TRANSVERSE CRACK DETERIORATION MODEL FOR JRCP

Dr. Lev Khazanovich
Dr. Michael I. Darter
Kurt D. Smith
ERES Consultants, Inc.

ABSTRACT

A transverse crack deterioration prediction model was developed for JRCP. This model was developed as a part of a larger rigid pavement performance study sponsored by the FHWA. The model is based on the performance of 111 JRCP sections surveyed under this study. The sections are located throughout the United States and represent different climatic regions and designs. Based on the analysis of the model, the effect of design features and site conditions (traffic and climatic variables) on expected pavement life were analyzed. Finally, the model was applied to develop recommendations for design of JRCP pavements to reduce crack deterioration.

INTRODUCTION

Low-severity transverse cracks are a normal occurrence in jointed reinforced concrete pavements (JRCP). These hairline cracks are expected to develop as the slab responds to drying shrinkage, thermal curling, and thermal contraction. Reinforcement is placed in JRCP to hold the cracks tight and prevent deterioration. Traditionally, the required reinforcement content has been determined using the subgrade drag theory, where the steel required to drag the slab over the subgrade without yielding is determined. This theory has been found to be inadequate. Repeated heavy load applications, environmental effects, and base support can result in the cracks breaking down and deteriorating. Medium- and high-severity transverse cracks in JRCP are spalled and often faulted, causing increased roughness and user discomfort, and they trigger the need for rehabilitation. This deterioration has occurred in many JRCP under heavy traffic designed with conventional methods.

This paper presents a crack deterioration prediction model for JRCP. This model was developed as a part of a larger rigid pavement performance study (RIPPER) sponsored by FHWA (*1*). The model is based on the performance of 111 JRCP sections surveyed under this study. Time series data was available on a majority of these section. The sections are located throughout the United States and represent different climatic regions and designs. The paper presents two- and three- dimensional plots that were developed by varying the selected variables over a range of values. Finally, the paper presents recommendations for design of JRCP pavements to reduce crack deterioration based on this model.

PRELIMINARY DATA ANALYSIS

The project database contains information on 159 JRCP sections, including time-series performance data for both 1987 and 1992. However, the data were examined and cleaned to remove pavement sections that exhibit severe D-cracking (medium- and high-severity) and a few that were considered outliers.

The factorial matrix of the distribution of the remaining 111 pavement sections is shown in table 1, separated by climatic region, percentage of longitudinal reinforcement (PERSTEEL), and age. The climate is categorized as cold (FI greater than 111 °C degree-day) or warm (FI less than 111 °C degree-day). Two age brackets are included (0 to 10 and 11 to 25), two types of bases are considered (stabilized and nonstabilized), and two reinforcement brackets (0.6 to 0.10 percent and 0.11 to 0.29 percent) are shown.

Overall, this table shows a fairly good distribution for pavements greater than 10 years old. The majority of the sections are located in cold climates and have a reinforcement steel content between 0.04 and 0.10 percent. There is also a fairly even distribution of pavement sections constructed on both stabilized (asphalt or cement) and nonstabilized bases.

CRACK DETERIORATION AND KEY FACTORS AFFECTING IT

Low-severity transverse cracks typically develop in JRCP over the first several years of pavement life. If the crack remains tight, aggregate interlock can provide sufficient shear load transfer across the crack. However, temperature movements and joint lock up from dowel corrosion lead to crack opening, which causes loss of load transfer and increased slab deflections from applied heavy traffic load which, in turn, may cause the loss of slab support and faulting. Intrusion of incompressibles may cause spalling of crack edges. Infiltration of chlorides causes corrosion of reinforcement, which results in steel rupture that greatly accelerates both crack faulting and spalling. Various field and laboratory studies over the past 15 years have shown that the following variables affect the deterioration of transverse cracks (spalling and faulting) in JRCP.(*2, 4, 6*)

Reinforcement Content

Increased reinforcement content reduces the amount of deteriorated cracks (*2, 3, 4*). JRCP containing less than 0.10 percent steel typically have a significant amount of deteriorated cracks, whereas JRCP with more than 0.20 percent steel typically exhibit very low amounts of cracking. A recent study evaluated the effectiveness of the AASHTO Design Guide (subgrade drag theory) to provide reinforcement for JRCP and found that the typical percentages determined for aggregate bases would result in large amounts of deteriorated cracking (*5*). Researchers in Texas found that the steel percentages obtained from the AASHTO Guide are inadequate and should be more in the range of 0.20 to 0.30 percent (*6*). Still other researchers found that in laboratory tests (fatigue loading across reinforced cracks) on large-scale test specimens, the 0.17 percent steel content commonly used in Michigan is inadequate for loading conditions encountered in the field (*4*).

Base/Subgrade Support

Stiffer subgrades reduce the amount of deteriorated cracks in JRCP (*2,4*). A stabilized base has a very large effect on reducing the amount of deteriorated transverse cracks in JRCP.

Climate

JRCP constructed in colder and wetter climates exhibited more transverse crack deterioration than those constructed in warmer climates, probably due to larger crack openings (*2,3*). Reinforcement design must consider local temperature and moisture conditions. In this study, several climatic variables were considered to characterize climatic conditions. These include Thornthwaite moisture index, number of days with temperature greater than 32 °C (90 °F), mean monthly temperature range, freezing index, degree-days below freezing, average annual precipitation, and mean annual air freeze-thaw cycles.

Traffic

Increased traffic loadings (ESALs) result in increased crack deterioration (*2,3,4*). In this study, traffic loading was characterized through cumulative number of equivalent 80-kN (18-kip) single axle load (ESAL) repetitions.

Pavement Age

Aging represents many mechanisms of crack deterioration, such as cyclic opening and closing of cracks, corrosion of reinforcement from repeated application of deicing salts, and numbers of freeze-thaw cycles.

Concrete Slab Parameters

Concrete slab was characterized in this study through the concrete modulus of elasticity and the slab thickness. These parameters reflect resistance of the surfaces of the crack to deterioration. An increase in concrete slab thickness reduces shear stress at the crack face. Higher modulus of elasticity reflects higher shear strength of the concrete.

Maximum Coarse Aggregate Size

The use of "large" top size durable coarse aggregate is effective at maintaining load transfer across transverse cracks. Smaller top size aggregates (i.e., 0.5 in [13 mm] or less) result in straight cracks through the depth and across the slab with little aggregate interlock to help provide load transfer (*7,8*). However, due to lack of information on aggregate size for the majority of the sections in the database, this parameter was not included in the JRCP crack deterioration model.

Among other variables that were considered in this study but did not appear to be significant in the final model are the AASHTO drainage coefficient, joint opening, mean joint width, joint seal type (several types are listed in the database), mean backcalculated modulus of subgrade reaction, and joint spacing.

REVIEW OF AVAILABLE MODELS

Several models for predicting crack deterioration of JRCP are currently available. One model, developed using data from the States, has the following form (2):

$$CRACKS = CESAL^{0.897}\,[7130.0\ JTSPACE/(ASTEEL * THICK\ 5.0)] + CESAL^{0.10}\,(2{,}281\ PUMP^{5.0}) + CESAL^{2.16}[1.81/(BASETYP + 1)] + AGE^{1.3}\,[0.0036\ (FI + 1)^{0.36}]$$

where:

CRACKS = total length of medium- and high-severity cracks, ft/mi.
CESAL = cumulative 18-kip (80-kN) ESALs in traffic lane, millions.
JTSPACE = mean transverse joint spacing, ft.
ASTEEL = area of reinforcing steel, in^2/ft width.
THICK = slab thickness, in.
PUMP = pumping severity (=0, if no pumping exists; =1, low severity; =2, medium severity; =3, high severity).
BASETYP = base type (= 0, nonstabilized aggregate; =1 stabilized aggregate [cement, asphalt]).
AGE = time since construction, years.
FI = freezing index.

A more recent model has the following form (*3*):

$$CRACKJR = -72.9 + 1.9\ CESAL + \frac{0.182}{PERSTEEL^2} + \frac{2473}{KSTATIC} + 0.687\ PRECIP$$

where:

CRACKJR = number of transverse cracks (medium- and high-severity)/mi.
CESAL = cumulative 80-kN (18-kip) ESAL applications in traffic lane, millions.
PERSTEEL = percentage of steel (longitudinal reinforcement).
KSTATIC = backcalculated static modulus of subgrade reaction, $lb/in^2/in$.
PRECIP = average annual precipitation, in.

Collectively, these models suggest several important variables influencing the development of deteriorated cracks in JRCP: ESAL applications, steel percentage, base type/support, joint spacing, and climatic factors (freezing index and precipitation).

MODEL DEVELOPMENT

A rigorous process was used to develop the transverse crack determination model (*1,3*). The final non-linear regression model is as follows:

$$CRACKJR = 0.621\ AGE^{2.5} * [3.146 * 10^{-4} * FI/THICK + (0.116 - 0.073\ BASE) * CESAL * (1 - e^{-0.032 * MI}) * e^{(7.55188 - 0.145 * 10^{-3} * Epcc - 66.5\ PERSTEEL + 0.725 * 10^{-3} * PERSTEEL * Epcc)}]$$

where:

CRACKJR = number of transverse cracks (medium- and high- severity)/km.
CESAL = cumulative 80-kN (18-kip) ESALs in traffic lane, millions.
PERSTEEL = percentage of steel (longitudinal reinforcement).
Epcc = mean backcalculated modulus of elasticity of concrete, million MPa.
THICK = PCC slab thickness, mm.
MI = Thornthwaite moisture index, if MI is greater than 1.
= 1, if MI is less than 1.
BASE = 0, if nonstabilized base exists.
= 1 , if stabilized (asphalt or cement) base exists.
FI = Freezing Index, degree °C days below freezing.

Statistics:

N = 111.
R^2 = 0.67.
RSE = 20.0 cracks/km (32 cracks/mi).

The actual versus predicted crack deterioration and residual versus predicted crack deterioration are given in figures 1 and 2, respectively. These figures show that prediction errors are symmetrically distributed around zero.

SENSITIVITY ANALYSIS AND DISCUSSION

The sensitivity plots of the key variables in the model are provided in figures 3 through 9. These three-dimensional plots are developed by varying the selected variables over a range of values and fixing all other variables at constant values. Because cumulative traffic is changing with age, it is assumed in these examples that traffic increases 3 percent annually. In the plots the traffic is characterized through cumulative traffic after 20 years, $CESAL_{20}$.

Figure 3 shows the combined effect of traffic and aging on JRCP crack deterioration. The JRCP is 229 mm (9 in) thick, modulus of elasticity of concrete is 34450 MPA (5,000,000 lb/in^2), and longitudinal reinforcement is 0.1 percent. An increase in the amount of traffic and pavement age leads to an increase in crack deterioration. Aging represents the progressive effects of climate on crack deterioration. Heavy traffic loading causes vertical shear in the reinforcement as crack opening increases and aggregate load transfer decreases.

Figures 4 and 5 illustrate that a higher percentage of longitudinal reinforcement reduces crack deterioration. This agrees with the results of a laboratory study conducted by Snyder that showed the effect of greater reinforcement on delaying the deterioration of transverse cracks (*9*, *10*). Effective longitudinal reinforcement holds cracks tight and increases shear resistance. A comparison of figures 4 and 5 also shows that the presence of a stabilized base reduces crack deterioration due to an increase in load transfer.

JRCP with more durable PCC should better resist crack deterioration. Because the modulus of elasticity of concrete is one of the indicators of concrete shear strength, it may be expected that an increase in modulus of elasticity improves pavement performance. Figure 6 shows that the model predicts a decrease in crack deterioration when the concrete modulus increases. This modulus of the slab was backcalculated from FWD deflection data.

The effects of climatic conditions are shown in figures 7 and 8. One can observe that crack deterioration is higher in cold and wet climates. One possible explanation of this effect is greater use of deicing salts in cold and wet climates that would accelerate corrosion of the reinforcement.

Figure 9 presents a comparison of JRCP crack deterioration on selected sections located in Ohio (all with the same design features) with the model prediction. Reasonable agreement is observed between the model predictions and field test data.

It is interesting to note that, like the LTPP crack deterioration model, the model developed in this study does not predict dependence of crack deterioration on joint spacing. This might be explained by the presence in the database of several long-jointed sections, such as section from Missouri and New Jersey, that performed exceptionally well.

Based on the results of the model, the following design features can be recommended to reduce JRCP crack deterioration:

- Higher percentage of reinforcement (greater than 0.11 percent).
- Use of more durable PCC in cold climates.
- Thicker PCC slab.
- Stabilized base.

Although this model provides reasonable prediction of JRCP crack deterioration, lack of information in the database did not permit investigation of the effect of several factors, such as reinforcement type, aggregate size, and aggregate type. As was reported by Snyder, the use of deformed longitudinal reinforcing wire and bars is effective in delaying the deterioration of transverse cracks (*7*). The use of deformed bars in a "hinged joint" design results in the best overall performance. Another factor determined by Snyder was maximum aggregate size (*4*). If maximum aggregate size is less than 25 mm, cracks are straight through the slab without interlock. This will fail quickly. Inability of the model to account for these factors results in the scatter evident in figure 1. Moreover, the empirical nature of the model makes it applicable only within the range of model parameters for the sections of the RIPPER database, as shown in table 2.

JRCP LONGITUDINAL REINFORCEMENT RECOMMENDATIONS

This study agrees with the previous field and laboratory studies on the importance of the amount of steel reinforcement in mitigating JRCP crack deterioration (faulting and spalling). Properly designed reinforcement keeps transverse cracks tight. This prevents loss of aggregate load transfer, excessive vertical movement of the crack, and does not allow crack faulting to develop. In addition, tight cracks do not accumulate incompressibles and, therefore, spall at a significantly lower rate.

The model presented above can be used to compute the required percent of reinforcement for any desired limiting criteria. A limiting value of 16 deteriorated transverse cracks/km (25 cracks/mi) is reasonable for design purposes. Based on that value, recommended longitudinal reinforcement contents are shown in table 3.

As shown in table 3, a minimum of 0.10 percent longitudinal reinforcing steel is recommended for JRCP. This value increases with increasing traffic loadings and in more severe climates. It should be noted that the design criteria of 16 deteriorated cracks/km (25 cracks/mi) is a mean predicted value, and that no safety factor has been included. Thus, the recommendations shown in table 3 represent a 50 percent level of reliability (that is, the selected reinforcement content should provide adequate performance in 50 of 100 pavements). To achieve a higher level of design reliability, the design engineer should select a greater amount of reinforcing steel.

It should be noted that the recommendations for reinforcement contents at the higher ESAL categories are based on extrapolations of the prediction model; only a few sections existed that had sustained greater than 20 million ESALs. Thus, the design recommendations for those higher ESAL categories should be used with caution.

In the design and construction of JRCP, the use of deformed bars or deformed welded wire fabric (WWF) is strongly recommended. Although smooth bars or wires have been used in the past, deformed bars or wires are more effective in keeping transverse cracks held tightly together (*9*). Smooth WWF is governed by ASTM A 185, whereas deformed WWF is governed by ASTM A 497.

A variety of WWF sizes are available for use in JRCP, and the sizes should be carefully selected to obtain the required reinforcing content. Generally, a minimum 0.225 in (6 mm) diameter wire is recommended for both transverse and longitudinal reinforcement (*7*). Minimum spacings of 4 in (102 mm) are recommended for both longitudinal and transverse wires to facilitate placement and vibration of concrete, whereas maximum spacings of 12 in (305 mm) and 6 in (152 mm) are recommended for longitudinal and transverse wires, respectively (*7*). A minimum 2.5 in (64 mm) cover is suggested for most WWF installations.

CONCLUSIONS

An empirical crack deterioration prediction model for JRCP was developed. The model is based on the performance of 111 JRCP sections located throughout the United States and representing different climatic regions and designs. The model projects the percentage of medium- and high-severity cracks in JRCP as a function of accumulated traffic; design features such as percentage of reinforcement, base type, PCC slab thickness and modulus of elasticity; climatic variables such as freezing index and moisture index; and pavement age.

The following is a summary of conclusions observed from the JRCP crack deterioration model:

- Crack deterioration increases with pavement age and traffic.
- Crack deterioration becomes significant within 10 years after construction.
- An increase in the amount of longitudinal reinforcement significantly reduces the number of deteriorated cracks.
- Crack deterioration is greater in cold and wet climates.
- The presence of a stabilized base decreases the amount of deteriorated cracks.
- An increase in modulus of elasticity of the concrete decreases the number of deteriorated cracks.

The model presented above was used to develop recommendations for design of longitudinal reinforcement content. Also, use of more durable PCC in cold climate, a thicker PCC slab, and a stabilized base were recommended.

LIST OF FIGURES

Figure 1. Actual versus predicted deteriorated transverse cracks/km.

Figure 2. Predicted versus residual deteriorated transverse cracks/km.

Figure 3. Sensitivity plot of the JRCP crack deterioration model showing effect of age and ESAL applications.

Figure 4. Sensitivity plot of the JRCP crack deterioration model showing effect of age and percentage of reinforcement (stabilized base).

Figure 5. Sensitivity plot of the JRCP crack deterioration model showing effect of age and percentage of reinforcement (nonstabilized base).

Figure 6. Sensitivity plot of the JRCP crack deterioration model showing effect of age and concrete modulus of elasticity.

Figure 7. Sensitivity plot of the JRCP crack deterioration model showing effect of age and freezing index.

Figure 8. Sensitivity plot of the JRCP crack deterioration model showing effect of age and moisture index.

Figure 9. Comparison of JRCP crack deterioration on selected Ohio sections (with same design features) with the model prediction.

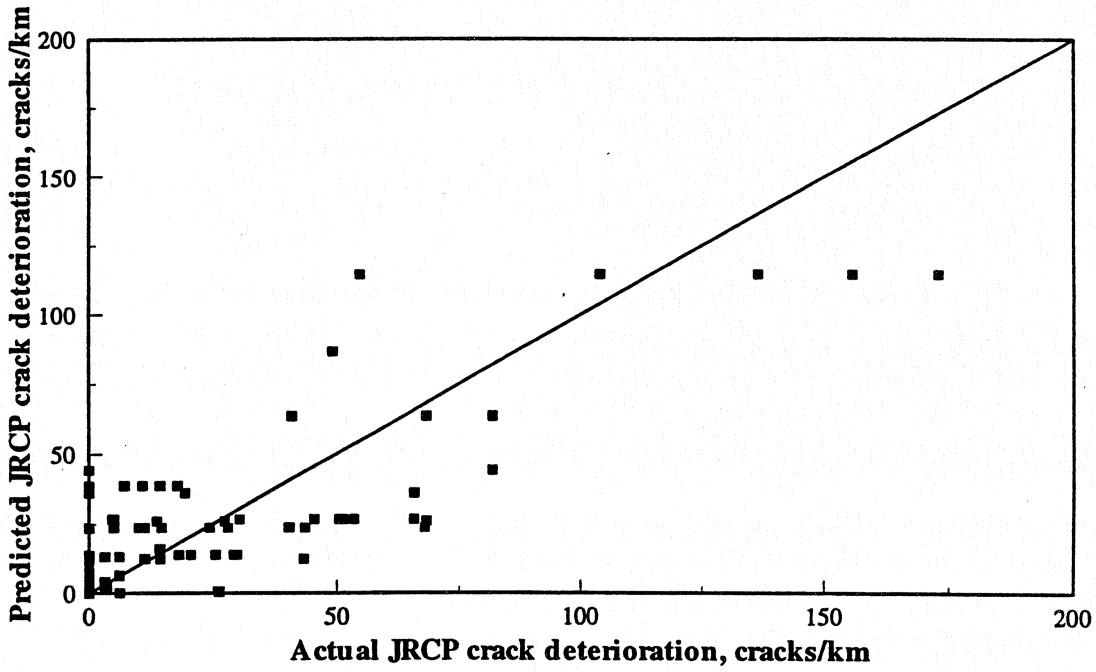


Figure 1. Actual versus predicted deteriorated transverse cracks/km.

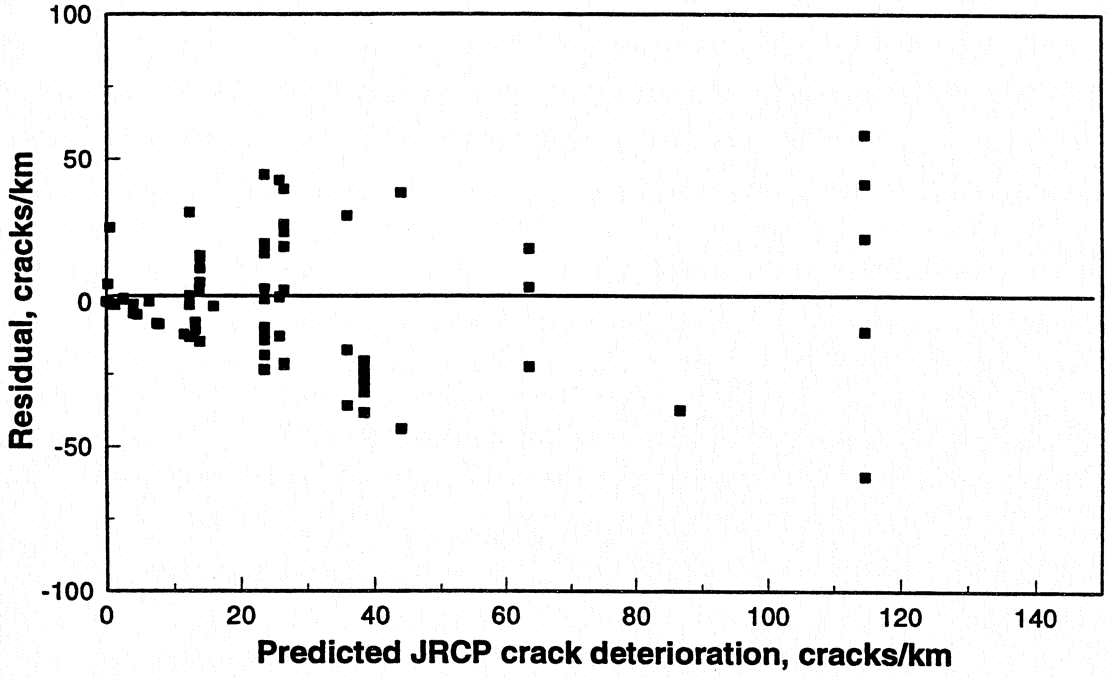


Figure 2. Predicted versus residual deteriorated transverse cracks/km.

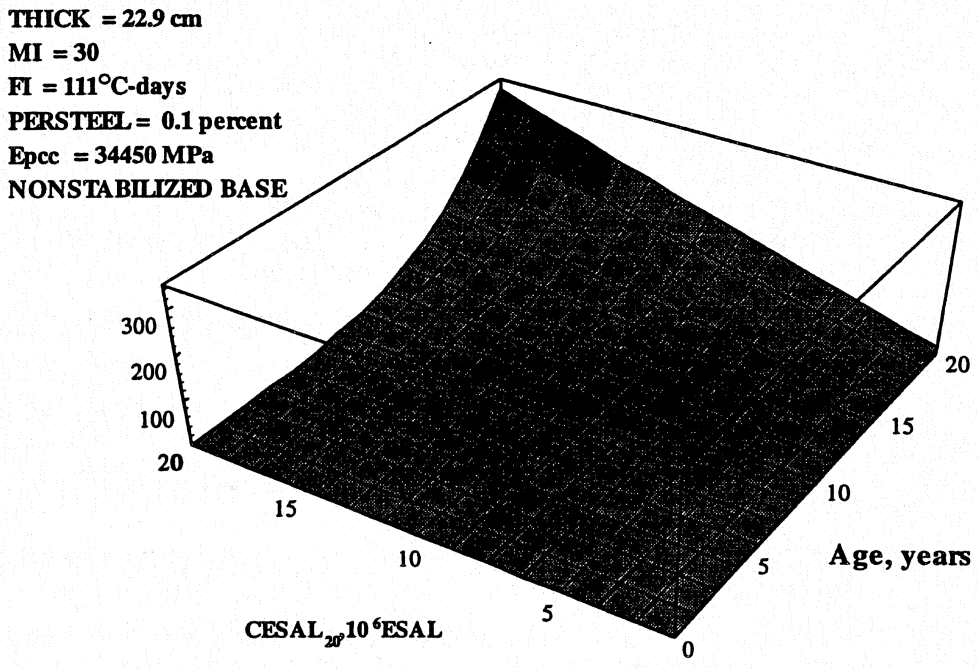


Figure 3. Sensitivity plot of the JRCP crack deterioration model showing effect of age and ESAL applications.

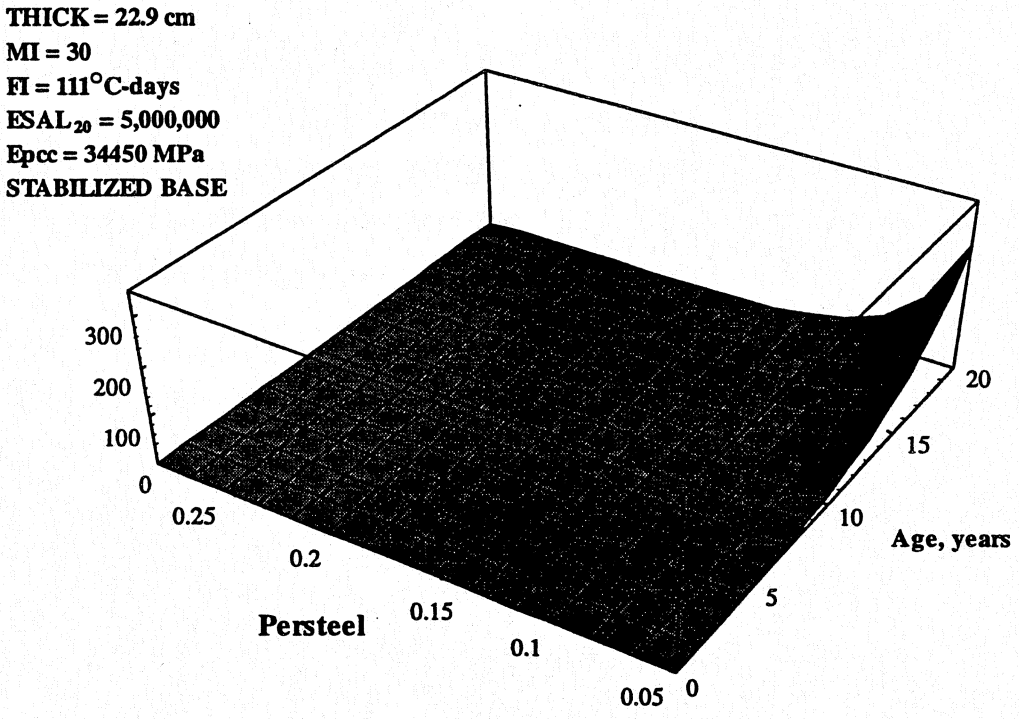


Figure 4. Sensitivity plot of the JRCP crack deterioration model showing effect of age and percentage of reinforcement (stabilized base).

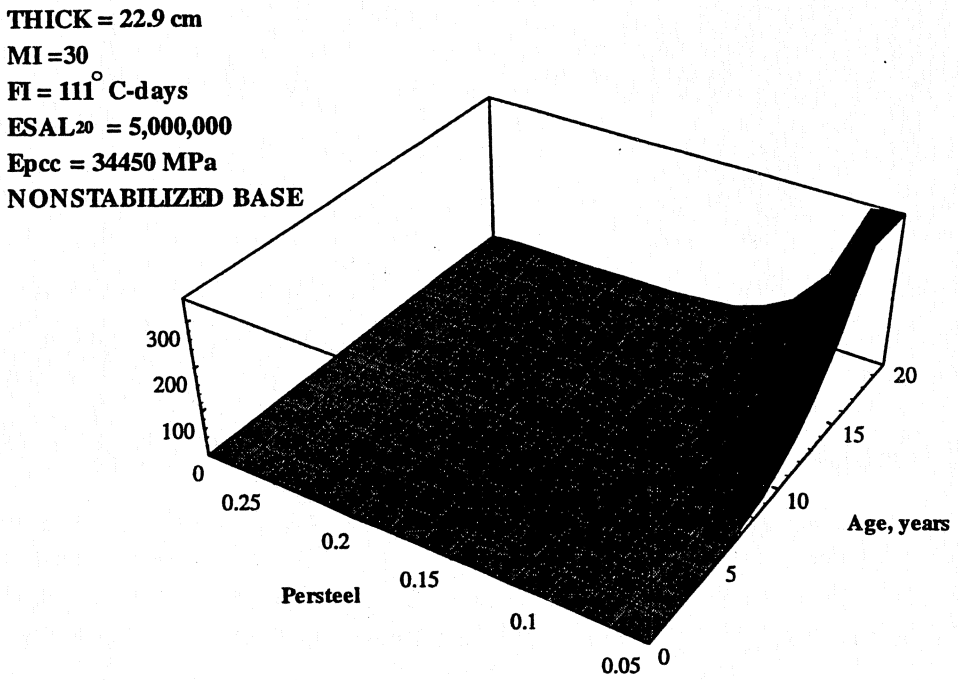


Figure 5. Sensitivity plot of the JRCP crack deterioration model showing effect of age and percentage of reinforcement (nonstabilized base).

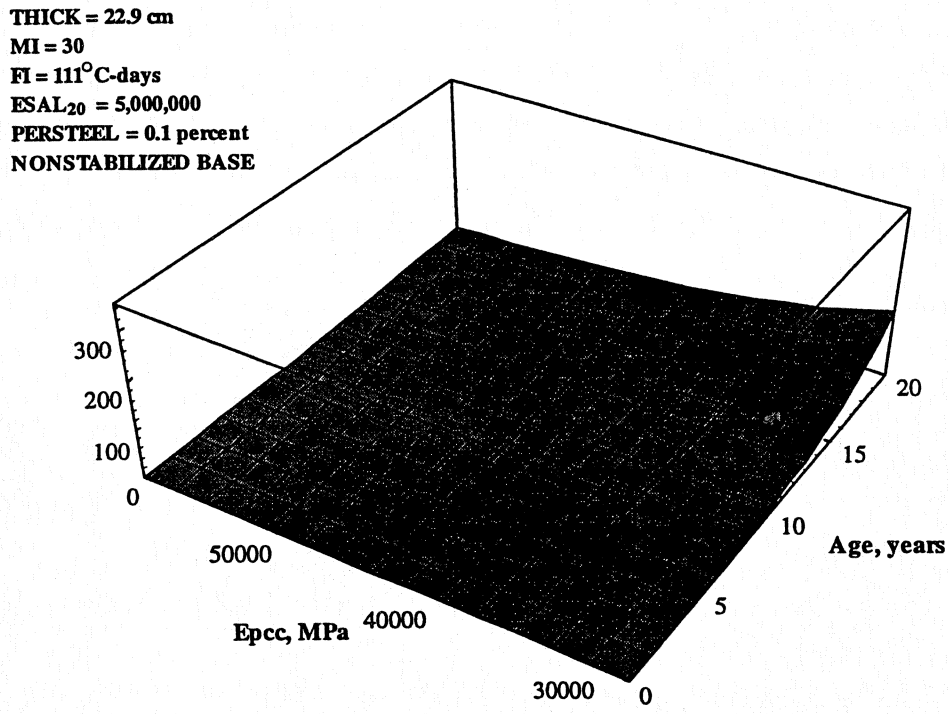


Figure 6. Sensitivity plot of the JRCP crack deterioration model showing effect of age and concrete modulus of elasticity.

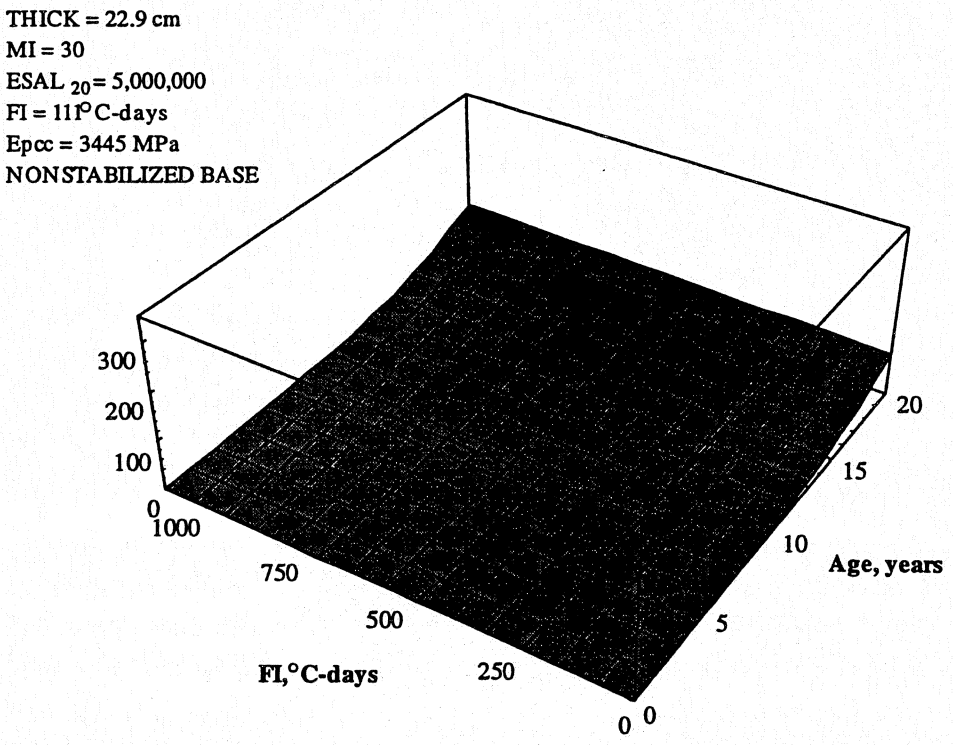


Figure 7. Sensitivity plot of the JRCP crack deterioration model showing effect of age and freezing index.

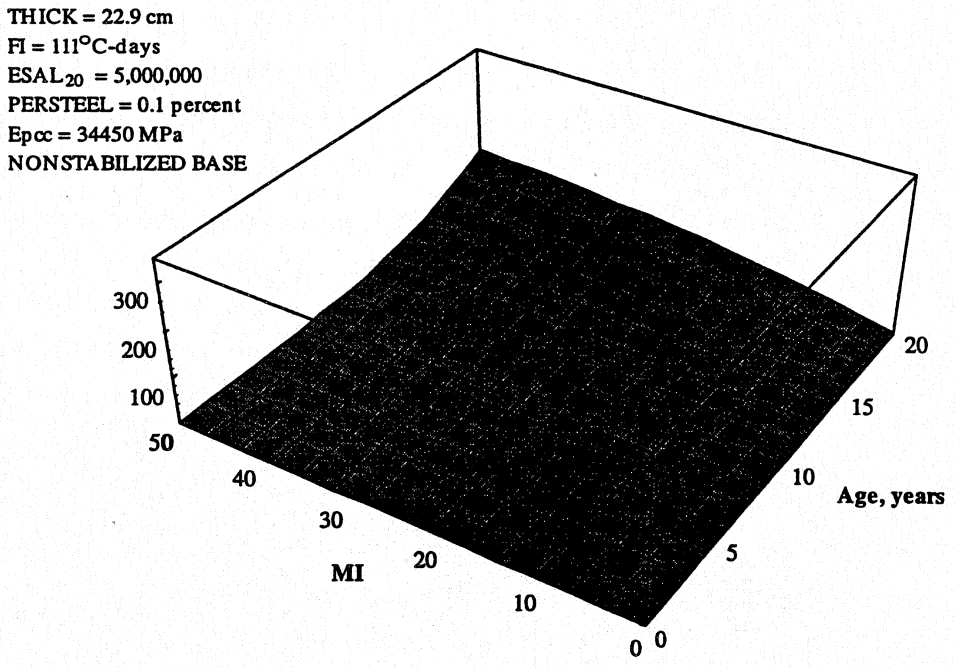


Figure 8. Sensitivity plot of the JRCP crack deterioration model showing effect of age and moisture index.

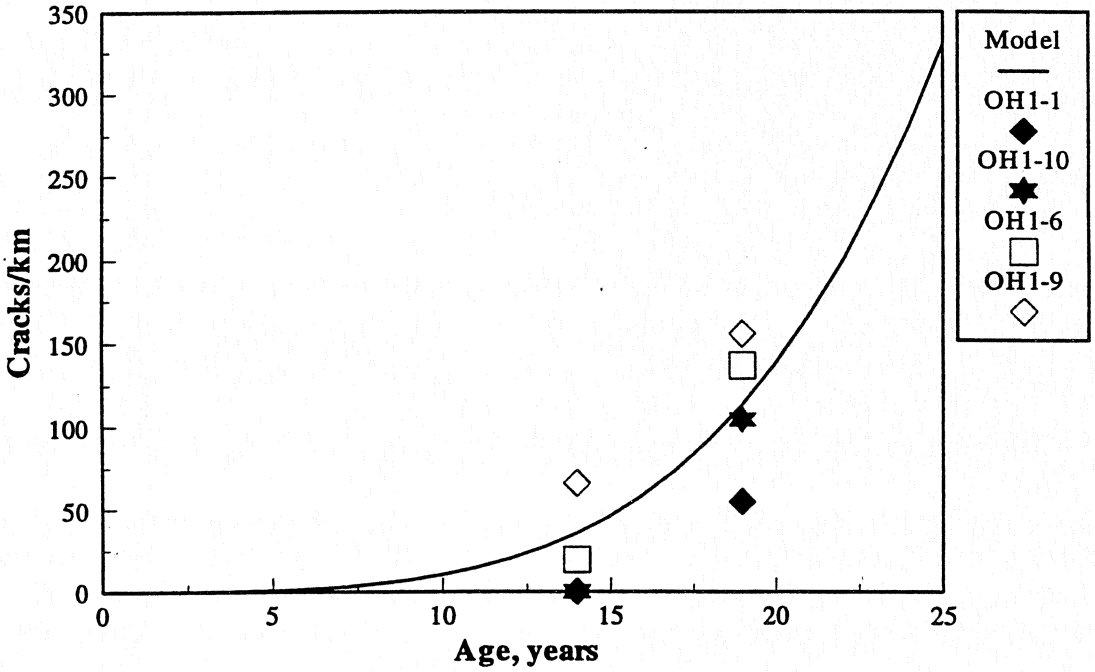


Figure 9. Comparison of JRCP crack deterioration on selected Ohio sections (with same design features) with the model prediction.

LIST OF TABLES

Table 1. Distribution of the pavement sections and designs used in the development of JRCP crack deterioration model.

Table 2. Ranges of model parameters in the RIPPER database.

Table 3. Minimum recommended percent longitudinal reinforcement for JRCP (50 percent level of reliability, 16 deteriorated cracks/km).

Table 1. Distribution of the pavement sections and designs used in the development of the JRCP crack deterioration model.

Climatic Region	PERSTEEL, percent	Age, years 0 - 10		Age, years 11 - 25	
		Aggregate Base	Stabilized Base	Aggregate Base	Stabilized Base
FI < 111 °C-days	0.04–0.10	0	0	9	4
	0.11–0.29	1	4	3	1
FI > 111 °C-days	0.04–0.10	7	4	29	30
	0.11–0.29	2	4	8	5
Total		10	12	49	40

Table 2. Ranges of model parameters in the RIPPER database.

Model Parameter	Minimum Value	Maximum Value
CESAL, million ESAL	0.3	16
PERSTEEL, percent	0.04	0.29
THICK, mm	200	250
MI	0	54
FI, °C-days	0	1250

Table 3. Minimum recommended percent longitudinal reinforcement for JRCP (50 percent level of reliability, 16 deteriorated cracks/km).

Base Type	ESALs millions	Wet-Freeze Climate	Wet-Nonfreeze Climate	Dry-Freeze Climate	Dry-Nonfreeze Climate
Aggregate	1	0.12	0.10	0.11	0.10
	5	0.15	0.10	0.15	0.10
	10	0.17	0.10	0.16	0.10
	25	0.19	0.12	0.18	0.12
	50	0.20	0.14	0.20	0.13
	100	0.22	0.15	0.21	0.15
Stabilized	1	0.10	0.10	0.10	0.10
	5	0.13	0.10	0.10	0.10
	10	0.15	0.10	0.10	0.10
	25	0.17	0.10	0.10	0.10
	50	0.18	0.12	0.11	0.11
	100	0.20	0.13	0.13	0.13

Notes: A minimum of 0.10 percent reinforcement is recommended.
Deformed bars or deformed welded wire fabric strongly recommended.
Base type: aggregate (nonstabilized) or stabilized (asphalt or cement).
ESALs: 80-kN (18-kip) single-axle load applications in traffic lane, millions.
Climatic zone:
Wet-freeze (Freezing Index = 275 °C degree-days; Thornthwaite Moisture Index = 30).
Wet-nonfreeze (Freezing Index = 0; Thornthwaite Moisture Index = 30).
Dry-freeze (Freezing Index = 275 °C degree-days; Thornthwaite Moisture Index = 0).Dry-Nonfreeze (Freezing Index = 0; Thornthwaite Moisture Index = 0).

REFERENCES

1. Yu, T. H., M. I. Darter, K. D. Smith, J. Jiang, and L. Khazanovich, *Performance of Concrete Pavements*: Volume III-Improving Concrete Pavement Performance, FHWA-RD-95-111, Federal Highway Administration, 1996.

2. Darter M. I., J. M. Beck, M. B. Snyder, and R. E. Smith, *Portland Cement Concrete Pavement Evaluation System-COPES*, NCHRP Report 277, Transportation Research Board, Washington, DC, 1985.

3. Simpson, A. L., J. B. Rauhut, P. R. Jordahl, E. Owusu-Antwi, M. I. Darter, and R. Ahmad, *Early Analysis of LTPP General Pavement Studies Data, Volume 3: Sensitivity Analyses for Selected Pavement Distresses*, Report SHRP-P-393, Strategic Highway Research Program, Washington, DC, 1994.

4. Bruinsma, J.E., Z.I. Raja, M.B. Snyder, and J.M. Vandenbossche, *Factors Affecting the Deterioration of Transverse Cracks in JRCP*, Final Report, Contract 90-0973, Michigan Department of Transportation, Lansing, MI, 1995.

5. Heinrichs, K. W., M. J. Liu, M. I. Darter, S.H. Carpenter, and A. M. Ioannides, *Rigid Pavement Analysis and Design*, FHWA-RD-88-068, Federal Highway Administration, Washington, DC, 1989.

6. Kunt, M. M. and B. F. McCullough, *Improved Design and Construction Procedures for Concrete Pavements Based on Mechanistic Modeling Techniques*, Research Report 1169-5F, Texas Department of Transportation, Austin, TX, June 1992.

7. *WSDOT Pavement Guide*, Volume 1—Pavement Policy, Washington State Department of Transportation, Olympia, WA, February 1995.

8. *Jointed Concrete Pavements Reinforced with Welded Wire Fabric*, Wire Reinforcement Institute, Inc., 1975.

9. Snyder, M.B., "Effect of Reinforcement Design and Foundation Stiffness on the Deterioration of Transverse Cracks in Jointed Reinforced Concrete Pavements," *Proceedings*, Third International Workshop on the Design and Evaluation of Concrete Roads, Vienna, Austria, 1994.

10. Bruinsma, J.E., Z.I. Raja, M.B. Snyder, and J.M. Vandenbossche, *Factors Affecting the Deterioration of Transverse Cracks in JRCP*, Final Report, Contract 90-0973, Michigan Department of Transportation, Lansing, MI, 1995.

ACKNOWLEDGMENTS

This work was carried out under FHWA Contract DTFH61-C-00053. The authors acknowledge the following individuals and highway agencies in assisting and supporting this research: Mr. Jamshid Armaghani, Florida Department of Transportation; Mr. Chuck Arnold, Michigan Department of Transportation; Mr. Roger Green, Ohio Department of Transportation; Mr. Terry Rutkowski, Wisconsin Department of Transportation; Mr. Larry Scofield, Arizona Department of Transportation; Mr. Bill Trimm, Missouri Department of Transportation; Mr. Walt Brubaker, West Virginia Parkways Economic Development and Tourism Authority; Mr. Gaylord Cumberledge, Pennsylvania Department of Transportation; Mr. Wouter Gulden, Georgia Department of Transportation; Mr. Tom Kazmierowski, Ontario Ministry of Transportation; Mr. David Lippert, Illinois Department of Transportation; Mr. Victor Mottola, New Jersey Department of Transportation; Mr. Robert Perry, New York State Department of Transportation; and Mr. David Rettnar, Minnesota Department of Transportation.

The authors are also grateful for the technical assistance and guidance provided by Mr. Jim Sherwood and Mr. Roger Larson of the FHWA..

DISCLAIMER

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or its use. The contents of this paper reflect the views of the authors, who are responsible for the accuracy of the data presented herein. The contents do not necessarily reflect the official policy of the Department of Transportation. This paper does not constitute a standard, specification, or regulation.