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

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LTPP

FOREWORD

This report documents recommendations for the design and construction of portland cement concrete (PCC) pavements. The recommendations were derived from the analysis of Long-Term Pavement Performance (LTPP) data.

The positive outcomes of this study are the recommendations for improving PCC pavement design and the development of prediction models to be used in pavement design and management. Most of the performance models developed are mechanistic-based, and this is expected to provide expanded capabilities for considering the effects of load- and climate-related stresses on PCC pavement performance. The development of mechanistic-based models agrees with current trends of upgrading the pavement design and evaluation process through the use of mechanistic-based design methods.

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 a variety of means to determine the beneficial effects of design features and construction practices on long-term performance. Emphasis was placed on identifying those specific design features that can be included during design to improve the performance of PCC pavements under various combinations of environmental and traffic loading conditions, and for different subgrade support conditions. The study focused on the development of practical recommendations that can be easily implemented by highway agencies to increase pavement life.

This volume provides a concise summary of the results that were obtained from the study. It includes an overview of the engineering and statistical analyses that were conducted and presents results that can be used by State highway agencies to obtain high-performance PCC pavements. Implementation of the recommendations will increase the reliability of PCC pavements.

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

FHWA No.	Vol No.	Short Title
FHWA-RD-98-053	II	Design Features and Construction Practices that Influence Performance of PCC Pavements
FHWA-RD-98-054	III	Improved PCC Performance Models

17. Key Words

Concrete pavement, design, construction, performance, distress, design guidelines, construction guidelines, life cycle cost

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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.

Symbol	When You Know	Multiply By	To Find	Symbol
		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

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* 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)

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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

Overview

Several variables influence the long-term performance of portland cement concrete (PCC) pavements. They can be classified into the site conditions at the location of the pavement, the design features that are incorporated into the pavement, and the construction practices that are followed to build the pavement. The site conditions include traffic loading, climate, and the support provided by the subgrade. Examples of the design features that influence performance include layer thicknesses, joint spacing, joint and load transfer design, reinforcement design, and subdrainage. Factors related to construction that can also have a significant influence on the performance of PCC pavements include mix design; method of paving; method of dowel installation; method of finishing, texturing, and curing; and the method used to form joints.

For designers to provide long-lasting PCC pavements, practical recommendations on these design features and construction practices are required. While there are several examples of pavements that have lasted for over 40 years, there have also been instances where PCC pavements have only lasted a fraction of their design lives. Typical reasons for such premature failures of PCC pavements include inadequate characterization of site conditions and the use of inappropriate inputs in the design process. Also, there are several examples of instances where the required design features have not been used for particular pavements; for example, not providing dowels for heavily trafficked PCC pavements has led to excessive faulting. Other reasons include deficient design features and poor construction practices.

Therefore, to build high-performance concrete pavements that will last a long time, designers need to understand clearly the influence of all these factors on long-term performance. Based on this understanding, the design features and construction practices that can promote good performance throughout the design life of the pavement can then be selected to construct high-performance concrete pavements. The primary objective of this study was to evaluate in-service PCC pavements from the Long-Term Pavement Performance (LTPP) study to quantify the influence of the site condition factors on long-term performance and to determine the beneficial effects of design features and construction practices.

This report provides information on the design features and construction practices that have been identified as influencing PCC pavement performance. It also provides recommendations on the design features and construction practices that can be used by pavement design engineers to improve long-term performance.

Background

To develop improved recommendations for the design and construction of high-performance concrete pavements, a study was conducted that had the following two specific objectives:

- Examine and analyze the rigid pavement LTPP data to determine design, site, and construction variables that influence the long-term performance of PCC pavements.
- Develop specific recommendations that can be implemented in design and construction to improve long-term performance.

These objectives were accomplished through extensive analysis of jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP) included in the LTPP General Pavement Studies (GPS) database in a two-part study. First, there was a comprehensive engineering and statistical evaluation of the in-service PCC pavements in the LTPP database to evaluate the effect of traffic loading, climate, subgrade support, and pavement design features on some of the key distress types: transverse joint faulting, transverse cracking, and roughness. Similarly, there was an evaluation of the effect of construction practices on the occurrence and progression of these key distress types. Details of the results of that part of the study are presented in volume II of this report.

Second, using the best tools currently available, improved mechanistic-based prediction models were developed for joint faulting, joint spalling, roughness, transverse cracking, and corner breaks (JPCP). The models were used in sensitivity analyses to quantify the influence of site conditions and to identify the effects of design features on PCC pavement performance. Volume III of this report provides detailed results on that part of the study. This volume of the report contains a summary of the findings and recommendations from the overall study presented in an easy-to-reference format. It is not intended to provide all the detailed information contained in volumes II and III; however, this volume highlights the important findings of the study.

Scope of Report

This volume of the report consists of six chapters. Chapter 2, which follows this introductory chapter, provides information that quantifies the effect of the site conditions—traffic loading, climate, and subgrade support—on long-term pavement performance. Information in this chapter was obtained from volume II and III of this report. Chapter 3 is a summary of findings from volumes II and III of this report and provides guidance and recommendations for selecting design features that will improve long-term pavement performance. Recommendations for construction practices are discussed in chapter 4. The information presented in chapter 4 is from volume II of this report.

Chapter 5 presents a summary of the design and site variables required as input for the improved distress and roughness prediction models that were developed as part of this study and presented in volume III. The effect of these variables on distress and examples of the models' application are also provided. Chapter 6 concludes this report. Although the report covers the three conventional PCC pavement types (JPCP, JRCP, and CRCP), emphasis is placed on JPCP.

2. EFFECT OF SITE CONDITIONS ON PCC PERFORMANCE

Introduction

Being able to effectively and accurately account for the effect of site conditions on PCC pavements is a very important part of pavement design. Assessing or quantifying the influence of traffic loading, climate, and subgrade support on performance is the first priority in pavement design, since this information is required in order to identify the design features that should be incorporated in the pavement to promote long life. A key part of this study was to evaluate the effect of traffic loading, climate, and subgrade support, both separately and together, on the occurrence and progression of the common distress types in PCC pavements using the LTPP data. This evaluation provided several results that should be of use to practicing pavement engineers. The key distress types that were evaluated are as follows:

- JPCP
    - Joint faulting
    - Transverse joint spalling
    - Transverse cracking
    - Corner breaks
    - Roughness
- JRCP
    - Transverse joint spalling
    - Roughness
- CRCP
    - Roughness

A comprehensive evaluation of the effect of several site-related variables on distress and roughness is presented in volumes II and III of this report. This chapter summarizes the key observations and recommendations that resulted from the evaluation.

Traffic Loading

Repeated traffic loading is the main source of the stresses, strains, and deformations within the pavement structure that leads to the development of distresses and roughness. Vehicles with different gross weights, axle types, and axle weight distributions can be converted into a standard measure to generally characterize traffic loading for design. The cumulative 80-kN equivalent single axle load (ESAL) is the standard traffic loading designation that is used in most design procedures.(1) Therefore, the effect of cumulative 80-kN ESAL's on the key PCC pavement distress types was investigated in this study. Set out below is a summary of the results obtained on the effect of cumulative ESAL's on JPCP JRCP, and CRCP performance as determined from the LTPP database.

Influence of Traffic Loading on JPCP

Repeated traffic loading contributes greatly to faulting, transverse cracking, corner breaks, and roughness. This finding is in agreement with the results of past studies.(2, 3, 4, 5, 6) Figures 1 through 4 illustrate the effect of increasing traffic load applications (ESAL's) on faulting, transverse cracking, corner breaks, and roughness, respectively. The plots are from prediction models developed with the LTPP data. A summary of the input variables for the models is presented in chapter 5 of this volume, and the actual models are presented and discussed in greater detail in volume III of this report.

Figure 1 illustrates that as the cumulative load applications increase, JPCP faulting increases rapidly in the beginning and then levels off. As shown by the figure and discussed in detail in the next chapter, design features such as dowels can be used to reduce the influence of traffic loading on faulting of JPCP. Similarly, figure 2 illustrates the effect of cumulative ESAL's on transverse cracking of JPCP. As shown, increasing the PCC slab thickness is one way to reduce the effect of traffic loading. Figures 3 and 4, respectively, illustrate the influence of traffic loading on corner breaks and roughness. Once again, traffic loading clearly increases the severity of corner breaks and roughness. However, design features can be used to minimize the negative effect of traffic loading on pavement performance. Increasing pavement thickness will reduce corner breaks, and the use of dowels will reduce roughness of JPCP.

Influence of Traffic Loading on JRCP

Figure 5 shows the effect of traffic loading on JRCP roughness. Increased traffic loadings increase the rate and occurrence of distress, and this is manifested as increased roughness. A key JRCP distress type that greatly affects roughness is joint faulting. Also, deterioration of transverse cracks in JRCP with repeated heavy loads contributes to roughness. Traffic loading, like other site conditions, usually cannot be influenced by the pavement designer. Therefore, distress and roughness developed as a result of increased traffic loading can be minimized only through the selection of design features and construction

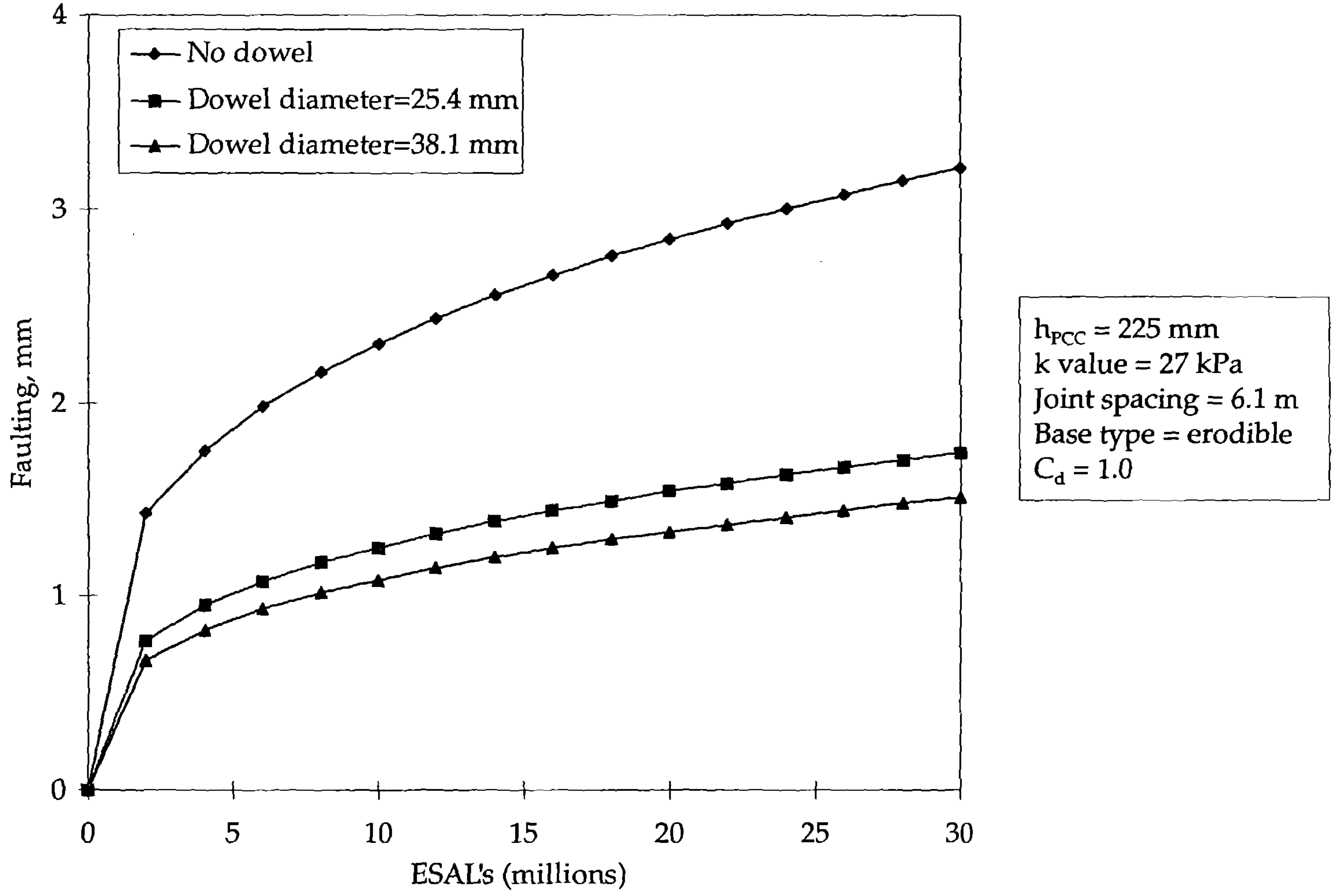


Figure 1. JPCP joint faulting versus traffic loadings, showing the effect of different dowel diameters.

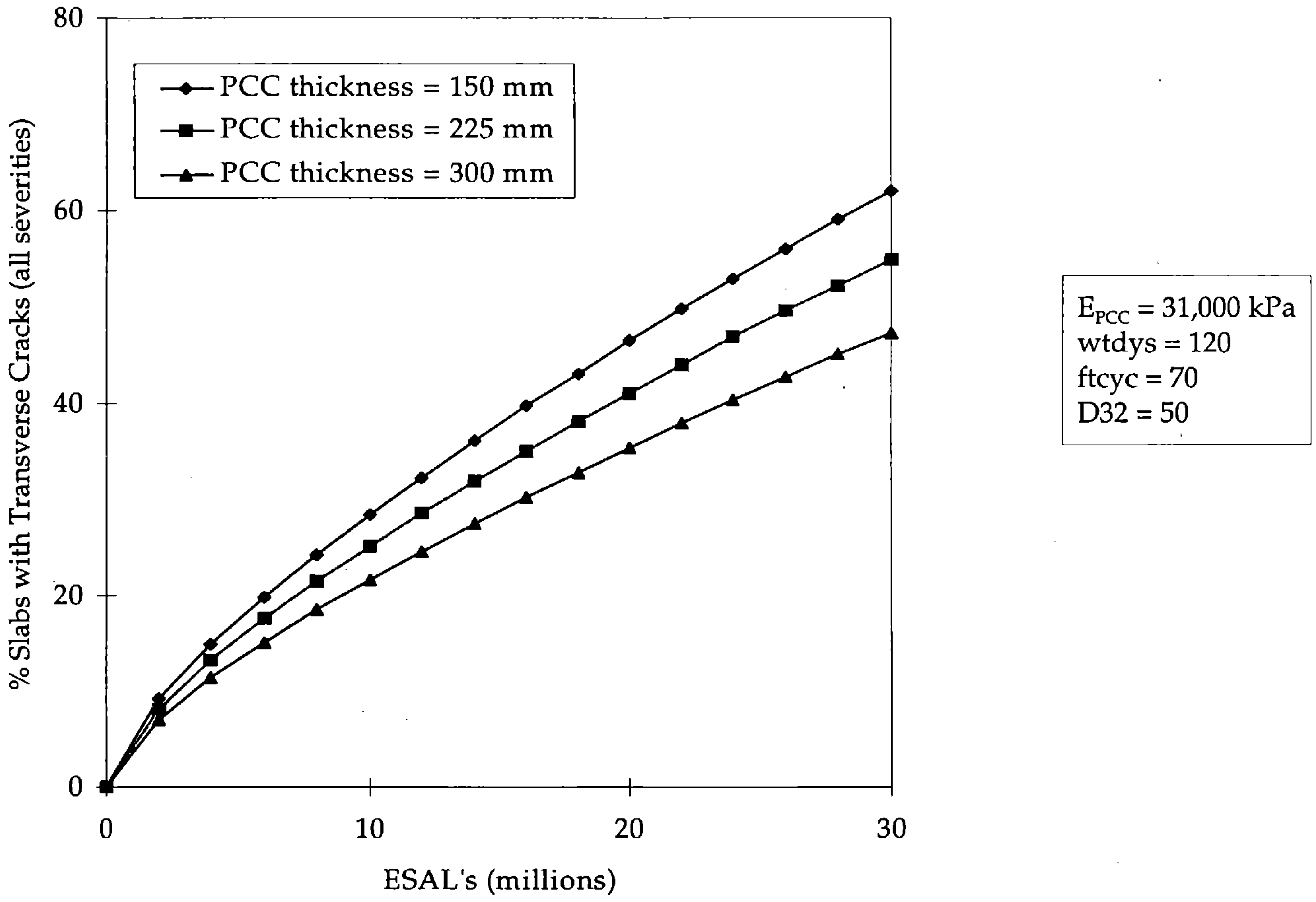


Figure 2. Percent slabs with transverse cracking versus traffic loadings, showing the effect of different PCC slab thickness.

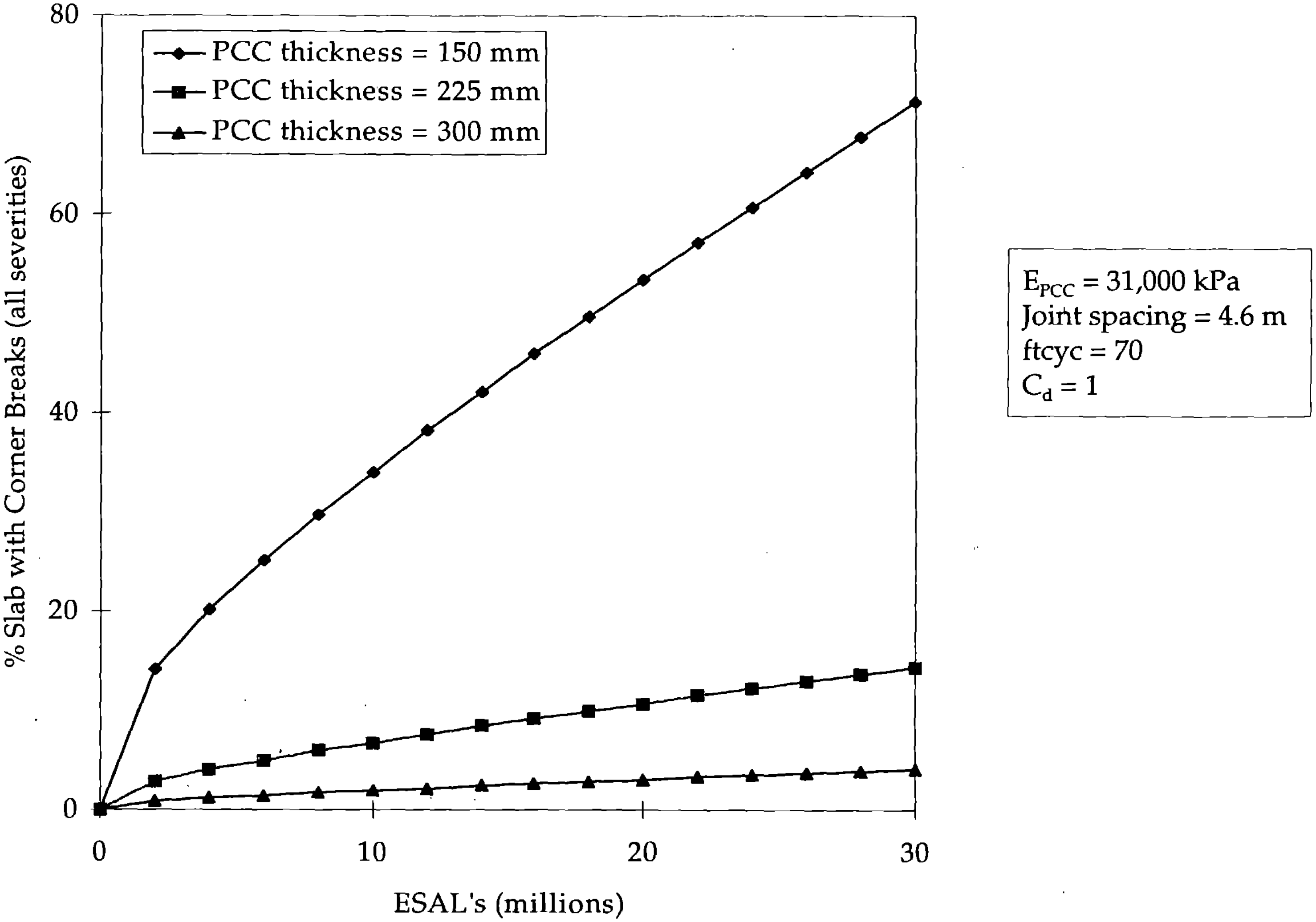


Figure 3. Percent slabs with corner breaks versus traffic loadings, showing the effect of different PCC slab thicknesses.

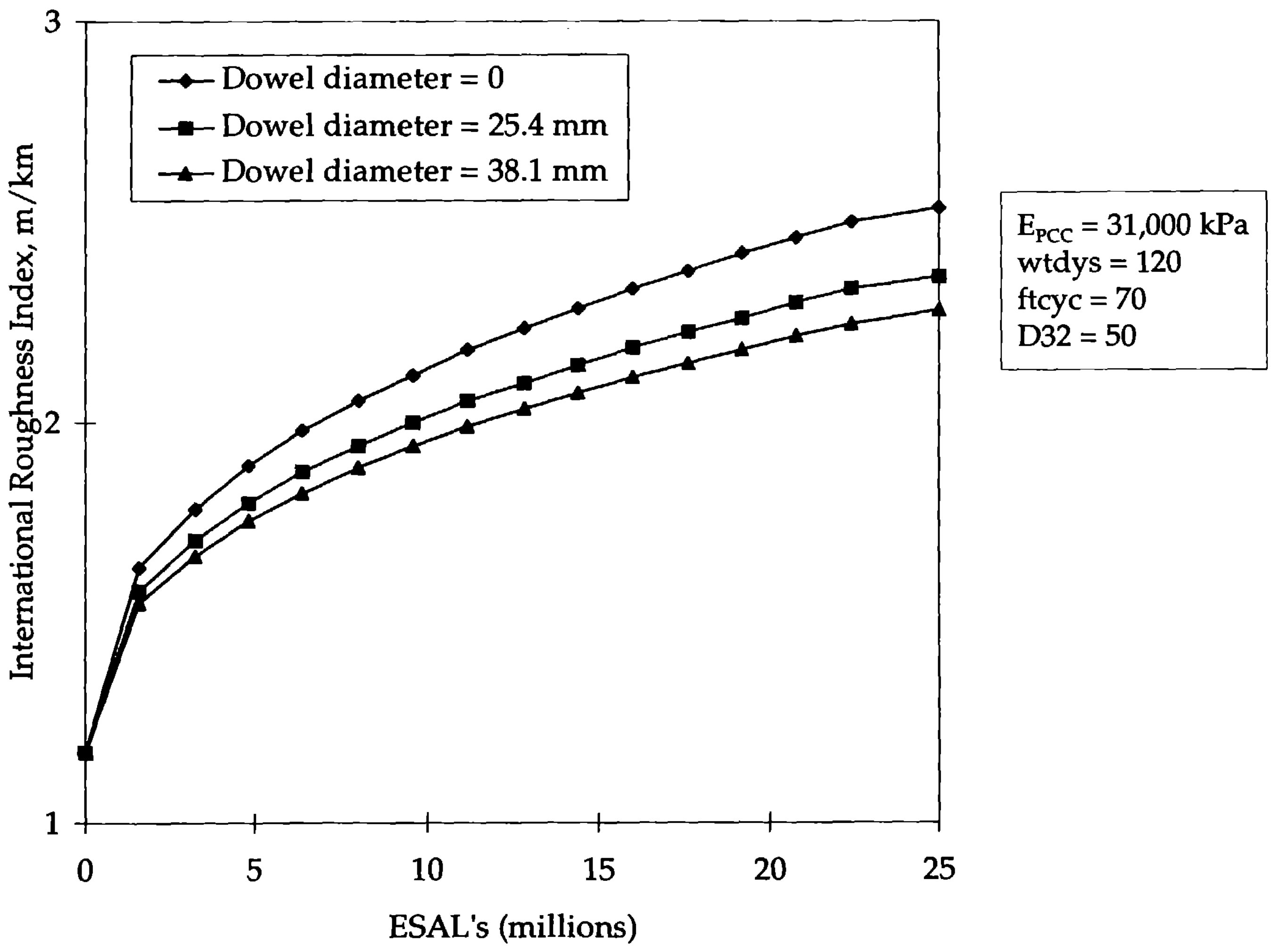


Figure 4. Plot of roughness versus traffic loadings, showing the effect of different dowel diameters.

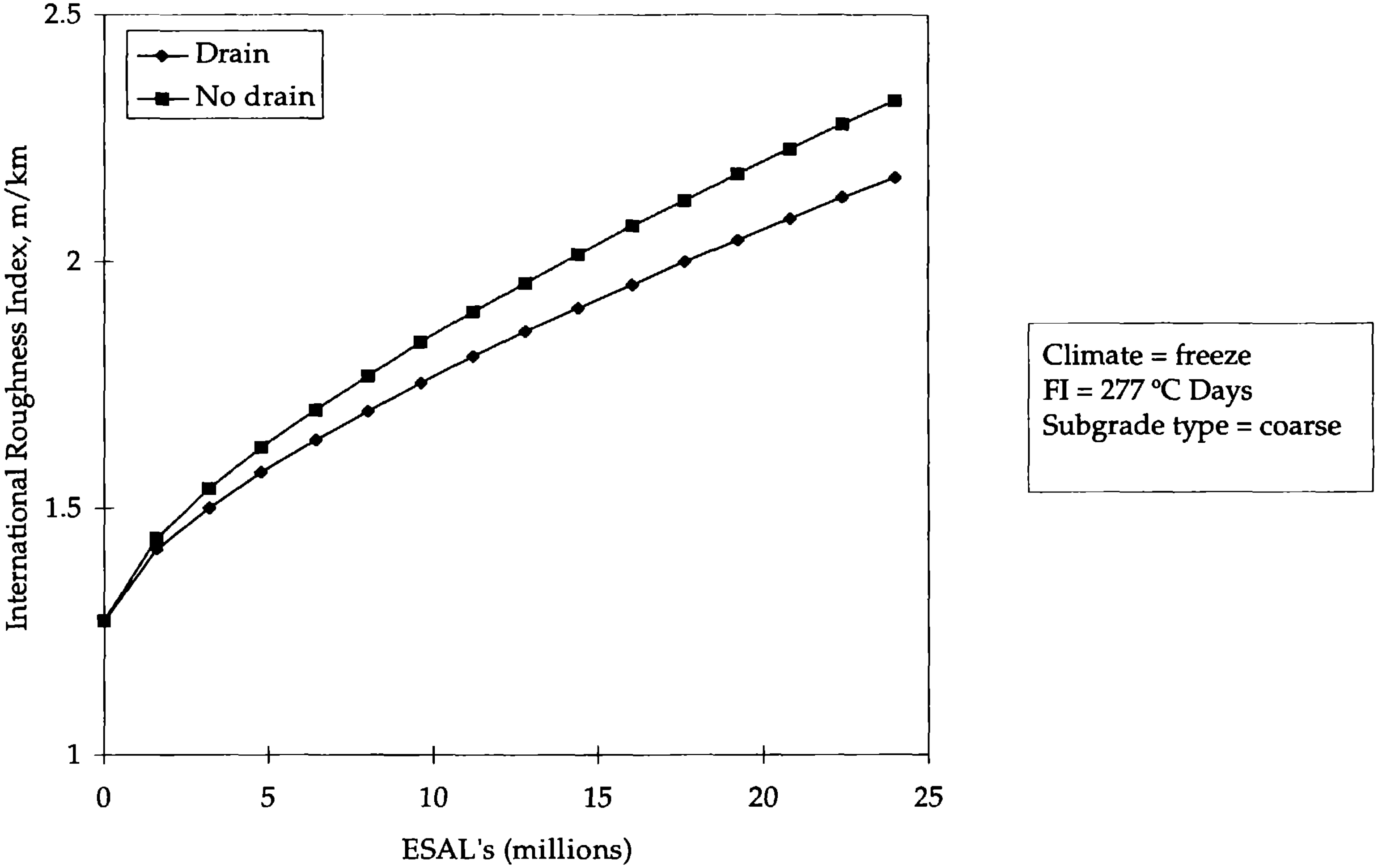


Figure 5. Plot of JRCP roughness versus traffic loadings, showing the effect of edgedrains.

practices that limit the occurrence of distress and roughness. The figure also shows that design features such as the provision of edgedrains can be used to minimize the effect of traffic loading on roughness.

Influence of Traffic Loading on CRCP

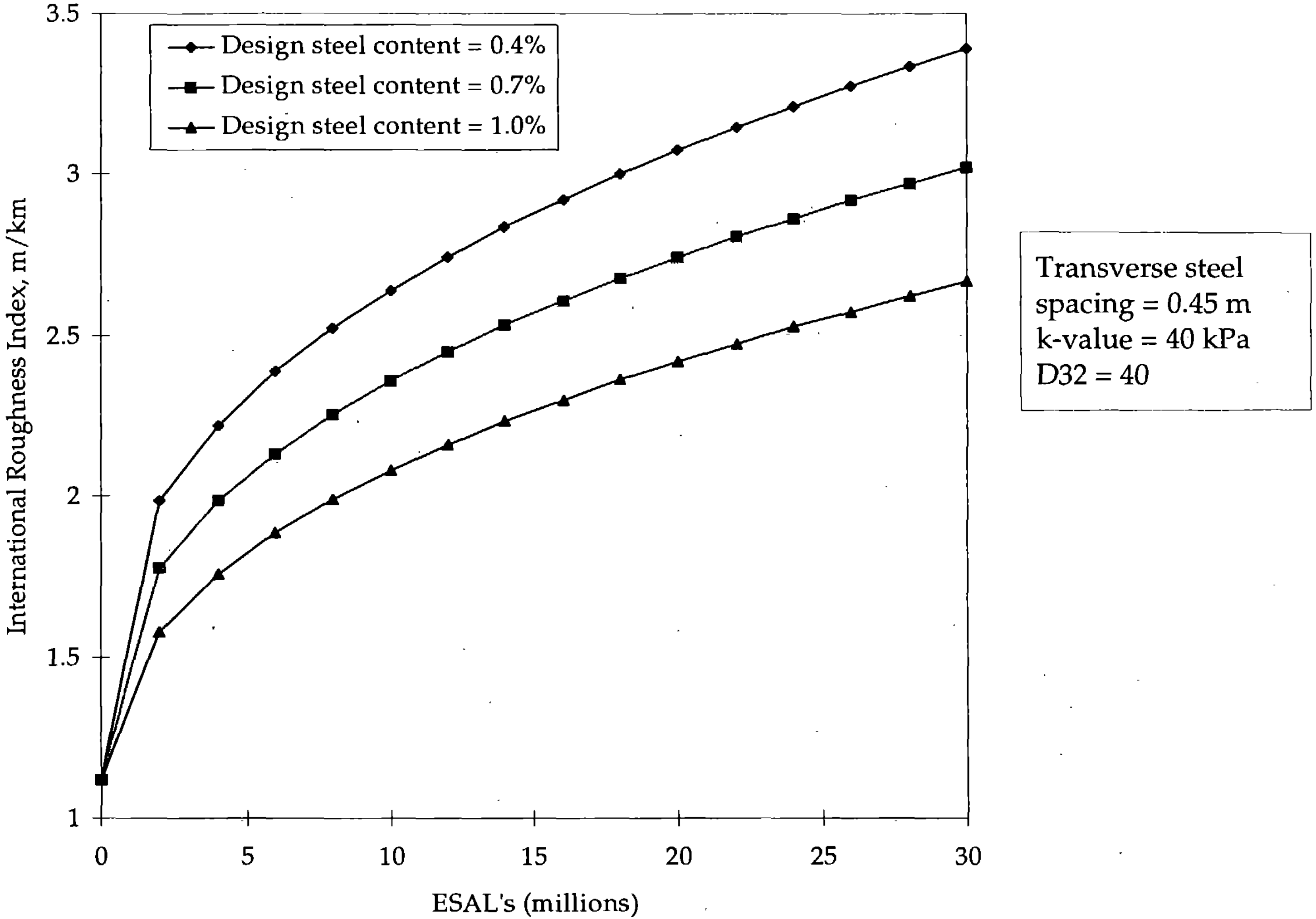
Figure 6 shows the effect of traffic loading on CRCP roughness. The plot is derived from prediction models developed as part of this LTPP study to predict distress and roughness. The figure shows that increasing traffic loading increases the roughness of CRCP. This is due to the development of different distresses that occur as a result of increased traffic loading, such as punchouts.(7, 8)

Punchouts and pumping are the key distress types in CRCP that are influenced by traffic loading. Traffic loading can also contribute to an increase in crack widths that eventually leads to steel rupture. Punchouts occur when two closely spaced cracks are present that cannot adequately transfer load by aggregate interlock, and the piece of pavement between the cracks acts as a "beam." With repeated traffic loading, a longitudinal crack will form in the cantilever beam within 0.6 to 1.2 m of the longitudinal edge joint of the pavement. Further traffic loading will cause rupture of the reinforcement and will cause the piece of pavement between the longitudinal joint and crack to break down further.

Any design feature that leads to reduced crack width will minimize punchouts. Past studies have shown that increasing the design steel content of CRCP reduces the severity of the distress and, therefore, roughness.(8, 9) Results from the sensitivity analysis of the CRCP roughness model developed as part of this study and illustrated in figure 6 show that steel content is one of the key design features that influences roughness. A comprehensive analysis of the effect of design features on roughness is presented in chapter 3 of this volume.

Influence of Climate on Pavement Performance

The effects of climate on pavement performance were investigated thoroughly as part of this study. The investigation consisted of both statistical analyses, such as analysis of variance and discriminant analysis, and mechanistic analysis used as the basis for estimating damage in model development and calibration. The primary climate variables identified as influencing pavement performance were classified as follows:



Transverse steel
spacing = 0.45 m
k-value = 40 kPa
D32 = 40

Figure 6. CRCP roughness versus traffic loadings, showing the effect of longitudinal steel content.

- Moisture Variables

  Climatic region (wet, dry)
  Annual number of wet days/annual mean precipitation

- Temperature Variables

  Climatic region (freeze or nonfreeze)
  Annual number of freeze-thaw cycles
  Annual mean temperature
  Average annual number of days with temperature above 32 °C

The effects of the key climate-related variables on distress and roughness are summarized in table 1. Table 1 shows that an increase in air temperature or the temperature gradient within the PCC slab increases the occurrence of joint spalling for both JPCP and JRCP. Also, JPCP located in climates with high annual freeze-thaw cycles and JRCP located in climates with high freezing index values tend to have an increased occurrence of spalling.

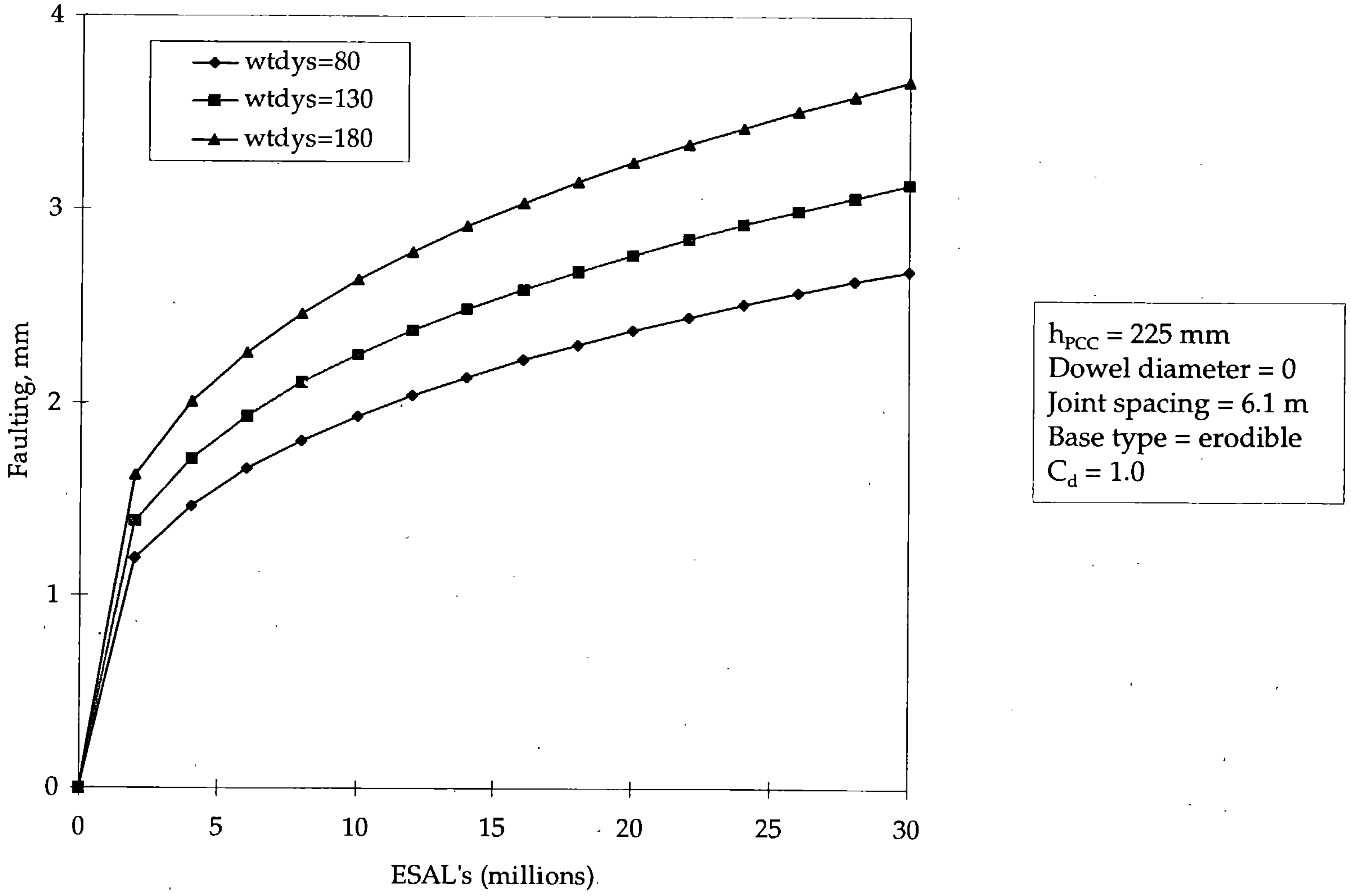
Figures 7 to 12 show the effects of several climate-related variables on the pavement distress types investigated as part of this LTPP study. Figure 7 illustrates the effect of wet days on JPCP faulting. The figure shows that an increase in the number of wet days increases the amount of faulting. Figure 8 illustrates the effect of annual number of wet days on transverse cracking. An increase in the annual number of wet days generally weakens the subgrade support or increases erosion and loss of support of a JPCP and results in higher deflections and increased transverse cracking. Figure 9 illustrates the effect of temperature (nonfreeze or freeze) on JPCP roughness. The figure shows that pavements located in the freeze climates experience more roughness than those in nonfreeze climates. Figure 10 illustrates the effect of precipitation on JRCP roughness; increasing precipitation increases the occurrence of moisture-related distresses and therefore increases roughness. Figures 11 and 12 illustrate the effect of the climate region (nonfreeze, freeze, wet, dry) and the annual number of days with temperature above 32 °C on CRCP roughness. Freeze climates appear to greatly affect the development of roughness of CRCP.

Influence of Subgrade Support on Pavement Performance

Table 2 summarizes the effect of subgrade support on distress formation. The modulus of subgrade reaction was backcalculated from FWD deflections and converted to a static value. Figures 13 to 16 also show the effect of subgrade type

Table 1. Summary of the effect of climate-related variables on pavement distress.

Climate variable	Classification	Influence on distress formation (✓ = increases distress)							
		Faulting	Transverse Joint Spalling		Transverse cracking	Corner Breaks	Roughness		
		JPCP	JPCP	JRCP	JPCP	JPCP	JPCP	JRCP	CRCP
Climate (moisture)	Wet	✓			✓				✓
Annual number of wet days	Increasing	✓							
Average annual precipitation	Increasing	✓					✓	✓	✓
Climate (temperature)	Freeze						✓		✓
Average annual freeze-thaw cycles	Increasing		✓		✓	✓			
Freezing index	Increasing			✓					
Annual average temp. and temperature gradient	Increasing		✓	✓	✓		✓	✓	✓
Days with temperature above 32 °C	Increasing								✓



h_{PCC} = 225 mm
Dowel diameter = 0
Joint spacing = 6.1 m
Base type = erodible
C_d = 1.0

Figure 7. Effect of annual number of wet days on JPCP faulting.

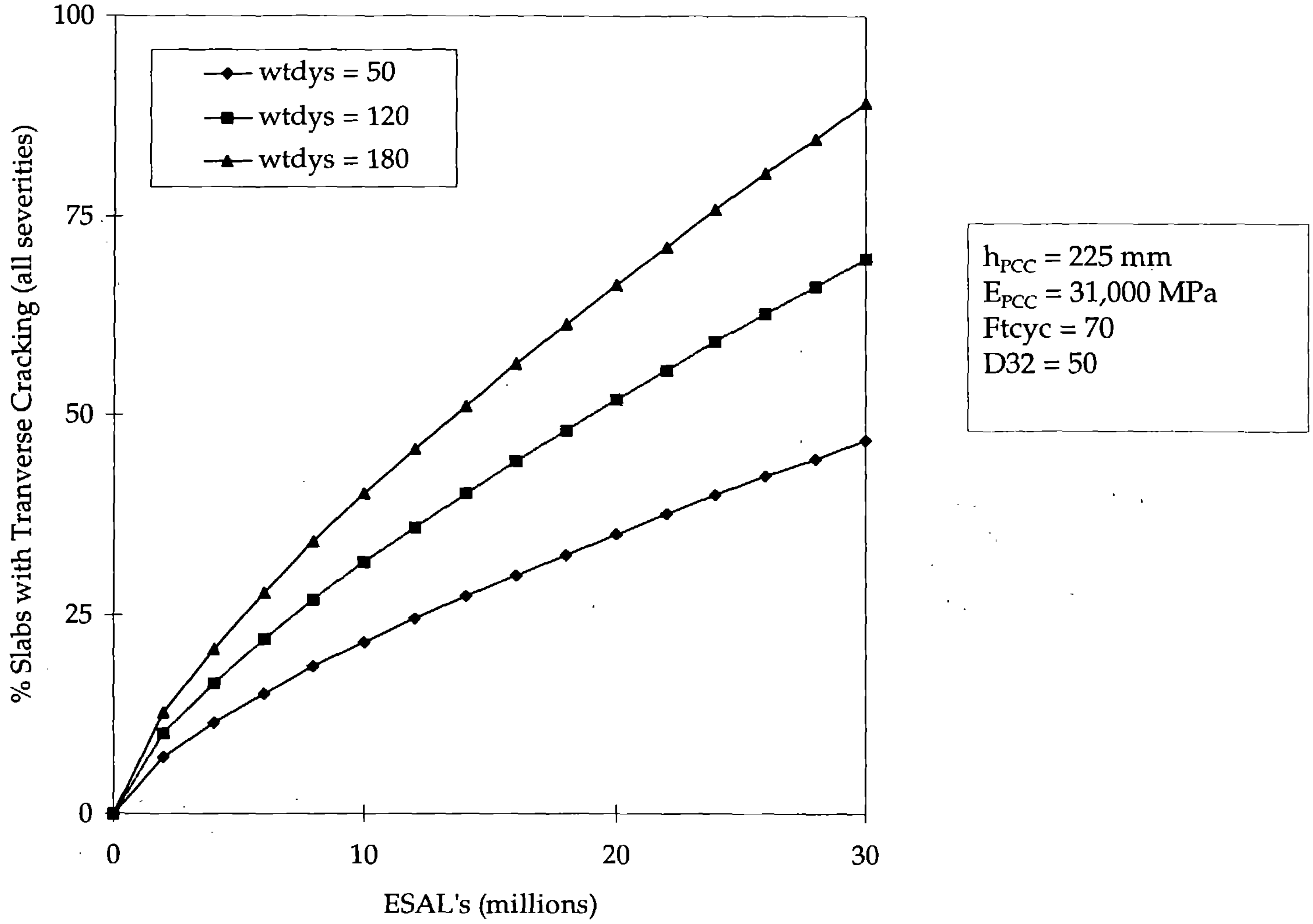


Figure 8. Effect of annual number of wet days on JPCP transverse cracking.

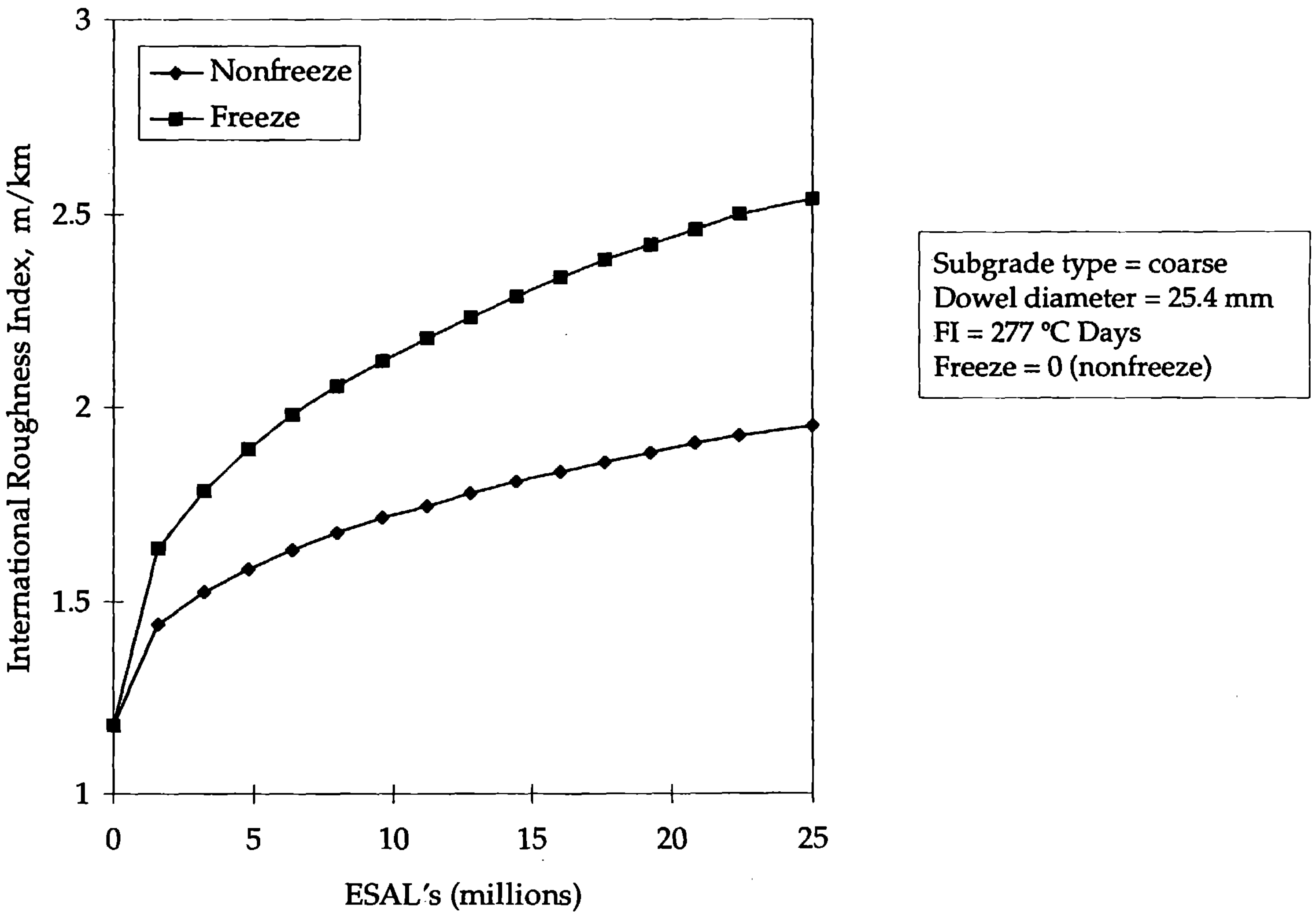


Figure 9. Effect of climate (freeze or nonfreeze) on IRI of JPCP.

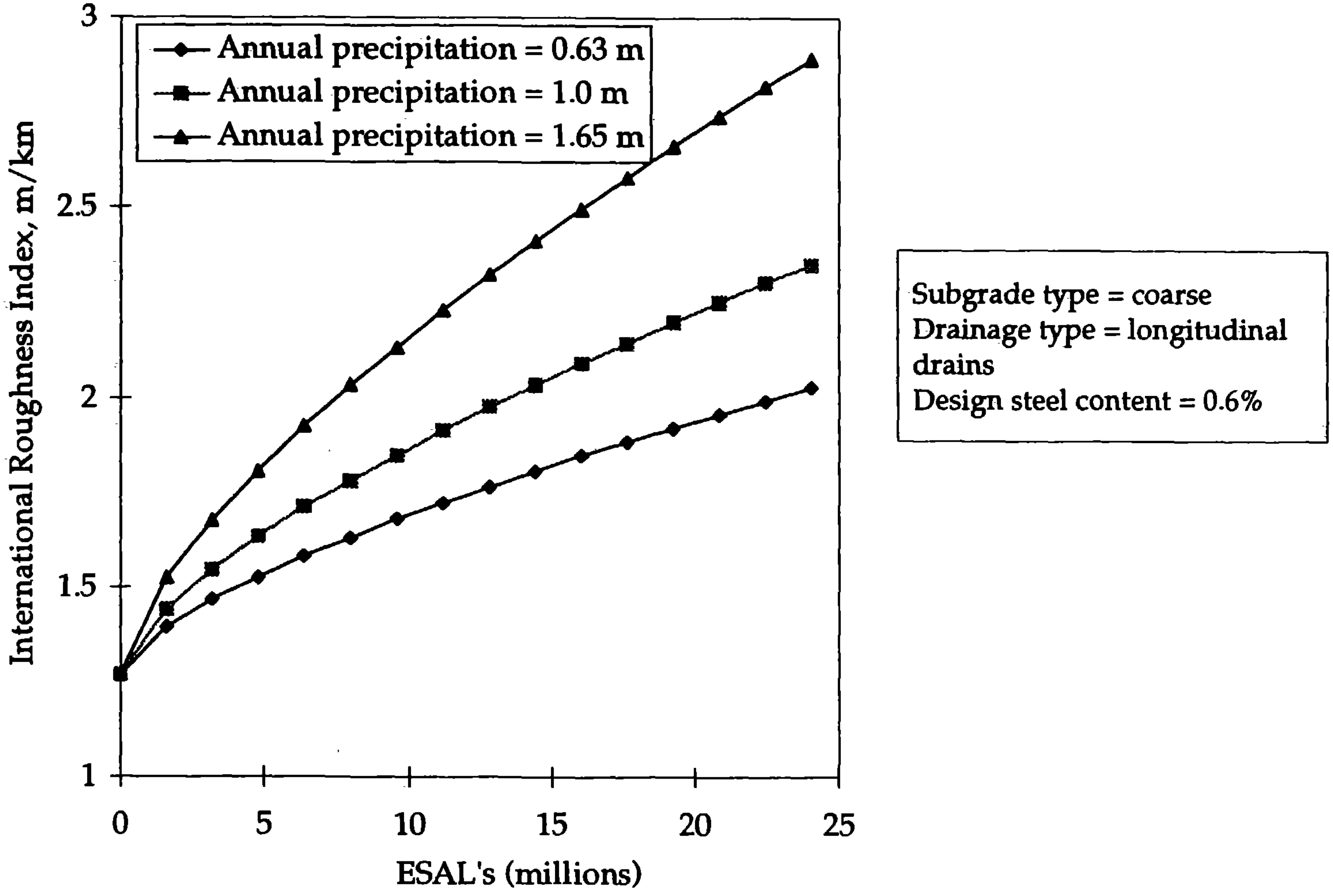
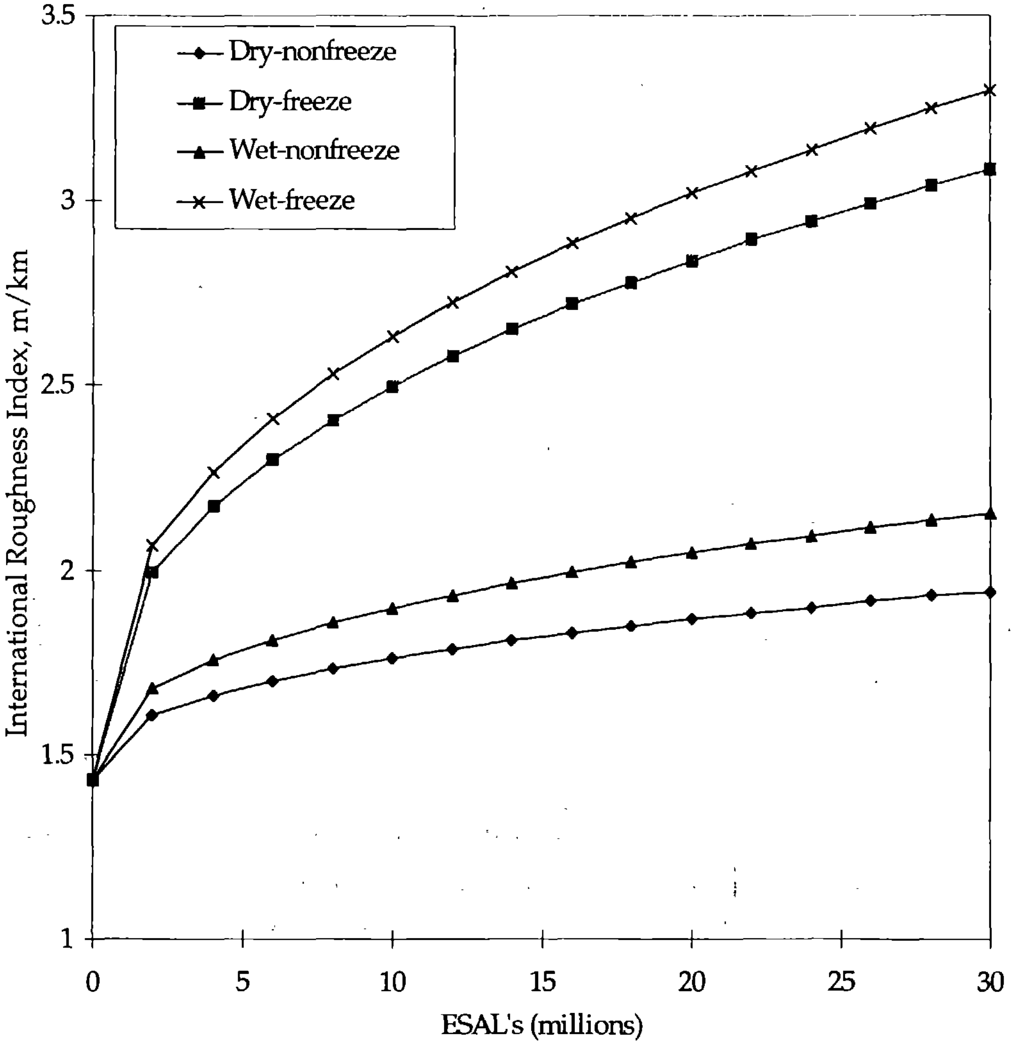


Figure 10. Effect of mean annual precipitation on IRI of JRCP.



k-value = 40 kPa/mm
D32 = 40
Design steel content = 0.7%
Steel spacing = 450 mm

Figure 11. Effect of climate (dry, wet, freeze, nonfreeze) on IRI of CRCP

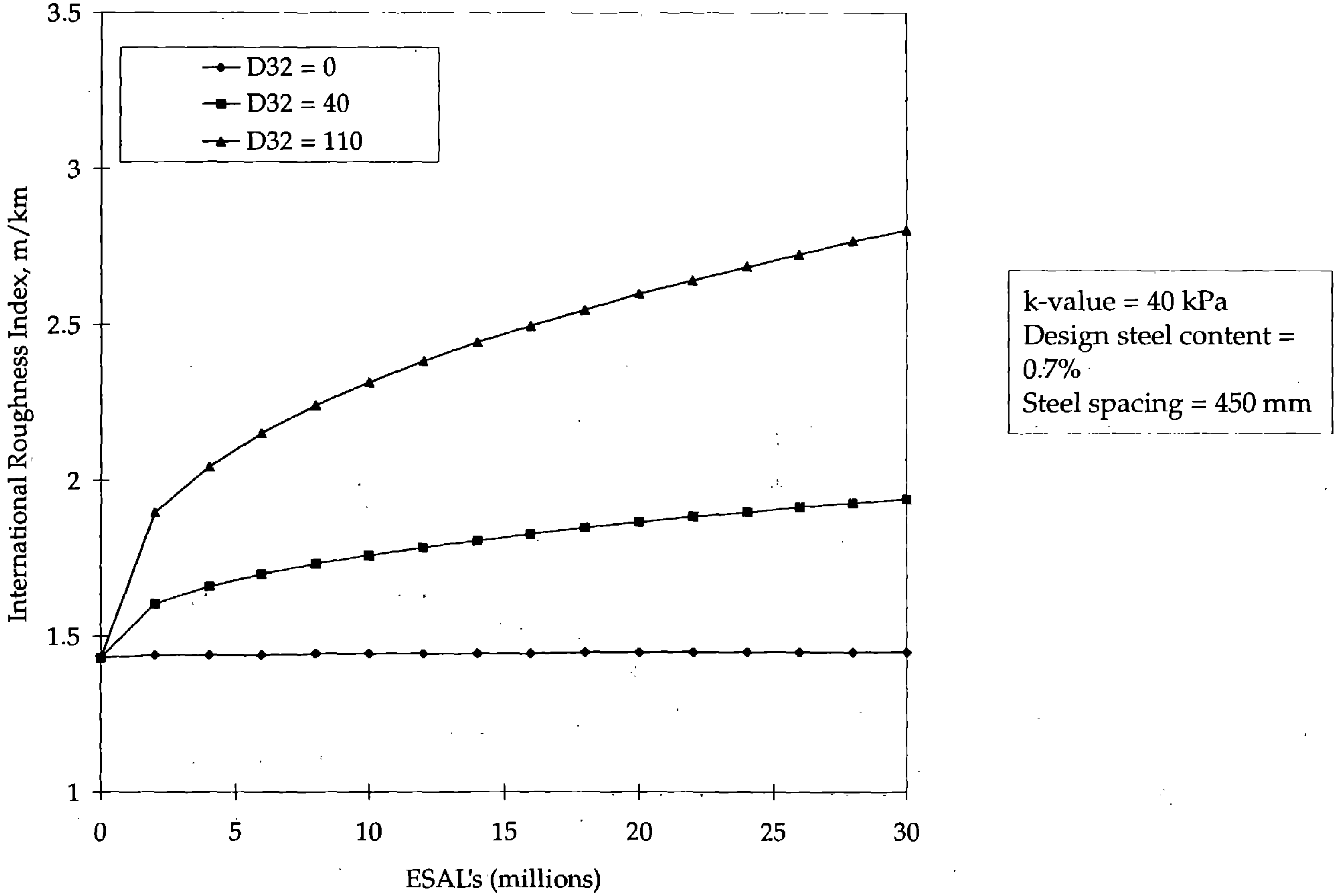


Figure 12. Effect of annual number of days with temperature above 32 °C on IRI of CRCP.

Table 2. Summary of the effect of subgrade support variables on pavement distress.

Climate variable	Classification	Influence on distress formation (✓ = increases distress)							
		Faulting	Transverse joint spalling		Transverse cracking	Corner breaks	Roughness		
		JPCP	JPCP	JRCP	JPCP	JPCP	JPCP	JRCP	CRCP
Subgrade type	Fine grained	✓			✓		✓	✓	✓
	Coarse grained								
Modulus of subgrade reaction	< 38 kPa/mm	✓	✓	✓					✓
	> 38 kPa/mm				✓				

and support on distress and roughness. Table 2 shows that increasing the modulus of subgrade reaction reduces JPCP faulting but increases transverse cracking. Increased subgrade support also reduced the occurrence of joint spalling in both JPCP and JRCP. Figure 13 shows that an increased modulus of subgrade reaction decreased faulting. Also, JPCP and JRCP constructed over fine subgrade material experience more faulting, transverse cracking, and roughness.

Figures 14, 15, and 16 also show that pavements constructed over coarse-grained subgrade material or material with higher modulus of subgrade reaction decrease roughness in JPCP, JRCP, and CRCP. The trends shown by the sensitivity plots are in agreement with the results from the statistical analysis presented in table 2.

Natural subgrades with a high fine material content are more susceptible to pumping and faulting, especially when located in wet environments. Several design features can be used to limit the negative effect of inadequate subgrade support or soil type on pavement performance.(10) Some of the design features are as follows:

- Treating the subgrade with lime or portland cement.
- Using a base course (treated or untreated).

The LTPP study shows that flexible base material such as an asphalt-treated base reduces both faulting and transverse cracking. Cement-treated (with sufficient cement content) and lean concrete bases are nonerodible and also reduce the occurrence of pumping and faulting; however, the use of very stiff bases (not bonded to the slab) results in increased transverse cracking. The LTPP study also showed that pavements constructed directly over the subgrade (treated or untreated) generally perform worse than those with a base course.

Summary of Site Condition

The LTPP data analysis results summarized in tables 1 and 2, and the sensitivity analysis plots from distress and roughness prediction models developed as part of this study, show the importance of considering traffic, climate, and subgrade support in the pavement design process. These site conditions, in most cases, cannot be controlled by the designer. However, the negative influences of adverse site conditions on pavement performance can be minimized by the selection of appropriate design features. Some of the design features identified in this study to minimize the most common distresses for JPCP are the provision of dowels, use of nonerodible base material, stronger

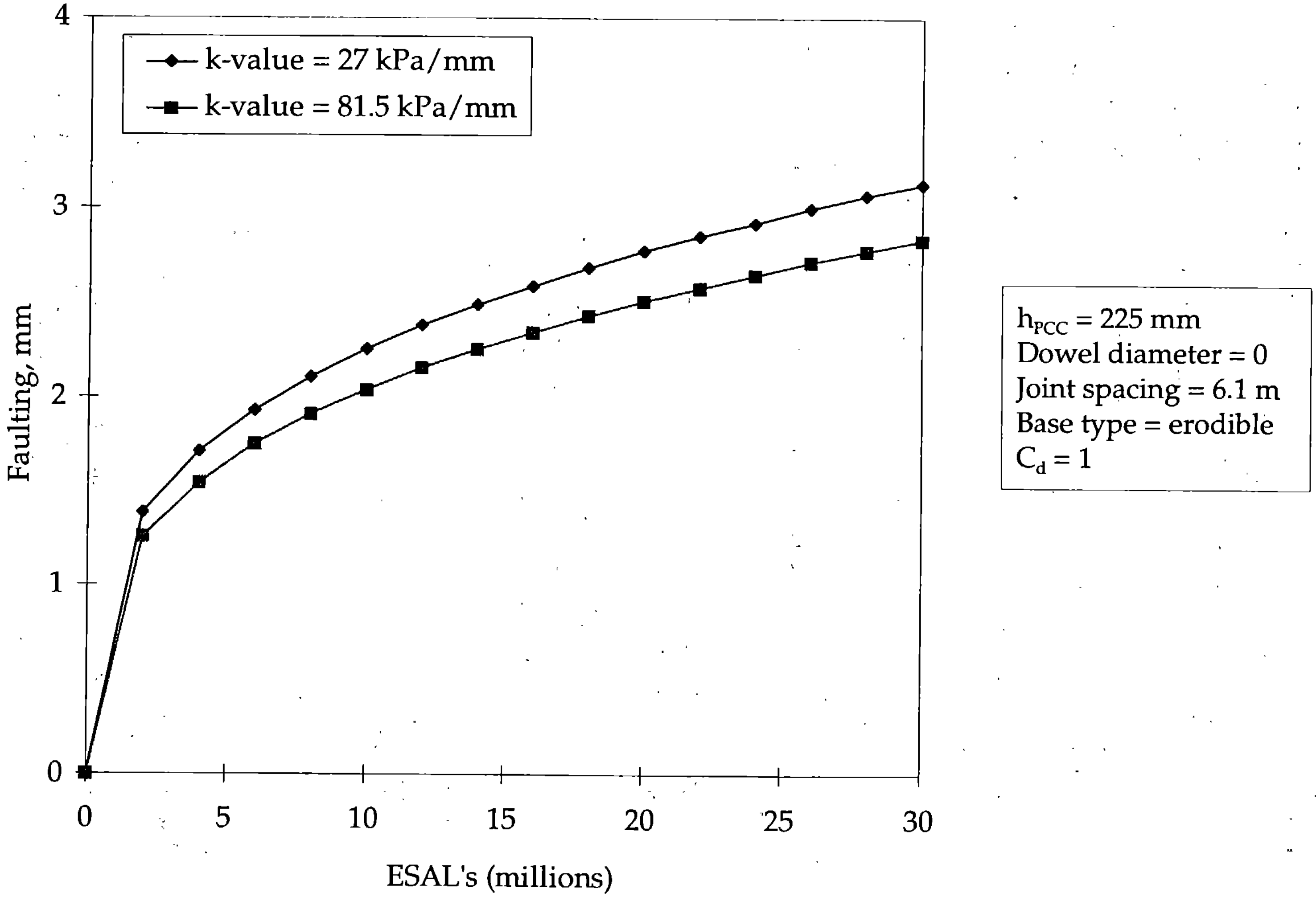


Figure 13. Effect of modulus of subgrade reaction on faulting for JPCP.

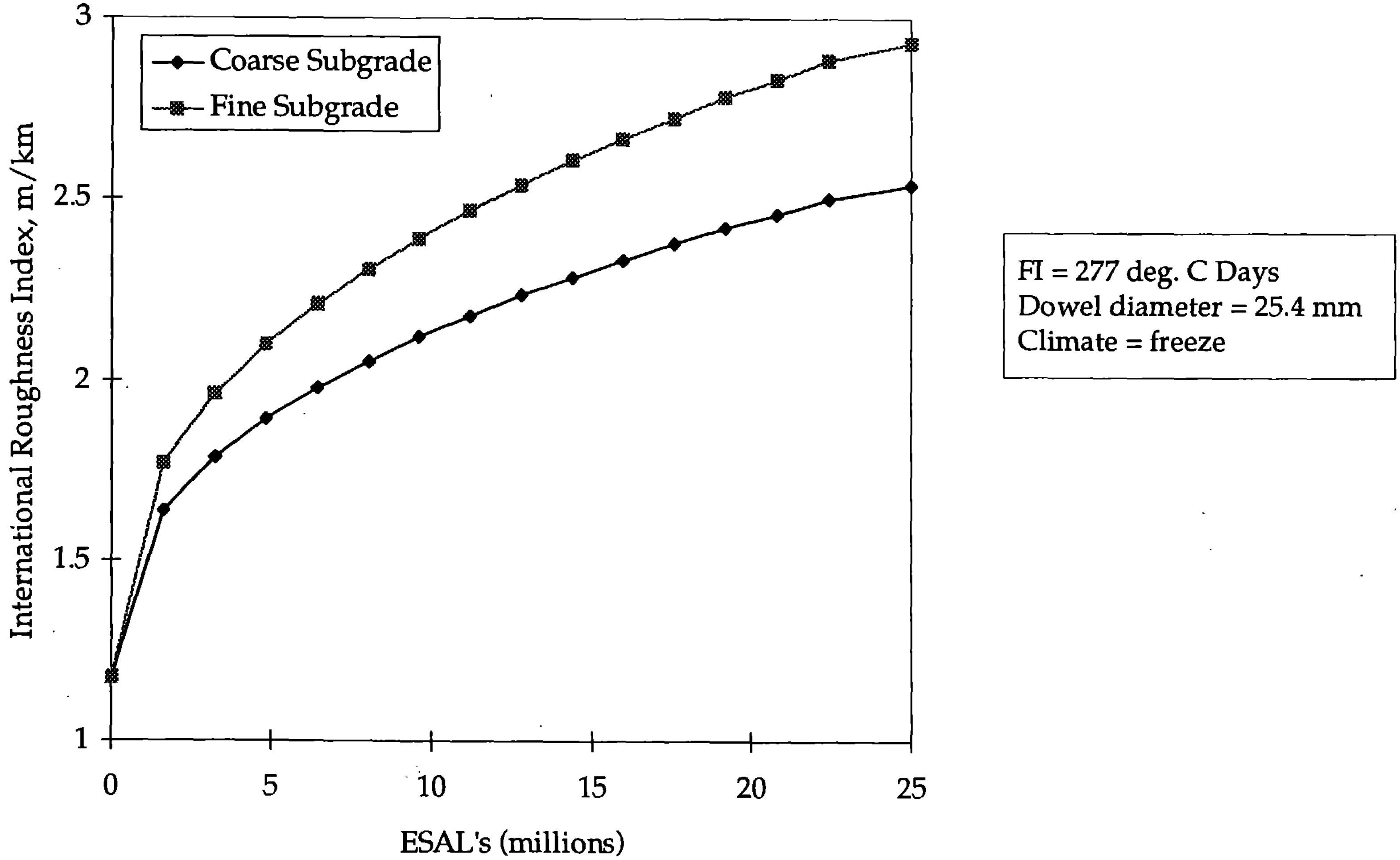
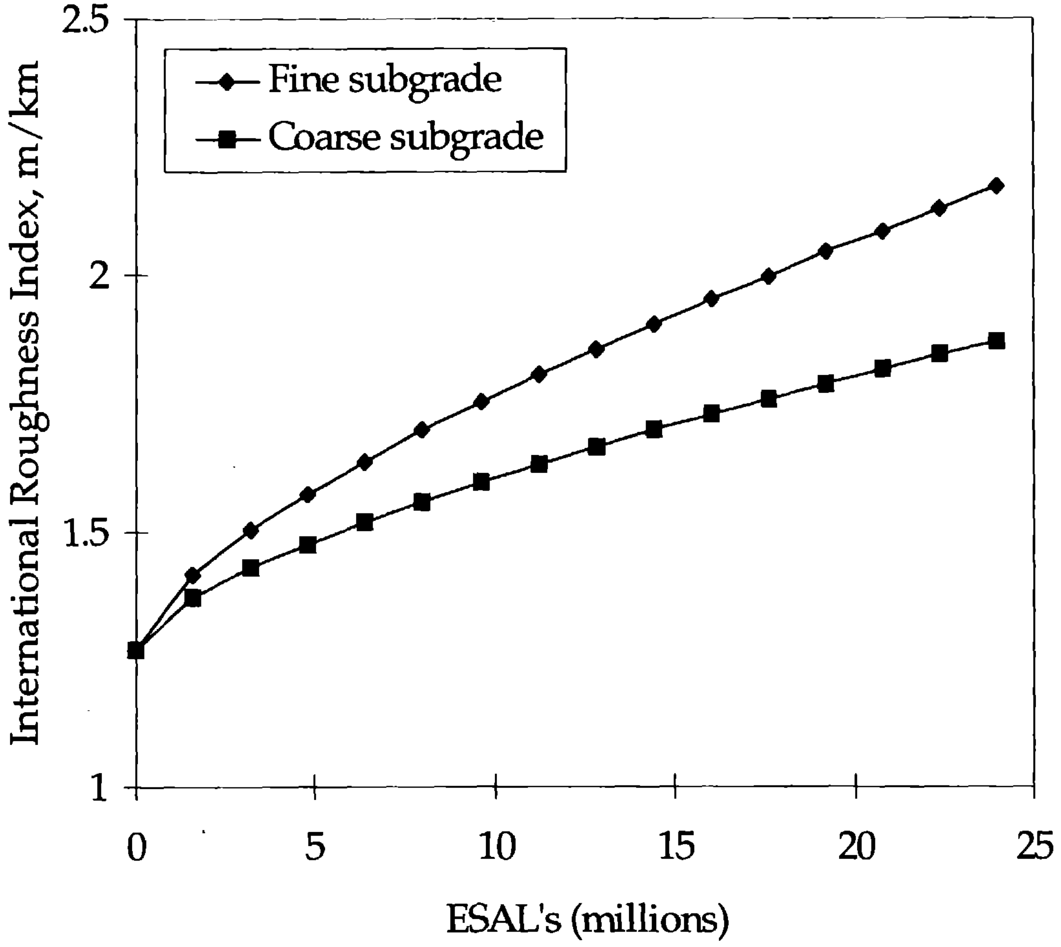


Figure 14. Effect of subgrade type (fine or coarse) on IRI for JPCP.



Design steel content = 0.6%
Annual Precipitation = 1 m
Drainage type = longitudinal drain
Subgrade type = coarse

Figure 15. Effect of subgrade type on IRI for JRCP.

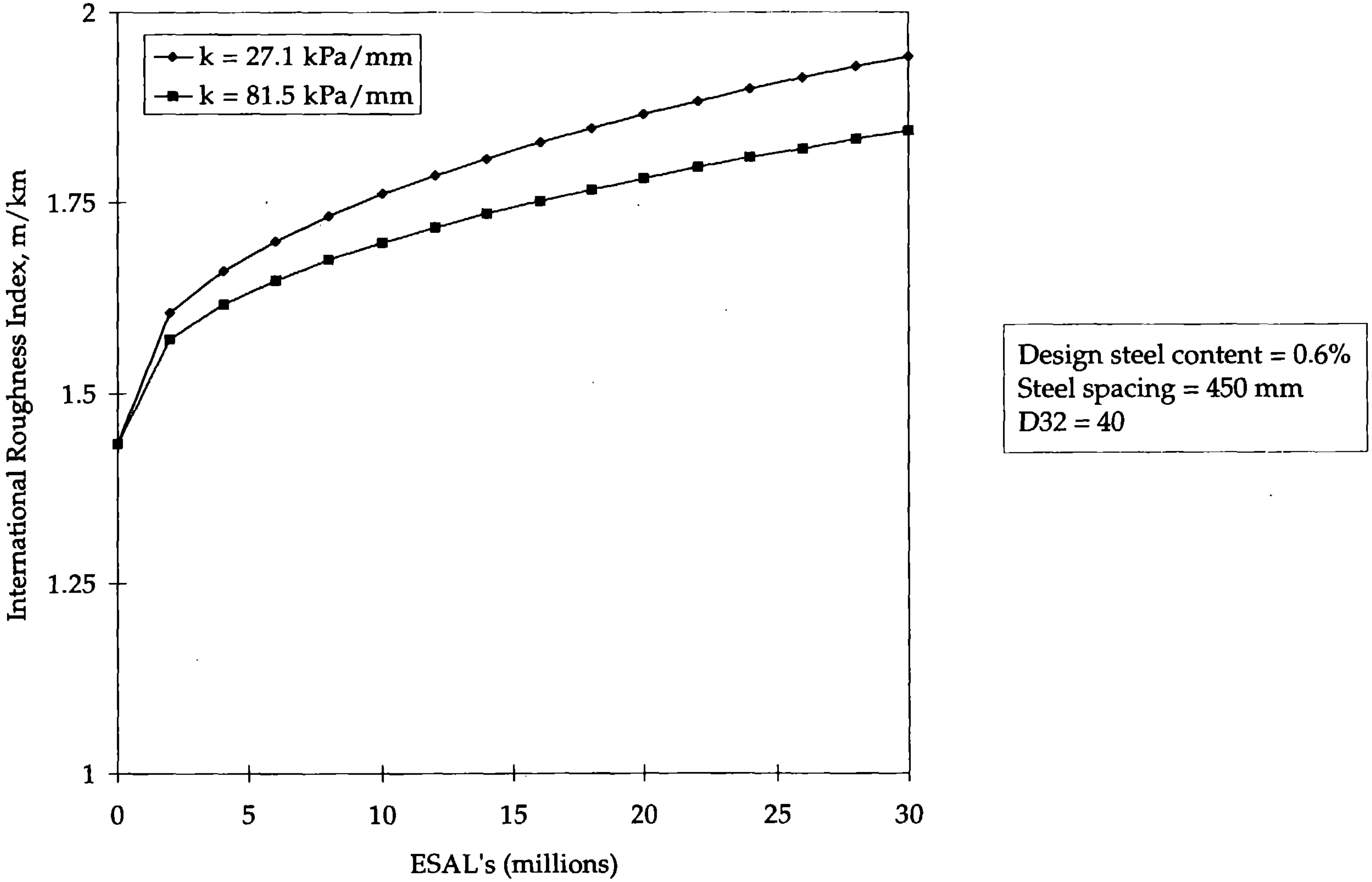


Figure 16. Effect of modulus of subgrade reaction on IRI for CRCP.

base/subbase material, and the use of thicker PCC slabs. The use of these design features to minimize distress and roughness is discussed in greater detail in the next chapter. The site conditions that most adversely affect performance are summarized as follows:

JPCP Faulting

- Increased traffic loading results in increased faulting.
- JPCP located in wet climates with greater than 140 wet days per annum or precipitation greater than 1 m/yr experience a higher degree of faulting than JPCP located in drier climatic regions.
- JPCP constructed over natural subgrade material classified as fine-grained experience a higher degree of faulting than JPCP located in regions with coarse subgrades or subgrades with less fine material content.

JPCP Transverse Joint Spalling

- Increased traffic loading results in increased transverse joint spalling.
- JPCP experience higher levels of spalling with increasing age.
- JPCP located in regions with higher annual freeze-thaw cycles experience more spalling.
- JPCP located in regions with higher temperature gradients within the PCC slab on higher climatic temperatures in general experience a higher degree of spalling.
- JPCP located over strong subgrade material generally experience less spalling.

JPCP Transverse Cracking

- Increased traffic loading results in increased transverse cracking.
- JPCP located in wet climates are more likely to crack transversely at the slab midsection than JPCP located in drier climatic regions.
- JPCP located in climates with mean temperature > 10 °C are more likely to crack than JPCP located in colder climatic regions.
- JPCP located on a stiff subgrade material (natural or treated) (k value > 38 kPa/mm) experience a higher degree of transverse cracking than JPCP located in regions with a softer subgrade soil.

JPCP Corner Breaks

- Increased traffic loading results in increased corner breaks.

- JPCP experience higher levels of corner breaks with increasing age.
- JPCP located in regions with higher annual freeze-thaw cycles experience more corner breaks.

JPCP Roughness

- Increased traffic loading results in increased roughness.
- JPCP located in wet climates experience more roughness than JPCP located in drier climatic regions.
- JPCP located in areas with mean temperature > 10 °C in general experience more roughness than JPCP located in colder climatic regions.

JRCP Transverse Joint Spalling

- Increased traffic loading results in increased transverse joint spalling.
- JRCP experience higher levels of spalling with increasing age.
- JRCP located in regions with higher annual freezing index experience more spalling.
- JRCP located in regions with higher temperature gradients within the PCC slab on higher climatic temperatures in general experience a higher degree of spalling.
- JRCP located over strong subgrade material generally experience less spalling.

JRCP Roughness

- Increased traffic loading results in increased roughness.
- JRCP located in climates with precipitation greater than 1 m/yr experience more roughness than JRCP located in other climatic regions.
- JRCP located in nonfreeze climates (mean temperature > 10 °C) experience more roughness than JRCP located in colder climatic regions.
- JRCP constructed over natural subgrade material classified as "fine" experience more roughness than JRCP located in regions with coarse subgrades or subgrades with less fine soil content.

CRCP Roughness

- Increased traffic loading results in increased roughness.
- CRCP located in nonfreeze environments (mean temperature > 10 °C) experience much less roughness than CRCP located in other climatic regions.

These results will help in selecting appropriate design features given the specific traffic, subgrade, and climate site conditions.

3. RECOMMENDATIONS FOR SELECTING DESIGN FEATURES OF CONCRETE PAVEMENTS

Introduction

This chapter provides recommendations for selecting pavement design features that will improve concrete pavement performance. The recommendations are based on results obtained from an evaluation of the LTPP database. The LTPP database was evaluated using both statistical and mechanistic analysis. The statistical analysis involved the use of basic techniques such as univariate and bivariate plots and more advanced concepts such as analysis of variance (ANOVA) and discriminant analysis. A comprehensive mechanistic analysis of the processes of distress development was also made. This resulted in the development of several mechanistic-empirical models for predicting pavement distress, such as transverse joint faulting, transverse cracking, corner breaks, transverse joint spalling, and roughness. Detailed results from these analyses are presented in volumes II and III of this report. This chapter presents a summary of the results and can be used as guidance for selecting pavement design features.

Design Features That Affect PCC Pavement Performance

The requirements for sound PCC pavement design include the following:

- Full consideration of site conditions, including uniform foundation support for the pavement, traffic, and climate.
- Selection of design features such as adequate slab thickness, quality concrete, widened lanes, joint spacing, joint load transfer (JPCP and JRCP), reinforcement (JRCP and CRCP), and others that will provide a smooth, long-lasting pavement.

The following design features were identified as those that affect distress formation and, therefore, long-term performance of PCC pavements:

- JPCP Joint Faulting

    Radius of relative stiffness of the pavement/subgrade
    Load transfer or dowels
    PCC slab thickness
    Base type (treated or untreated) and modulus

Skewed joints
Subdrainage

- JPCP Transverse Joint Spalling

    Joint sealant characteristics
    PCC slab thickness
    PCC slab elastic modulus

- JPCP Transverse Cracking

    Load transfer or dowels
    PCC slab thickness
    PCC elastic modulus
    Modulus of rupture of the PCC slab
    Base type (treated or untreated)

- JPCP Corner Breaks

    PCC slab thickness and elastic modulus
    Joint spacing
    Subdrainage

- JPCP Roughness

    Base type
    PCC slab thickness and modulus
    Subdrainage
    Edge support (widened lane, flexible or rigid shoulder)
    Load transfer or dowels

- JRCP Transverse Joint Spalling

    Joint sealant characteristics
    PCC slab thickness and elastic modulus

- JRCP Roughness

    PCC slab thickness
    Joint spacing
    Subdrainage

- CRCP Roughness

  PCC slab thickness
  PCC slab steel content
  Subdrainage
  Base type

Detailed summaries of the effects of these design features on PCC pavement performance are presented in the next sections.

JPCP Faulting

Effect of Radius of Relative Stiffness

JPCP pavements with a higher radius of relative stiffness experience less faulting. Results show that JPCP with radius of relative stiffness greater than 1.15 m experience little or no faulting. Pavements with a high radius of relative stiffness values have lower deflections and experience less pumping and faulting. This is in agreement with the results of several past studies and mechanistic analysis. (2, 6)

The radius of relative stiffness of a pavement is dependent on several design variables, namely modulus of subgrade reaction, PCC modulus, PCC thickness (very strong effect), and PCC Poisson's ratio. The values of these design variables should be selected to maximize the radius of relative stiffness to reduce the potential for faulting.

Effect of Load Transfer (Dowels)

The data analysis results show that doweled JPCP experience less faulting than undoweled JPCP. Load transfer provided at joints and cracks of concrete pavements has an enormous influence on the occurrence of faulting. Good load transfer from installed load transfer devices reduces the high slab deflections at the joint, reducing the potential for pumping and faulting. This improves the performance of concrete pavements. Therefore, it is good practice to provide load transfer for all JPCP that will carry heavy truck traffic. The characteristics of the dowel that influence load transfer are the diameter, length, and spacing. Whether the dowel is coated is also another important consideration in design. Typically, round steel bars between 25.4 and 38 mm diameter, 450 mm long, and spaced at 300-mm centers have been used as dowels. Figure 17 illustrates the effect of different dowel diameters on predicted faulting.

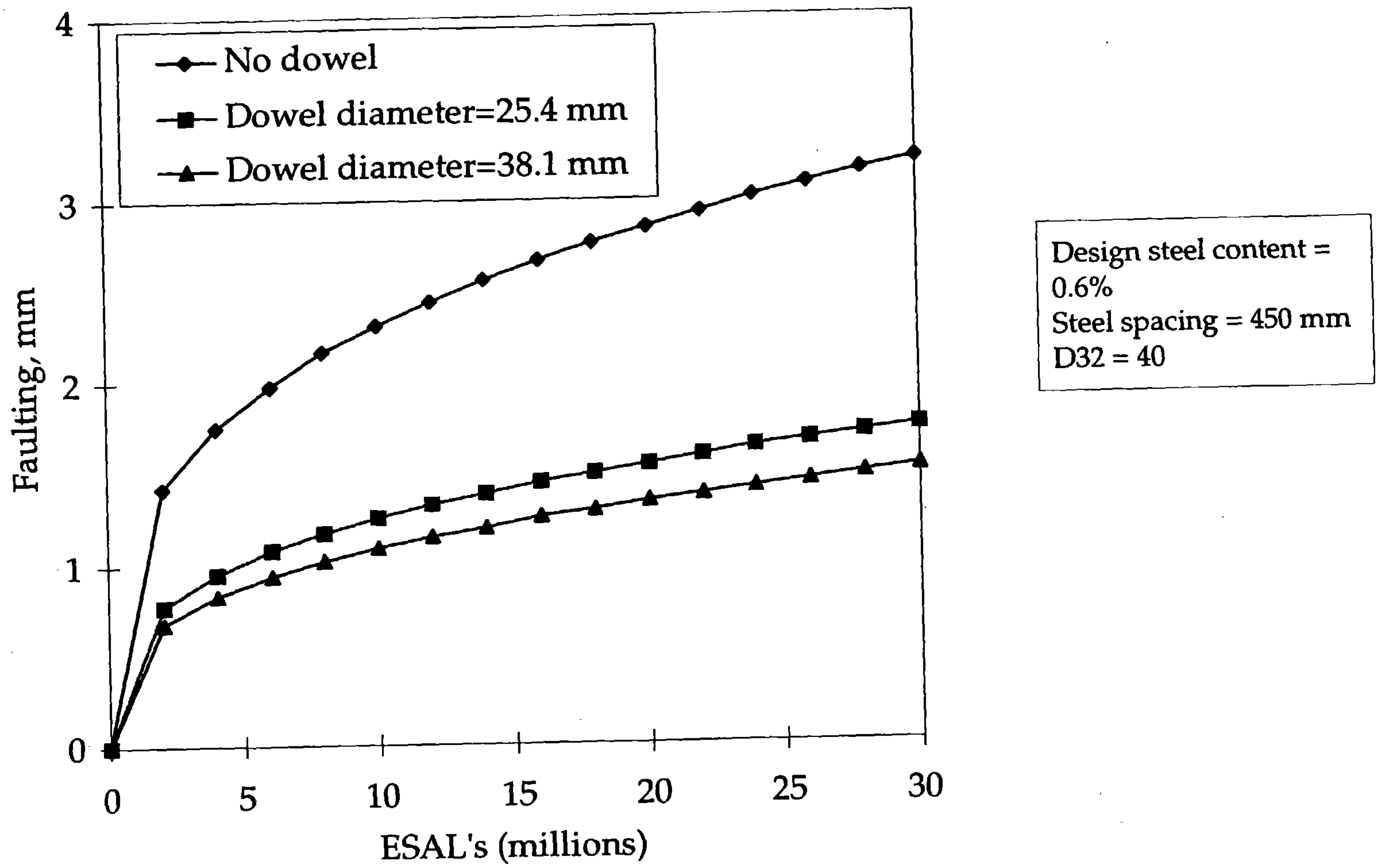


Figure 17. Influence of dowels on JPCP faulting.

Figure 17 clearly shows that dowels (of a minimum size of 25.4 mm) greatly decrease faulting of jointed concrete pavements. Increasing the dowel diameter further reduces faulting to a level that is acceptable from a ride quality aspect.

Effect of PCC Slab Thickness

Pavements with thicker PCC slabs experience less faulting. Thicker PCC slabs reduce the deflections at the slab edges and corners, and hence, reduce pumping and faulting. The effect of PCC slab thickness on the predicted faulting is illustrated in figure 18. Increasing PCC slab thickness increases the stiffness of the concrete pavement. Increasing pavement stiffness results in a reduction in deflections at the joints, and this is believed to be responsible for the decrease in faulting.

Effect of Base Type and Modulus

JPCP pavements with treated bases (asphalt or portland cement) experience less faulting than pavements with untreated bases. This is because the most common mechanism for erosion and faulting is possible only if the top of the base material is saturated and is erodible. Most treated bases are less erodible and, therefore, have a reduced potential for pumping. The influence of the type of base, shown in figure 19, was investigated using sensitivity plots of the faulting model developed. The plots show that there is a tremendous reduction in faulting for pavements constructed using a nonerodible base, such as lean concrete, portland cement-treated, and asphalt-treated bases.

Also, pavements with a higher base modulus generally experience less faulting because an increase in base modulus results in less erosion and deflections at the PCC slab joints. Results presented in volume II of this report show that JPCP with higher base modulus values experience the least amount of faulting.

Effect of Skewed Joints

Transverse joints can be either skewed or square. Skewness can range up to about 0.6 to 0.9 m per lane width. The analysis shows that JPCP with skewed joints experience less faulting than those with square joints. The use of skewed joints is a means of reducing the magnitude of deflections at a joint. Deflections are reduced because wheels of the same axle strike the joints at different times, reducing the load the axle imparts on one side of the joint.

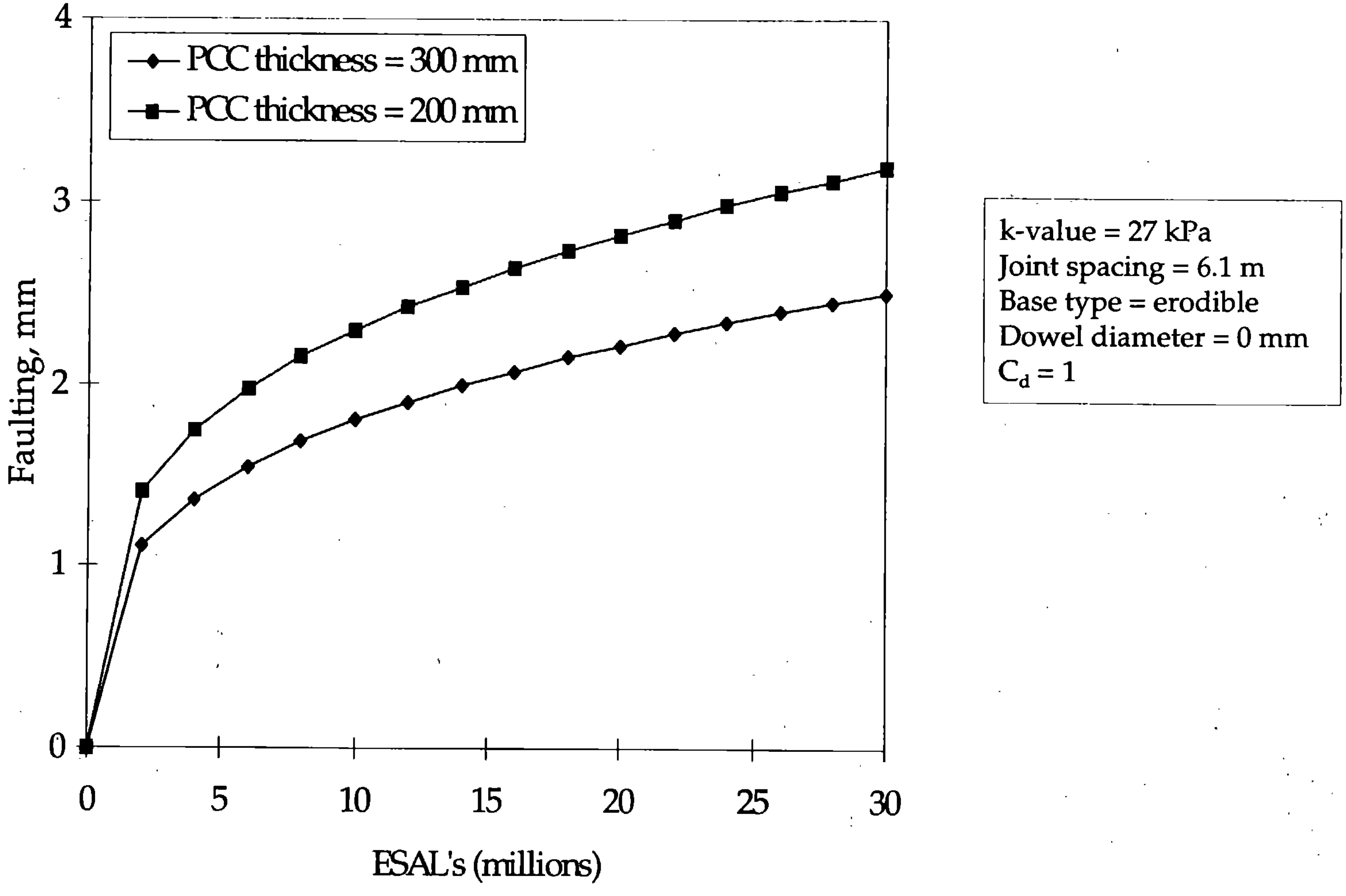


Figure 18. Influence of slab thickness on JPCP faulting.

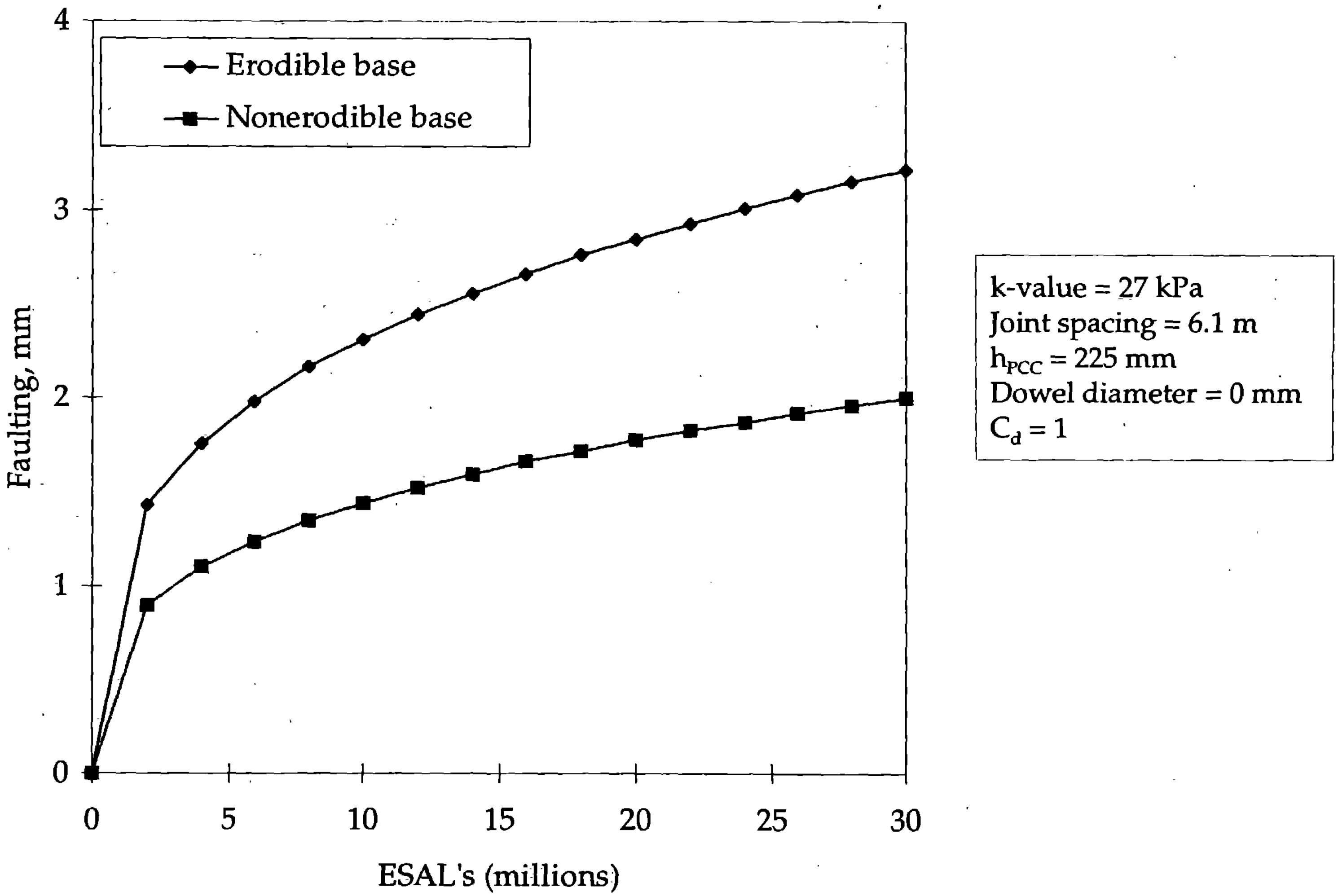


Figure 19. Influence of base type on JPCP faulting.

Effect of Subdrainage

The provision of positive drainage in the LTPP pavements generally reduced the occurrence of moisture-related distresses, such as pumping and faulting. Adequate drainage reduces the amount of free water within the pavement structure and reduces the potential for erosion and pumping of the underlying pavement materials. The provision of drainage is most necessary for JPCP located in wet climatic regions, where moisture-related distresses are common.

JPCP Transverse Joint Spalling

Effect of Joint Sealant Characteristics

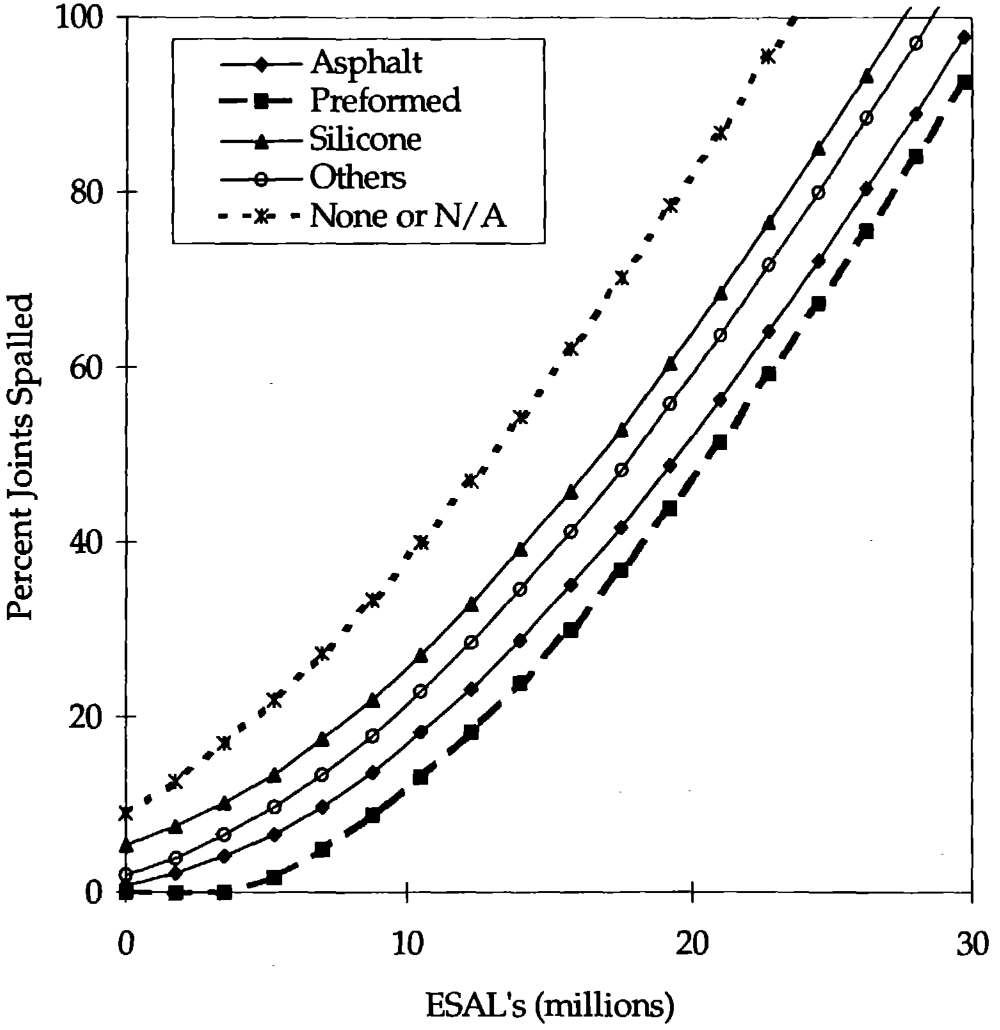
The influence of sealants on joint spalling is illustrated by the sensitivity plot shown in figure 20. In all cases, the worst condition was for joints without any sealants (presumably filled up with incompressibles). The magnitude of the difference between the pavements with and without sealants is an indication of the importance of sealing joints. For those pavements with sealed joints, there is also an appreciable effect of the type of sealant used and the amount of spalling that occurs. Preformed sealants are far better at reducing joint spalling than the other types of sealants. The performance of the other types of sealants is comparable.

Effect of PCC Slab Thickness

The analysis shows that increasing PCC slab thickness reduces the tensile stresses generated around the upper part of a joint, where spalling occurs. The sensitivity analysis presented in volume III of this report shows that increasing slab thickness reduces tensile stresses generated around the joints considerably. Such a reduction in stress is significant because the occurrence of spalls is related to excessive tensile stresses around pavement joints. Increasing slab thickness, therefore, is beneficial and reduces the occurrence of spalling.

Effect of PCC Elastic Modulus

Increasing the PCC slab elastic modulus generally increases the tensile strength of the pavement and decreases the potential for spalling. This was observed from the finite element analysis conducted as part of this study and presented in volume III of this report.



Relative humidity = 67 percent
Temperature range = 14 °C
h_{PCC} = 225 mm
E_{PCC} = 30,000 MPa

Figure 20. Plot of percent JPCP spalling versus traffic for the different joint sealant materials evaluated.

JPCP Transverse Cracking

Effect of Load Transfer (Dowels)

JPCP pavements with dowels perform better (less transverse cracking) than those without. Dowels provide load transfer across the joints of adjacent slabs. Load transfer reduces bending moments and stresses at the top of the midsection of the slab. The reduction of stresses and deflections at this location lowers the possibility of top-down transverse cracking.

Effect of PCC Slab Thickness and Modulus

JPCP pavements with thicker slabs experience less transverse cracking. In general, thicker slabs are able to withstand wheel loads and temperature stresses better than thinner ones, resulting in less bending moments, stresses, and deflections. Figure 21 is a plot of percent slabs with transverse cracks versus cumulative ESAL's for different slab thicknesses. The plot shows that there is a rapid increase in the amount of transverse cracks in a pavement as the slab thickness decreases. An increase in PCC modulus generally increases pavement strength decreasing transverse cracking.

Effect of Concrete 28-Day Modulus of Rupture

JPCP pavements with modulus of rupture values less than 4485 kPa experience more transverse cracking than pavements with values greater than 4485 kPa. Results from past studies and engineering principles show that pavements with lower modulus of rupture values are less likely to withstand the stresses of wheel loads and are more likely to fracture and crack.(2, 3, 11, 12)

Effect of Base Type

The provision of a base of any kind reduces the occurrence of transverse cracking. JPCP constructed with a base over the subgrade experience less transverse cracking than JPCP constructed directly over a subgrade (natural or treated). Therefore, a base is recommended for all high-type pavements to limit transverse cracking of JPCP. On the whole, granular bases and asphalt-treated bases exhibit lower cracking than cement-treated or lean concrete bases. According to the LTPP data, there is no significant difference in cracking for granular and asphalt-treated bases. However, the use of untreated granular bases could increase the potential for faulting.

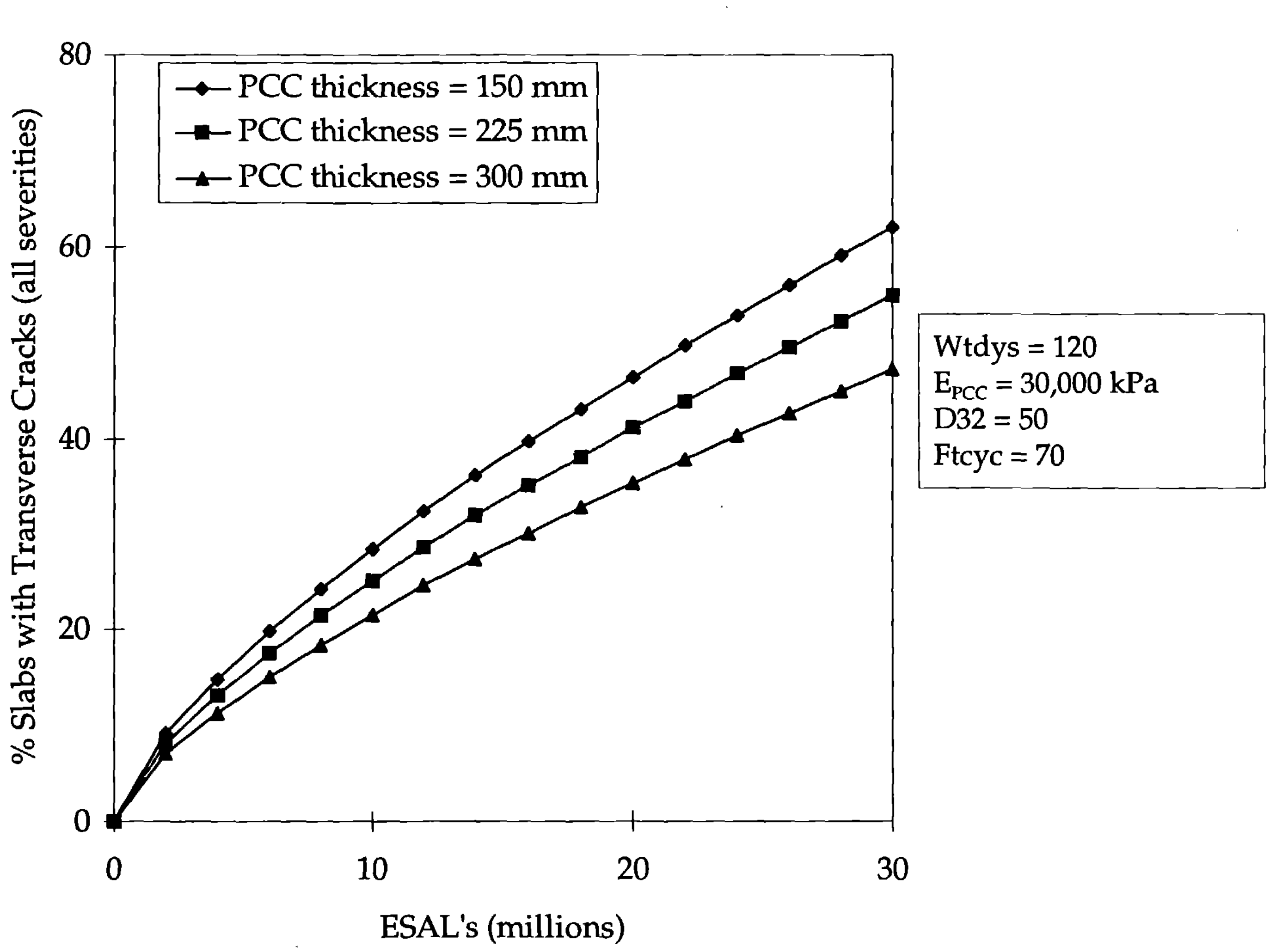


Figure 21. Influence of PCC slab thickness on JPCP transverse cracking.

JPCP Corner Breaks

Effect of PCC Thickness and Elastic Modulus

Figure 22 is a plot of percent slabs with corner breaks versus cumulative ESAL's for different slab thicknesses. The plot shows that there is a rapid increase in the amount of corner breaks in a pavement as the slab thickness decreases. As PCC slab thickness decreases, the tensile stresses generated within the pavement increases, resulting in corner breaks. Also, it will take longer for a microcrack to propagate from the bottom to the top of a PCC slab as the slab thickness increases. This observation adds to the benefits derived from increasing PCC slab thickness.

An increase in PCC elastic modulus generally increases pavement strength and decreases the occurrence of corner breaks.

Effect of Joint Spacing

Figure 23 is a plot of percent slabs with corner breaks versus cumulative ESAL's for different PCC slab joint spacing. The plot shows that there is an increase in the amount of corner breaks in a pavement as the joint spacing increases. This is in agreement with engineering principles and previous research results.(2, 4, 11)

Effect of Subdrainage

The provision of positive drainage in the LTPP pavements generally reduced the occurrence of moisture-related distresses, such as pumping. Adequate drainage reduces the amount of free water within the pavement structure and reduces the potential for erosion and pumping of the underlying pavement materials that results in loss of support of the PCC slab and, hence, corner breaks.

JPCP Roughness

Effect of Base Type

Base type (treated or untreated) shows no significant influence on JPCP roughness. However, further evaluation of the data seems to indicate that the stiffer the base, the less the roughness experienced. This was found to be true for

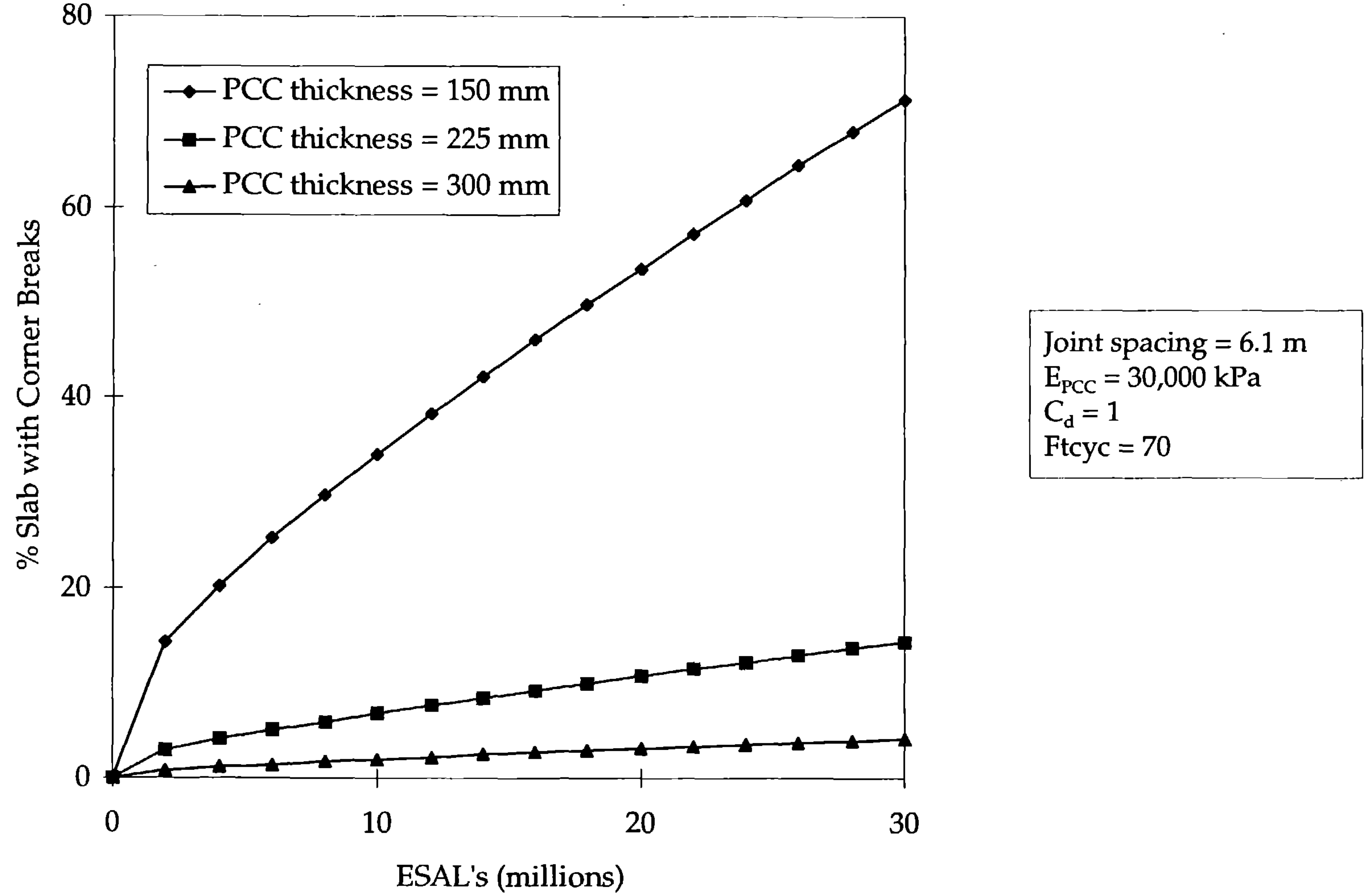


Figure 22. Percent slabs with corner breaks versus cumulative ESAL's for different slab thicknesses.

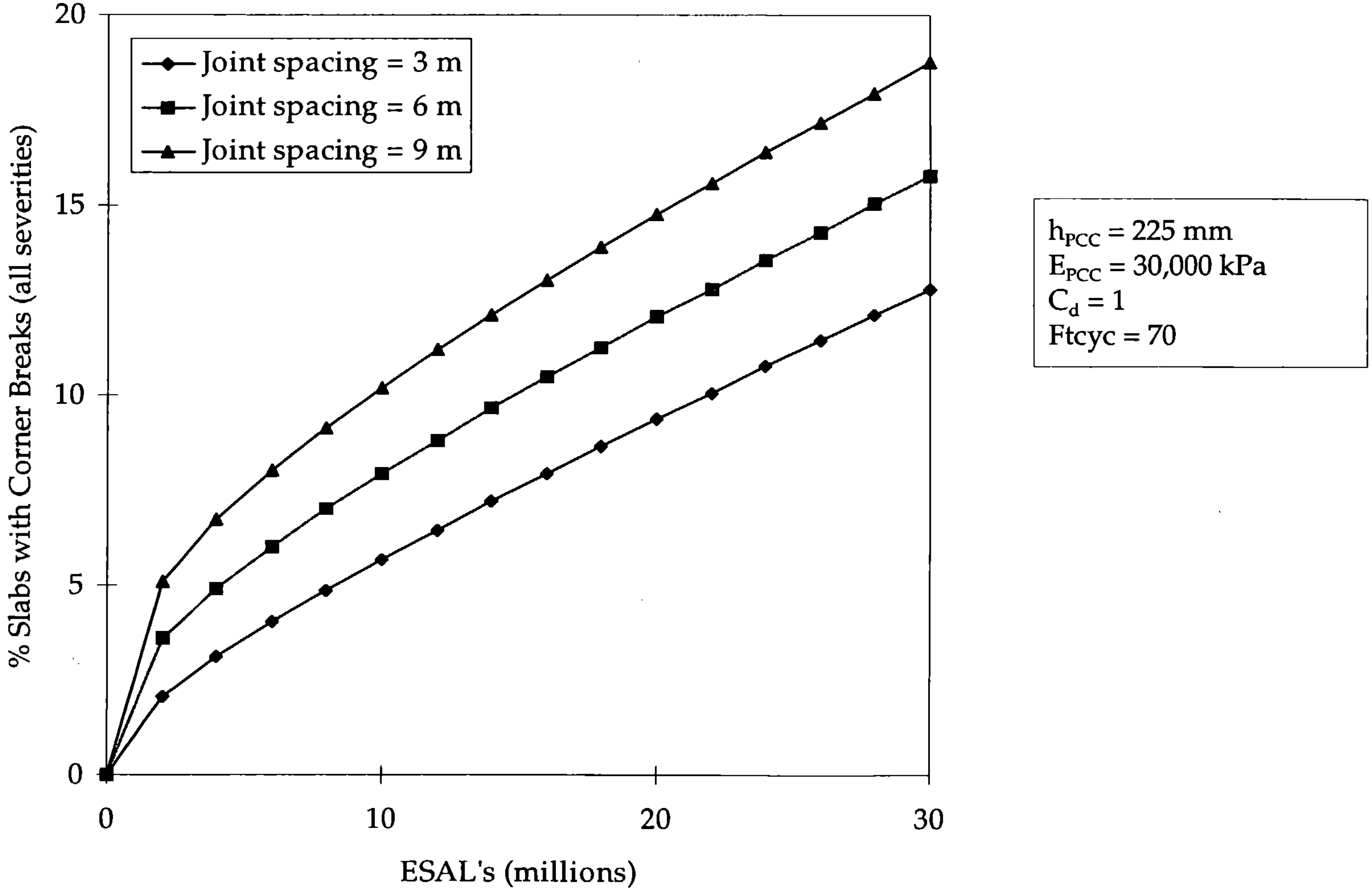


Figure 23. Plot of percent slabs with corner breaks versus cumulative ESAL's for different PCC slab joint spacing.

thinner pavements (< 250 mm), as well as for thicker pavements (> 250 mm). Pavements with stiffer bases or foundations are stronger and experience less deflections for a given traffic loading. Therefore, such pavements may be less susceptible to distress and roughness development in general.

Effect of PCC Thickness and Modulus

The analysis shows that pavements with thicker PCC slabs (> 250 mm) have more roughness than those with thinner PCC slabs. This may be because thicker pavements are generally more difficult to construct. Consequently, they may be built rougher than thinner sections and remain rougher throughout the pavement's design life. The LTPP data show that JPCP with higher PCC modulus exhibit lower roughness. The PCC modulus correlates positively with flexural strength and thus lower fatigue damage and cracking and, therefore, less roughness.

Effect of Subdrainage

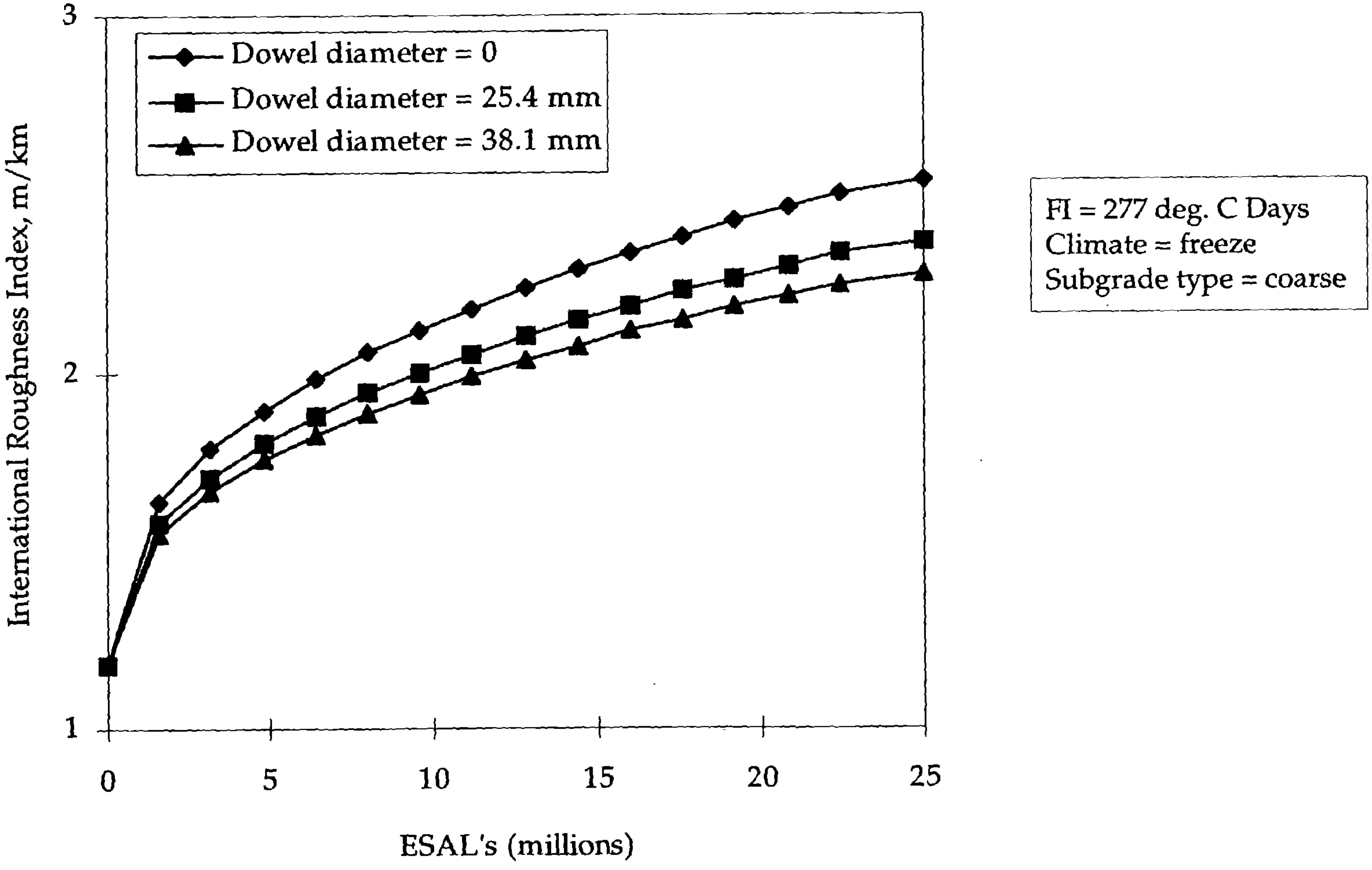
The provision of positive subdrainage to a JPCP generally reduces roughness. Improved subdrainage reduces the amount of faulting and transverse cracking. Reducing the occurrence and severity of distress reduces roughness.

Effect of Edge Support

Jointed concrete pavements with PCC tied shoulders or widened lanes tend to experience less distress and, hence, less roughness. The edge support increases load transfer at the joints and increases the rigidity of the slab. This reduces the critical bending stresses and deflections at the midsection and joints of the slabs when subjected to wheel loads.

Effect of Load Transfer (Dowels)

JPCP pavements with dowels are smoother than those without dowels. Dowels provide load transfer across the joints of adjacent slabs. Load transfer reduces deflections and faulting at the joints, and also transverse cracking. This results in lower roughness. Figure 24 shows a plot of ESAL's versus roughness for different dowel diameters. The plot was developed from a JPCP roughness prediction model developed as part of this study. According to the plot, increased dowel diameter reduces roughness. The model clearly shows the importance of using dowels and also shows that increasing the dowel diameter reduces the progression of roughness.



FI = 277 deg. C Days
Climate = freeze
Subgrade type = coarse

Figure 24. Influence of dowel diameter on JPCP roughness.

JRCP Transverse Joint Spalling

Effect of Joint Sealant Characteristics

The effect of the different types of sealants on joint spalling of JRCP was not much different from that observed for the JPCP model. Figure 25 illustrates the influence of the different joint sealant conditions. For JRCP, unsealed joints were also found to spall more, and the type of sealant used has an influence on spalling. However, silicone sealants and not preformed sealants seem to provide the best protection against spalling, followed by preformed sealants. Joints with rubberized asphalt sealants do not perform as well and seem not to be much better than unsealed joints.

Effect of PCC Slab Thickness and Elastic Modulus

The effect of both PCC slab thickness and elastic modulus on JRCP joint spalling is similar to that for JPCP. The effects for JPCP discussed in detail in the preceding sections are therefore applicable to JRCP.

JRCP Roughness

Effect of PCC Thickness

The LTPP database shows significant roughness values for JPCP with PCC thickness less than 225 mm and those greater than 300 mm. JRCP with thin PCC slabs have a reduced load-carrying capability and are more susceptible to distress and roughness. Also, JRCP with PCC thickness greater than 300 mm experience more roughness because of difficulties with constructing thicker JRCP sections. A previous study found that the thicker JRCP were indeed constructed rougher than thinner JRCP.(13)

Effect of Joint Spacing

JRCP with joint spacing greater than 13.7 m tend to experience more roughness than those with shorter joint spacing. Horizontal slab movement due to temperature changes and vertical deflections from curling increase for JRCP with longer joint spacing (greater than 13.7 m). Also, JRCP with longer joint spacing may develop more deteriorated transverse cracks. Reducing joint spacing will enhance JRCP performance.

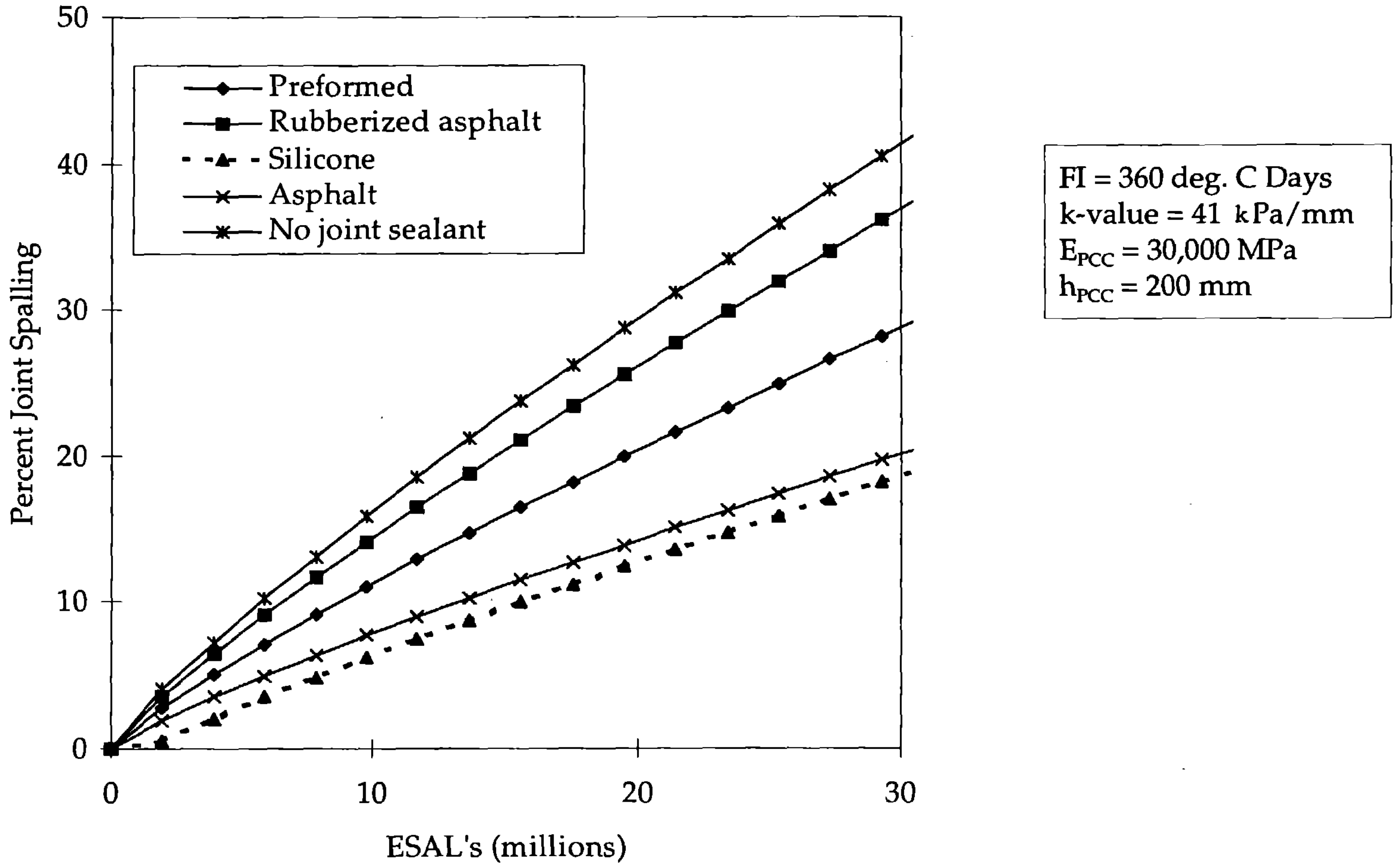


Figure 25. Influence of joint sealant type on JRCP transverse joint spalling.

Effect of Subdrainage

The provision of positive subdrainage to a JRCP generally reduces distress and roughness. Improved subdrainage (primarily through edgedrains and granular embankments) reduces the amount of water within the pavement structure, thereby reducing the potential for weakening and pumping of the underlying pavement materials. The comparative effect of different drainage facilities such as edgedrains and permeable bases was not analyzed due to insufficient data; however, the provision of drainage is recommended for enhanced JRCP performance.

CRCP Roughness

Effect of PCC Thickness

The analysis shows that pavements with thicker PCC slabs (> 250 mm) have more roughness than those with thinner PCC slabs. This is similar to the trend observed for JPCP. The reasons for this are most likely similar and may be because thicker pavements are generally more difficult to construct. Consequently, they may be built rougher than thinner sections and remain rougher throughout the pavement's design life.

Effect of Design Steel Content

CRCP with increased steel content has lower IRI, as illustrated in figure 26. This result is reasonable and is in agreement with recent observations in Belgium and the U.S. that indicate that higher steel contents for CRCP are beneficial, as they keep the cracks that form tight.(9, 10) Although the higher steel contents induce more cracking in CRCP, as long as they are kept tight this does not appear to cause a problem.

Effect of Subdrainage

The provision of positive subdrainage to a CRCP generally reduces roughness. Adequate subdrainage reduces the amount of water within the pavement structure, thereby reducing the potential for pumping and weakening of the underlying pavement materials.

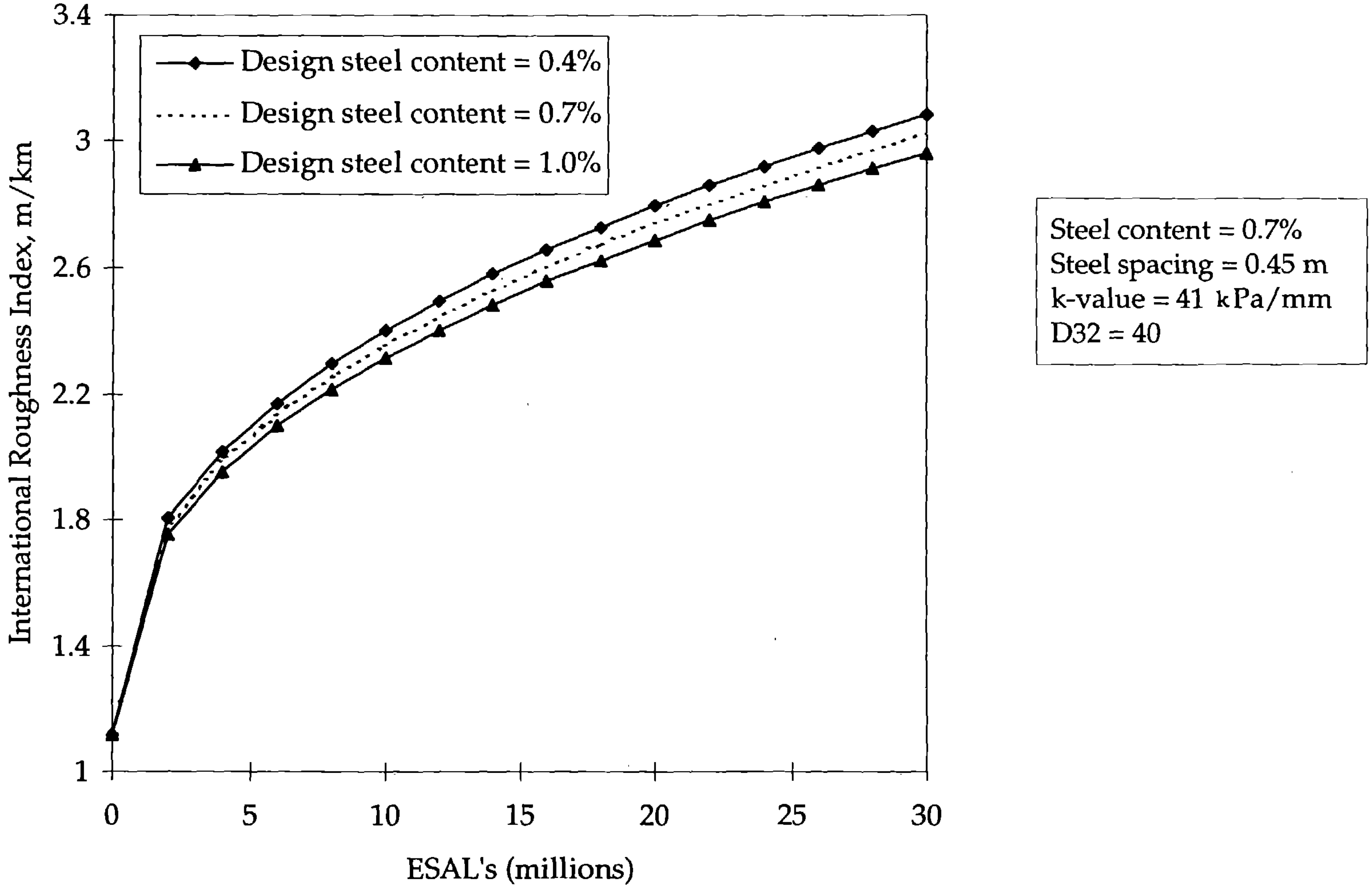


Figure 26. Influence of design longitudinal steel content on CRCP roughness.

Effect of Base Type

An increase in base thickness and the use of treated bases result in less roughness for CRCP. This agrees with both empirical and mechanistic analyses from past studies, which show that a stronger pavement structure generally experiences less distress and, therefore, less roughness.

Summary

The design features that influence concrete pavement performance are summarized in tables 3 through 10. The tables show the effect of the design features on the different pavement and distress types analyzed. These should serve as guidance for selecting design features when designing PCC pavements.

Table 3. Effect of key pavement design features on JPCP transverse joint faulting.

Key design feature	Effect on JPCP joint faulting
Radius of relative stiffness	Increasing the radius of relative stiffness significantly reduces the progression of faulting.
Load transfer or dowels	JPCP with dowels of at least 25.4 mm in diameter can reduce faulting by at least one-half. The larger the dowel diameter, the more the reduction in faulting for any given set of site conditions and design features.
PCC slab thickness	Thicker JPCP exhibit significantly less faulting than thinner slabs.
Base type/modulus	A nonerodible base (e.g., lean concrete) appreciably decreases faulting in comparison to erodible bases, such as untreated aggregates.
Skewed joints	Pavements with skewed joints fault less than those with square joints. However, skewed joints with dowels are not recommended. Dowels can control faulting without skewing the joints.
Subdrainage (Drainage coefficient, C_d)	Increasing the drainage coefficient by improving subdrainage (edgedrains and granular embankment), thus reducing the extent of pavement saturation for long periods, reduces faulting.

Table 4. Effect of key JPCP design features on transverse joint spalling.

Design feature	Effect on JPCP joint spalling
Joint sealant characteristics	In general, pavements with sealants experience less spalling than those without. Among the different sealants, preformed sealants perform best in terms of reduction in joint spalling. Also, stiffer sealants cause more spalling.
PCC slab thickness	Pavements with thicker PCC slabs experience less spalling in general.
PCC slab elastic modulus	Stiffer PCC slabs (i.e., higher elastic modulus) experience less spalling because of the increased strength of the pavements.

Table 5. Effect of key pavement design features on JPCP transverse cracking.

Key design feature	**Effect on JPCP transverse cracking**
Load transfer or dowels	Pavements with dowels experience less transverse cracking. Load transfer reduces bending moments and stresses throughout the PCC slab and particularly at the top of the PCC slab. The reduction of stresses and strains at this location lowers the possibility of top-down cracking.
PCC slab thickness and elastic modulus	JPCP with thicker slabs (likely higher flexural strength) experience less transverse cracking. JPCP with a stiffer PCC slab exhibit less transverse cracking.
Modulus of rupture	JPCP with increased modulus of rupture values exhibit less transverse cracking.
Base type	Pavements with treated bases generally experience less transverse cracking; however, cement-treated and lean concrete bases are susceptible to transverse cracking. The use of flexible (AC-treated) bases considerably reduces the occurrence of transverse cracking.

Table 6. Effect of key JPCP design features on corner breaks.

Design feature	**Effect on JPCP corner breaks**
Joint spacing	Longer joint spacing will increase the occurrence of corner breaks.
PCC slab thickness and elastic modulus	Thicker slabs experience less corner breaks. Stiffer PCC slabs experience less corner breaks.
Subdrainage	A higher drainage coefficient will reduce the occurrence of corner breaks.

Table 7. Effect of key pavement design features on JPCP roughness.

Key design feature	**Effect on JPCP roughness**
Base type	Pavements with treated bases generally experience less roughness; however, cement-treated and lean concrete bases are more susceptible to transverse cracking.
PCC slab thickness and modulus	Thicker PCC slabs tend to be rougher. This is because thicker PCC slabs are often constructed rougher than thinner slabs, and the high initial roughness is maintained throughout the pavement life.
Subdrainage (Drainage coefficient, C_d)	Increasing the drainage coefficient by improving positive subdrainage reduces moisture-related distresses such as faulting and, hence, roughness.
Edge support	Pavements with tied PCC shoulders or widened lanes experience less roughness. This is because tied shoulders and widened lanes provide additional load transfer at the joints and between the JPCP and concrete shoulder, reducing stresses and deflections and, therefore, load-related distresses and roughness.
Load transfer or dowels	Use of dowels in JPCP pavements reduces roughness. Increasing the dowel diameter reduces faulting, further reducing roughness.

Table 8. Effect of key JRCP design features on transverse joint spalling.

Design feature	**Effect on JRCP joint spalling**
Joint sealant characteristics	In general, pavements with sealants experience less spalling than those without. Among the different sealants, silicone sealants perform best in terms of reduction in joint spalling.
PCC slab thickness	Pavements with thicker PCC slabs experience less spalling in general.
PCC slab elastic modulus	Stiffer PCC slabs (i.e., higher elastic modulus) experience less spalling because of the increased strength of the pavements.

Table 9. Effect of key pavement design features on JRCP roughness.

Key design feature	**Effect on JRCP roughness**
PCC slab thickness	Thicker JRCP slabs have increased roughness. This is because thicker PCC slabs are often constructed rougher than thinner slabs, and the high initial roughness is maintained throughout the pavement's life.
Joint spacing	Pavements with longer joint spacing experience more roughness.
Subdrainage	The provision of positive drainage for JRCP will reduce the progression of moisture-related distresses and, therefore, roughness.

Table 10. Effect of key pavement design features on CRCP roughness.

Key design feature	Effect on CRCP roughness
PCC slab thickness	Thicker CRCP slabs increase the progression of roughness. This is because thicker slabs are often constructed rougher than thinner slabs, and the high initial roughness is maintained throughout the pavement life.
Steel content	CRCP with a higher steel content exhibit less roughness.
Subdrainage	CRCP with edgedrains exhibit less roughness.
Base type	CRCP with treated bases generally experience less roughness.

4. RECOMMENDATIONS FOR CONSTRUCTION OF PCC PAVEMENTS

Introduction

The construction of PCC pavement demands careful coordination between the construction practices that must be followed at different stages. These construction practices can be grouped into two phases: (1) practices required to prepare the existing subgrade to an acceptable condition ready for placement of the base and PCC slab and (2) paving operations, formation of joints, and smoothness considerations. Both phases play a critical role in the overall performance of PCC pavements. The LTPP database has a number of data elements that can be used to quantify and evaluate the effect of pavement construction practices on performance. A summary of the data elements is presented below and was used as the basis for evaluating the effects of construction practices on performance. Note that due to the extreme complexity of construction, these findings should be considered tentative until confirmed by further studies.

- Curing method.
- Texture method.
- Dowel placement method.
- Joint forming method.

This chapter summarizes results from the evaluation of the effect of construction practices on pavement performance presented in volume II of this report. The influence of construction practices on the development of the following three distress/performance indicators was evaluated:

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

Brief descriptions of the effect of these construction practices on pavement performance and distress formation are provided in the next few sections. The effect of construction practices on pavement performance is presented in table 11. The information presented is the result of an analysis of the LTPP database to determine the effect of construction practices on distress.

Table 11. Summary of construction practices on pavement performance.

Construction practice	Classification	Effect on distress type			Average ranking*	Remarks ✓ = better performance
		JPCP faulting	JPCP cracking	Roughness		
Dowel placement method	Others	3	X	X	3	
	Mechanically installed	2	X	X	2	
	Preplaced in baskets	1	X	X	1	✓
Joint forming method	Sawed	2	X	X	2	
	Plastic insert	1	X	X	1	✓
Coarse aggregate content of concrete mixture	less than 1800 kg/m^3	X	2	X	2	
	greater than 1800 kg/m^3	X	1	X	1	✓

* Ranking of 1 implies better performance for the respective pavement and distress type.

Table 11. Summary of construction practices on pavement performance (cont'd).

Construction practice	Classification	Effect on distress type and ranking			Average ranking	Remarks ✓ = better performance
		Faulting	Cracking	Roughness		
Fine aggregate content of concrete mixture	less than 1300 kg/m^3	X	1	X	1	✓
	greater than 1300 kg/m^3	X	2	X	2	
Concrete curing method	membrane	X	X	3	3	
	polythene	X	X	1.5	1.5	✓
	burlap	X	X	1.5	1.5	✓
Concrete texture method	astroturf	X	X	6	6	
	others	X	X	5	5	
	broom	X	X	4	4	
	tine	X	X	3	2	✓
	burlap drag	X	X	2	2	✓
	grooved float	X	X	1	2	✓

Effect of Construction Practices on Joint Faulting

Effect of Dowel Placement Method

The LTPP data evaluated show that pavements with dowels preplaced in baskets experience less faulting than pavements with dowels placed mechanically. The cause of this result is unknown but may be related to the better alignment and stability obtained because of the care taken by workmen in placing the dowels manually. However, in recent times, improved dowel placement equipment has been developed, and this may have improved the performance of pavements with mechanically installed dowels.

Effect of Joint Forming Method

The LTPP data evaluated show that pavements with joints formed with plastic inserts experience less faulting than those with joints formed by sawing. The reason for this needs to be investigated further.

Effect of Construction Practices on PCC Transverse Cracking

Effect of Coarse and Fine Aggregate Content

PCC pavements with more coarse aggregates (greater than 1800 kg/m^3) and less fines (less than 1300 kg/m^3) experience 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 and more durable. They have a higher resistance to fracture and cracking.

Effect of Construction Practices on Roughness

Effect of Curing

PCC pavements cured with burlap and polyethylene have significantly less roughness than those cured with a membrane. Effective curing is the best way to avoid early age cracking and disintegration of the concrete slab due to excessive stresses resulting from temperature and shrinkage. The early age cracks usually grow with age and traffic load applications into transverse cracks, corner breaks, and spalling, which all increase roughness. Therefore, using burlap or polyethylene should be considered to minimize future distresses and roughness.

Effect of Concrete Texture Method

The mode of finishing the PCC pavement slab surface has a great influence on roughness. Previous studies have shown that pavements built with a high initial roughness mostly stay rougher than those built smoother. The LTPP data show that pavements that were textured with astroturf and brooms exhibit higher roughness; pavements finished with the grooved float and burlap drag had lower roughness.

Summary

These findings should be considered tentative. Further study is needed for confirmation.

Faulting

The construction features that influence faulting were found to be related to the pavement joint or the strength of the concrete. Data analysis results show that the joint forming method, dowel placement method, and load transfer mechanism all influence faulting. Using dowels preplaced in baskets and joints formed using proper plastic inserts appeared to reduce faulting.

Transverse Cracking

The main construction-related factor that seems to influence the occurrence of transverse cracking was the amount of coarse aggregate in the concrete mix. The greater this variable, the lower the amount of transverse cracking.

Roughness

The most influential construction feature on roughness is the method of finishing. Specifications to control the method of finishing will therefore be beneficial and will reduce the current levels of roughness experienced on pavements. The three texture methods showing the lowest roughness were grooved float, burlap drag, and tining. Other LTPP studies showed that initial smoothness was extremely important to future smoothness of the pavement.(13)

5. APPLICATION OF DISTRESS PERFORMANCE MODELS

Introduction

Important products obtained from this study are the performance prediction models that can be used to determine whether a given pavement design will meet certain performance criteria. Mechanistic-empirical models are recommended because they more realistically consider the mechanism of distress formation. The critical checks recommended for concrete pavements include the following:

- Faulting for doweled and nondoweled JPCP.
- Transverse joint spalling for JPCP and JRCP.
- Transverse cracking of JPCP.
- Corner breaks for JPCP.
- Roughness for JPCP, JRCP, CRCP.

Each of the models should be used to predict distress over the design period for the applicable PCC pavement design, and the results should be checked against the performance criteria of the agency. The models can also be used for analysis of the cost effectiveness of design alternatives. A summary of the variables required as input for models developed as part of this study and examples of the models' applications are presented in this chapter. This chapter presents examples of how the models developed were tested and used to determine their suitability. The methods of model formulation, calibration, and limitations identified in the model development process are discussed fully in volume III of this report.

Faulting of JPCP (Models Provided in Chapter 4, Volume III)

Faulting of JPCP is the most critical distress related to ride quality. A faulting model was developed as part of this study with data available from the GPS 3 pavement sections in the LTPP database and is recommended for checking design. A summary of the input variables required for use in the model developed is presented in table 12. The actual faulting model and procedure for calculating faulting using that model are given in volume III of this report.

Table 12. Summary of variables required for estimating faulting.

Dependent variable	Independent variables	Effect on joint faulting*
Transverse joint faulting, mm	Cumulative number of 80-kN axle wheel load applications	+
	PCC elastic modulus, kPa	-
	PCC thickness, mm	-
	Modulus of subgrade reaction, kPa/mm	-
	Dowel diameter, mm	-
	Drainage coefficient	-
	Annual number of wet days	+
	BASE, Base, or subbase type, 0=erodible 1=nonerodible	-

* Positive indicates that an increase in this variable results in an increase in faulting.

Transverse Joint Spalling for JPCP and JRCP (Models Provided in Chapter 5, Volume III)

The mechanism of spalling is yet to be fully understood. However, spalling is believed to be caused by several interacting mechanisms, including stresses imposed by both traffic and environmental forces, as well as inadequate quality control during construction. Although traffic may have some effect on spalling, environmental factors constitute the largest contributor to development of the distress. Two models were developed as part of this study for estimating the percentage of transverse joints with spalling (all severities) for JPCP and JRCP, and they are recommended for design checking. A summary of the input variables required for use in the models is presented in tables 13 and 14. The actual spalling models and the procedure for calculating the percent joints with spalling for a given pavement section are given in volume III of this report.

Table 13. Summary of variables required for predicting JPCP joint spalling.

Predicted variable	Dependent variables	Effect on joint spalling
JPCP transverse joint spalling (percent of joints spalled)	Cumulative number of 80-kN axle wheel load applications	+
	Joint spacing, m	+
	PCC coefficient of thermal expansion	+
	Thermal gradient within the PCC slab	+
	PCC drying shrinkage strain	+
	Subbase friction factor	+
	Depth of sealant, mm	+
	Modulus of sealant or incompressibles, kPa/mm	+
	PCC elastic modulus, kPa	-
	PCC thickness, mm	-
	Modulus of subgrade reaction, kPa/mm	-
	Pavement age in years	+
	Average daily temperature range, °C	+
	Average daily relative humidity range for the month of construction	-
	Average annual freeze-thaw cycles	+

* Positive indicates that an increase in this variable results in an increase in joint spalling.

Table 14. Summary of variables required for predicting JRCP joint spalling.

Predicted variable	Dependent variables	Effect on joint spalling
JRCP transverse joint spalling (percent of joints spalled)	Cumulative number of 80-kN axle wheel load applications	+
	Joint spacing, m	+
	PCC coefficient of thermal expansion	+
	Thermal gradient within the PCC slab	+
	PCC drying shrinkage strain	+
	Subbase friction factor	+
	Depth of sealant, mm	+
	Modulus of sealant or incompressibles, kPa/mm	+
	PCC elastic modulus, kPa	-
	PCC thickness, mm	-
	Modulus of subgrade reaction, kPa/mm	-
	Pavement age in years	+
	Average annual freezing index, °C days	+

* Positive indicates that an increase in this variable results in an increase in joint spalling.

Transverse Cracking for JPCP (Models Provided in Chapter 6, Volume III)

Transverse cracks are a major cause of structural failure of JPCP. They develop from the repeated application of heavy axle loads and as the slab responds to drying shrinkage, thermal curling, and thermal contractions. Medium- and high-severity transverse cracks in JPCP cause increased roughness and user discomfort, and trigger the need for rehabilitation. A model was developed as part of this study for estimating the percentage of slabs with transverse cracks (all severities), and it is recommended for design checking. A summary of the input variables required for use in the model developed is presented in table 15. The actual transverse cracking model and the procedure for calculating the percent slabs with transverse cracking for a given pavement section are given in volume III of this report.

Corner Breaks for JPCP (Models Provided in Chapter 6, Volume III)

Corner breaks also are a major cause of structural failure in JPCP. They develop as the slab corners are subjected to repeated application of heavy axle loads. PCC slabs with inadequate load transfer or weak underlying material are susceptible to corner breaks. Corner breaks in JPCP cause increased roughness, user discomfort, and trigger the need for rehabilitation. A model was developed as part of this study for estimating the percentage of slabs with corner breaks (all severities), and it is recommended for design checking. A summary of the input variables required for use in the model developed is presented in table 16. The actual corner breaks model and the procedure for calculating the percent slabs with corner breaks for a given pavement section are given in volume III of this report.

Table 15. Summary of variables required for estimating transverse cracking.

Dependent variable	Independent variables	Effect on transverse cracking*
Transverse cracking (percent of slabs cracked)	Cumulative number of 80-kN axle wheel load applications	+
	PCC elastic modulus, kPa	-
	PCC thickness, mm	-
	Pavement age in years	+
	Average annual number of freeze-thaw cycles	+
	Annual number of wet days	+
	Average annual number of days with temperature above 32 °C	+

* Positive indicates that an increase in this variable results in an increase in transverse cracking.

Table 16. Summary of variables required for estimating corner breaks.

Dependent variable	Independent variables	Effect on corner breaks*
Corner breaks (percent of slabs cracked)	Cumulative number of 80-kN axle wheel load applications	+
	PCC elastic modulus, kPa	-
	PCC thickness, mm	-
	Drainage coefficient, C_d	-
	Joint spacing, m	+
	Pavement age in years	+
	Average annual number of freeze-thaw cycles	+

* Positive indicates that an increase in this variable results in an increase in corner breaks.

Roughness for JPCP, JRCP, and CRCP (Models Provided in Chapter 7, Volume III)

Roughness is the irregularity of the pavement surface. In general, road users consider roughness the most important criterion when deciding on the state or condition of a road. Rough roads lead to user discomfort, increased travel times, and higher vehicle operating costs that can lead to millions of dollars in losses to the general economy. Although the structural performance of a pavement is most important to highway designers, the complaints generated by rough roads often contribute to a large part of the rehabilitation decisions made by State highway agencies. Three models were developed as part of this study for estimating roughness for JPCP, JRCP, and CRCP, and they are recommended for design checking. A summary of the input variables required for use in the roughness models developed is presented in table 17. The actual roughness models are given in volume III of this report.

Table 17. Summary of variables required for predicting IRI for the three pavement types (JPCP, JRCP, and CRCP).

Predicted variable	**Dependent variables**	**Effect on roughness***
JPCP IRI (m/km)	Cumulative number of 80-kN axle wheel load applications	+
	Dowel diameter, mm	-
	Elastic modulus of PCC slab, kPa	+
	Pavement age since construction, in years	+
	Freezing index in degree days (°F days)	+
	FREEZE (pavements located in climates with average mean temperature less than 12.75 °C)	+
	Subgrade type 1=coarse-grained, 0=fine-grained	-
	Average annual number of wet days	+
JRCP IRI (m/km)	Cumulative number of 80-kN axle wheel load applications	+
	Percent steel per area for PCC slab	+
	Presence of edgedrain, 1 = edgedrain, 0 = no edgedrains	-
	Pavement age since construction, in years	+
	Average annual precipitation, in mm	+
	Subgrade type 1=coarse-grained, 0=fine-grained	-
CRCP IRI (m/km)	Cumulative number of 80-kN axle wheel load applications	+
	Percent steel per area for PCC slab	-
	Pavement age since construction, in years	+
	Average annual number of days with temperature above 32 °C	+
	DRY (pavements located in climates with average precipitation less than 0.6 m)	-
	FREEZE (pavements located in climates with average mean temperature less than 12.75 °C)	+
	Modulus of subgrade reaction, kPa/mm	-

* Positive indicates that an increase in this variable results in an increase in roughness.

Suitability of Prediction Models

The models presented in this chapter have all been checked using both diagnostic statistics and sensitivity analyses to determine their suitability. In all cases, the models were found to be in agreement with sound engineering principles and judgment. These models can therefore be used for checking new pavement design. Detailed procedures for using these models and discussions on their limitations are presented in volume III of this report.

Examples of Application of Performance Models

The assessment of PCC pavement performance and failure is based on critical levels of the common distresses that occur. The distress and roughness prediction equations developed under this study may be used for a variety of applications. Examples of possible applications are as follows:

- Evaluation of a pavement design obtained through a standard procedure.
- Evaluation of the cost-effectiveness of designs.

The application of these models can be best explained by using examples. Example 1 uses prediction models to check and evaluate a new pavement design. Example 2 uses prediction models to evaluate the cost-effectiveness of alternative pavement designs.

Checking the Design of New Pavements with Prediction Models

The inputs to each of the prediction models must be obtained first. If the predicted distress at the end of the initial performance period exceeds some defined critical level, the pavement design will be considered inadequate, and modifications to certain design inputs may be appropriate. Some suggested critical distress levels used in the examples presented in this chapter are given in table 18. An example application of using the models for checking concrete pavement design is as follows:

Table 18. Suggested critical values for key performance indicators.

Performance indicator	JPCP	JRCP
Joint faulting	3.05 mm	6.1 mm
Transverse cracking	30 percent	30 deteriorated transverse cracks/km
Corner breaks	10 percent	10 percent
Joint spalling	50 percent of joints	25 percent of joints
IRI	2.7 m/km	2.7 m/km

Example 1

Pavement design features

Pavement type = JPCP without dowels
Modulus of subgrade reaction, k = 20.4 kPa/mm
Joint spacing = 6.1 m
Standard lane slab width = 3.65 m
Joint sealant type = Silicone joint sealant (modulus = 99,425 kPa/mm)
Drainage coefficient = 0.7 (poor)
PCC elastic modulus = 24,150 MPa
PCC thickness = 200 mm
Dowel diameter = 0 mm (no dowels)
Base type = erodible (untreated aggregate)
Sealant depth = 50.8 mm

Climatic variables

Wet climate, precipitation = 1.016 m/yr
Freezing Index, FI = 278 degree days (cold climate)
Annual air freeze-thaw cycles = 70
Temperature range = 6.66 °C
Annual number of wet days = 50 (precipitation > 12.7 mm)
Relative humidity = 60 percent
Days with temperature above 32 °C = 40

Performance variables

Performance period = 20 yrs
ESAL applications = 20 million

Evaluation of Design

Iteration No. 1 - Initial pavement design

Predicted mean transverse joint faulting = 4.6 mm (high)
Predicted mean transverse joint spalling = 42.8 percent (high)
Percent slabs with transverse cracking = 42.51 percent (high)
Percent slabs with corner breaks = 20.3 percent (high)
Predicted IRI = 2.4 m/km (rough)

The design is not adequate because the levels of all five distresses are above acceptable or too close to the acceptable values to ensure an adequate safety factor. Some design features should be modified to obtain more acceptable levels of distress.

Iteration No. 2 - The following inputs are used in the next iteration:

Drainage coefficient C_d = 1.2 (permeable treated base with edge drain)
Base type = Nonerodible
Dowel diameter = 25.4 mm
Depth of sealant = 12.7 mm
Elastic modulus of PCC = 31,000 MPa
PCC thickness = 300 mm

The revised design results in the following projected distress levels after 20 years and with 20 million ESAL applications:

Predicted faulting = 0.75 mm
Predicted spalling = 38 percent
Slabs with transverse cracking = 28.5 percent
Slabs with corner breaks = 3.46 percent
Predicted IRI = 2.18 mm/km

The levels of the distresses are reduced considerably in all cases (refer to iteration 1) and, based upon the results of this final iteration, the revised design is acceptable, with the exception of transverse cracking, which will require a thicker slab (e.g., 350 mm). The acceptability of the distress levels is based on the values in table 17, which presents recommendations for critical levels of pavement distress at which some form of rehabilitation is required. The critical distress levels are subjective and depend on the performance standards of the State highway agency in question or the local experience of the design and maintenance engineer. The evaluation of this design illustrates the use of distress and roughness equations and shows that distress and roughness models are very important tools in pavement design and evaluation.

Comparing Cost-Effectiveness of Alternative Designs

Good management of pavements can provide several benefits for highway agencies at both the network and project levels. Foremost among these benefits is the selection of more cost-effective design alternatives. Whether new construction, rehabilitation, or maintenance is concerned, an evaluation of cost-effectiveness can help management achieve the best possible performance value for the public dollar.

At the project level, detailed consideration is given to alternative designs, construction, maintenance, or rehabilitation activities for a particular roadway section or project within the overall program. By comparing the costs and benefits among alternative designs, an optimum strategy is identified that will provide the desired benefits and service levels at the least total cost over the analysis period. Figure 27 presents a flow chart of a procedure for selecting alternative designs based on performance models. The pavement that is most cost-effective is selected. The process of selecting the most cost-effective pavement design is explained with the following example.

Example 2

Pavement design features for Design Alternative 1

Pavement type = JPCP
Subgrade modulus, k = 54.33 kPa/mm
Joint spacing = 4.6 m
Joint sealant type = silicone joint sealant
Drainage coefficient = 1.1
PCC elastic modulus = 31,000 MPa
PCC thickness = 300 mm

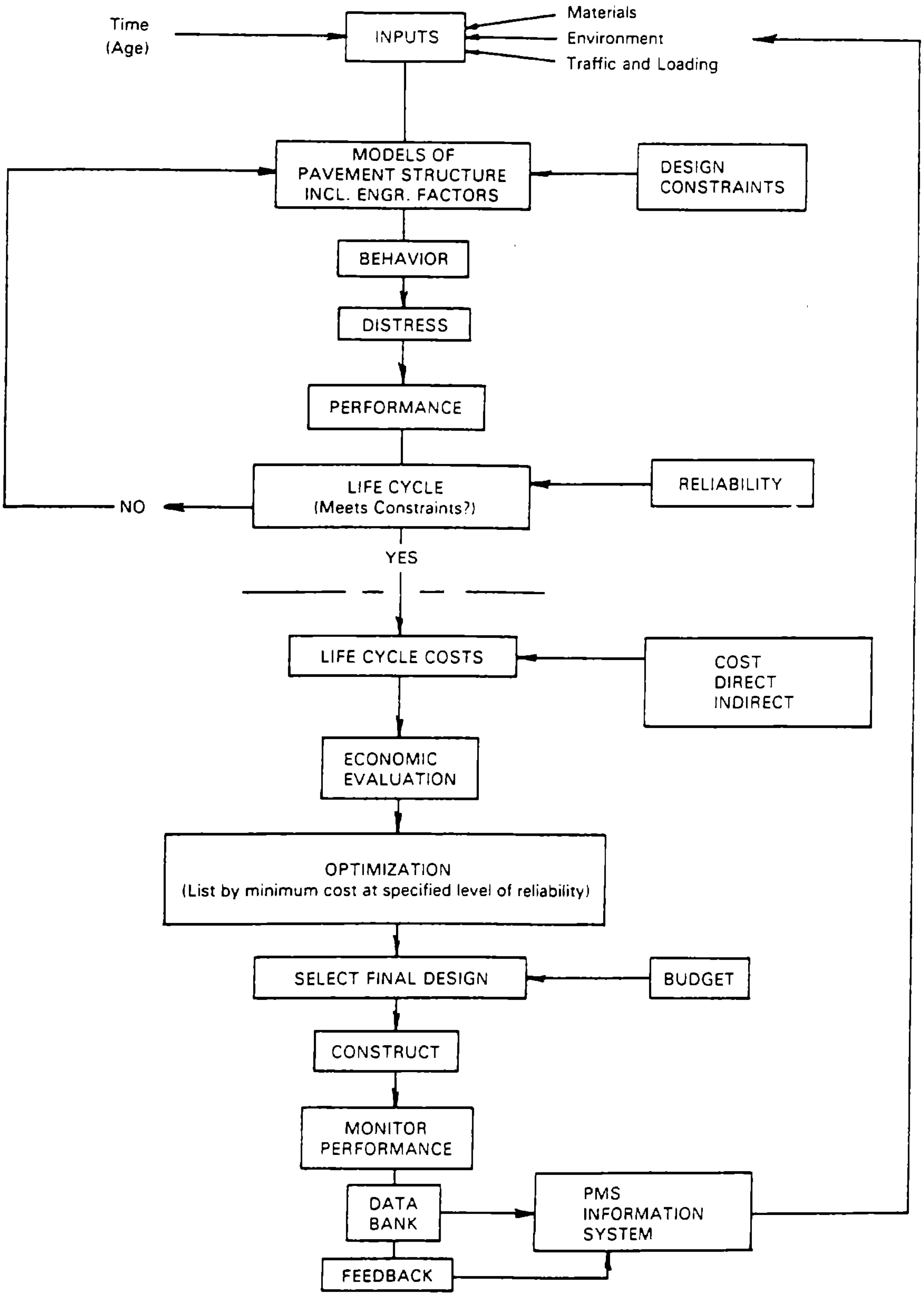


Figure 27. Schematic diagram of pavement design practice with emphasis on cost-effectiveness.(14)

Climatic variables

Wet climate precipitation = 1.3 m/yr
Annual number of wet days = 50
Freezing index = 555 degree days below freezing
Annual number of air freeze-thaw cycles = 75

Pavement design features for Design Alternative 2

Pavement type = JPCP
Granular base, k = 20.4 kPa/mm
Joint spacing = 9.15 m
Joint sealant type = silicone joint sealant
Drainage coefficient = 0.65
PCC elastic modulus = 24,150 MPa
PCC thickness = 200 mm
(The climate variables remain the same)

Performance variables

Performance period = Determined based on critical distress values in table 10
Maximum IRI = 2.7 m/km
Maximum faulting = 3.05 mm
Maximum spalling = 40 percent of joints with low, medium, and high severity
Transverse cracking = 50 percent
Corner breaks = 50 percent

A comparison of the two design alternatives is given in table 19. The percent cost and life as calculated are as follows:

$$Percent\ Cost = 100*\frac{Cost\ of\ Alternative\ 1}{Cost\ of\ Alternative\ 2} - 1 \tag{1}$$

$$Percent\ Life = 100*\frac{ESAL's\ 1}{ESAL's\ 2} - 1 \tag{2}$$

If the percent increase in life is greater than the percent increase in cost, then Design Alternative 1 is more cost-effective. However, if the percent increase in life is less than the percent increase in cost, then the design alternative is not more cost-effective.

It is obvious from the analysis presented in table 19 that alternative 1 is more cost-effective. Performance equations are used in this manner on a routine basis by design engineers to evaluate different pavement design alternatives and strategies.

Table 19. Comparison of cost-effectiveness of two alternate pavement designs.

	Alternate Design 1	**Alternate Design 2**
Faulting (ESAL's/millions to reach critical)	30 +	7
Spalling (ESAL's/millions to reach critical)	23.6	20.5
Transverse cracking (ESAL's/millions to reach critical)	20	12
Corner breaks (ESAL's/millions to reach critical)	30	26
IRI (ESAL's/millions to reach critical)	23	19
Cost of design	$2.0 million	$1.6 million
Lifespan of design (ESAL's)	$20*10^6$	$7*10^6$
Percent cost	124 percent	
Percent life	185 percent	
More cost-effective design	✓	

Summary

This chapter has presented two different ways performance models are used. The models were used in the evaluation of pavements designed using standard design procedures and in selecting between alternative pavement designs. They indicate the wide variety of ways in which performance models can be used. However, these models must be used with care and not extend beyond the inference space for which they were developed.

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made based on the findings of this project:

- There are three major site conditions that a pavement designer must deal with: traffic loadings, subgrade support, and climate. Each of these site conditions was found to be significant in the performance of PCC pavements.

- There are several critical design features that must be fully considered in the design process. These design features include transverse joint load transfer system, base type (erodible or nonerodible), provision of subdrainage, joint spacing for JPCP and JRCP, widened slab, shoulders, and reinforcement for JRCP and CRCP. Findings regarding the effect of each of these design features on performance have been provided for consideration in the design and construction process.

- Commonly used pavement design procedures and other standards for highways are often adequate; however, the independent checking for critical distress types will minimize the potential for distress and early failure.

- The distress and roughness prediction models developed as part of this study are effective tools for use in design evaluation, pavement management, and for evaluating the cost-effectiveness of alternative pavement designs.

- The construction features that influence faulting were found to be related to the pavement joint or the strength of the concrete, namely, joint forming method and dowel placement method. Using dowels in preplaced baskets and joints formed using proper plastic inserts showed reduced faulting; however, newer technology may have improved on the process of joint construction.

- The main construction-related factor that influences the occurrence of transverse cracking is the amount of coarse aggregate in the concrete mix. The greater this variable, the lower the amount of transverse cracking.

- The construction feature most influential on roughness was the method of finishing. Specifications to control the method of finishing will therefore be beneficial and will reduce the current levels of roughness experienced on pavements. The three texture methods that result in the lowest roughness are grooved float, burlap drag, and tining. Past research has shown that initial roughness is critical to future roughness, but this was not examined in the present study.

- Important products obtained from this study are performance prediction models that can be used for pavement design evaluation and the assessment of the cost-effectiveness of alternative designs, as well as recommendations on the selection of design features for PCC pavements.

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