MECHANISTIC ANALYSIS OF FACTORS LEADING TO PUNCHOUT DEVELOPMENT FOR IMPROVED CRCP DESIGN PROCEDURES

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ABSTRACT

The design of continuously reinforced concrete pavements (CRCP) has traditionally focused on the design of the steel reinforcement relative to the development of the crack pattern but with little emphasis on how characteristics of the crack pattern influence pavement performance. Recent developments associated with the mechanistic-based 2002 Design Guide (under development in NCHRP Project 1-37A) have further reinforced the importance of mechanistic relationships between the design parameters and pavement response to enable pavement performance predictions. To enhance the predictability of CRCP performance, a mechanistically sound relationship that relates the design parameters of crack spacing distribution, crack width, load transfer efficiency of the transverse cracks, and support conditions to pavement structural response needs to be incorporated in the design procedure. The results of this effort would benefit the development of a comprehensive mechanistic-based design procedure for CRCP.

INTRODUCTION

Continuously reinforced concrete pavement (CRCP) is Portland cement concrete (PCC) pavement constructed with continuous longitudinal steel reinforcement and no intermediate transverse contraction joints. Within 2 years after construction, CRCP develops a transverse cracking pattern, typically spaced 0.6 to 1.8 m (2 to 6 ft) apart. For newly constructed CRCP, transverse cracks are initially tightly held together and maintain high load transfer.

The cracking pattern is affected by many factors, including environmental conditions at the time of construction, the amount and depth of steel reinforcement, PCC material and mix

characteristics, friction between the slab and the subbase, and concrete strength. However, experience indicates the more steel reinforcement, the closer and tighter the cracks. The design of CRCP has traditionally focused on the design of the steel reinforcement relative to the development of the crack pattern but with little emphasis on how other design-related characteristics may influence pavement performance.

Recent developments associated with the new mechanistic-based 2002 Guide for Design of New and Rehabilitated Pavement Structures have further reinforced the utility of mechanistic relationships to enhance performance predictions to be made based on specific factors that effect the crack pattern. The major structural distress of CRCP is punchout, which consists of an area enclosed by two closely spaced transverse cracks, a short longitudinal crack, and the edge of the pavement or a longitudinal joint that is associated with loss of support.

CRCP Punchout Mechanism

The causes and factors associated with CRCP punchouts have been the topic of many investigations *(1 to 7)*. One of the first studies, by LaCourserie and Darter *(3, 4)*, describes the mechanism of edge punchout based on the field investigations of punchout distress in CRCP in Illinois. This study showed the development of high tensile stress at the top of the slab about 1 m from the longitudinal edge of the slab as a result of poor load transfer at the surrounding transverse cracks. Crack spacing has also been shown to significantly affect the magnitude of the critical tensile lateral stresses on the top of the slab. However, no mechanistic relationship was established between crack spacing and level of load transfer efficiency across the transverse cracks.

Zollinger et al. *(7)* reported that punchouts in field studies were invariably accompanied by severe subbase erosion and loss of support. As was pointed out by Zollinger and Barenberg *(6)*, poor support conditions can cause rapid deterioration of load transfer capacity due to excessive shear stresses induced by high deflection. Environmentally induced upward slab curling and warping, coupled with loss of crack load transfer, also contribute to high tensile stresses at the top of the slab.

Deterioration of load transfer effectively isolates the loaded portion of the slab between the deteriorated transverse cracks from the adjacent pavement. As a result, only a narrow concrete panel bounded by two transverse cracks carries the wheel load. This situation leads to the development of high top tensile stresses. As repetitive heavy truck loading continues, a short longitudinal fatigue crack forms between the two transverse cracks. Any further wheel loads cause the portion of the concrete slab bounded by the transverse cracks to develop a short longitudinal crack, and the pavement edge to break off and settle into the eroded area resulting in an edge punchout.

Field Data Investigations and Data Analysis

Analysis of CRCP data collected through the Long-Term Pavement Performance Program (LTPP) and analysis of data from CRCP constructed in Illinois and Texas *(8 to 11)* indicate the following factors (and their combination) may have a significant effect on CRCP performance and punchout distress:

- Longitudinal reinforcement (steel percentage, bar diameter, location)
- Slab thickness
- PCC material and mix characteristics
- Construction techniques (construction temperature, curing, crack control, etc.)
- Friction between the concrete slab and base
- Foundation support
- Base erodibility
- Drainage

To develop a mechanistic-empirical CRCP design procedure, it is very important to assess significance of different factors affecting CRCP performance and incorporate these factors in mathematical models that could be implemented in the design procedure. As was found through literature review and analysis of field data, crack spacing, load transfer (and associated crack width), and loss of support are the parameters that have the most affect on the CRCP critical responses. While crack spacing distribution stabilizes in a couple of years after concrete placement, load transfer and erosion change with time and require iterative modeling techniques to capture the time-dependent behavior of these parameters. These modeling procedures are presented in some detail in this paper.

CRACK SPACING CHARACTERISTICS AND PUNCHOUT POTENTIAL

LTPP data for CRCP sections indicates that punchout potential is greater when a large variability in crack spacing exists, resulting in higher probability of the narrow CRCP panels being positioned next to the wide CRCP panels, and in cases of cluster cracking. The LTPP CRCP cracking data obtained from photographic surveys using the PADIAS system were used to analyze the relationship between mean crack spacing and standard deviation of crack spacing. The analysis indicates that LTPP CRCP sections with larger crack spacing usually have larger standard deviation of crack spacing, as shown in figure 1.

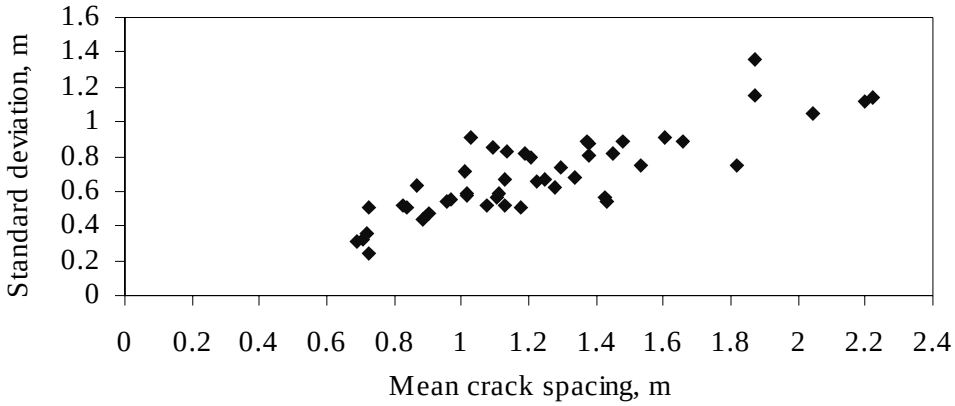

Figure 1. Comparison between mean crack spacing and standard deviation computed for LTPP GPS 5 sections.

The size of the CRCP panels that exhibited punchout also was analyzed using LTPP data. The results of the analysis, presented in figure 2, indicate the majority of punchouts that developed on the CRCP panels were about 0.3 to 0.6 m (1 to 2 ft) wide.

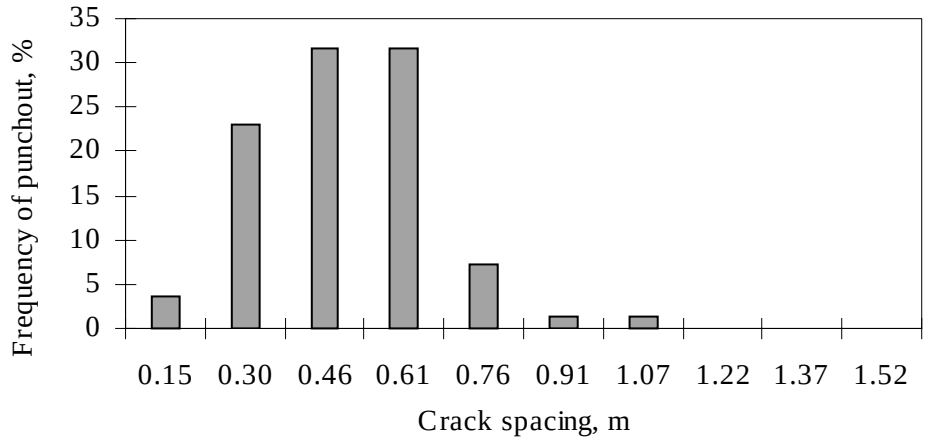

Figure 2. Analysis of frequency of punchout occurrence on different CRCP panel sizes from LTPP GPS-5 experiment sections.

MODELING OF LOAD TRANSFER DETERIORATION

As was indicated by previous investigations, loss of transverse crack load transfer is a precursor of punchout development. As load transfer wears out, top transverse stresses caused by heavy axle load repetitions increase potentially leading to the formation of a short longitudinal crack between two adjacent transverse cracks. In this section a complex relation between the CRCP design parameters of crack spacing, crack width, and load transfer efficiency of the transverse cracks is discussed.

Crack load transfer efficiency (LTE) due to aggregate interlock can be related to the following two parameters:

- *Crack width* – dependent on crack spacing, concrete set temperature, steel content, PCC shrinkage, and subbase friction
- *Aggregate interlock wear-out* – which degrades a crack's ability to transfer vertical traffic loads from one side of the crack to another

Crack Width Component

The width of the transverse crack is fundamental to many aspects of CRCP performance, as it plays a dominant role in controlling the degree of load transfer capacity provided at the crack and is used to determine the required design steel content. Crack width is affected by several time-dependent design parameters, as shown in the following formula for a single layer of steel:

$$cw_i = L\left(\varepsilon_{shri} + \alpha_{PCC}\Delta T_{\zeta m}\right) - L\frac{c_{2i}}{E_{PCCi}}\left(\frac{L\,U_m P_b}{c_{1i} d_b} + C\sigma_0\left(1 - \frac{2h_s}{h_{PCC}}\right) + \frac{L}{2} f\right) \quad (1)$$

Where

cw_i = Average crack width at the depth of the steel for each time increment *i*, mm (mils)
L = Crack spacing, mm
$\varepsilon_{shr\,i}$ = Unrestrained concrete drying shrinkage at the steel depth for each time increment *i*
α_{PCC} = Concrete CTE, $°C^{-1}$ ($°F^{-1}$)
$\Delta T_{\zeta m}$ = Seasonal drop in PCC temperature at the depth of the steel °C (°F)
$c_{1\,i}$ = First bond stress coefficient for time increment *i (13)*
$c_{2\,i}$ = Second Bond stress coefficient for each time increment *i (13)*
$E_{PCC\,i}$ = Concrete modulus of elasticity for the time increment *i*, kPa (psi) *(12)*
P_b = Percent steel, fraction
d_b = Reinforcing steel bar diameter, mm (in)
U_m = Peak bond stress, kPa (psi) *(13)*
h_{PCC} = PCC slab thickness, mm (in)
h_s = Depth to steel, mm (in)
f = Subbase friction coefficient from test data or using AASHTO recommendations.
C = Bradbury's correction factor for slab size *(14)*
$\sigma_{0\,i}$ = Westergaard nominal environmental stress factor for slab curling and warping for each time increment *i*, kPa (psi)

$$\sigma_{0\,i} = \frac{E_{PCCi}\varepsilon_{tot}}{2(1-\mu_{PCC})} \quad (2)$$

Where

μ_{PCC} = Poisson's ratio
ε_{tot} = Equivalent total environmental strain *(15)*

For any given project, crack widths vary widely along the project. One way to consider this variability is to correlate crack width with variability in crack spacing. Figure 3 shows differences in crack width predicted for three different crack spacing, assuming all other parameters to be constant. Fluctuations in crack width over design life are affected by seasonal changes in thermal and moisture strains. Gradual crack width opening is attributed primarily to drying shrinkage.

Once the crack opening is predicted, it could be related to the ability of the crack to transfer vertical shear load using the following relationship *(7)*:

$$s_{oi} = 0.0312 \cdot (0.039 h_{PCC})^{1.4578} \cdot e^{-0.032(0.039 cw_i)} \quad (3)$$

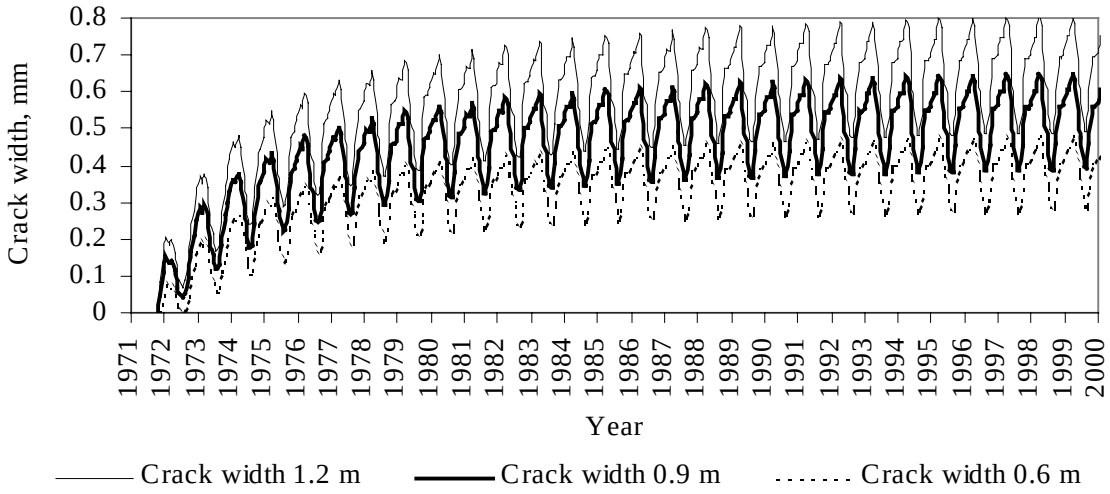

Figure 3. Time history of changes in crack opening over pavement life predicted using data for LTPP GPS-5 Section 175849 in Illinois.

Where

s_{oi} = Dimensionless seasonal shear capacity based on crack width calculated for each time increment *i*

h_{PCC} = Thickness of the slab, mm (in)

cw_i = Crack width as a function of time from equation (1), mm (mils)

Aggregate Interlock Wear-out Component

As the concrete slab is subjected to axle load applications, vertical crack surfaces are subjected to repetitious shearing forces that lead to aggregate wear-out and decrease crack load transferring capacity. To account for aggregate wear-out, the crack shear capacity computed in formula (3) for each time increment *i* is reduced by some loss of shear capacity that accumulates over time. The total shear capacity of the transverse cracks for any given instance in pavement life can be characterized using the following formula *(7)*:

$$s_i = s_{oi} - \sum_{i=1}^{i-1} \sum_{j} \left(0.069 - 2.75 \cdot e^{-cw_i / 0.039 h_{PCC}}\right) \left(\frac{n_{ji}}{10^6}\right) \left(\frac{\tau_{ij}}{\tau_{ref\,i}}\right) \quad (4)$$

Where

s_i = Total crack shear capacity at time increment *i*.

s_{oi} = Crack shear capacity based on crack width for time increment *i*.

cw_i = Crack width for time increment *i*.

h_{PCC} = Thickness, mm (in)

n_{ji} = Number of equivalent corner load applications for time increment *i*, load level *j*.

τ_{ij} = Shear stress on the transverse crack at the corner due to load level *j* applied during time increment *i*, kPa (psi)

$\tau_{ref\,i}$ = Reference shear stress derived from the PCA test results for time increment *i*, kPa (psi)

Coefficients in the equation (3) and (4) were modified from the original values used in the reference *(7)* based on the analysis of the additional data from CRCP sections from the LTPP GPS-5 experiment.

Load Transfer Prediction Model

To relate crack shear capacity to crack load transfer efficiency, an intermediate parameter called crack stiffness was used *(16)*:

$$Log(J_{ci}) = ae^{-e^{-\left(\frac{J_S-b}{c}\right)}} + de^{-e^{-\left(\frac{s_i-e}{f}\right)}} + ge^{-e^{-\left(\frac{J_S-b}{c}\right)}} \cdot e^{-e^{-\left(\frac{s_i-e}{f}\right)}} \quad (5)$$

Where

$J_{c\,i}$ = Stiffness of the transverse crack for time increment *i*.

s_i = Dimensionless shear capacity for time increment *i*.

J_s = Stiffness of the shoulder/slab longitudinal joint from the table below.

Table 1. Stiffness of the shoulder/slab longitudinal joint

Shoulder Type	**(AGG/k*l*)$_s$**
Granular	0.04
Asphalt	0.04
Tied PCC	4

Once the $J_{c\,i}$ parameter is known, load transfer efficiency on the transverse crack at any instance of time can be found using the modified formula originally developed by Ioannides *(17)*, as follows:

$$LTE_{TOT\,i} = 100 * \left(1 - \left(1 - \frac{1}{1 + \log^{-1}\left[(0.214 - 0.183\frac{a}{\ell_i} - \log(J_{ci}) - R)/1.18\right]}\right)\left(1 - \frac{LTE_{Base}}{100}\right)\right) \quad (6)$$

Where

$LTE_{TOT\,i}$ = Total crack LTE due to aggregate interlock, steel reinforcement and base support for time increment *i*, %.

P_i = Radius of relative stiffness computed for time increment *i*, mm (in).

a = Radius for a loaded area, mm (in).

R = Residual dowel-action factor to account for residual load transfer provided by the steel reinforcement.

LTE_{BASE} = Load transfer efficiency contributed by the base layer from the following table, %.

Table 2. Load transfer efficiency of the base layer.

Base Type	LTE_{BASE}
Aggregate base	20%
ATB or CTB base	30%
LCB base	40%

The formula for total crack LTE takes into account load transfer provided by aggregate interlock on transverse cracks, steel reinforcement, and base support.

The following example compares the results of the predicted LTE deterioration process with the field data obtained for LTPP GPS-5 section 175849. The field LTE values were computed from the Falling Weigh Deflectometer (FWD) measurements taken on two separate surveys (November 1989 and July 1994). Table 3 summarizes the characteristics of this LTPP section. As shown in figure 4, predicted and measured mean LTE values are very close. Measured values were taken at 18 and 23 years after construction.

Table 3. Characteristics of the LTPP GPS-5 Section 175849.

Section Characteristics	Values
Concrete estimated at elastic modulus at 28 day	20,670 MPa (3,000,000 psi)
Slab thickness	183 mm (7.2 in)
Depth to steel	76 mm (3 in)
Percent of longitudinal reinforcement	0.7%
Steel bar diameter	16 mm (0.63 in)
Base material description	ATB
Shoulder type	Asphalt Concrete
Measured mean crack spacing	0.75 m (30 in)
Cumulative axle loading	13,000,000 ESAL
Annual truck volume growth	2%
Analysis period	1971 to 1994

The crack shear capacity and associated LTE values are very sensitive to the ratio of crack width over thickness. The higher the ratio, the lower initial shear capacity and faster the rate of LTE deterioration. For a given PCC thickness, wider cracks would deteriorate first. Wider cracks are usually associated with pairs of slabs with large mean crack spacing. The situation is most critical when a narrow loaded slab segment is located next to a wide slab segment.

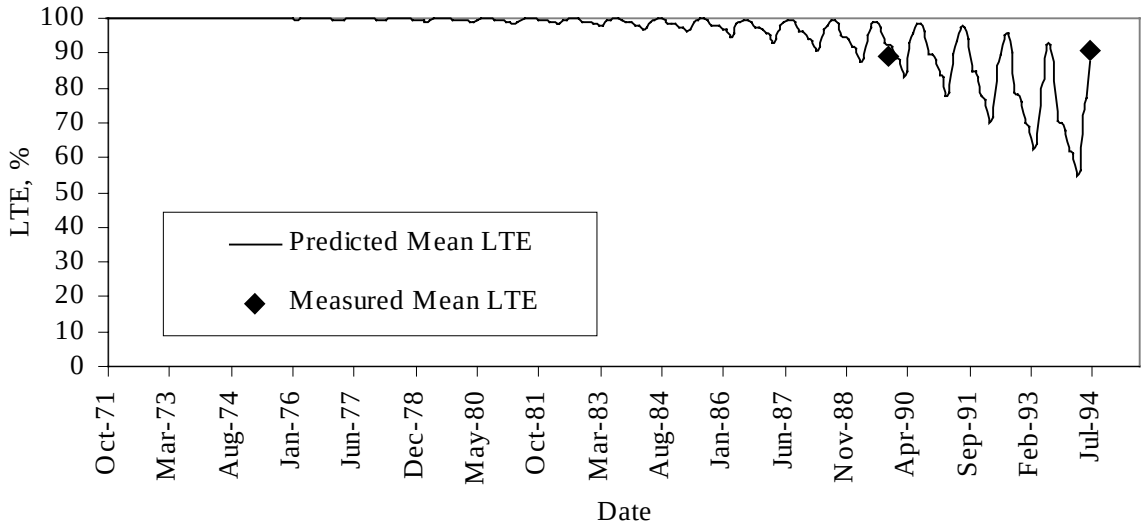

Figure 4. Comparison of predicted and measured total LTE for LTPP GPS-5 section 175849 in Illinois.

MODELING OF BASE ERODIBILITY

Support conditions proved to be one of the critical factors affecting critical tensile stresses and accelerating the punchout development process *(1, 6, 7).* To simulate the loss of support process due to pumping, the annual rate of erosion was estimated using the following formula recently developed by the 2002 Guide research team based on modified PIARC recommendations *(18 to 21).*

$$RE = (-9.398 + 0.434P_{200} + 1.977EROD + 0.012PRECIP) \quad (7)$$

Where
RE = Yearly rate of increase in erosion extension beneath the slab, mm/year (in/year).
P_{200} = Percent subgrade passing the no. 200 sieve.
PRECIP = Mean annual precipitation, mm (in).
EROD = Base erodibility index from the table below.

Table 4. Erodibility factor based on modified PIARC erodibility class.

EROD	**Material Description***
1	Lean concrete with 8 percent cement; bituminous concrete with 6 percent asphalt cement, or a permeable drainage layer.
2	Cement treated granular material with 5 percent cement manufactured in plant; bitumen treated granular material with 4 percent asphalt cement.
3	Cement-treated granular material with 3.5 percent cement manufactured in plant; bitumen treated granular material with 3 percent asphalt cement.
4	Granular material treated in place with 2.5 percent cement, treated soils.
5	Untreated granular material.

- Modified from original PIARC recommendations.

MECHANISTIC MODELING OF CRITICAL TENSILE STRESSES

To simulate CRCP structural response, a finite element model was created using the ISLAB2000 rigid pavement analysis finite element software. The LTE and base erodibility models described in the previous section were utilized to compute LTE and void extent for different seasonal and annual increments over the pavement design life. Other time-dependent parameters that were used in the model were PCC strength gaining with age and seasonal moisture and nighttime temperature gradients through concrete slab thickness. Axle loading was applied to the central CRCP panel in the lane adjacent to the shoulder. The critical top tensile stresses in the longitudinal direction were investigated for the various combinations of material characteristic, environmental parameters, and axle loading. An example of the model graphical output is shown in figure 5.

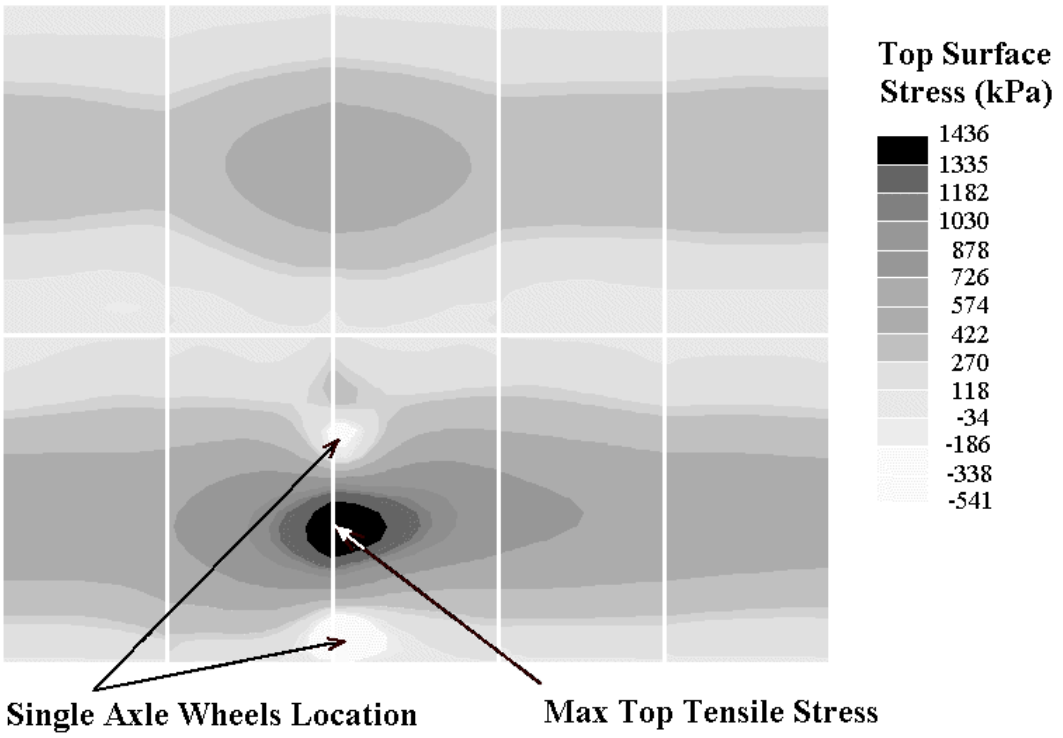

Figure 5. Example of CRCP model output from ISLAB2000.

The combination of crack spacing and crack LTE was found to have the most significant effect on CRCP critical response. Narrow crack spacing coupled with low LTE produce high top tensile stress (as shown in figures 6 and 7) that could lead to punchout development. This theoretical finding is strongly supported by the results of the LTPP data analysis that show the average width of the PCC segment that will develop a punchout is 0.43 m (17 inches). Critical stresses on narrow segments are magnified even more in the presence of slab curling and in the case of erosion along the pavement-shoulder edge, as demonstrated in figures 8 and 9.

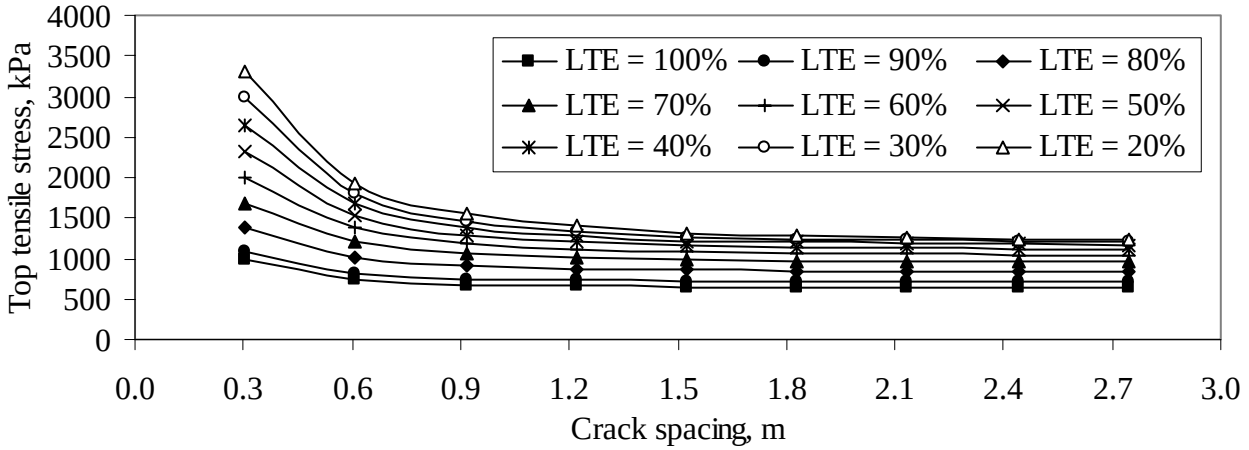

Figure 6. Effect of crack spacing and crack load transfer efficiency on critical CRCP stresses resulting from single axle loading at 80 kN (18,000 lb) for a model with PCC thickness=203 mm (8 in), E=27.5 GPa (4,000,000 psi), k=54.2 MN/m^3 (200 pci).

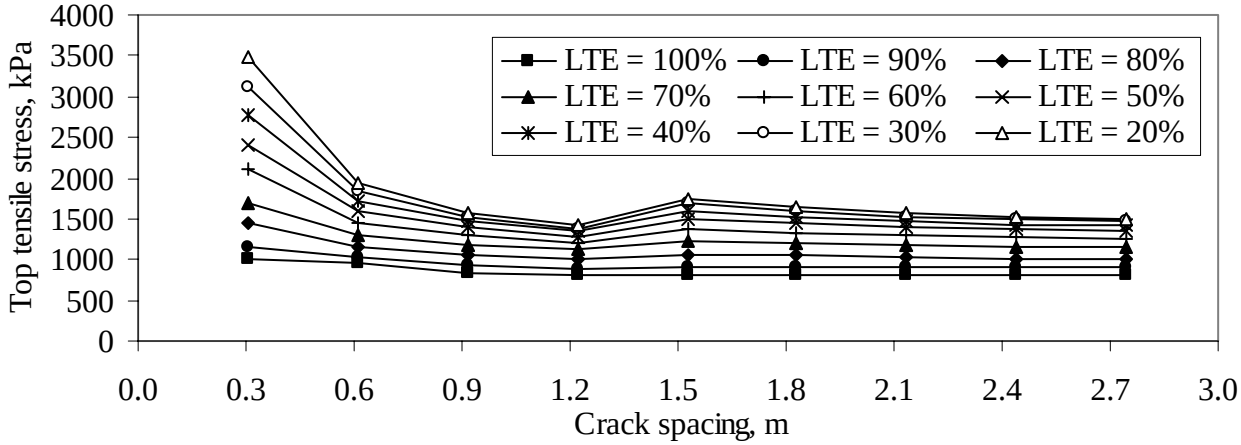

Figure 7. Effect of crack spacing and crack load transfer efficiency on critical CRCP stresses resulting from tandem axle loading at 160 kN (36,000 lb) for a model with PCC thickness=203 mm (8 in), E=27.5 GPa (4,000,000 psi), k=54.2 MN/m^3 (200 pci).

FATIGUE DAMAGE MODELING

Once critical stresses are known, accumulated fatigue damage could be estimated over the design life and used to predict punchout distress. According to Miner's hypothesis, each truck axle load passage contributes to overall pavement damage that accumulates over time. For CRCP, Miner's hypothesis is implemented in the following form (cracking failure mode):

$$D_{ij} = \sum_i \sum_j n_{ij} / 10^{2.13\left(\frac{MR}{\sigma_{ij}}\right)^{1.2}} \quad (8)$$

Where

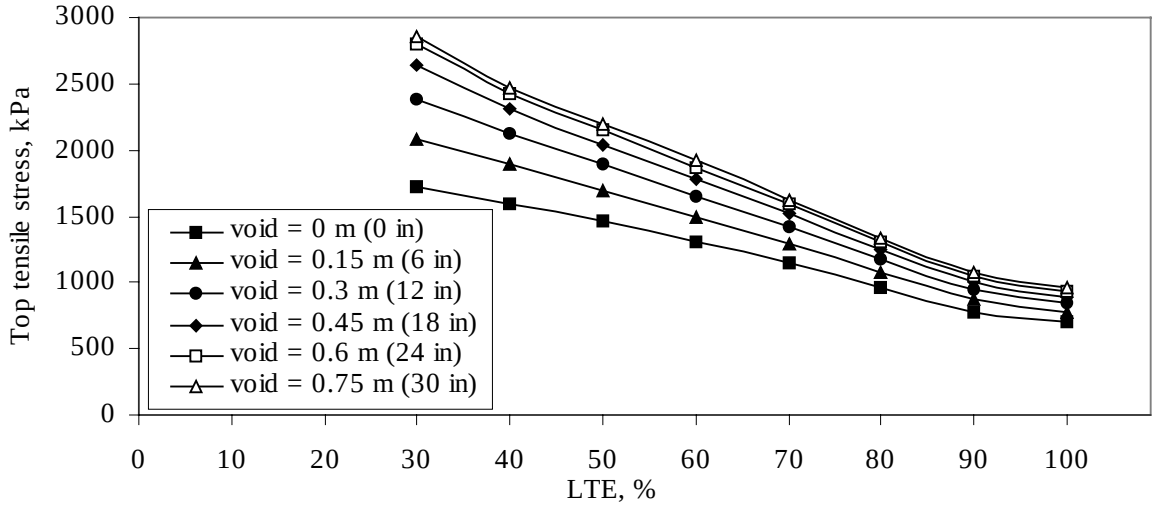

Figure 8. Effect of loss of support along the edge on critical CRCP stresses for a model with 0.6 m (2 ft) crack spacing, PCC thickness=203 mm (8 in), E=27.5 GPa (4,000,000 psi), k=54.2 MN/m^3 (200 pci).

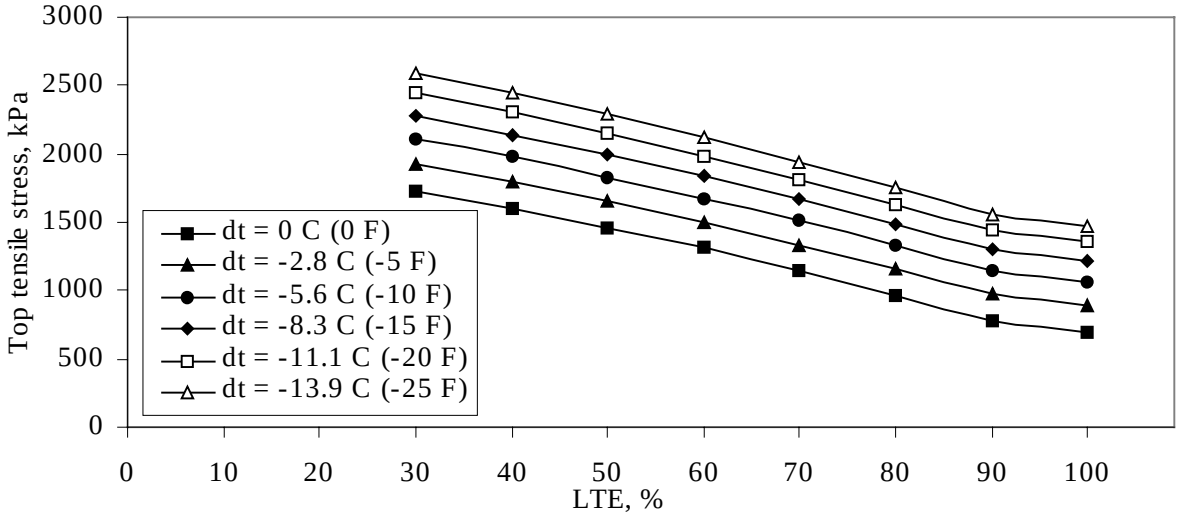

Figure 9. Effect of environmental slab curling on critical CRCP stresses for a model with 0.6 m (2 ft) crack spacing, PCC thickness=203 mm (8 in), E=27.5 GPa (4,000,000 psi), k=54.2 MN/m^3 (200 pci).

n_{ij} = Number of single or tandem axle loads of the *j*th magnitude applied during time increment *i*.

MR_i = Modulus of rupture during time increment *i*, kPa (psi).

Φ_{ij} = Bending stress computed for design conditions of time increment *i*, kPa (psi).

Since the damage prediction is cumulative as a function of tensile stresses at different instances over the life of the pavement, accurate prediction of stress changes over the design life is important. The analysis period is subdivided into time increments based on pavement design

life, concrete strength gain, subgrade support, and climatic conditions relative to their effect on crack width and load transfer. The example in figure 10 demonstrates differences in predicted accumulated damage for four different percentages of steel reinforcement. Different percent steel resulted in different mean crack spacing and, hence, different LTE of the transverse cracks. All other design inputs and traffic conditions were modeled identically for all four combinations using data from LTPP CRCP section 175849 in Illinois.

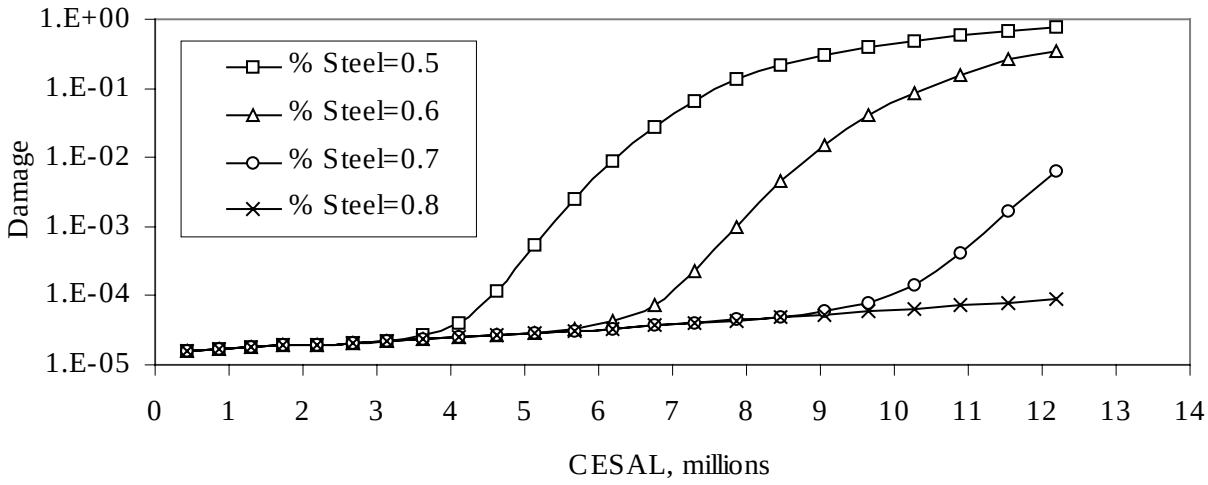

Figure 10. Comparison of cumulative damage predicted over time for four models with different steel percentages.

SUMMARY AND CONCLUSIONS

A method for predicting CRCP performance, as suggested in this paper, is based on a process associated with the development of punchouts. Punchout development is directly related to the formation of a longitudinal crack between two adjacent transverse cracks and the amount of erosion present. This crack initiates at the top of the slab and propagates downward through the CRCP. The development of the longitudinal crack is, in turn, related to the accumulated fatigue damage caused by a slab bending in the transverse direction.

Based on field and analytical results, previous studies have shown the critical bending stress is located at the slab top located about 1 to 1.5 m (40 to 60 in) from the slab edge. The higher the stress, the greater the fatigue damage and the potential for punchout development in CRCP. It is critical to control the development of punchouts in CRCP to ensure desired performance. Successful CRCP design can be assured through adequate crack width/thickness combinations, uniform crack opening and crack spacing distribution, and the provision of uniform support conditions throughout the life of the pavement

To ensure that a CRCP design will perform as required over the design period, it is desirable to place limits on crack width/thickness combinations. A structural model that can assess the effect of the steel on the crack width relative to the prediction of crack spacing for a given base friction, temperature drop, and applied drying shrinkage was presented in this paper. Crack width was

shown to vary directly with crack spacing (when all other parameters are constant) and increasing with time over the design period.

The crack LTE was modeled as a function of crack width, slab thickness, base and shoulder type, and applied traffic loading. The process of incremental crack LTE deterioration was modeled mechanistically through simulation of shear deterioration process as a result of the repetitive axle loading. The model was based on the assumption obtained from the previous studies that very little LTE deterioration occurs even under heavy axle loading if crack width over thickness ratio is maintained above certain level (corresponding to 92 percent LTE or above).

The analytical models for crack width, crack LTE, and subgrade support presented in the paper are time-dependent, thus providing necessary inputs for incremental damage accumulation modeling over pavement design life. The results presented in this paper provide practical means for prediction of changes in the design parameters and associated pavement responses based on sound, mechanistic-based principles coupled with the results of laboratory observations and analysis of long-term pavement performance data. The analytical procedure summarized in this document is currently being utilized as the main structural model for the design of CRCP as part of the 2002 Design Guide.

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