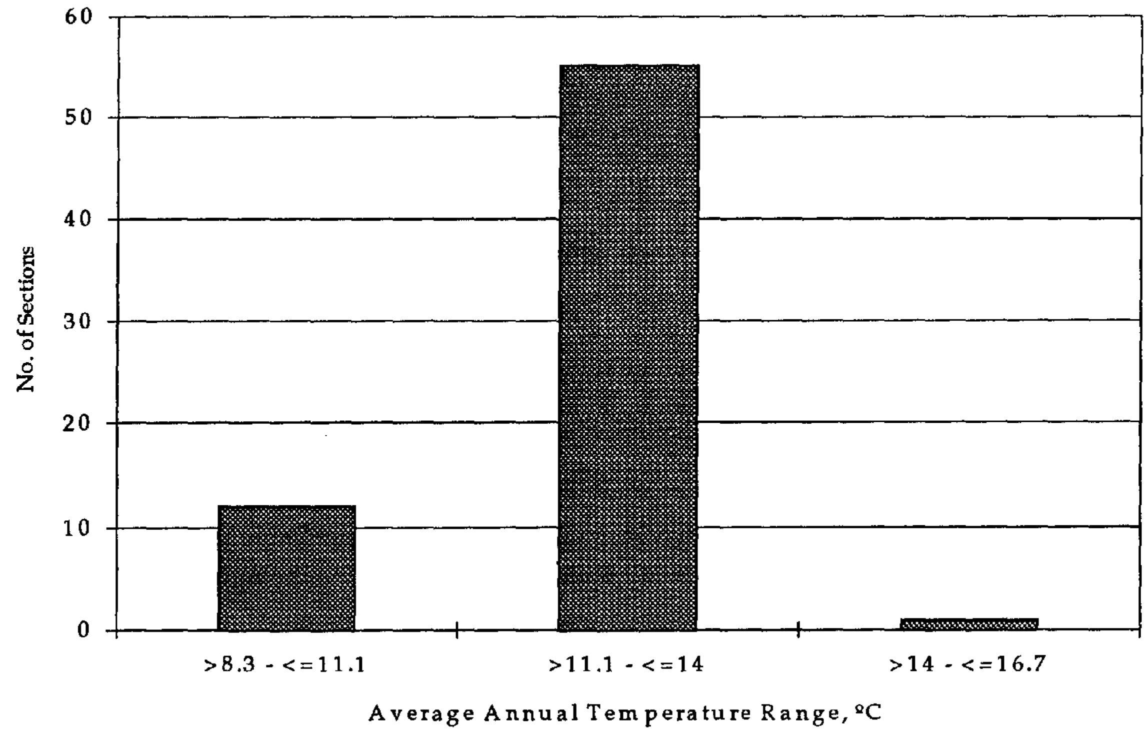


Figure 128. Histogram of available average annual temperature range data for JRCP (GPS-4) LTPP sections.

Average Annual Temperature Range

The average annual temperature range was available for 68 of the 69 JRCP sections, and it varied from 10 to 15.7 °C, with a mean of 11.8 °C, a median of 11.7 °C, and a standard deviation of 0.8 °C. An analysis of the average annual temperature range within different climatic regions revealed a slightly larger mean value for the sections with dry conditions. More specifically, the sections in the dry-freeze region had a mean temperature range value of 13.3 °C, and the sections in the wet-freeze and wet-nofreeze regions had mean values of 11.7 and 11.88 °C, respectively. A histogram of the average annual temperature range data from the 68 JRCP sections is presented in figure 129.

Subgrade Properties

Two important subgrade properties that had related data available in the LTPP database were subgrade type and backcalculated static k-value. The availability of the data and some important statistics are discussed below.

Subgrade Type

Subgrade type information was available for all 69 JRCP LTPP pavement sections. The subgrade types were classified into *fine-* and *coarse-*grained categories based on

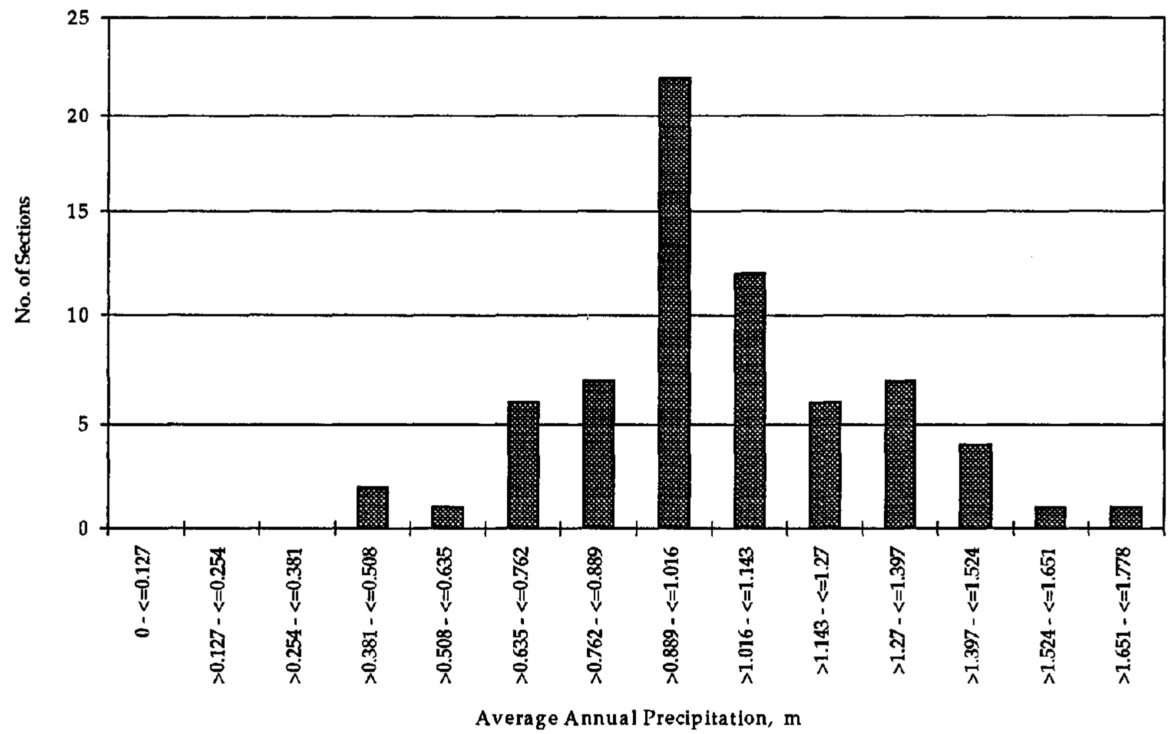


Figure 129. Histogram of average annual precipitation data for JRCP (GPS-4) LTPP sections.

subgrade material descriptions in the database. The majority of the JRCP sections in the database (72 percent—50 of 69) have fine-grained subgrade soils. The majority of the observed subgrade soils in the wet regions are fine-grained (74 percent—49 of 66), whereas the majority in the few sections in the dry-freeze region are coarse-grained (66 percent—2 of 3). Detailed numbers for the wet regions show that 75 percent (30 of 40) of the sections in the wet-freeze region and 73 percent (19 of 26) of the sections in the wet-nofreeze region have fine-grained subgrade soils.

Static k-value

The static k-value was backcalculated from FWD data available for 54 of the 69 JRCP sections in the LTPP database. The backcalculated static k-values for the 54 sections ranged from 18.2 to 120 kPa/mm, with a mean of 39.9 kPa/mm, a median of 36.12 kPa/mm, and a standard deviation of 21.2 kPa/mm. An analysis of the backcalculated static k-value within different climatic regions showed a slightly higher mean value for the sections in the dry-freeze region. More specifically, the mean values were calculated to be 51.07 kPa/mm for the dry-freeze region, 39.4 kPa/mm for the wet-freeze region, and 39.4 kPa/mm for the wet-nofreeze region. A histogram of the backcalculated static k-value data for all 54 JRCP sections with available FWD data is presented in figure 130.

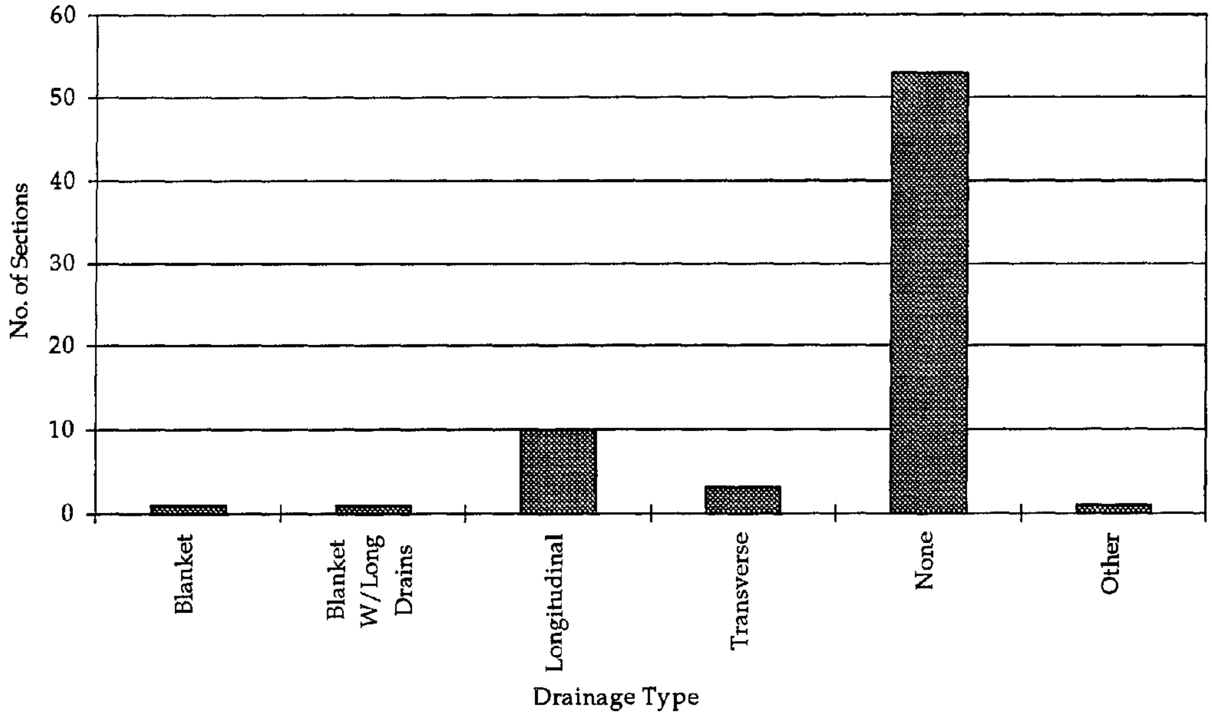


Figure 130. Bar chart of subdrainage types for all JRCP (GPS-4) LTPP sections.

Subdrainage

Two important subdrainage characterizing variables related to data available in the LTPP database were subdrainage type and presence of longitudinal drains. The availability of the data and some important statistics are discussed below.

Subdrainage type information was available for all 69 JRCP LTPP pavement sections, with the majority of the sections showing no subdrainge (77 percent—53 of 69). Other listed subdrainge types included *blanket* (1 percent—1 of 69), *blanket with longitudinal drains* (1 percent—1 of 69), *longitudinal drains* (14 percent—10 of 69), *transverse drains* (4 percent—3 of 69), and *other* (1 percent—1 of 69). Figure 131 contains a bar chart showing the number of JRCP sections constructed with each subdrainage type.

The LTPP data showed that only 16 percent (11 of 69) of all of the JRCP sections were constructed with longitudinal drains (subdrainage types of *longitudinal drains* or *blanket with longitudinal drains*). As expected, a higher percentage of the sections in the wet climatic regions were constructed with longitudinal drains. More specifically, longitudinal drains were used in 23 percent (9 of 40) of the wet-freeze sections, 8 percent (2 of 26) of the wet-nofreeze sections, and 0 percent (0 of 3) of the dry-freeze sections.

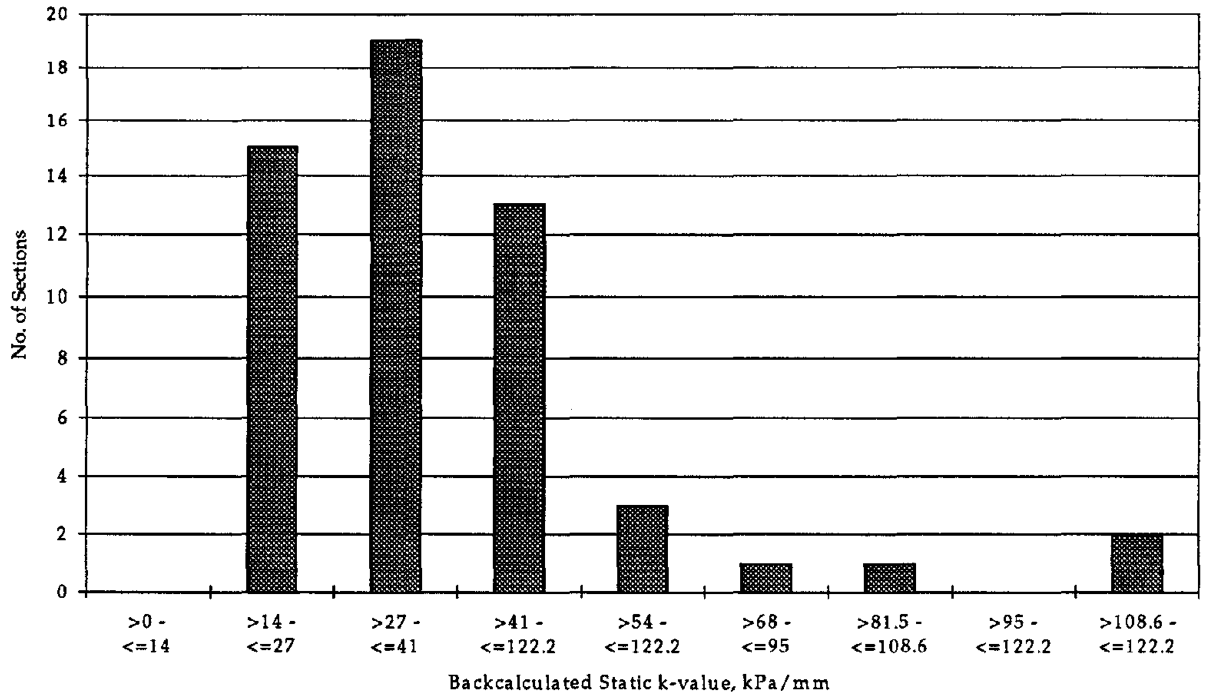


Figure 131. Histogram of available backcalculated static k-value data for JRCP (GPS-4) LTPP sections.

Construction Practices

As indicated in the last chapter, many construction-related practices directly influence the performance of JRCP pavements. A variety of slab placement related construction practice data were available in the LTPP database and are described here. The data are not presented by climatic region, as no general trends between climatic regions were observed.

Paver Type

Data on the type of paver used for construction were available for 59 of 69 JRCP pavement sections in the LTPP database. Of those 59 sections, 80 percent (47 of 59) were constructed using a *slip-form* paver, 15 percent (9 of 59) used a *side-form* paver, and 5 percent (3 of 59) used an unidentified paver type marked as *other* in the database.

Curing

Data on the method of curing used for construction were available for 57 of 69 JRCP pavement sections in the LTPP database. Of those 57 sections, nearly all of the sections (91 percent—52 of 57) were cured with a *curing compound.* For the remaining five sections, one section used a *burlap blanket* and four sections used *white polyethylene.*

Concrete Texture Method

Data on the method of texture used for construction were available for 54 of 69 JRCP pavement sections in the LTPP database. Of those 54 sections, the most frequently used method (44 percent—24 of 54) was a *burlap drag*. For the remaining 30 sections, 20 sections were tined (description of *tine* used in the database), 4 used a *broom*, 3 sections used a *grooved float*, 2 used *astroturf*, and 1 used a *tine and astro turf* combination. Figure 132 contains a bar chart showing the distribution of sections among different texture methods.

Transverse Joint Forming Method

Data on the transverse joint forming method used during construction were available for 66 of 69 JRCP pavement sections in the LTPP database. Of those 66 sections, the majority of the sections (86 percent—57 of 66) were *sawed*. For the remaining 9 sections, 1 section used a *plastic insert*, 4 used a *metal insert*, and 4 used a method falling into the *other* category.

Joint Sealant Type

Six different transverse joint sealant types were observed for the 69 JRCP sections in the LTPP database. Of the 69 sections, 33 percent (23 of 69) used *rubberized asphalt*, 23 percent (16 of 69) were assumed to be unsealed (sealant type was blank in the database), 16 percent (11 of 69) used a *preformed* seal, 12 percent (8 of 69) used an *asphalt* seal, 3 percent (2 of 69) were sealed with *low-modulus silicone*, and 13 percent (9 of 69) fell into the *other* category. Figure 133 contains a bar chart showing the distribution of sections among the different transverse joint sealant types.

Reinforcing Steel Placement Method

Data on the reinforcing steel placement method used during construction were available for 56 of the 69 JRCP pavement sections in the LTPP database. Of those 56 sections, the most frequently used method (46 percent—26 of 56) was the placing of the reinforcement *between concrete layers*. Other observed methods included *chairs* (36 percent—20 of 56), *mechanically* (16 percent—9 of 56), and *other* (2 percent—1 of 56).

Load Transfer Mechanism

Load transfer type information was available for all 69 JRCP LTPP pavement sections, with the majority of the sections using *round dowels* (96 percent—66 of 69). The remaining 3 sections showed 1 percent (1 of 69) used *I-beams* and 3 percent (2 of 69) fell into the *other* category. Data for the dowel diameter were available for all 66 JRCP sections with round dowels. The dowel diameter of these sections ranged from 6.35 to 38.1 mm, with a mean of 29.4, a median of 31.75, and a standard deviation of 30.2 mm. A histogram of the available dowel diameter data is presented in figure 134.

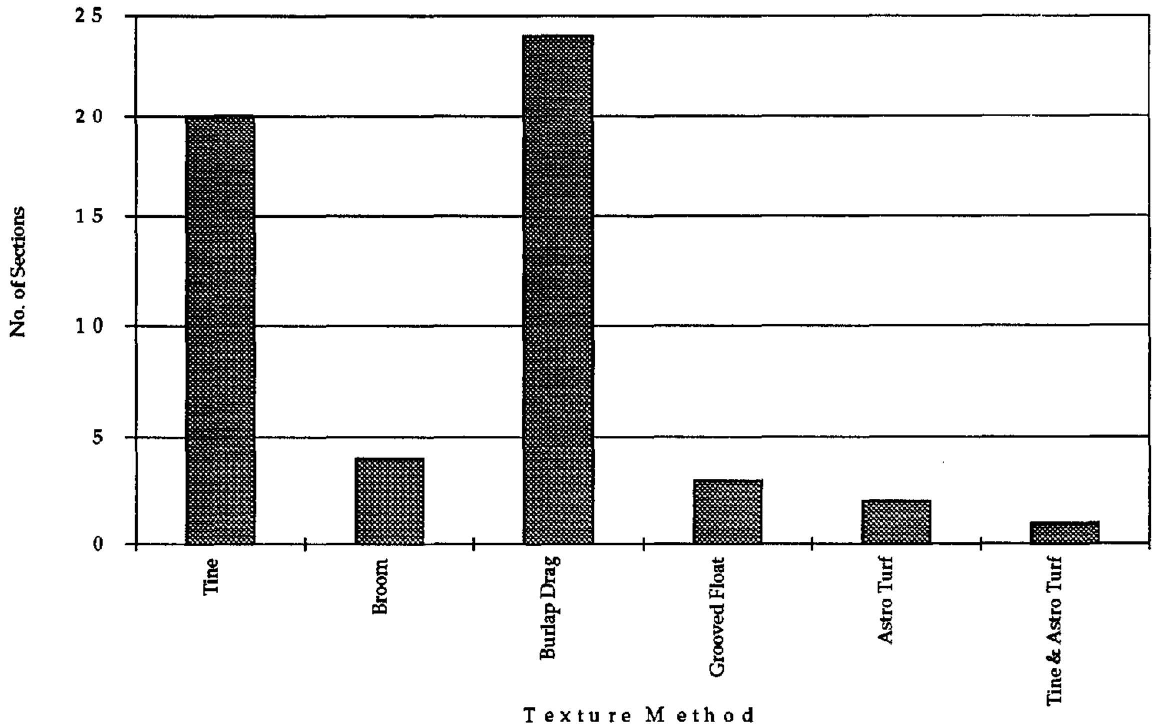


Figure 132. Bar chart of texture methods for available JRCP (GPS-4) LTPP sections.

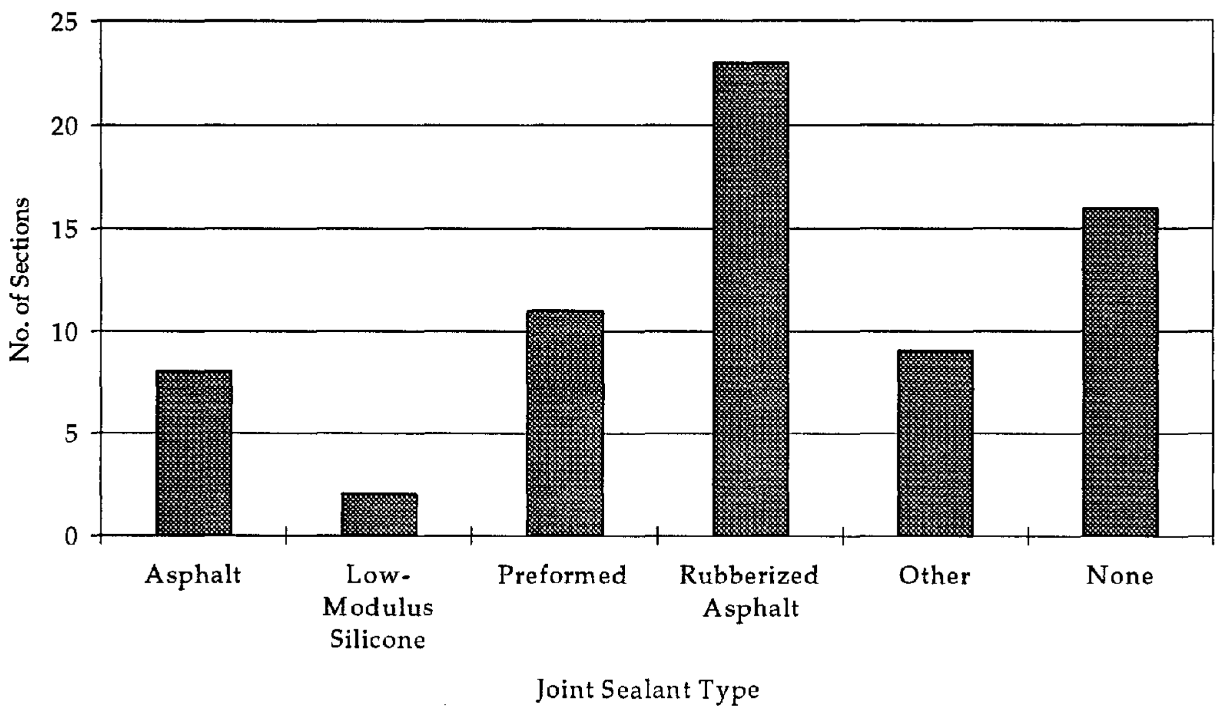


Figure 133. Bar chart of transverse joint sealant types for all JRCP (GPS-4) LTPP sections.

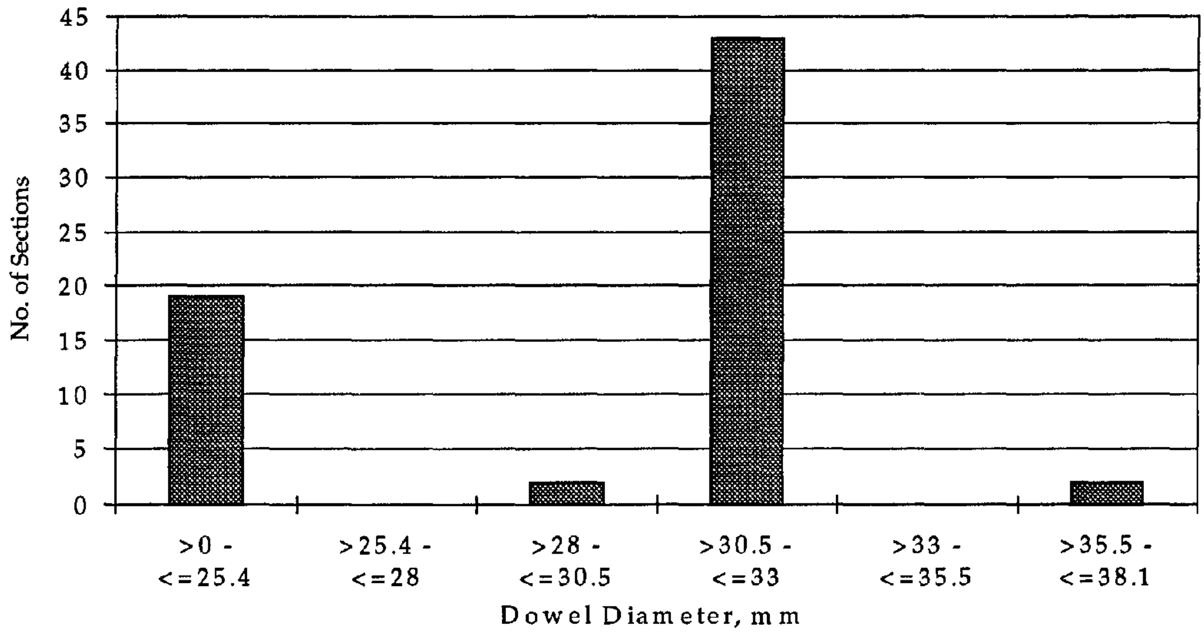


Figure 134. Histogram of available dowel diameter data for JRCP (GPS-4) LTPP sections

An analysis of the dowel diameter within different climatic regions showed no significant differences between the mean values of the sections in different climatic regions.

Continuously Reinforced Concrete Pavements

The LTPP database contains a variety of data elements for 85 CRCP pavement sections (GPS-5). These sections (from 29 States) are divided among the four climatic regions in the following manner:

- Dry-Freeze: 8 sections
- Dry-Nofreeze: 8 sections
- Wet-Freeze: 29 sections
- Wet-Nofreeze: 40 sections

Pavement Age and Traffic

The sections range in age from 6.7 to 33.5 years, with a mean of 19.3, a median of 19.9, and a standard deviation of 6.3 years. A histogram of CRCP section age is provided in figure 135. Traffic data were available for 72 of the 85 CRCP sections. These sections show a wide range of load-carrying requirements, with average traffic ranging from 12 to 3,447 KESAL's per year, with a mean value of 432, a median of 294, and a standard deviation of 603 KESAL's. A histogram of KESAL's per year for CRCP sections is contained in figure 136.

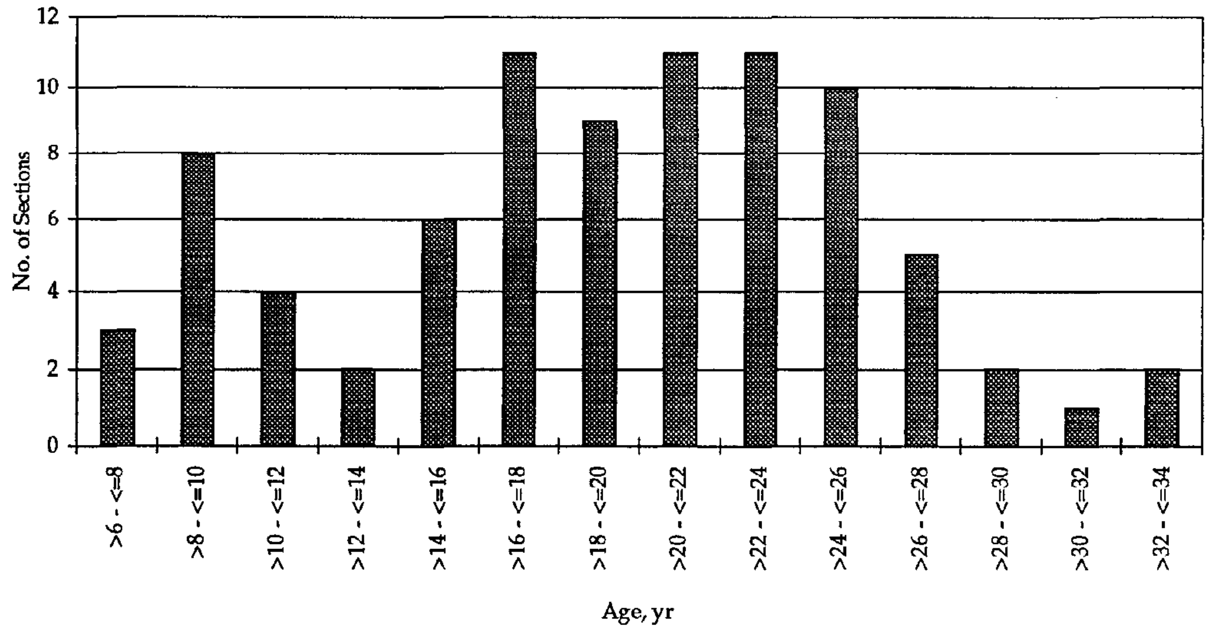


Figure 135. Histogram of age for CRCP (GPS-5) LTPP sections.

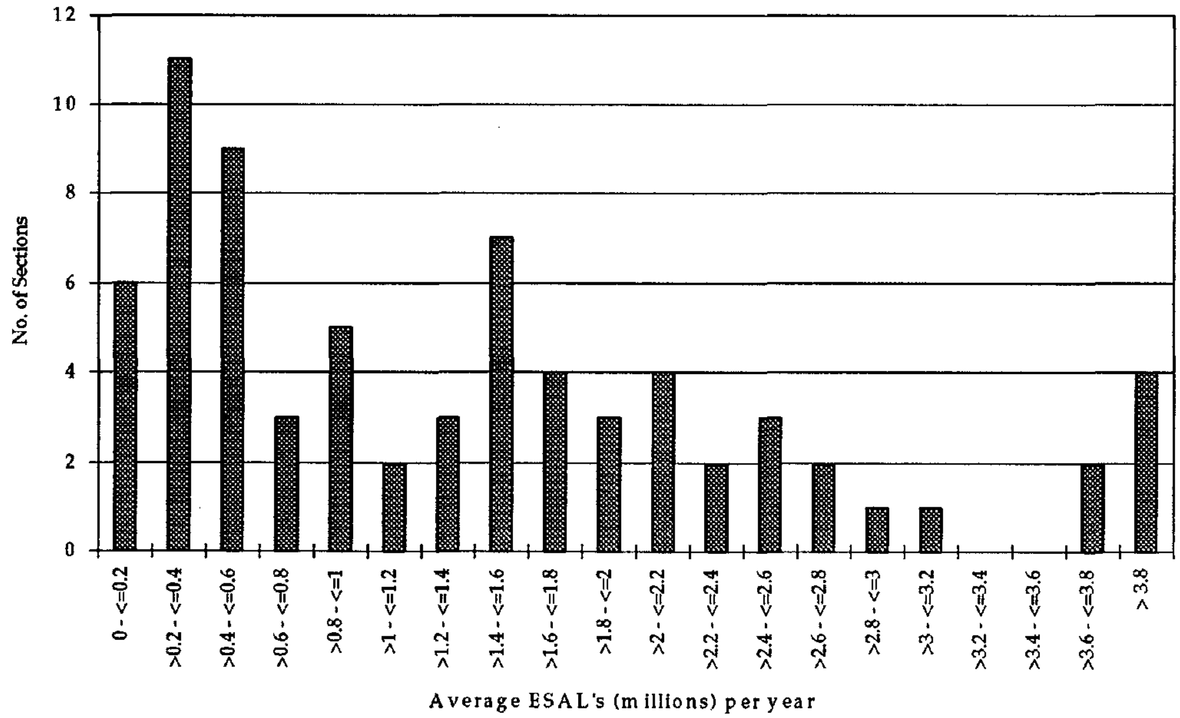


Figure 136. Histogram of KESAL's for CRCP (GPS-5) LTPP sections.

Design Features

Slab Thickness

Likewise, the slab thicknesses for all 85 CRCP sections range between 157.5 and 216 mm, with a mean of 223.5 mm, a median of 213.4 mm, and a standard deviation of 28 mm. A histogram of slab thickness for CRCP sections is contained in figure 137.

PCC Elastic Modulus and 28-day Modulus of Rupture

PCC elastic modulus and 28-day modulus of rupture data were obtained for only 62 and 63 of the 85 CRCP sections, respectively. The availability of the data within each climatic region consisted of 8 of 8 sections in the dry-freeze region, 7 of 8 in the dry-nofreeze region, 19 of 29 in the wet-freeze region, and 28 of 40 in the wet-nofreeze region.

The available PCC elastic moduli data for the 62 CRCP sections ranged from 17,305 to 37,867 MPa, with a mean of 28,292 MPa, a median of 27,672 MPa, and a standard deviation of 4,064 MPa. A histogram of the PCC elastic moduli for these available sections is presented in figure 138.

In an analysis within each climatic region, the largest climatic region elastic modulus mean value was observed in the wet-nofreeze region (28,638 MPa) while the smallest was the mean of the available sections in the dry-nofreeze region (37,288 MPa). The available 28-day PCC modulus of rupture data for the 63 CRCP sections ranged from 2.15 to 6.64 MPa, with a mean of 4.83 MPa, a median of 4.78 MPa, and a standard deviation of 0.83 MPa.

A histogram of the 28-day PCC modulus of rupture for these available sections is presented in figure 139 In an analysis within each climatic region, the largest climatic region 28-day PCC modulus of rupture mean value was observed in the wet-nofreeze region (4.88 MPa), whereas the smallest was the mean of the available sections in the wet-freeze region (4.77 MPa).

Base Type

Base type information was available for all 85 CRCP LTPP pavement sections. The database contained 12 different base type definitions used for these sections. Of the 12 observed base types for these sections, 2 were classified as *granular*, and the remaining 10 were classified as *stabilized*. Using these two more general classifications, it was observed that 80 percent (68 of 85) of the sections were constructed with a stabilized base, with the remaining 20 percent (17 of 85) having a granular base. Figures 140 and 141 illustrate the number of sections constructed with each base type.

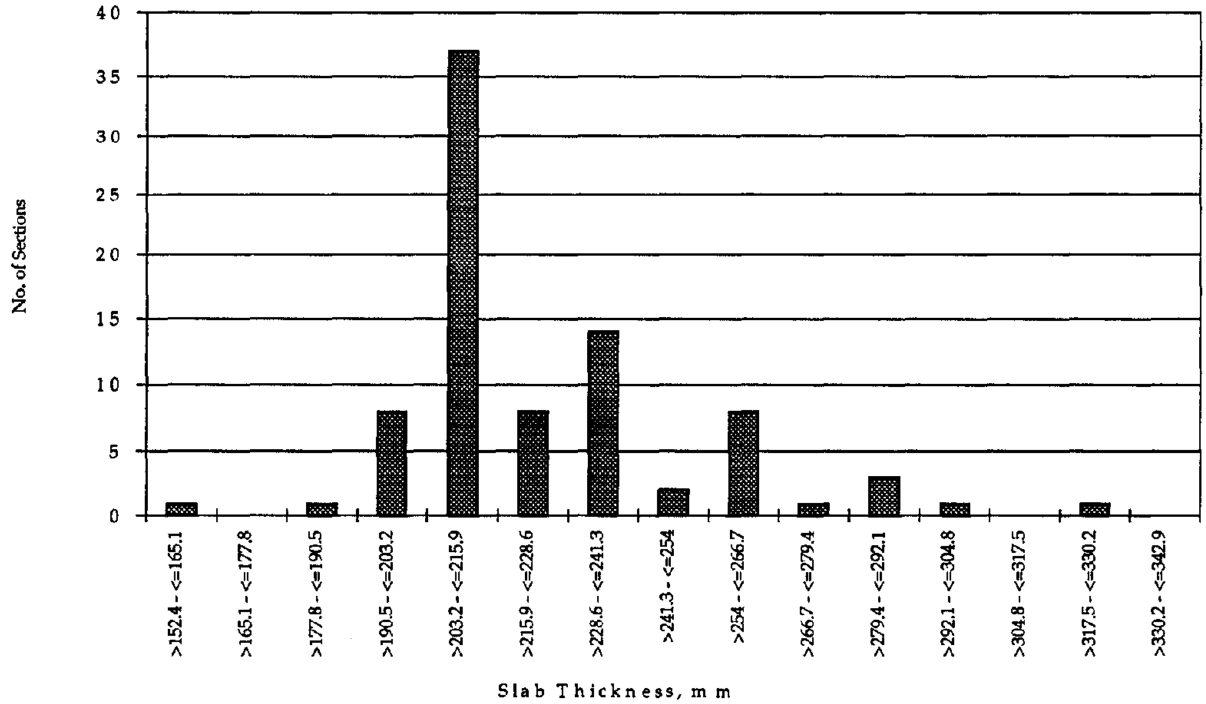


Figure 137. Histogram of slab thickness for CRCP (GPS-5) LTPP sections.

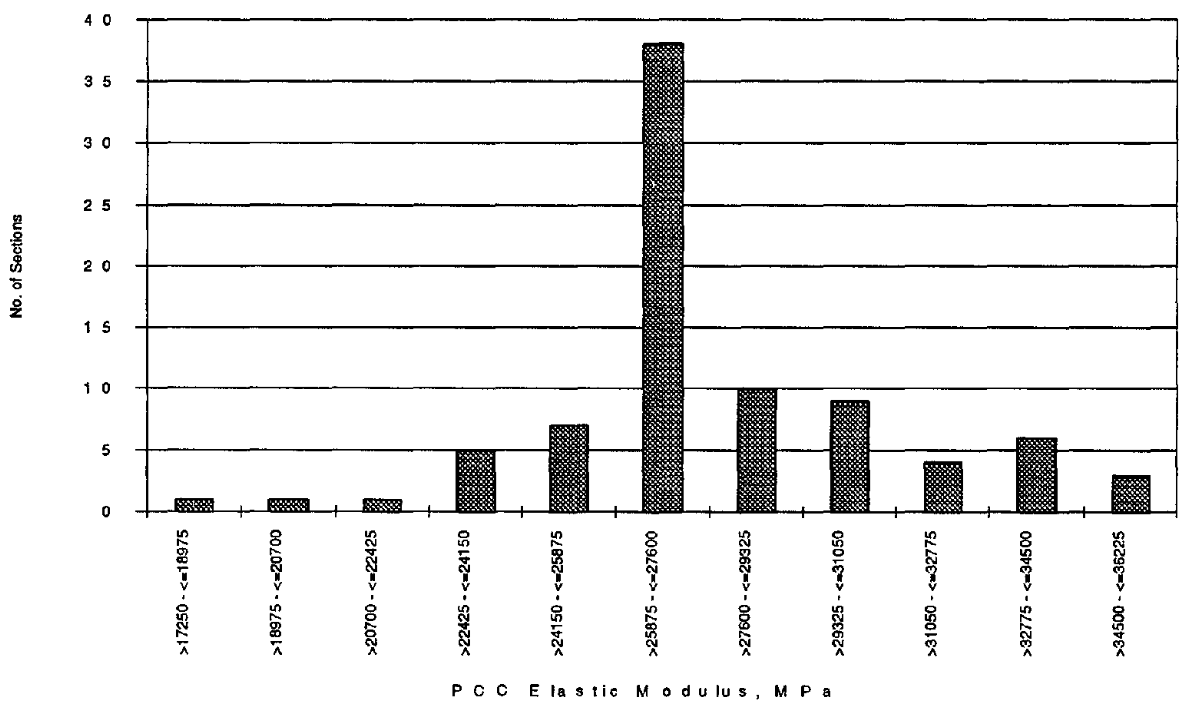


Figure 138. Histogram of available PCC elastic moduli for CRCP (GPS-5) LTPP sections.

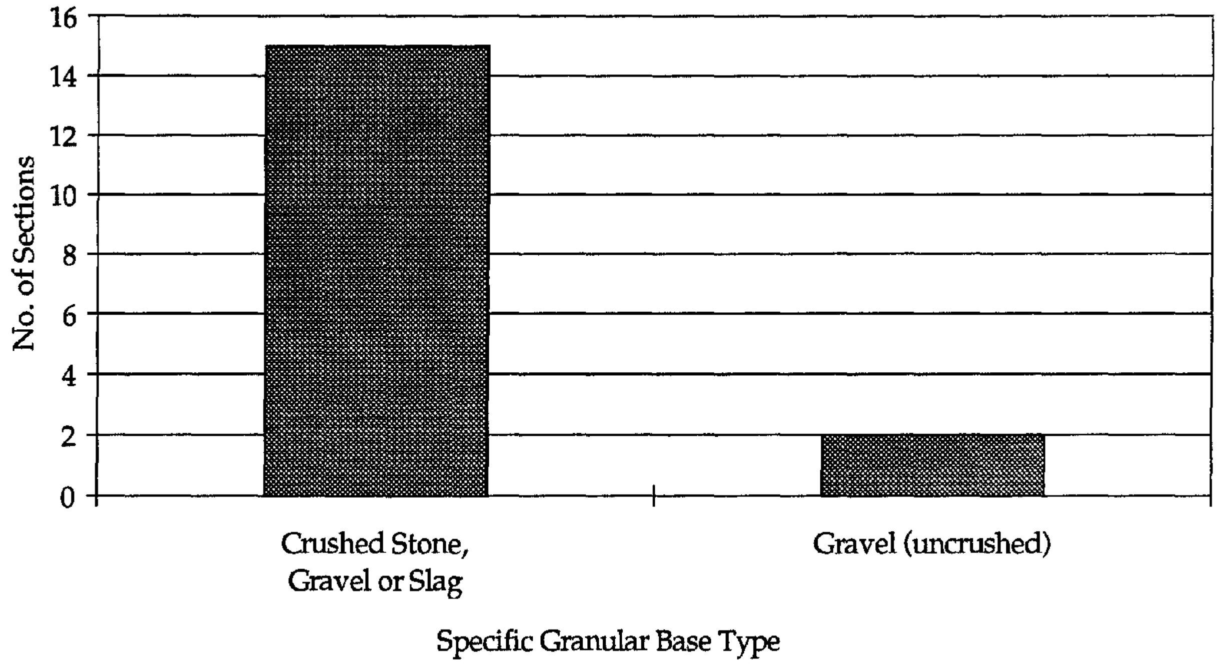


Figure 139. Bar chart of specific granular base types for all CRCP (GPS-5) LTPP sections.

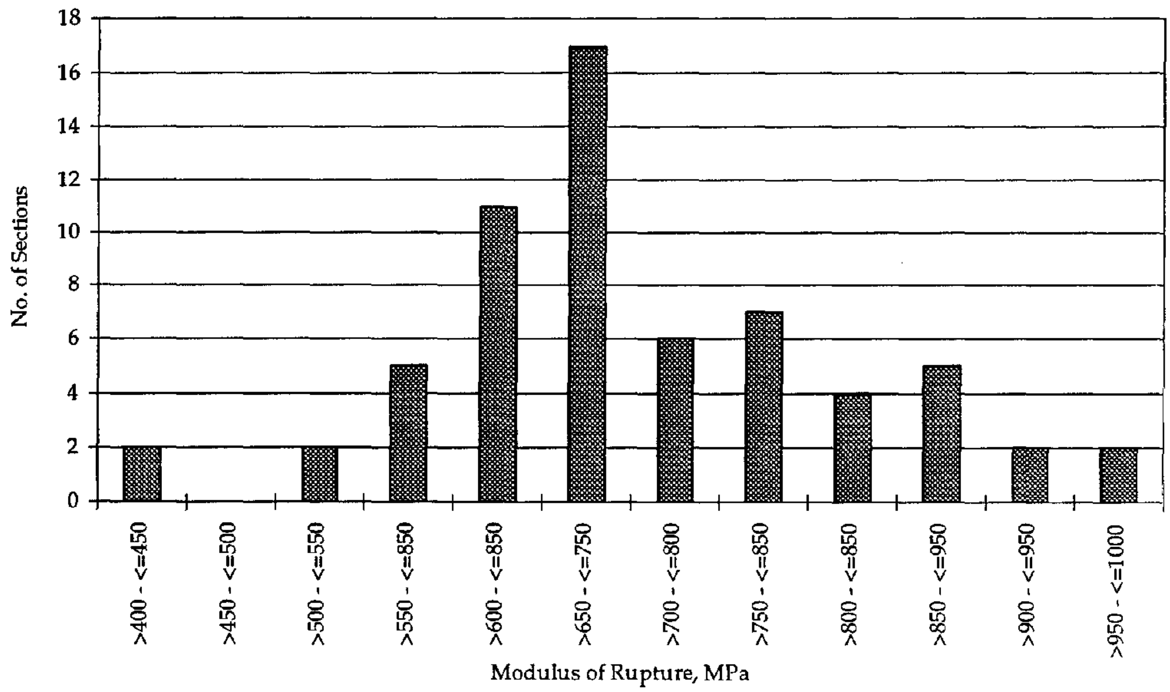


Figure 140. Histogram of available 28-day PCC modulus of rupture for CRCP (GPS-5) LTPP sections.

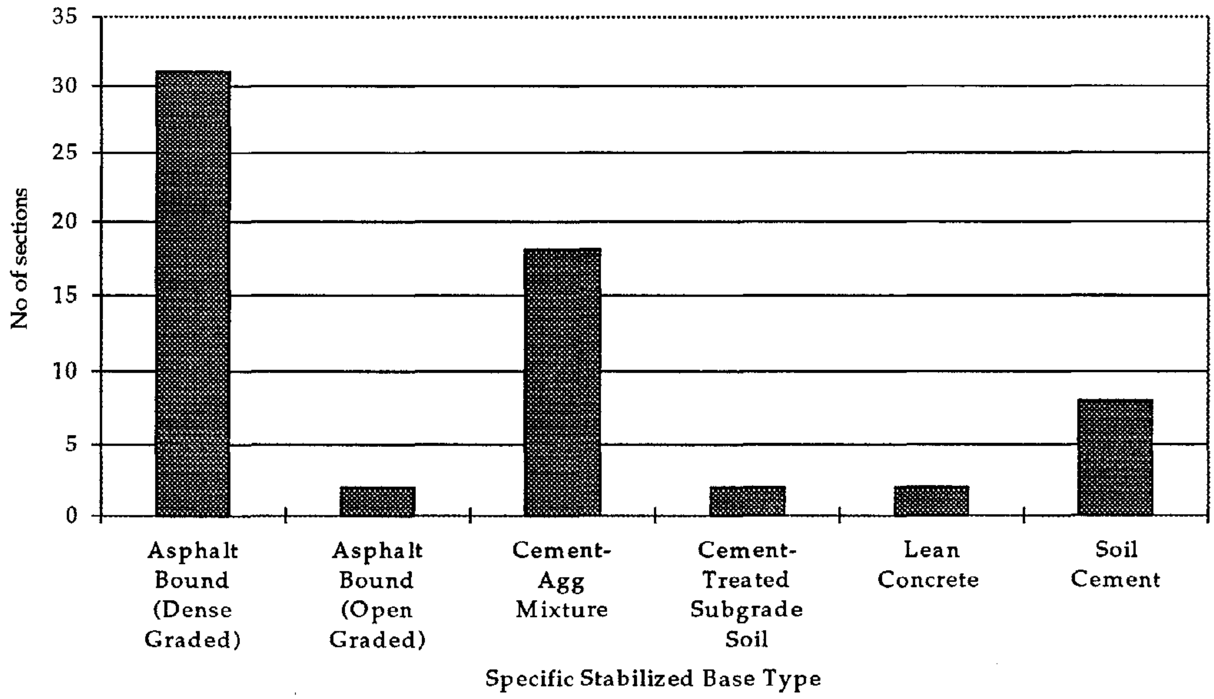


Figure 141. Bar chart of specific stabilized base types for all CRCP (GPS-5) LTPP sections.

An analysis of the base types within and between different climatic regions showed that the majority of sections in all climatic regions were constructed with stabilized bases. More specifically, stabilized bases were constructed for 75 percent (6 of 8) of the sections in the dry-freeze region, 100 percent (8 of 8) of the sections in the dry-nofreeze region, 59 percent (17 of 29) of the sections in the wet-freeze region, and 93 percent (37 of 40) of the sections in the wet-nofreeze region.

A more detailed look at the specific base types shows that the most frequently observed granular base type in all four climatic regions is titled *crushed stone, gravel, or slag*. The most frequently used stabilized base type for 3 of 4 climatic regions (excluding the dry-freeze region) is titled *asphalt bound (dense graded, hot laid, central plant mix)*. The most frequently observed in the dry-freeze region is *cement-agg mixture.* The frequency of granular and stabilized base types summarized by climatic region is presented in tables 28 and 29.

Widened Lanes

Three different constructed lane widths were observed for the 85 JPCP sections, with the majority being 3.6 m (95 percent—81 of 85). Three sections were constructed with a 4-m width, and 1 section was constructed with a 4.3-m lane width.

Table 28. CRCP sections with granular base types, summarized by climatic region.

Base type	Climatic region			
	Dry-freeze	Dry-nofreeze	Wet-freeze	Wet-nofreeze
Crushed stone, gravel, or slag	2	0	10	3
Gravel (uncrushed)	0	0	2	0
Total	2	0	12	3

Table 29. CRCP sections with stabilized base types, summarized by climatic region.

Base type	Climatic region			
	Dry-freeze	Dry-nofreeze	Wet-freeze	Wet-nofreeze
Asphalt bound (dense-graded, cold laid)	0	1	1	0
Asphalt bound (dense-graded, hot laid)	2	6	6	17
Asphalt bound (open-graded, cold laid)	0	0	1	0
Asphalt bound (open-graded, hot laid)	0	0	0	2
Cement-aggregate mixture	3	1	5	9
Cement-treated subgrade	0	0	0	2
Lean concrete	1	0	1	0
Lime-treated subgrade	0	0	1	0
Pozzolanic-aggregate mixture	0	0	0	1
Soil cement	0	0	2	6
Total	6	8	17	37

Shoulder Type

Four different outer shoulder types were used for the 85 CRCP sections in the LTPP database, with the majority being asphalt concrete (56 percent—48 of 85). The remaining outer shoulder types consisted of *PCC* (26 percent—22 of 85), *surface treatment* (14 percent—12 of 85), and *granular* (4 percent—3 of 85). Figure 142 contains a bar chart showing the distribution of sections among different outer shoulder types.

Design Steel Content

Design steel content data were available for 84 of the 85 CRCP sections, and values ranged from 0.50 to 1.16 percent, with a mean of 0.62 percent and a median of 0.60 percent. A histogram of the available design steel content is presented in figure 143. No significant differences in design steel content were observed between different climatic regions (the mean value was 0.60 percent for each region).

<u>Site Conditions</u>

Freezing Index

Freezing index was available for all 85 CRCP sections, and it varied from 0 to 1,300 degree days (°C-days), with a mean of 241, a median of 123, and a standard deviation of 289 degree days. As expected, an analysis of the mean freezing index within different climatic regions showed much larger mean values for the regions with freeze conditions. More specifically, the sections in the dry-freeze and wet-freeze regions had mean values of 563 and 453 degree days, respectively, and the sections in the dry-nofreeze and wet-nofreeze regions had mean values of 73 and 58 degree days, respectively. A histogram of the freezing index data from the 85 CRCP sections is presented in figure 144.

Annual Number of Freeze-Thaw Cycles

Average annual freeze-thaw cycles were available for all 85 CRCP sections, and the number of cycles varied from 7.8 to 154.9, with a mean of 70.7, a median of 76.2, and a standard deviation of 29.5. As expected, an analysis of the average annual freeze-thaw cycles within different climatic regions showed larger mean values for the regions with freeze conditions.

More specifically, the sections in the dry-freeze and wet-freeze regions had mean values of 109.0 and 87.1, respectively, and the sections in the dry-nofreeze and wet-nofreeze regions had mean values of 67.4 and 51.9, respectively. A histogram of the available average annual freeze-thaw cycle data from the CRCP sections is presented in figure 145.

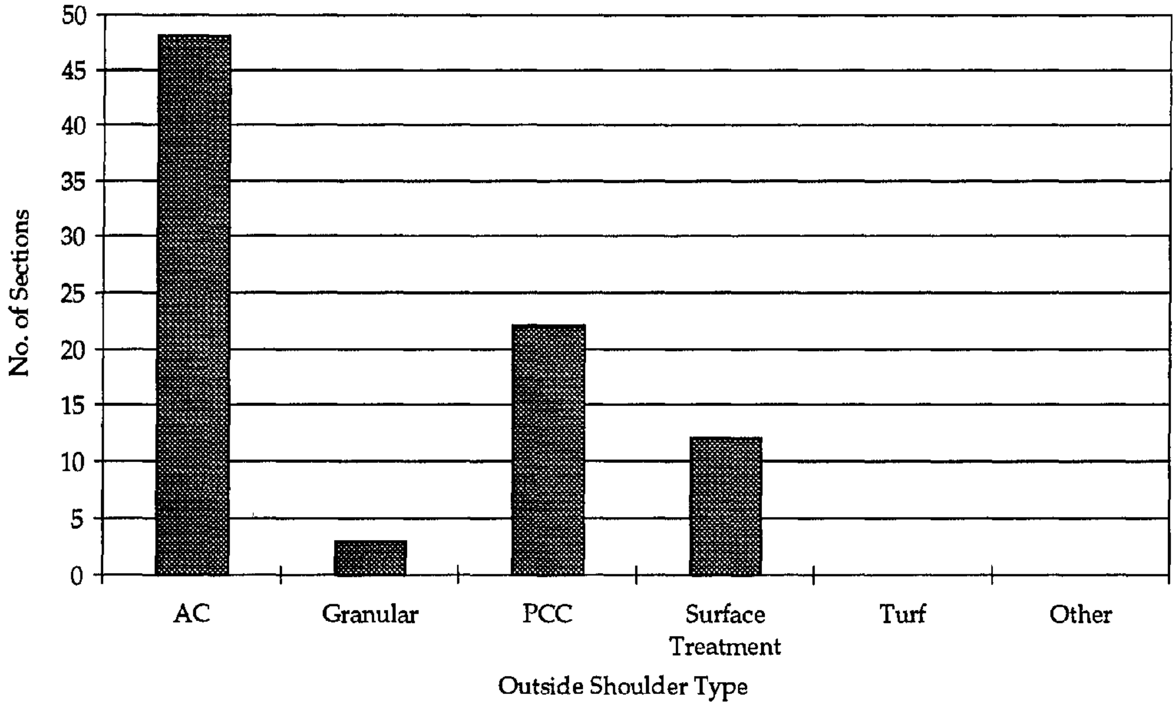


Figure 142. Bar chart of outer shoulder types for all CRCP (GPS-5) LTPP sections.

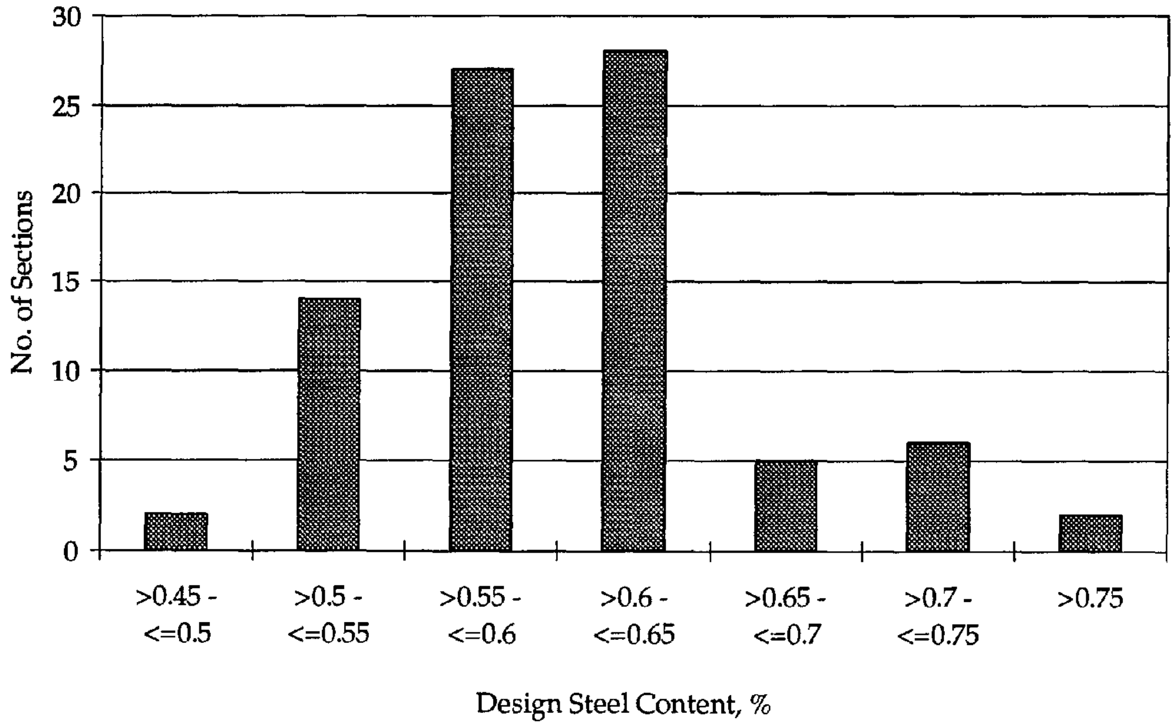


Figure 143. Histogram of available design steel content data for CRCP (GPS-5) LTPP sections.

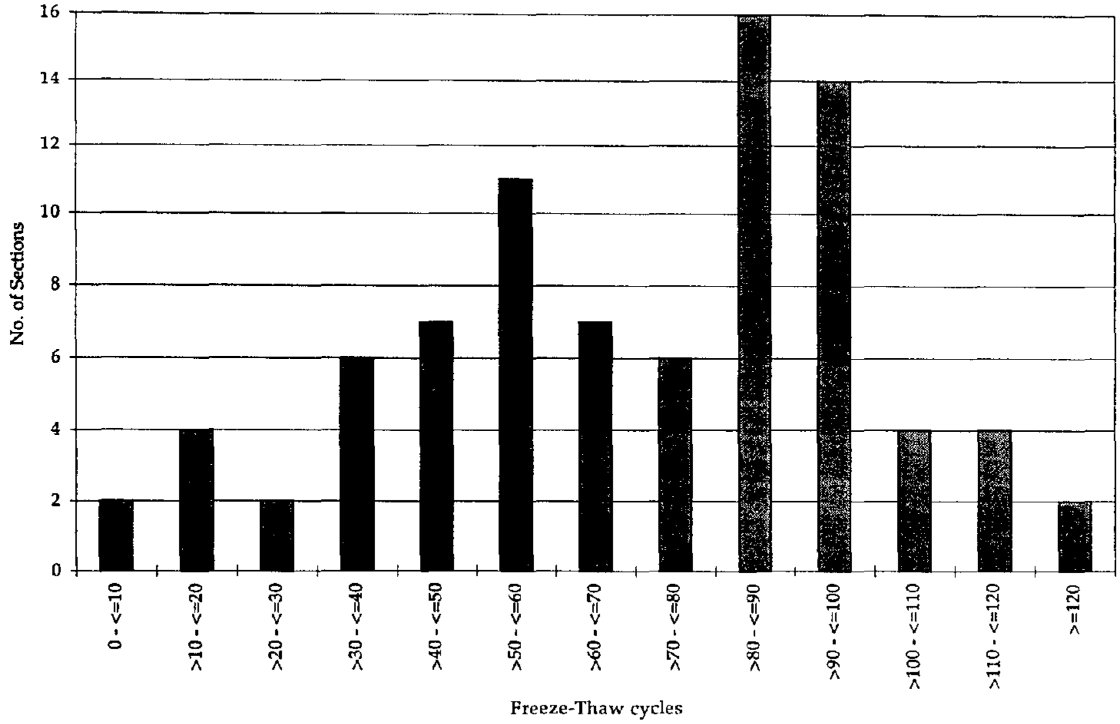


Figure 144. Histogram of average annual freeze thaw cycle data for CRCP (GPS-5) LTPP sections.

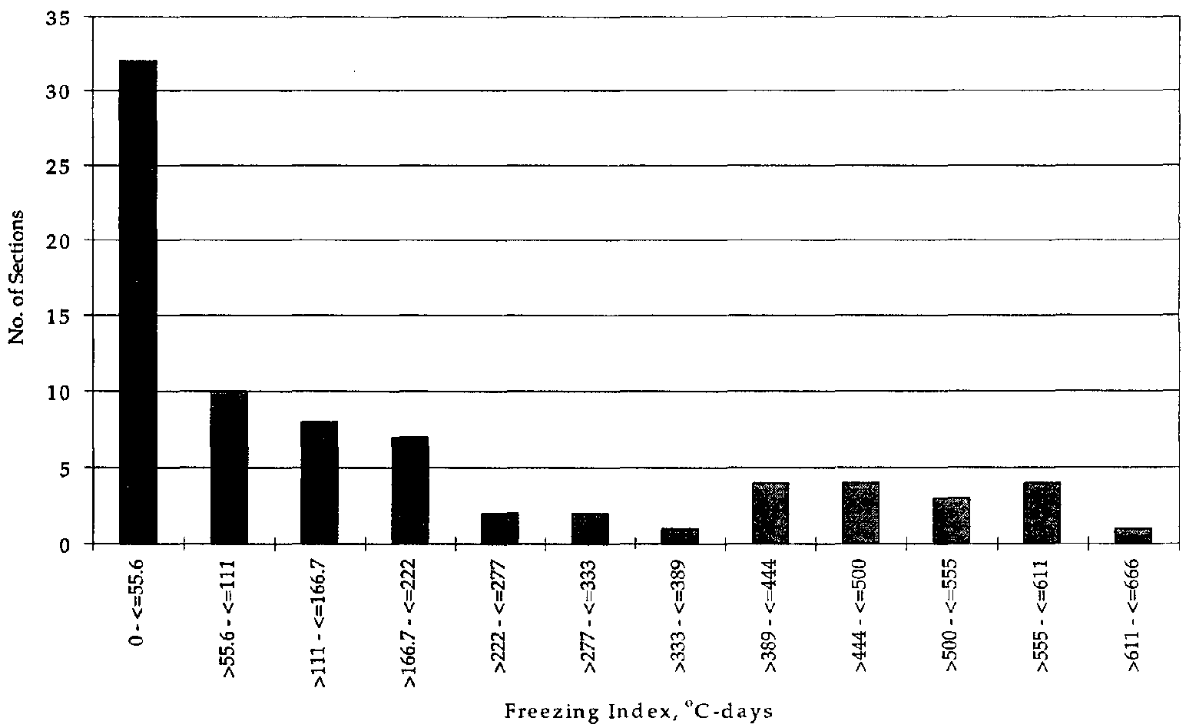


Figure 145. Histogram of freezing index data for CRCP (GPS-5) LTPP sections.

Annual Precipitation

The average annual precipitation ranged from 0.18 to 1.7 m, with a mean of 0.96 m, a median of 0.98 m, and a standard deviation of 0.33 m for all 85 sections. As expected, an analysis of the average annual precipitation within different climatic regions showed larger mean values for the regions with wet conditions. More specifically, the sections in the wet-freeze and wet-nofreeze regions had mean values of 0.97 m and 1.16 m, respectively, whereas the sections in the dry-freeze and dry-nofreeze regions both had mean values of 0.42 m. A histogram of the average annual precipitation data for the CRCP sections is presented in figure 146.

Average Annual Temperature Range

The average annual temperature range was available for 84 of the 85 CRCP sections, and it varied from 9.2 to 17.2 °C, with a mean of 12.5 °C, a median of 12.27 °C, and a standard deviation of 1.6 °C. An analysis of the average annual temperature range within different climatic regions revealed slightly larger mean values for the sections with dry conditions.

More specifically, the sections in the dry-freeze and dry-nofreeze regions had mean temperature range values of 13.9 and 15.5 °C, respectively, and the sections in the wet-freeze and wet-nofreeze regions had mean values of 11.55 and 12.3 °C, respectively. A histogram of the average annual temperature range data from the 84 CRCP sections is presented in figure 147.

Subgrade Properties

Two important subgrade properties that had related data available in the LTPP database were subgrade type and backcalculated static k-value. The availability of the data and some important statistics are discussed below.

Subgrade Type

Subgrade type information was available for all 85 CRCP LTPP pavement sections. The subgrade types were classified into *fine-* and *coarse*-grained categories based on subgrade material descriptions in the database. The majority of the CRCP sections in the database (60 percent—51 of 85) have fine-grained subgrade soils. The majority of the observed subgrade soils are fine-grained in all climatic regions.

Detailed numbers show that fine-grained subgrade soils exist for 63 percent (5 of 8) of the sections in the dry-freeze region, 75 percent (6 of 8) of the sections in the dry-nofreeze region, 62 percent (18 of 29) of the sections in the wet-freeze region, and 55 percent (22 of 40) of the sections in the wet-nofreeze region.

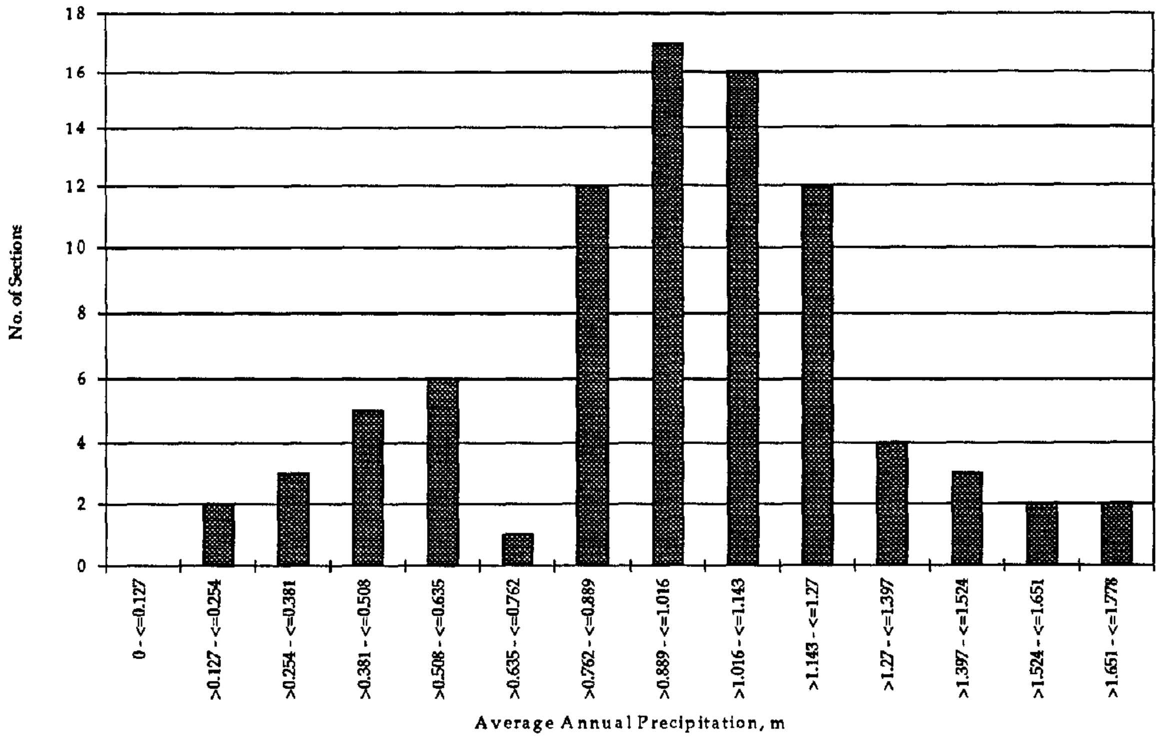


Figure 146. Histogram of average annual precipitation data for CRCP (GPS-5) LTPP sections.

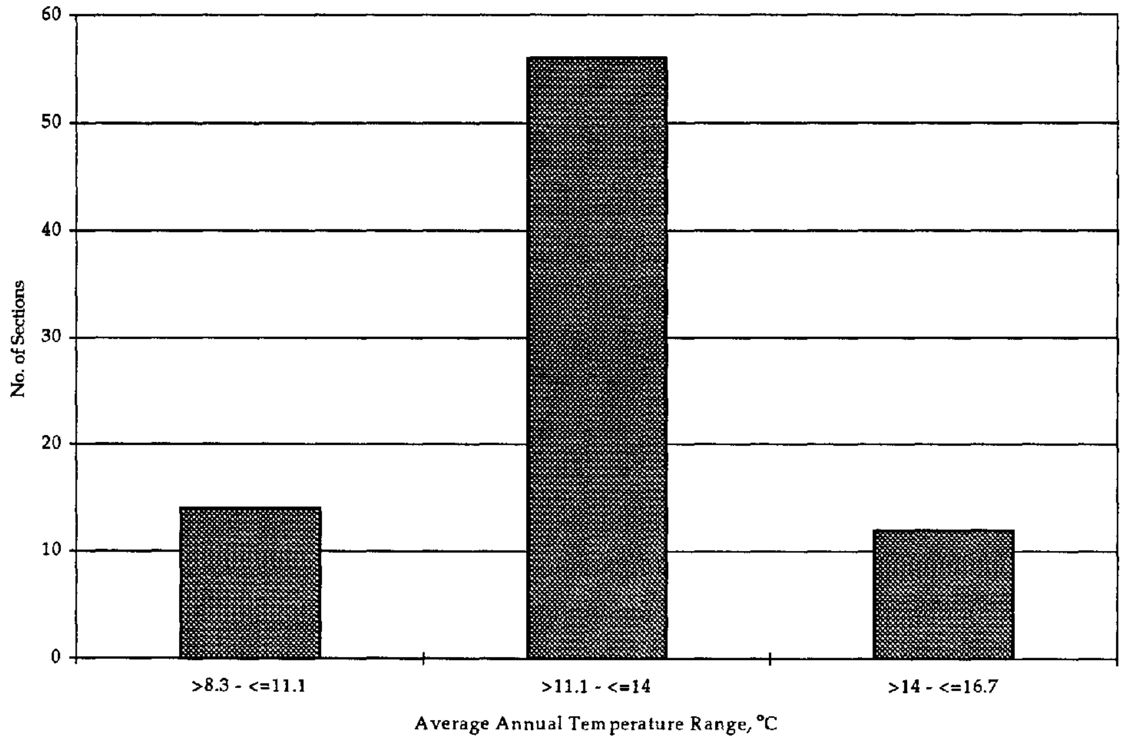


Figure 147. Histogram of available average annual temperature range data for CRCP (GPS-5) LTPP sections.

Static k-value

The static k-value was backcalculated from FWD data available for 80 of the 85 CRCP sections in the LTPP database. The backcalculated static k-values for the 80 sections ranged from 18 to 230 kPa/mm, with a mean of 51 kPa/mm, a median of 42.1 kPa/mm, and a standard deviation of 33.7 kPa/mm. An analysis of the backcalculated static k-value within different climatic regions showed slightly higher mean values for the sections in the regions with nofreeze conditions. More specifically, the mean values for the sections were calculated to be 67.04 kPa/mm and 55.14 kPa/mm for the dry-nofreeze and wet-nofreeze regions, respectively, and 43.2 and 41.8 kPa/mm for the dry-freeze and wet-freeze regions, respectively. A histogram of the backcalculated static k-value data for all 80 CRCP sections with available FWD data is presented in figure 148.

Subdrainage

Two important subdrainage characterizing variables related to data available in the LTPP database were subdrainage type and presence of longitudinal drains. The availability of the data and some important statistics are discussed below. Subdrainage type information was available for all 85 CRCP LTPP pavement sections, with the majority of the sections showing no subdrainage (71 percent—60 of 85). Other listed subdrainge types included *blanket* (1 percent—1 of 85), *blanket with longitudinal drains* (1 percent—1 of 85), *longitudinal drains* (21 percent—18 of 85), *transverse drains* (2 percent—2 of 85), and *other* (4 percent—3 of 85). Figure 149 contains a bar chart showing the number of CRCP sections constructed with each subdrainage type.

The LTPP data showed that only 24 percent (20 of 85) of all of the CRCP sections were constructed with longitudinal drains. As expected, a higher percentage of the sections in the wet climatic regions were constructed with longitudinal drains. More specifically, longitudinal drains were used in 45 percent (13 of 29) of the wet-freeze sections, 18 percent (7 of 40) of the wet-nofreeze sections, 0 percent (0 of 8) of the dry-freeze sections, and 0 percent (0 of 8) of the dry-nofreeze sections.

Construction Practices

Paver Type

As indicated in the last chapter, many construction-related practices directly influence the performance of CRCP pavements. A variety of different slab placement related construction practice data were available in the LTPP database and are described here. The data are not presented by climatic region, as no general trends between climatic regions were observed. Data on the type of paver used for construction were available for 73 of 85 CRCP pavement sections in the LTPP database. Of those 73 sections, 96 percent (70 of 73) were constructed using a *slip-form* paver and 4 percent (3 of 73) used a *side-form* paver.

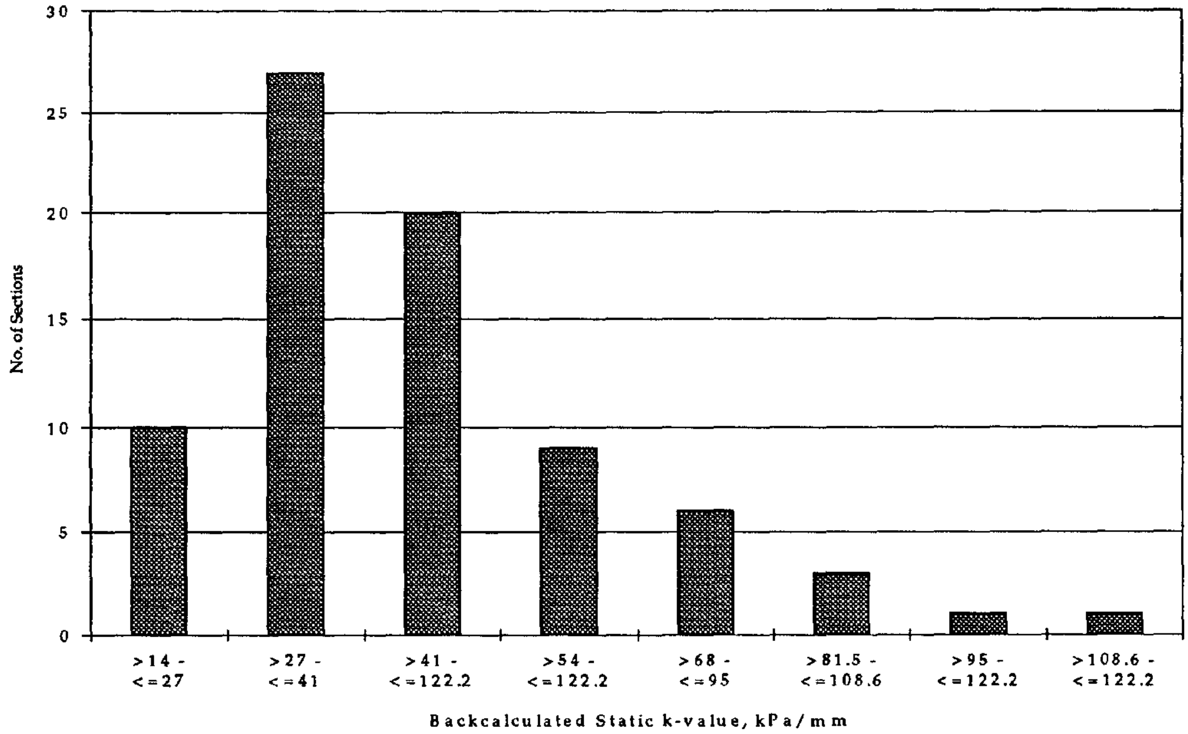


Figure 148. Histogram of available backcalculated static k-value data for CRCP (GPS-5) LTPP sections.

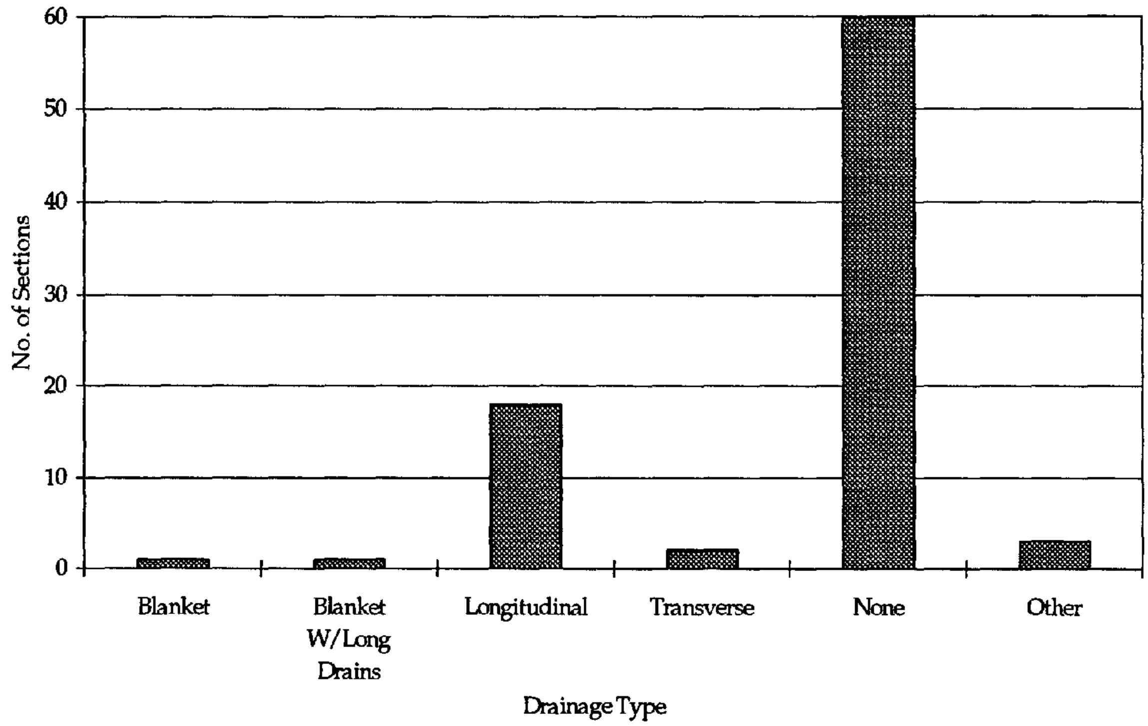


Figure 149. Bar chart of subdrainage types for all CRCP (GPS-5) LTPP sections.

Curing

Data on the method of curing used for construction were available for 76 of 85 CRCP pavement sections in the LTPP database. Of those 76 sections, nearly all of the sections (97 percent—74 of 76) were cured with a *curing compound*. For the remaining two sections, one section used a *burlap blanket*, and one section fell into the *other* category.

Concrete Texture Method

Data on the method of texture used for construction were available for 72 of 85 CRCP pavement sections in the LTPP database. Of those 72 sections, the majority of them (56 percent—40 of 72) were *tined*. For the remaining 32 sections, 4 sections used a *broom*, 18 sections used a *burlap drag*, 5 used a *grooved float*, 2 used *astroturf*, 1 used a *tine and astro turf* combination, and 2 sections were marked as *other*. Figure 150 contains a bar chart showing the distribution of sections among different texture methods.

Steel Placement Method

Data on the reinforcing steel placement method used during construction were available for 79 of the 85 CRCP pavement sections in the LTPP database. Of those 79 sections, the most frequently used method (66 percent—52 of 79) was *chairs*. Other observed methods included *mechanically* (30 percent—24 of 79), *between concrete layers* (1 percent—1 of 79), and *other* (3 percent—2 of 79).

Reinforcing Steel Type

Reinforcing steel type information was available for only 83 of the 85 CRCP LTPP pavement sections. The majority of the sections used *deformed bars* (96 percent—80 of 83). Of the remaining 3 sections, 3 percent (2 of 80) used *welded wire fabric*, and 1 percent (1 of 83) fell into the *other* category.

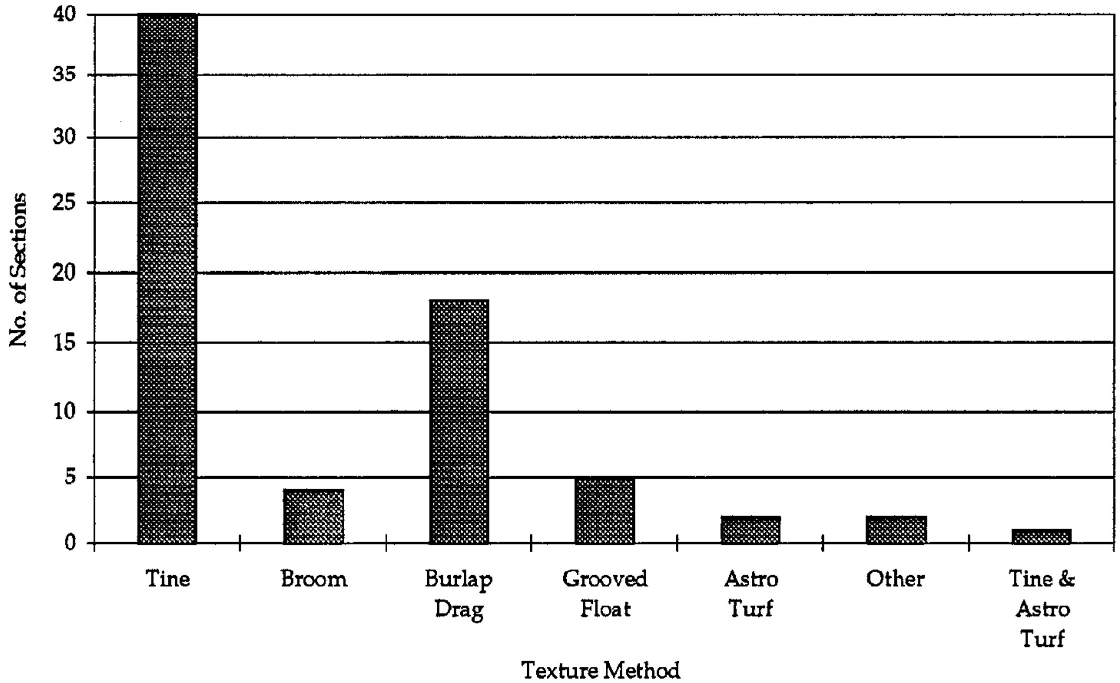


Figure 150. Bar chart of texture methods for available CRCP (GPS-5) LTPP sections.

APPENDIX B

REVIEW OF FACTORS THAT INFLUENCE PERFORMANCE OF PCC PAVEMENTS

Introduction

The primary features and practices that are used in the design and construction of PCC pavements significantly influence their long-term performance. The climatic region in which they are constructed also has an influence on the long-term performance of pavements. Therefore, to improve the design and construction procedure of concrete pavements, with the aim of improving pavement performance, it is necessary to identify the design features and construction practices that influence the development and progression of distress and, hence, performance.

Recommendation can then be provided for maximizing the influence of those design features and construction practices that exert a positive effect on performance and minimizing the influence of those design features and construction practices that exert a negative effect. For this study, the primary features that influence pavement performance are classified into three categories: the site conditions at the location of the pavement, the design features selected for the pavement, and the construction practices that are followed when the pavement is built.

The site conditions provide important information that is used by the pavement engineer to select a design. These include items such as traffic loading, climate, and the support provided by the subgrade. The design features are those design elements selected by the engineer (based on the site conditions) that will directly influence the pavement's performance. Examples of these design features include the type of pavement (JPCP, JRCP, or CRCP), material types, material strengths, layer thicknesses, joint spacing, joint and load transfer design, reinforcement design, and drainage. Construction practices include those that are related to the placing of the concrete slab and the installation of design features, and have an effect on the pavement's performance. Examples of such construction practices include mix design, type of paver used, method of dowel installation, method used to form joints, method of curing, method of finishing, and initial smoothness.

The goal of this chapter is to present design features and construction practices that influence the performance of conventional types of PCC pavements identified from past research studies. Common pavement problems associated with each pavement type are identified, and brief descriptions of the influence of the primary features and construction practices associated with each are presented. Although JPCP, JRCP, and CRCP are discussed, emphasis is placed on JPCP because this pavement type is by far the most common type of PCC pavement in the United States.

Site Conditions

Traffic loading, climate, and the support provided by the roadbed soil play a major role in the design of concrete pavements. All three factors are inputs for current PCC pavement design methods and significantly influence the pavement design process and outcome.[10, 11] In addition, it is the interacting effect of traffic loading, climate, and the support provided by the subgrade throughout the pavement's life that is responsible for distresses that occur.[1, 2, 3, 9, 12] The key effects of these factors are discussed in greater detail in the following sections.

Traffic Loading

Traffic loading plays a key role in the performance of all types of pavements. Repeated heavy traffic axle loads on JPCP pavements can lead to fatigue damage, resulting in cracking of the slab and pumping of the base and subgrade at the corner of slabs.[1, 9] This pumping can lead to transverse joint faulting and further cracking at slab corners as a result of the loss of support at those locations.[13] For JRCP and CRCP, heavy axle loads and volumes can also cause the deterioration of existing transverse cracks, which can lead to the breakdown of the cracks, steel rupture, spalling, and faulting.[14] In CRCP, the breakdown and widening of cracks that are closely spaced will eventually lead to punchouts.

All these reasons make the evaluation of the effect of traffic loading on the performance of PCC pavements very critical, especially since traffic volumes continue to increase steadily. In addition, truck loads continue to get heavier, and the increased use of new types of multiple axle configurations and tire types, including super-singles and singled-out duals, have resulted in existing pavements being subjected to loadings far in excess of what was originally anticipated.

Although there are several parameters that can be used to characterize traffic loading, the cumulative 80-kN equivalent single axle load (ESAL's) is the most often used parameter by State highway agencies to determine the structural requirements for pavements, and it is an essential input for many of the existing design procedures.[10, 15] In most instances it provides an accurate measure of the traffic applied to a given pavement section. In the following sections, the influence of traffic loading on the performance of JPCP, JRCP and CRCP are described by discussing the key distress types that are influenced by traffic loading.

Influence of Traffic Loading on JPCP

Distresses occurring on pavements can be classified as traffic related or otherwise. Some of the common JPCP traffic-related distresses are faulting and two types of cracking (transverse fatigue cracking at the midslab and corner cracking). Faulting occurs mostly in JPCP with inadequate load transfer and an erodible base or subgrade underlying material. Transverse cracking usually occurs as a result of excessive deflections at the slab midsection due to inadequate slab thickness or underlying support. This is the typical mode of failure of JPCP in midslab.[16] Repeated traffic loading at the slab edge, midway between transverse joints, results in the development of critical stresses at the bottom of JPCP. The stresses develop plastic strains and build up energy in the PCC material, leading to the initiation of microcracks at the bottom of the PCC slab. The microcracks expand further and propagate through the PCC slab, developing into transverse cracks with more repeated loading.[9] Factors that have an effect on the stresses generated at the bottom of the PCC slab will have an influence on the occurrence of the transverse cracks.

A review of current design procedures and past research studies shows that design features of the slab, such as the thickness, the support provided by the base and subgrade, friction between base and slab, and modulus of the concrete slab all affect the stresses induced within the PCC pavement slab.[1, 3, 9, 10, 17] Also, finite element analysis has shown that increasing pavement thickness and the support provided by the base and subgrade reduces stresses and deflections at the slab midsections when subjected to wheel loads and, therefore, distress such as transverse cracking.[18]

Corner cracks are caused by repeated heavy traffic loading on slabs that have inadequate or weak support at the corners.[11] The mechanism of the development of corner breaks is similar to that described for transverse cracking. The application of traffic load at the corner of a concrete pavement slab will cause critical horizontal tensile stresses at the top of the slab along a line diagonal to the corner, resulting in the formation of microcracks. Repeated application of loads at the corner and the cumulative effect of the resulting critical tensile stresses, strains, and energy at the top of the slab causes the microcracks to propagate, resulting in corner breaks.[19, 20]

The ability of the slab to transfer load at the corner to adjacent slabs through dowels or other load transfer devices reduces the magnitude of the horizontal tensile stresses and, therefore, the rate of occurrence of corner breaks.[21] Other factors that will reduce the magnitude of the horizontal tensile stress and, therefore, reduce the occurrence of corner breaks include an increased slab thickness, higher concrete flexural strength, better foundation or subgrade support, and adequate subdrainage.[3]

Faulting is also another key distress type of undoweled JPCP that is highly influenced by traffic loading and has a considerable effect on the performance of pavements.[2, 13] Faulting can occur at the joints or cracks of JPCP when there is pumping and erosion of the base, subgrade, or underlying material beneath the leave slab of a concrete pavement. This occurs when water accumulates under the slab, at the corners, joints, and cracks. The sudden impact of traffic load moving over a joint or crack causes the water to be ejected from under the leave slab with some considerable force.[13] If the support material is erodible, the force of ejection may be enough to erode the support material and move it backward to lift the approach slab, creating a void under the leave slab. The material movements and voids result in faulting.

Excessive faulting of a short-jointed JPCP will lead to considerable discomfort of the traveling public as a result of the increased roughness. Faulting can be controlled by the use of dowels in both JPCP and JRCP.[1,3,9]

In addition to the key distress types that are predominantly caused by repeated application of heavy loads, traffic loading also often contributes to the further deterioration of certain distresses whose primary cause may not be load related. For example, repeated heavy traffic loading will increase the rate of deterioration of random transverse cracks that form near joints that are improperly constructed. Also, traffic loading can cause longitudinal cracking in some cases where there is a loss of support due to foundation movements. Lastly, when longitudinal joints are improperly constructed, it is sometimes possible for curling and warping of the slab to occur in the transverse direction. This curling and warping, in combination with repeated heavy traffic loading, can lead to longitudinal cracking, often in the wheel path.[22]

Influence of Traffic Loading on JRCP

The key JRCP distress types that are influenced by traffic loading include the deterioration of transverse cracks, faulting, and corner breaks. Cracking in JRCP occurs as a result of the temperature shrinkage that develops over the longer spans of slabs used for that pavement type.[23] When properly designed, the reinforcement in JRCP is supposed to keep the cracks tight and prevent the intrusion of incompressible materials and water into them. However, repeated traffic loading will eventually cause the cracks to deteriorate. Heavy traffic loads and an increase in the number of applications will hasten the deterioration of cracks. Excessive variations in temperature (causing the cracks to open wider) accompanied by inadequate reinforcement (causing the cracks to lose their ability to transfer load by aggregate interlock) will also increase the rate of deterioration of transverse cracks.[23,24]

Corner breaks do not occur in JRCP. This is because all JRCP have doweled load transfer. The presence of dowels at the transverse joint (near the corner and in the wheel path) eliminates corner breaks because of a reduction in the corner stresses, strains, and energy buildup due to the transfer of load to adjacent slabs.[1] As with JPCP, faulting in JRCP is directly related to the pumping and erosion of the material beneath the leave slab caused by the repeated application of heavy traffic loading. Also, the mechanism is similar to the sudden impact of traffic load on a leave slab, causing the ejection of material from beneath the leave slab. This material piles underneath the approach slab and results in an elevation difference between the slabs.[21,25]

There are also distress types for JRCP that are not primarily caused by load, but deteriorate further with repeated load. These include random transverse cracks that occur near transverse joints that are improperly constructed. Repeated applications of heavy traffic will cause such transverse cracks to deteriorate at a faster rate. Similarly, the improper construction of longitudinal cracks can sometimes lead to the occurrence of load-related longitudinal cracks that are parallel to the centerline.[22]

Climate

Variations in temperature and moisture have a great influence on several of the distresses that develop in concrete pavements. The daily variations of temperature and moisture through a concrete slab lead to temperature and moisture gradients that cause restrained curling and warping stresses.[19, 20, 26, 27] Often, these stresses by themselves are not critical, but become critical in JPCP and JRCP when the stresses caused by traffic loads are superimposed. Because of the closely spaced cracks that form in CRCP, restrained curling and warping stresses usually are not a problem. However, in some instances, a badly constructed longitudinal joint can cause curling and warping stresses to develop in the transverse direction, leading to longitudinal cracking with the application of repeated heavy traffic loads.[22, 28]

For a jointed concrete pavement, a positive temperature gradient during the daytime will cause the slab to curl downward at the corners.[18, 19] Unrestrained curling causes the pavement to lose contact with the underlying support material at the center. The resulting restrained curling stresses can significantly increase mid-slab edge bending stresses at the bottom of the slab when traffic loads are applied. Similarly, during the night, a negative temperature gradient can cause the slab to curl upward, causing a loss of support at the corners. Combined corner stresses in the top fibers of a curled slab induced when traffic loads are applied can be excessive and lead to corner breaks and transverse cracks.[3]

The curling experienced by jointed concrete pavements can be exacerbated by permanent construction curling.[29, 30] This occurs during construction, when there is a high positive temperature differential within the slabs as they set and harden. Because the slabs are flat when they harden with this high positive temperature differential, there is most likely going to be a permanently curled upwards slab when the top of the slab gets cooler and contracts as the initial temperature gradient at the time of hardening and setting reduces due to the influence of lower ambient temperatures. This phenomenon has been observed in Texas and Florida in the United States, as well as in several other countries, including Chile, Germany, and Britain.[19, 20, 31] The upward curling will lead to further loss of support at the corners of jointed pavements and increase the stresses that occur at the top of the slabs when loads are applied.

These stresses can have a substantial effect on the performance of concrete pavements that are placed on very stiff foundations. The results from a study of a pavement that was built over a relatively stiff cement-treated base showed significant curling and warping of the pavement.[30] The results from a study in Chile also point to a high occurrence of transverse cracking and corner breaks for concrete pavements with cement-treated aggregate bases that were built over old asphalt concrete and PCC pavements (mean of 23 percent).[31] Similar designs of concrete pavements with cement-treated aggregate bases constructed on the natural subgrade showed lower levels of cracking (mean of 6 percent). It was observed that all of the pavement sections remained in a permanently upward warped/curled position that resulted in measurable rocking of the undoweled pavement slabs when loaded at the corner for undoweled JPCP.

Climatic conditions also have a significant influence on the distribution of moisture and free water in pavements. The volume changes that accompany the loss or gain of moisture in concrete slabs can influence performance in several ways. In hardened concrete, loss of water from within leads to irreversible drying shrinkage. Non-uniform or differential shrinkage can lead to warping and cause warping stresses to be developed in a concrete pavement.[30] Warping also results in a loss of support along the slab edges that can lead to high stresses when traffic loads are applied.[26,32] The effect of warping is especially significant in dry climates. Warping can be characterized by an equivalent temperature gradient that causes the same amount of damage or deterioration.

Subgrade

The structural support provided by the subgrade is an important factor in the design of PCC pavements, and it has an influence on the long-term performance of concrete pavements. Therefore, most of the existing design procedures require a subgrade support parameter, such as the subgrade k-value, as an input.[10,11] Several important observations were made in recent studies on the support for PCC pavements.[28,33] Uniformity of support appears to be as dominant a factor as the stiffness of the subgrade to PCC pavement performance. Weak subgrades that provide non-uniform support will reduce the life of a concrete pavement, but stiffer subgrades that are able to provide uniform support all year round tend to lead to better performing concrete pavements. Therefore, it is also important to accurately characterize the loss of support at the corners, joints, and edges of PCC pavements since they hasten the occurrence of excessive distress.

However, for pavements that experience excessive curling and warping, a very stiff subgrade can lead to excessive distresses. A study in Chile showed a high occurrence of transverse cracking (mean of 23 percent slabs with distress) and corner breaks for concrete pavements built on cement-treated aggregate bases placed over old asphalt concrete and PCC pavements.[31] Similar concrete pavement designs with the cement-treated base constructed over natural subgrade showed much lower levels of cracking (mean of 6 percent). It is believed that the less stiff natural subgrade allowed some settlement of the pavement, causing a reduction in stresses because of the uniform support that is provided.

Other important parameters of the subgrade that have been shown to have an influence on performance are whether the subgrade is coarse-grained or fine-grained and the percentage of the subgrade material that passes the 0.075-mm sieve size.[26] These factors are directly related to the susceptibility of the subgrade to pumping, erosion, frost heave, and swelling that result in distresses such as faulting, corner breaks, and load-related longitudinal cracking. Subgrades with a high percentage of fines are more likely to be susceptible to pumping, frost heave, and swelling.[34,35] Therefore, an important goal in design is to find a means for reducing the influence of the fine-grained portions of the subgrade through treatment with additives such as lime or cement, or simply by removal and replacement with granular material.[36,37,38,39,40]

PCC Pavement Design Features

The primary design features used in the design of PCC pavements depend on the type of pavement facility, the site of the pavement, and climatic conditions of the site. Following are the design features identified for JPCP, JRCP, and CRCP that have a considerable influence on pavement design and construction. Emphasis is placed on the design features of JPCP since it is the primary rigid pavement type used in the United States.

Transverse Joint Spacing

Joint spacing is an important design feature for JPCP and JRCP.[41] Short joint spacings are recommended for JPCP to control transverse cracking. A widely accepted rule of thumb is that the transverse jointing spacing for JPCP in meters should not exceed 0.02 times the thickness of the pavement slab in millimeters. Typically, JPCP slabs are less than 6 m long.[42] Shorter transverse joint spacing will lead to less curling, a reduction of bending stresses, and smaller joint openings due to seasonal temperature variation. However, the resulting increase in the number of joints in the pavement increases construction costs and the potential for future joint-related distress, such as faulting.

Longer transverse joint spacings can be used for JRCP as long as adequate reinforcement is provided to hold tight the cracks that eventually form in them as a result of drying shrinkage.[24,43] Typically, the joint spacing for JRCP ranges from 6 to 18 m. With the longer spans, transverse cracks develop quite quickly midway between the joints. As long as the reinforcement design is adequate and the cracks are kept tight, they will not be detrimental to performance. However, the repeated application of heavy traffic loads often causes the cracks to break down and deteriorate with time because of inadequate reinforcement.

Joint Orientation

The transverse joints of JPCP and JRCP can either be skewed or square. Also, the joint spacings can be uniform or variable. Skewness can range up to about 0.6 to 0.9 m per 3.6-m lane width. There has been some concern about the effect of skewed versus square joints and uniform versus repeated variable joint spacing on PCC pavement performance. Significant corner cracking was observed in slabs with skewed joints on I-75 in south Florida.[18] Random joint spacings vary across the United States. A typical design is the California 3.65-3.95-5.8-5.5 m random joint spacing. More cracking has been reported in the longer slabs of pavements with such random spacings.[2,12]

Researchers in Australia report that the skew of joint has been reduced to 1 in 10 (i.e., an angle of 84°) because of occasional incidence of corner cracking.[44] They also report of a change in Australia from the use of the randomized joint spacing to a uniform 4.2-m joint spacing. However, it is not believed that this is necessarily the influence of the variable joint spacing, but evidence of the general propensity of longer concrete slabs to crack.

Load Transfer

Load transfer provided at joints and cracks of concrete pavements has an enormous influence on performance.[3,20,21,33,41] The discontinuities at the joints often represent the weakest link in rigid pavements and tend to be the location of extensive distress with the repeated application of heavy traffic loads. With inadequate load transfer, loads that are applied at one side of a joint or crack will produce high slab deflections and excessive stresses and strains, which can lead to pavement distresses such as faulting, pumping, and corner breaks. Insufficient foundation support at the joint or crack often compounds the problem and contributes to even higher stresses and distress. Good load transfer from installed load transfer devices and aggregate interlock can reduce high slab deflections and excessive stresses, improving the performance of concrete pavements.[1,2,3,9,25] Therefore, it is typically good practice to provide load transfer for all jointed concrete pavements that will carry heavy truck traffic.

Dowels are an effective means for providing load transfer in both JPCP and JRCP. The characteristic of the dowel that influences load transfer is primarily the diameter. The length and dowel spacing also influence load transfer. The long-term performance of dowel bars is greatly influenced by the specific climate properties and aggregate composition and properties, and whether they are coated. Typically, round steel bars between 25.4 and 38.1 mm thick, 460 mm long, and spaced at 300 mm centers have been used as dowels.[1,2,3,21,42]

Adequate load transfer for short jointed JPCP and JRCP, as well as load transfer across the cracks of JRCP and CRCP, can also be obtained by aggregate interlock. Concrete with hard, angular aggregates can provide good aggregate interlock, and significant load transfer can be obtained at the joints of thicker slabs of short-jointed pavements. Large sized aggregates are critical in the PCC mixture to ensure adequate aggregate load transfer. Appreciable load transfer can also be obtained at cracks that have not deteriorated into working cracks. Good support provided by the underlying material improves load transfer at joints and cracks.[23]

PCC Slab Thickness

The thickness of pavements is provided as a function of the structural capacity required to meet the demands of the site conditions: traffic loading, climate, and subgrade. Most of the State highway agencies use the AASHTO pavement design procedure to determine the thickness, which typically ranges from 150 to as much as 350 mm.[42] The AASHTO thickness design procedure does not differ for the different pavement types; the same thickness is developed for a particular set of traffic loading, climate, and subgrade conditions. However, in past practice there was a tendency to reduce the thickness of CRCP. This reduction was to account for what was believed to be the beneficial effects of the continuous reinforcement in CRCP and the resulting high degree of load transfer across transverse cracks.[45] The practice of thickness reduction for CRCP was supported by extensive survival analysis in Illinois.

Adequate thickness must be provided to carry repeated heavy traffic loads that are applied. An inadequate thickness will lead to most of the key load-related distresses, including faulting of JPCP and JRCP, fatigue cracking of JPCP, corner breaks of JPCP and JRCP, and punchouts of CRCP.

PCC Slab Material Properties

Good quality conventional concrete mixes that will provide high quality concrete are adequate for PCC pavements. Mixes with the proper water/cement ratio, high quality aggregates, adequate cement content, and the appropriate air-entrainment that are placed, consolidated, finished, and cured using the proper construction techniques will provide concrete with adequate strength, durability, and performance. Maximum sized aggregates are critical for adequate load transfer at the joints and cracks.[23]

The thermal properties of the concrete slab are directly related to the thermal properties of the PCC constituent materials. These properties influence the distribution of thermal gradients within the slab, curling, and thermal expansion and contraction of the slab. All of these effects have an important influence on performance. Desirable thermal properties are obtained by selecting the appropriate materials.

The hardness and moisture susceptibility of the aggregates used in the concrete mixes also has an influence on the development of moisture-related distress in PCC. In areas subjected to a large number freeze-thaw cycles, the durability of the PCC slab is an important consideration. PCC slabs constructed with D-cracking susceptible aggregates will show the distress with time, especially when drainage conditions are poor and water is available for absorption into the aggregates.[46, 47]

PCC Slab Strength Properties

The primary strength parameters of the PCC slab that are important to design include parameters such as flexural strength, the elastic modulus, and compressive strength. Most design procedures use flexural strength to characterize concrete strength for design. Flexural strength can be determined from third-point loading or from midpoint loading. Both methods are used by highway agencies; however, the flexural strength determined from third-point loading is specified by most States. A recent survey of State practices in NCHRP Project 1-32, *Systems for Design of Highway Pavements*, showed that only 8 out of the responding 37 State highway agencies that use concrete flexural strength for design use midpoint loading flexural strength.[42]

Base and Subbase

A base or subbase layer are nearly always provided under the PCC slab. The base and subbase provide structural capacity to the pavement and can serve as a means for providing uniform support. A base can also be used to facilitate drainage when an open-graded aggregate base material or other permeable base layer is used. A thick base or subbase layer that is not frost susceptible is also sometimes used to protect the pavement from frost. The features of a base or subbase that influence pavement performance include the type, thickness, and strength.[48]

The types of base and subbase used under PCC pavements include unbound granular material, stabilized or treated (asphalt or cement) bases, lean concrete bases (LCB), and treated and untreated permeable bases. Permeable bases are provided to promote positive subdrainage. In general, a thick, good quality, unbound granular material will provide uniform support and offer protection against frost where it is required. A lean concrete base will provide even more support, as well as a non-erodible base. Stabilized or treated bases, such as bituminous bound bases and cement- or lime-treated bases, can also provide uniform support. However, there are recent indications that such lime-treated base and subgrade materials do not remain bound for long periods of time. Observations of pavements in Europe indicate that a good combination for PCC pavements is the use of a lean concrete, stabilized, or treated base over a thick unbound granular subbase.[49]

Reinforcement

The reinforcement used in JRCP and CRCP has a considerable influence on performance. The reinforcement in both pavement types is used to hold the transverse cracks developed from temperature-induced stresses tightly together. Reinforcement in JRCP typically consists of welded wire fabric or rebars that are placed mid-depth in the concrete slab. Rebars are the typical type of reinforcement used in CRCP. Grade 40 or 60 steel is commonly used for both JRCP and CRCP. It is always important that adequate concrete cover is provided for the reinforcement steel. A considerably higher amount of steel is used in CRCP than in JRCP.[48]

Widened Lanes/Shoulders

Widened lanes have been used for all the rigid pavement types. This involves the construction of a 4.25-m-wide truck (design) lane, but with the edge paint stripe still placed at 3.6 m. This design moves heavy truck traffic away from the slab edge and provides a significant reduction in pavement stresses and deflections. This results in significant reductions (up to 50 percent) in distresses such as faulting and cracking.[12] Widened lanes provide significantly better performance results than tied concrete shoulders.

The presence and type of shoulder have an influence on concrete pavement performance. Although an AC shoulder can be adequate from a safety standpoint, it does not improve the load transfer at the longitudinal lane/shoulder joint and does not contribute to structural capacity. A tied concrete shoulder that is monolithically constructed with the traffic lanes, however, will significantly reduce bending stresses and deflections at the mid-slab locations of a concrete pavement. Also, a properly tied shoulder with a sealed longitudinal joint can reduce the infiltration of surface water along the longitudinal joint and limit the occurrence of moisture-related distress such as pumping.

In recognition of these benefits, the PCA design procedure, for example, allows for a decrease in thickness by 25.4 mm if a tied concrete shoulder is used.[50] The AASHTO design procedure also specifies a lower load transfer coefficient, J, (i.e., essentially a reduction in thickness by an inch) when a tied PCC shoulder is present. In general, for a given set of conditions, a lower J value is associated with an increase in structural capacity.[10] In spite of these examples, the results from a recent study indicate that such reductions may not be significant at joints. Therefore, such thickness reductions may not be justified unless it can be determined that a substantial tie design is provided that gives long-term longitudinal load transfer.[24]

Adequate load transfer at the longitudinal joint can be achieved with tie bars that have the proper diameter, spacing, and length. Typical designs consist of No. 5 bars about 50 diameters long, placed mid-depth of the slab at a spacing between 450 and 760 mm.[48] Keyed joints used in combination with tie bars can improve the load transfer at the longitudinal joint, but because they are difficult to construct properly, keyed joints are not often used. Keyed joints that are not tied are not recommended.[51] Transverse joints in the shoulder are designed using the same principles recommended for transverse joints in the mainline pavement. Short spans (typically less than 6 m) are used for JPCP shoulders; longer joint spacings are used for JRCP shoulders when they are reinforced.

Subdrainage

Inadequate subdrainage that holds excessive water will contribute to moisture-related distress such as D-cracking, pumping, and faulting in concrete pavements. Poor subdrainage can cause erosion of the subbase or subgrade and lead to a loss of support. With this loss of support, application of repeated heavy traffic loading will lead to pumping of the underlying material, and eventually to corner cracking and faulting of transverse joints. Inadequate subdrainage can also lead to the creation of a bathtub condition that will lead to increased freeze-thaw damage of the PCC layer and cause D-cracking.[3] It also leads to the weakening of the subgrade, increasing the potential for higher deflections and pumping. Therefore, the provision of good subdrainage is essential to the long-term performance of concrete pavements.

Permeable aggregate bases, non-erodible permeable treated bases with separator layer, edge drains/underdrains, and ditches can be used to provide good subdrainage. The subdrainage base is placed directly under the last stabilized layer under the concrete slab to intercept the water that infiltrates through the pavement joints and cracks. An aggregate separation layer between the permeable base or non-erodible treated base and the underlying subbase or subgrade is necessary to prevent fines from the subbase or subgrade from pumping into the permeable base and clogging it up, thus ensuring good subsurface drainage.[48] The water can be carried through a permeable base or intercepted by a non-erodible treated base and carried through a system of underdrains to an edge drain system and drainage ditch along the side of the pavement. It is essential that adequate provisions are made to ensure that the subdrainage is coordinated with surface drainage provisions.

Construction Practices

The various practices followed during construction can have an enormous influence on the performance of concrete pavements. In this section, the key practices used in the construction of PCC pavements are identified. However, only those practices on which information is available in the LTPP database and that can be examined in this study are discussed. Because a majority of the LTPP GPS sections were constructed several years ago, some of the construction practices presented are outdated.

The practices can loosely be divided into the mix design practices for the concrete mixture and the paving practices used to construct the pavement. Emphasis is placed on the paving practices. Typically, the influence of mix design on the performance on PCC pavement is characterized by characteristics of the concrete mix and properties of the hardened concrete. Examples of characteristics of the concrete mix include the water/cement ratio, cement content, air content, and slump. More details related to the influence of mix design on pavement performance are provided in the section below. Unfortunately, the available LTPP data related to mix design are inadequate to permit extensive study of the specific mix design variables.

Mix Design

The mix design practices used for pavements are similar to those used for concrete for all types of construction. The goal is to provide good quality concrete that will meet specified workability, strength, and durability characteristics. Aggregates should be of sufficient type and size, and not be susceptible to freeze-thaw durability damage, alkali-silica reactivity (ASR), and excessive thermal expansion/contraction. A maximum aggregate size of 38.1 to 50.8 mm is specified by most agencies, as are maximum LA Abrasion and soundness limits.[48] Also, most agencies place limits on the amount of aggregates susceptible to durability damage or ASR that can be used in concrete for pavements. Air-entrainment is required in regions that experience substantial freeze-thaw cycles. The type of cement selected must meet the needs of the pavement, as must the amount of cement and any other additives that are added.

Paving Practices

There are also several factors related to the paving operation that influence PCC pavement performance. They include the construction method, lane width, number of pavement layers placed, method of dowel bar placement, curing, ambient temperature and relative humidity at the time of construction, and finishing practices. Other factors that are related to the finished pavement include the method of forming transverse and longitudinal joints, sealing of joints, and texturing of the pavement's surface.

PCC layers are typically constructed using a slip-form paver. In current slip-form paving operations the PCC layer can often be placed in one lift. The method used to install mechanical load transfer devices could possibly have an influence on performance. One advantage of the slip-form pavers used to construct pavements is that most are equipped with an automatic dowel bar inserter. The dowels are placed either by vibrating them downward into the wet concrete or by intrusion. In the United States, dowel bars are typically installed by pre-placing them on baskets or chairs.[3]

The predominant method of curing of PCC pavements in the United States is by the use of a membrane curing compound.[48] Other methods include the use of wet burlap curing blankets and polyethylene sheeting. Typically, curing is conducted over a 72-hour period, although a few State agencies specify longer hours. The curing process has an influence on the temperature generated in the concrete several hours after construction. The stresses generated can cause the development of microcracks at the edges of the PCC slab, eventually resulting in spalling.[52] The predominant methods of finishing of the concrete surface to obtain the right texture are tining, burlap drag, and brooming. The depth and width of tinings vary considerably. Methods of forming the transverse and longitudinal joint grooves in the PCC slab include sawing and the use of plastic inserts.

Summary

PCC pavement design has primarily consisted of determining the slab thickness, which is most commonly achieved through the use of a design procedure such as AASHTO or PCA.[50] However, many other design features (e.g., base type, joint spacing, load transfer, and drainage design) are known to influence PCC pavement performance, although they are not accounted for directly in most design procedures. To provide an adequate design, every significant design feature must be analyzed by considering the pavement system as a whole. That is, all of the components of a PCC pavement must not only be designed to be structurally adequate by themselves, but also to function together successfully as a structural system. The failure to adequately consider each of these components and to consider their interaction as a structural system has led to premature failures of many pavements.

Several past research studies have been reviewed in this chapter, and some of the design features and practices that influence PCC pavement performance have been identified. Following is a prioritized list of the features and practices that will be investigated (using LTPP data) to quantify their influence on performance.

Site Conditions

Traffic Loading (ESAL's)
Climatic Regions and Related Climatic Variables
- Freezing Index
- Annual Freeze-Thaw Cycles
- Average Annual Precipitation, m
- Average Annual Temperature Range, °C

Subgrade Type
Backcalculated Static k-value, kN/mm^3

Design Features

Slab Thickness
Transverse Joints
- Joint Spacing
- Presence of Random Joint Spacing
- Joint Orientation (Presence of Skewed Joints)

Subdrainage
- Type of Drainage
- Presence of Longitudinal Drains

Base Type
PCC Elastic Modulus
PCC Slab Strength (Flexural Strength)
Lane Width
Outside Shoulders or Edge Support
Load Transfer Design
- Type of Load Transfer
- Presence of Dowels
- Dowel Diameter

Reinforcement
- Reinforcing Steel Type
- Design Steel Content, percent

<u>Construction Practices</u>

Paver Type
Method of Curing
Method of Texturing
Transverse Joints
- Method of Forming Transverse Joints
- Joint Sealant Types
- Initial Roughness
- Method of Dowel Placement

On the basis of the pavement failure mechanisms described previously and the availability of distress data in the LTPP database, the following three distress indicators were chosen to judge and quantify pavement performance:

- Transverse joint faulting.
- Transverse cracking.
- Roughness (IRI).

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