# Evaluation of Top-Down Cracking in Thick Asphalt Pavements and the Implications for Pavement Design

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**Surface-initiated longitudinal wheelpath cracks (or top-down cracks) had been observed in both cores and trench sections removed from asphalt concrete highway pavements. Cracking was documented in both thin and thick pavement sections and the mechanisms for surface crack propagation were explained. An approach was developed using a combination of fracture mechanics and finite element modeling to analyze a cracked pavement and predict the response of the pavement near the crack tip and throughout the depth of the asphalt concrete layer. Prediction of pavement response indicated that the mechanism for crack propagation was primarily tensile and that the influence of pavement structure and load spectra (magnitude and position) is significant. Load positioning and temperature-induced stiffness gradients in the asphalt concrete were shown to have the most effect on crack propagation, along with asphalt and base layer stiffness. The mechanism provided an explanation for crack propagation that confirmed observations of crack growth in the field. Crack growth was divided into stages according to crack length and depending on various structural characteristics. A concept called "time of low crack-growth activity" was formulated that considers the magnitude of tension and crack length as a function of time. Most importantly, the mechanism and details of top-down cracking were described and may be considered before selecting an appropriate perpetual pavement system.**

Over the last several years, surface-initiated longitudinal wheelpath cracking has been plaguing Interstate highways as the predominant mode of failure in Florida. A similar problem has been reported in Europe and is apparently more prevalent in other parts of the United States as well. Several different combinations of cracks have been observed, such as single cracks in either wheelpath, both wheelpaths (as seen in Figure 1), between the wheelpaths, and even multiple longitudinal cracks in the wheelpaths. Extensive work has been done by researchers at the University of Florida and the Florida Department of Transportation to identify the causes and solutions to this problem.

In the past, cracking has always been assumed to start at the bottom of asphalt concrete and propagate upward through the layer. Various factors have been evaluated with respect to the response at the bottom of the pavement layer (at a location centered underneath load) and structure was shown to have a strong effect. However, visual inspection of cores and trench sections clearly showed that cracks initiate at the surface of the asphalt concrete and propagation downward in the layer, as seen in Figure 2.

FIGURE 1  Lane exhibiting surface-initiated longitudinal cracks in both wheelpaths.

FIGURE 2  Core extracted from wheelpath illustrates crack opening at surface.

Detailed investigation of this distress has been published in other forums and the objective of this paper is to summarize the findings related to top-down cracking. The findings are presented particularly as they relate to perpetual pavements in the following areas:

- Mechanisms for initiation and propagation,
- Key factors dominating the mechanisms, and
- Implications for mitigation and design.

## FINDINGS FOR CRACK INITIATION

During the study, particular attention was paid to pavement surface stresses and their input to the distress mechanism. Tire-pavement interface stresses, including lateral stresses, thermal stresses, and induced stiffness gradients, were all analyzed. Tire-pavement interface stresses measured on an instrumented steel-bed device were obtained for a variety of truck tire types and of tire-inflation pressures and loads, and the resulting stresses were applied to the pavement models. Of particular interest were the transverse stress reversals that are induced under the ribs of radial truck tires. Analysis of thermal stresses revealed that a critical condition for high tension exists over a brief period of time, particularly during winter evening hours.

Pavement structure was also evaluated as a contributing factor for surface-initiated longitudinal wheelpath cracking. Both layer stiffness and thickness were varied to values typically found on Interstate highways. The sensitivity analysis showed that the magnitude of surface stresses was greatest in thicker pavements, as a result of decreased bending, under the widest tire rib.

Therefore, the primary contributors to surface-initiated longitudinal wheelpath cracking are transverse contact stresses induced by radial truck tires; thermal stresses may also have some influence. In some cases, cracks may be induced by differences in paving equipment (as suggested by researchers in Illinois DOT).

From preliminary findings that showed that pavement structure (thickness and stiffness) had little effect on surface stresses, it appears that this problem may be addressed through the use of improved asphalt mixtures with higher fracture resistance. In addition, measured tire-pavement interface stresses are instrumental in the proper evaluation of pavement cracking performance and must be considered.

## MECHANISMS FOR CRACK PROPAGATION

The potential causes for crack initiation were discovered; however, an explanation for propagation of top-down cracks past the initial stage was needed. One reason was that neither tire contact nor thermal surface stresses could be used to describe the propagation of top-down cracks. A relatively small zone of tension, approximately 1 cm deep, was predicted at the surface of the pavement. Therefore, research work was conducted to define the damage mechanisms and further identify factors that control propagation.

A parametric study was conducted to isolate the effects of various parameters on surface crack propagation. Some of the parameters evaluated include: load spectra (positioning with respect to crack and measured vertical and lateral tire contact stresses), cracks and discontinuities, crack depth, asphalt pavement thickness (Interstate highway pavements are typically thick and stiff), and surface and base-layer stiffness. The range of values for these factors is illustrated in Figure 3. Stiffness gradients induced in the asphalt concrete layer, due to daily temperature and environmental fluctuations, were also analyzed for their influence on crack growth.

Fracture mechanics was the analytical procedure selected for the prediction of crack growth. Stress intensity factors were computed to define the response behavior at the crack tip. That is, a local description of the crack tip region was provided and the stresses in the process zone (or contours) ahead of the crack tip were predicted. The three parameters used in the evaluation are defined as follows:

Mode I Stress Intensity Factor, $K_{\mathrm{I}} \approx \lim \sigma_{xx} * (2\pi r)^{1/2}$
Mode II Stress Intensity Factor, $K_{\mathrm{II}} \approx \lim \tau_{yx} * (2\pi r)^{1/2}$
Fracture Energy Release Rate, $J = (K_{\mathrm{I}}^2 + K_{\mathrm{II}}^2) * (1 - \nu^2)/E$

where

$\sigma_{xx}$ = transverse stress
$\tau_{yx}$ = shear stress
$\nu$ = Poisson’s ratio
$r$ = vertical distance away from crack tip
$E$ = stiffness modulus

Results of the parametric study indicated the effects of pavement structure. Tension was found to be the overwhelming contributor to failure and greatly exceeded the magnitude of shear at the crack tip, indicating that crack growth is primarily through Mode I opening. Figure 4 illustrates the difference in magnitude between the tension and shear stress intensity factors. The figure also indicates that a higher stiffness ratio (asphalt to base-layer stiffness) increases tension at the crack tip. The most critical factor for tension at the crack tip was found to be load position. The magnitude of tension then depended on the crack length, as shown in Figure 5.

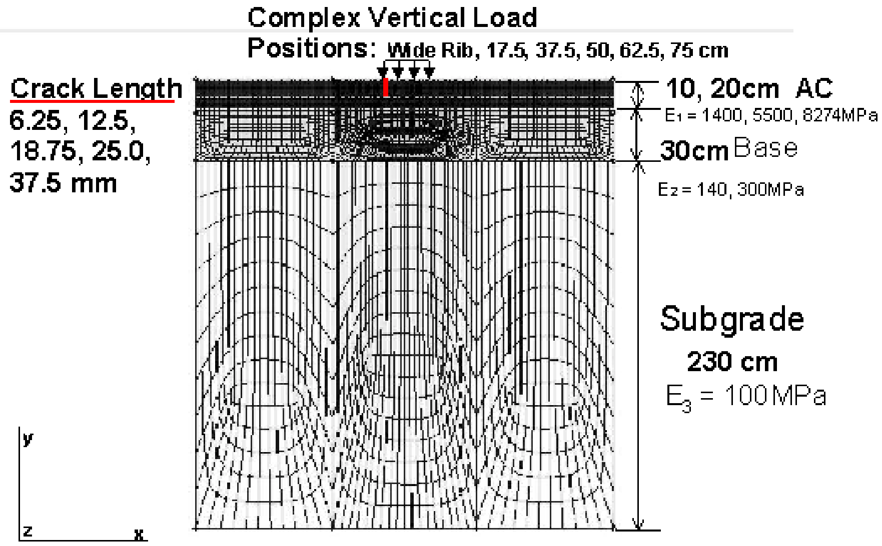

**FIGURE 3 Pavement model showing parameters evaluated for identification of factors critical to propagation of surface cracking (AC = asphalt concrete, *E* = stiffness modulus).**

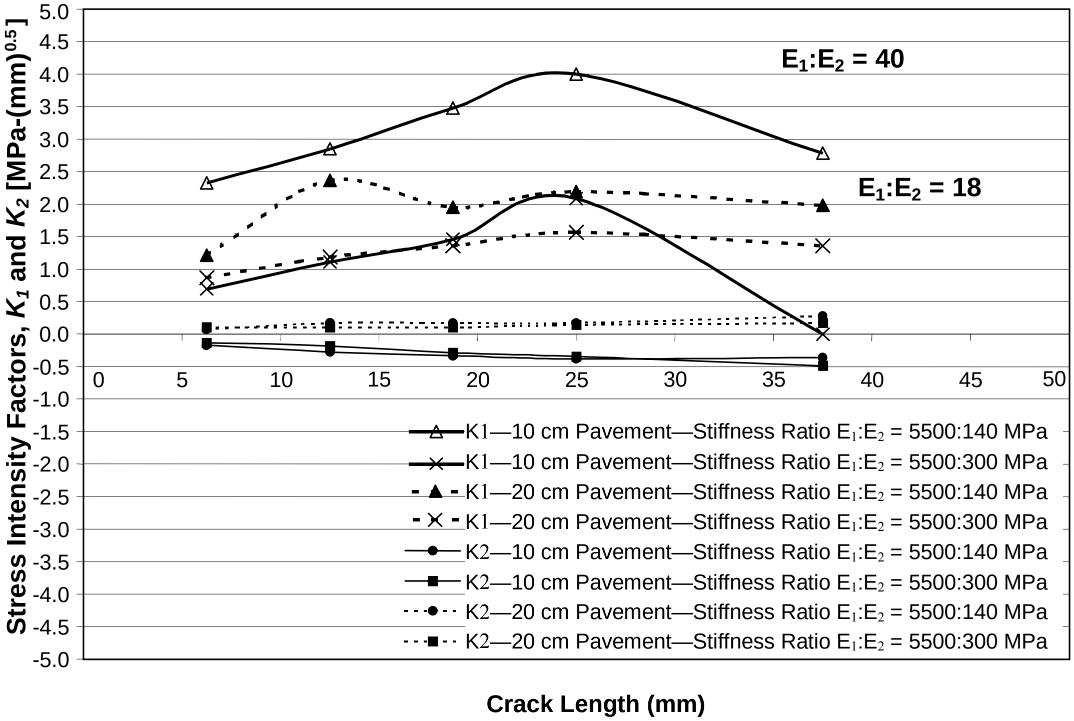

**FIGURE 4 Comparison of failure modes: magnitude of tensile fracture ($K_I$) versus shear fracture ($K_{II}$) for one loading case (62.5 cm from crack).**

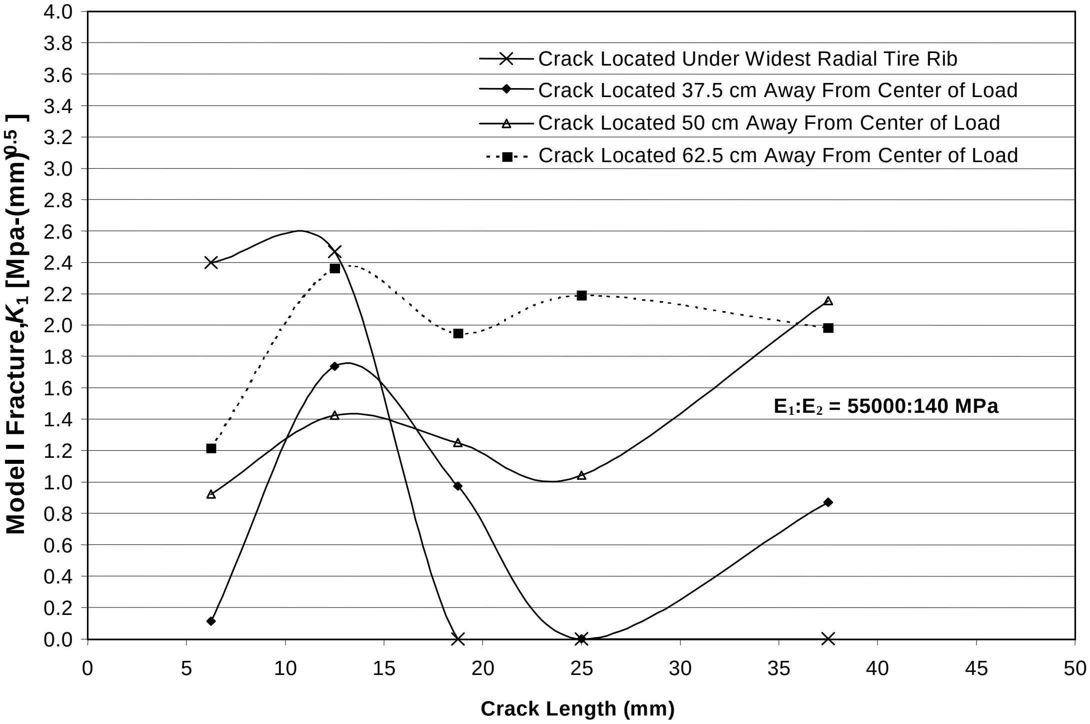

**FIGURE 5 Effect of load positioning on opening at the crack tip for 20-cm surface layer with a high stiffness ratio.**

The parametric study also included identifying the influence of stiffness gradients on crack growth. The stiffness gradients selected for this study were based on measurements taken from a FHWA study in northcentral Florida. Temperature differentials, age-hardening, and sudden rains all contribute to the inducing of sublayers of variable stiffness within asphalt concrete. The four gradient configurations determined for the evaluation are defined as follows:

- Case 1: Uniform temperature distribution (i.e., no stiffness gradient) mean pavement temperature computed at 1/3-depth when temperature conditions are warm.
- Case 2: Sharpest temperature gradient near surface—temperatures at 7 p.m. represent this condition.
- Case 3: Highest temperature differential between surface and bottom of asphalt concrete layer—temperatures at 5 a.m. represent this condition.
- Case 4: Rapid cooling near the surface represents case of sudden rain showers.

Finite element analysis of the pavement models indicated a major increase in tension at the crack tip. Figure 6 illustrates the tensile stress intensity at the crack tip at each stiffness gradient combination for a given pavement structure and load position. Observation of the figure shows that tension predicted in the stiffness gradient cases was sometimes as much as seven times greater in magnitude than in the case of a pavement with uniform stiffness. However, an asphalt concrete of uniform stiffness would never truly predict maximum crack growth. For this reason, analyzing the pavement as a layer of variable stiffness is a key factor in the prediction of surface crack propagation.

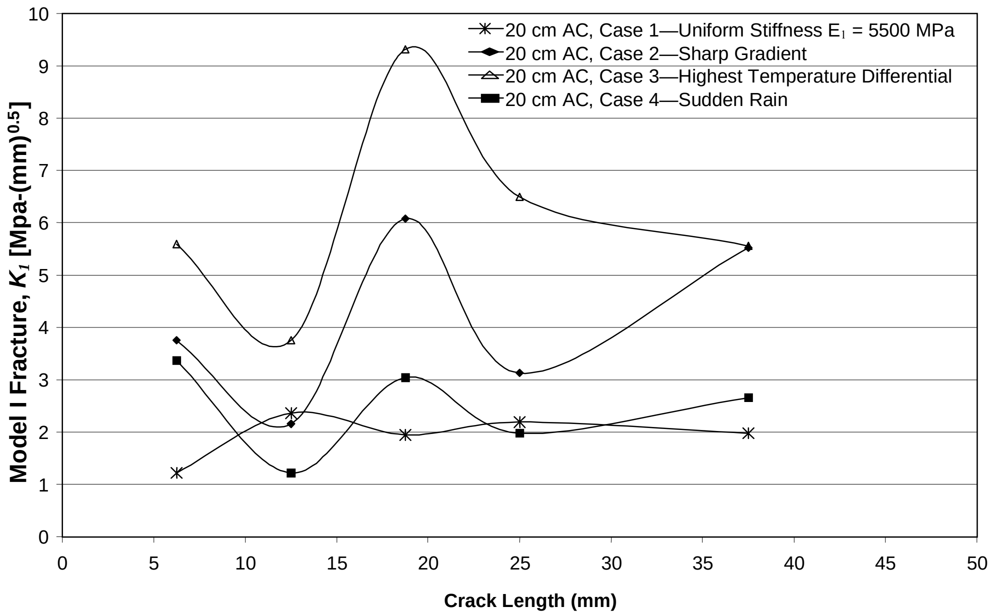

**FIGURE 6 Effect of temperature-induced stiffness gradients on stress intensity $K_1$ predicted at crack tip for 20-cm AC (load centered 75 cm from crack; base stiffness $E_2$ = 140 MPa; AC = asphalt concrete).**

## STAGES OF CRACK GROWTH

Interpretation of the findings from the parametric study led to defining of stages of crack growth. The two stages of crack growth for this study were defined as short cracks (6.25- to 12.5-mm depth) and intermediate cracks (18.75- to 37.5-mm depth). Evaluating the problem from this perspective helped to isolate the implications of various load spectra. Analyses indicated that both load wander and magnitude are instrumental in the cracking mechanism. For example, further observation of Figure 5 reveals that the critical load position is not always directly in the wheelpath on top of the crack. In fact, the location of the critical load position will depend on the crack length, the pavement structural characteristics, and even the type of stiffness gradient induced. For this reason, a need exists to determine how many loads actually induce tension at the crack tip.

It was also observed that the magnitude of tension varied depending on crack length, as a function of loading position and the other factors as seen in Figure 7. From extensive observation of all data, a conceptual idea was formulated that would define a "time of low crack-growth activity." Within this concept, cracks would be allowed to develop to a certain intermediate length. A time of "low crack-growth activity" would be defined as the time period where the stress intensities are relatively low and cracks are not inclined to propagate. Then, at the first indications of increased cracking, pavement rehabilitation could be applied before the crack exceeded the predetermined intermediate length. It is critical to rehabilitate the pavement early in the cracking process, depending on the time available before the crack rate speeds up.

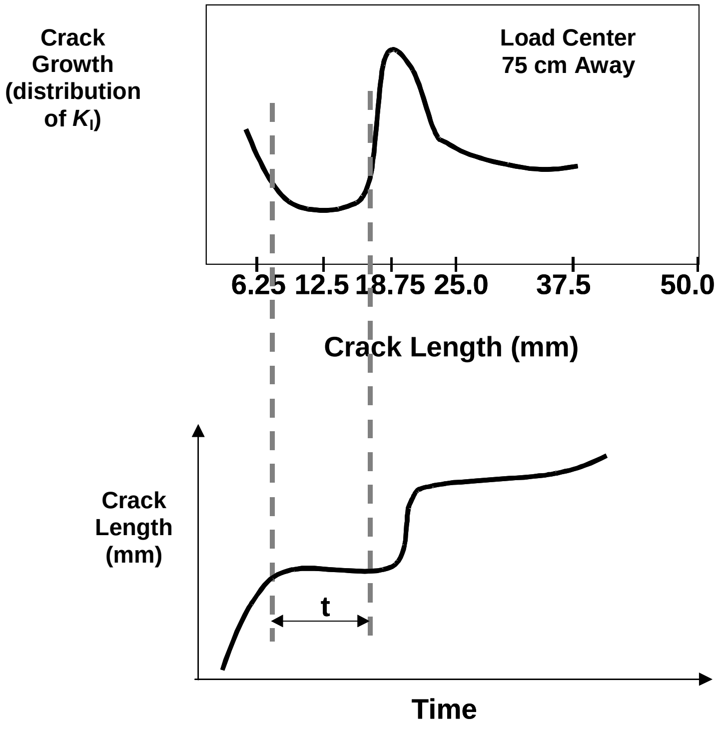

**FIGURE 7 Potential for crack growth and time available for identification and rehabilitation for 20-cm pavement and given load spectrum. (*t* = time available for identification and rehabilitation.)**

Analyses indicated that for given load spectra, the cracking potential varies with crack length and apparently slows at intermediate crack lengths. The distribution of $K_1$ can then be translated to a crack growth potential as the crack length increases, as shown in Figures 7 and 8. Knowing the crack growth potential may then lead to the development of a pavement management approach defining a time period in which to perform rehabilitation. The conceptual "Time of Crack Growth Activity" can be applied to individual field sections depending on recorded load wander, pavement structure, and seasonal temperatures.

## IMPLICATIONS FOR DESIGN

Comprehensive analyses showed that top-down cracks develop even in thick pavements that may not be susceptible to other forms of damage. In addition, the mechanisms for top-down cracking cannot be captured without considering critical factors such as realistic contact stresses, temperature-induced stiffness gradients, load spectra (magnitude and wander), and the presence

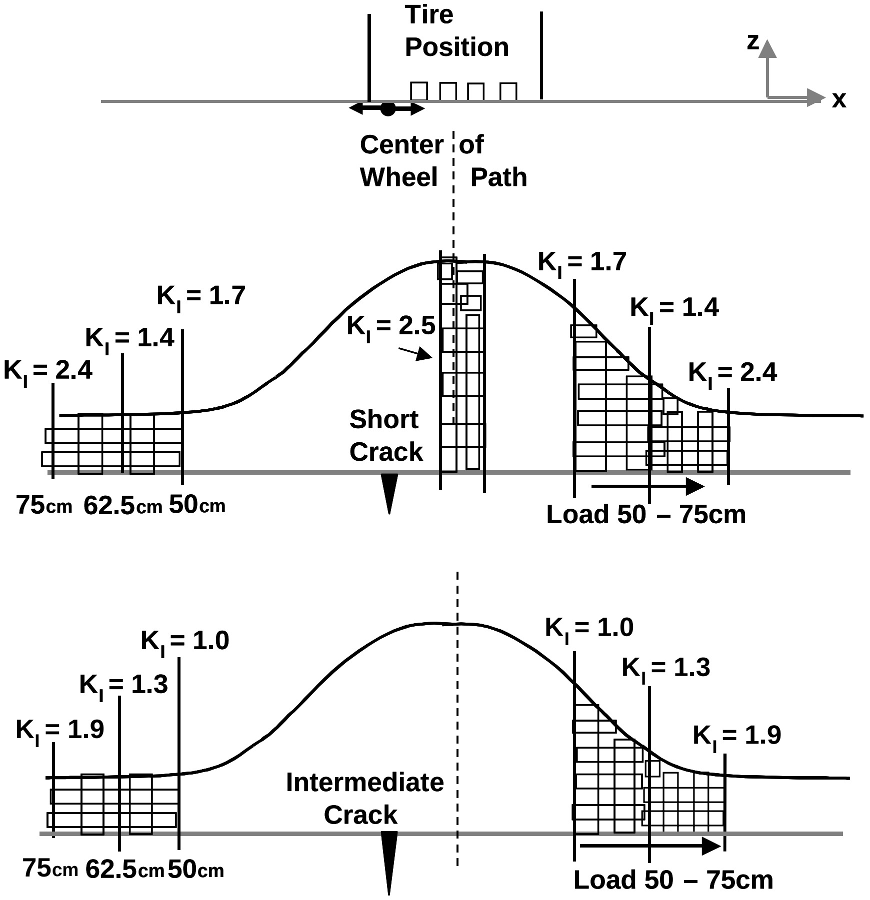

**FIGURE 8 Transverse distribution of load within wheelpath and critical load positions for cracking in a 20-cm asphalt concrete layer of uniform stiffness ($E_1$). [AC = asphalt concrete; fracture stress intensity ($K_1$) in MPa $(mm)^{0.5}$]**

of cracks and discontinuities as described through use of fracture mechanics. Consideration of these factors would indicate that employing a design approach using averaged pavement and load conditions is inadequate and will not predict cracking since critical conditions must be identified. It appears that fracture mechanics is then necessary for predicting the cracking mechanism through its description of stress redistributions at the crack tip and its identification of local effects. Likewise, stiffness gradients were shown to significantly intensify the cracking mechanism, which implies that analyzing with a uniform layer stiffness would be unrealistic and would not capture the true magnitude of tension generated in the pavement.

Evaluation of all data suggests that mitigation of top-down cracking should be addressed primarily through the implementation of more crack-resistant surface materials and use of less damaging truck tires. Thus, a focus for prevention should concentrate on improving surface materials, communication with tire designers, and pavement design-management techniques. Since cracking potential was shown to increase with asphalt concrete thickness, the use of multiple overlays may actually exacerbate crack growth, indicating that mill-replace techniques may be a better alternative for mitigation of top-down cracks.

## CONCLUSIONS

Based on the findings of the comprehensive analytical and field study, propagation of surface-initiated longitudinal wheelpath cracks is a Mode I tensile failure mechanism and occurs only under critical conditions. Finite element analysis of a cracked pavement was conducted to define the critical design conditions at which crack growth will occur, as a function of several pavement structural factors that were varied to determine their individual effects on crack propagation. Results indicated that it is necessary to model cracks and discontinuities and predict stress redistributions at the crack tip, as well as compute the direction of crack growth. The analyses showed that crack growth must be analyzed using realistic load spectra to adequately predict pavement performance since load positioning was found to be the overriding contributor to crack growth. In particular, to predict failure and to determine future design conditions, load wander must be considered along with the use of measured tire contact stresses.

It may also be concluded that additional factors must be included in a future approach to pavement design, such as crack length and temperature-induced stiffness gradients in asphalt concrete, because of their significant effect on the tensile response of surface cracks. Therefore, a sensitivity analysis should be developed for determining the rate of crack growth relative to time. Once the crack-growth rate relative to time is a defined parameter, it may be adopted as a pavement management strategy. It is suggested that the period of time when the crack rate slows down should be defined; however, additional field and mixture information is needed to define this length of time in order to establish guidelines for pavement management.

## ACKNOWLEDGMENTS

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