MECHANISTIC INVESTIGATION OF REFLECTION CRACKING OF ASPHALT OVERLAYS

Michael S. Luther, Alden and Stilson and Associates, Columbus, Ohio; and
Kamran Majidzadeh and Che-Wei Chang, Ohio State University, Columbus

In this paper, a mechanistic approach to the study of reflection cracking is discussed, and the limitations of empirical methods of analysis are briefly reviewed. Based on the concept of mixed-mode fracture, it is shown that, for the analysis of reflection cracking, the concept of a strain-energy-density factor is more applicable since it considers provisions for incorporating the effect of other modes of fracture. Theoretical analysis using a prismatic finite element program has been used to verify the postulated mechanisms. In addition, the results of laboratory experiments on model overlay structures are presented and indicate that the hypothesis of mixed-mode fracture is relevant.

•REFLECTION cracking refers to the cracking of a flexible resurfacing or overlay above underlying cracks or joints. The importance of this type of pavement distress became apparent to highway engineers in the middle 1950s when many resurfacing projects experienced premature cracking failures in zones of underlying joints or cracks in the old rigid pavement. This new problem presented unique maintenance difficulties because, when cracks develop, retardation of decreasing surface characteristics in areas immediate to the reflected crack is not an easy task. It has been recognized that this distress mode is a direct result of some damage process occurring in the underlying pavement structure. Several full-scale field evaluations have been conducted with the premise that reflection cracking is caused by differential vertical or horizontal movement at joints, cracks, and pavement edges of the underlying rigid pavement (1). Furthermore it has been observed that the asphalt overlay does not possess the strength to resist the induced stresses due to such movements. Past research has dealt with prevention rather than rational examination of the associated damage process.

Essentially, investigators have adopted three approaches to prevent reflection cracking, one of which is the concept of strengthening of the resurfacing layer. Several projects have unsuccessfully used wire mesh reinforcement in the bituminous overlay material to more evenly distribute induced stresses (1, 2, 3). Unfortunately, the wire mesh did not reduce the incidence of reflection cracking significantly, and its use has been abandoned. In a number of studies, attempts have been made to increase overlay strength by increasing its thickness (4). This was also unsuccessful because reflection cracks often developed in less than a year in resurfacings of up to 5 in. (12.7 cm) in thickness. Recently, additives have been introduced into overlay mixtures to impart increased ductility needed to absorb joint and crack movements of the underlying rigid slabs (5). Currently, sufficient evidence is not available about whether such additives can add enough ductility and yet retain the required mix stability.

The reduction of underlying slab movements has been considered as another approach to prevent occurrence of reflection cracking. Louisiana and Minnesota have attempted to reduce the incidence of reflection cracking by breaking up concrete pavements before resurfacing (6, 7). Although this method has been successful to a limited extent, pave-

---

Publication of this paper sponsored by Committee on Design of Composite Pavements and Structural Overlays.

ment cracking may destroy the structural integrity of the base, thereby increasing the probability of other types of distress.

In another preventive approach, Michigan and California have attempted to reduce stress transfer between the overlay and the pavement structure by adding soil cushion or bond breaking agents such as wax paper and aluminum foil between the rigid and flexible layers. This approach, although partially effective, also might result in stability problems in the resurfacing layer.

Considering the ever rising cost of road maintenance, the preventive approach based on trial and error or reliance on the experience of others no longer seems to be valid. Clearly, a thorough rational investigation is needed to identify the damage process resulting in reflection cracking to formulate a mechanistic approach for overlay design purposes. Based on concepts initially presented at the Austin conference (8) and subsequently further developed, it is postulated that reflection cracking is a result of fatigue fracture of the asphalt material over a zone of weakness (crack or joint) and that these fracture and fatigue processes can be analyzed by using fracture mechanics principles. Investigations at Ohio State University with model flexible pavements have clearly shown that fatigue fracture of asphalt materials can be studied and predicted by using fracture mechanics principles (9, 10). In this paper, results of research obtained from the first phase of an investigation concerning the applicability of fracture mechanics to rational analysis of reflection cracking are discussed. This initial phase of the study deals only with traffic-induced stresses and the identification of appropriate fracture mechanics theory to describe the damage resulting from such stresses. However, later phases of the study will consider the influence of thermal stresses on the incidence of reflection cracks. Fortunately, as presented in this paper, the mechanistic approach is primarily concerned with the stress state existing near flaws or crack tips; thus thermal effects can be easily accounted for by superposition of thermal and load-induced stresses. It is hoped that this study will bring about a greater understanding of rational overlay design.

THEORETICAL CONSIDERATIONS

Inherent in the application of fracture mechanics theory is the hypothesis that fracture initiates from some preexisting flaw that acts as a stress concentration in the material. Subsequent stress application leads to eventual fatigue of the overstressed material and growth of the flaw until it becomes a visible crack. There is abundant evidence that such small flaws exist in asphalt materials (11).

The process of crack initiation differs among various materials. In certain alloys, polymers, and heterogeneous compositions, such as asphalt materials, because of the presence of inherent flaws, it is reasonable to expect a crack to initiate at the first few cycles of load application (16). There is abundant evidence that flaws do exist in asphalt materials (9, 10, 11, 13). In fact, the presence of such flaws has been used to establish a design method to predict the fatigue life of flexible pavements by researchers at Ohio State University (13).

It is thus reasonable to hypothesize that overlay cracking is the end product of fatigue growth of a subsurface crack whose origin was a small flaw in the asphalt material. Furthermore, the flaw most likely to develop into a crack is the one subjected to the maximum stress concentration. In an asphalt overlay of a rigid pavement, the maximum stress concentration occurs at flaws over underlying zones of weaknesses (joints or cracks) in the rigid base and thus gives rise to reflection cracks.

In fracture mechanics, the elevation of stresses at the vicinity of discontinuities or flaws can be represented by the stress-intensity factor K, as follows:

$$\sigma_{ij} = r^{-1/2}\left[K_1 f_{ij}^{I}(\theta) + K_2 f_{ij}^{II}(\theta) + K_3 f_{ij}^{III}(\theta)\right] \tag{1}$$

where K_1, K_2, and K_3 represent stress intensity factors corresponding to three modes of fracture as shown in Figure 1 in which $f_{ij}(\theta)$ is a geometrical function. For mode I fracture, the opening mode, the magnitude of stress field for small-scale yielding is given as

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{xy}\end{Bmatrix} = \frac{K_1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\begin{Bmatrix}1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\\ 1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\\ \sin\frac{\theta}{2}\cos\frac{3\theta}{2}\end{Bmatrix} \tag{2}$$

with similar expressions for the other modes involving K_2 and K_3. The stress intensity factor depends on the load, specimen geometry, and crack configuration and can be evaluated experimentally or by analytical techniques. The critical limit of the respective K values (K_{1c}, K_{2c}, and K_{3c}) are material properties known as the critical stress-intensity factors with K_{1c} having been determined by using beam specimens whose dimensions fulfill the established fracture mechanic criteria. K_{2c} and K_{3c} values have not been established for asphalt or other materials, nor has a literature search revealed the establishment of standard criteria to perform K_{2c} and K_{3c} tests.

In previous research conducted at Ohio State University concerned with the fatigue and fracture analysis of sand-asphalt slabs resting on an elastic foundation and beams on elastic foundation, the applicability of mode I analysis has been sufficiently demonstrated. Specifically, the experimental results for beam on elastic foundation have indicated that sand-asphalt requirements for mode I fracture are fulfilled. However, an examination of the fracture propagation process of coarse-grained asphalt concrete mixtures and the study of probable mode of failure of overlay structures suggest that the use of mode I alone may not be sufficient and in fact might lead to substantial error. It should be noted that application of classical Irwin K_c theory is based on the assumption that the crack is in a normal position to the applied tensile stresses. However, because of irregular crack patterns resulting from material nonhomogeneity, such as aggregate concentration on nonsymmetric loading conditions, the crack direction will not align perpendicular to the loading direction and would result in the invalidity of the K_c theory.

To study the limitations of mode I fracture analysis to overlay design, one should consider the state of stresses and displacements in the vicinity of underlying joints and cracks. The hypothetical pavement system in Figure 2 shows a typical jointed concrete pavement overlayed with an asphalt layer. Because of the discontinuities, a 0.22-in. (0.56-cm) crack in the concrete layer and an initial 0.25-in. (0.63-cm) flaw in the bottom of the overlay, this structure cannot be analyzed by using available multilayer elastic programs. Therefore, a prismatic solid finite element program initially developed by Wilson and modified by Chang has been used to describe the stress-strain states existing in this pavement structure. This program approximates a three-dimensional analysis by giving the element depth (actually forming prism-shaped elements) with the load expressed as a known function in the depth z direction.

Figures 3 and 4 are plots of σ_x and σ_y and τ_{xy} as a function of r (distance from crack centerline) along the bottom of the asphalt layer for a load placed symmetric to the crack. The σ_x is compressive throughout, increasing greatly with r less than 0.3 in. (0.76 cm). Even in the zone next to the flaw tip, the σ_x stresses are compressive. Further analysis shows that the neutral axis is approximately 5 in. (12.7 cm) above the bottom of the concrete layer and that the crack in the asphalt layer closes rather than opens when it is externally loaded.

To determine the stresses that exist as load approaches the joint, analyses for the same pavement structure are performed with the loaded area offset a distance equal to the load radius from the crack centerline (Figure 5). As expected, the nonsymmetric loading produces a large change in the stress distribution at the bottom of the asphalt layer as shown by Figure 6. Again all the σ_x and σ_y stresses along the bottom are com-

Figure 1. Modes of fracture.

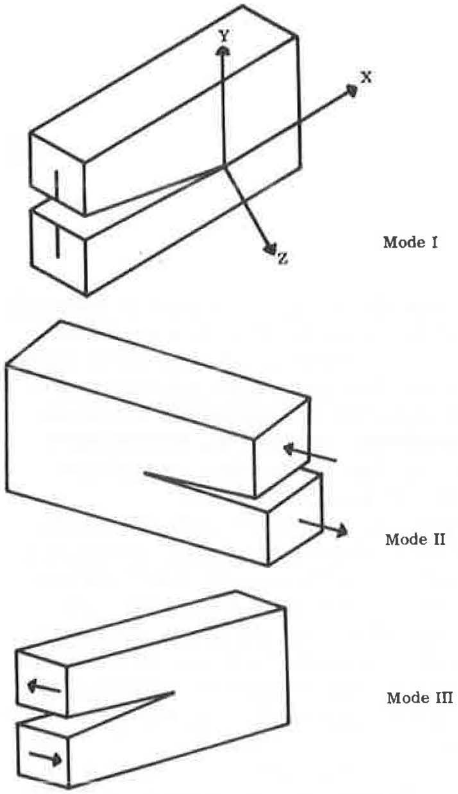
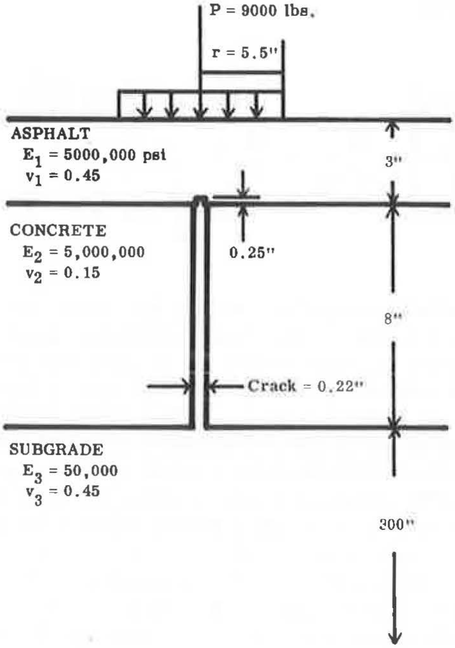


Figure 2. Finite element pavement with load symmetric to crack.



pressive with high localized stresses near the crack tip. Most important, however, is the fact that the shear stresses near the crack tip show a substantial increase from 0 to 40 psi (0 to 276 kPa). It is also noted that, in such a loading position, the shear stresses produced are maximum, and bending mode fracture (mode I) does not prevail.

Figure 7 shows how the value of subgrade modulus E_3 affects the magnitude of the shear stress developed at the overlay interface for the nonsymmetrically loaded situation. It is apparent that lowering the modulus from 50,000 to 5,000 psi (344 to 34 MPa) only significantly affected the shear stresses in the immediate vicinity of the crack and increased the τ_{xy} maximum value by about 50 percent.

Therefore, the results of this theoretical stress distribution indicate that, as a result of external load,

1. An asphalt overlay over a rigid pavement is subjected to compressive stresses throughout its depth (even in the vicinity of a crack) in both horizontal and vertical directions,
2. Shear stress in the vicinity of the crack tip is the parameter most affected by load position and subgrade modulus, and
3. Any preexisting flaws in the asphalt layer over the underlying concrete crack close when a load is applied.

Thus, it is important to conclude that a load associated with failure of overlay structures (i.e., reflection cracking) is predominately influenced by shear fracture rather than by the opening mode, bending fracture. However, when the effects are considered of other induced stresses that are caused by variation in the thermal region and by geometrical change, such as shrinkage expansion and construction, the opening mode

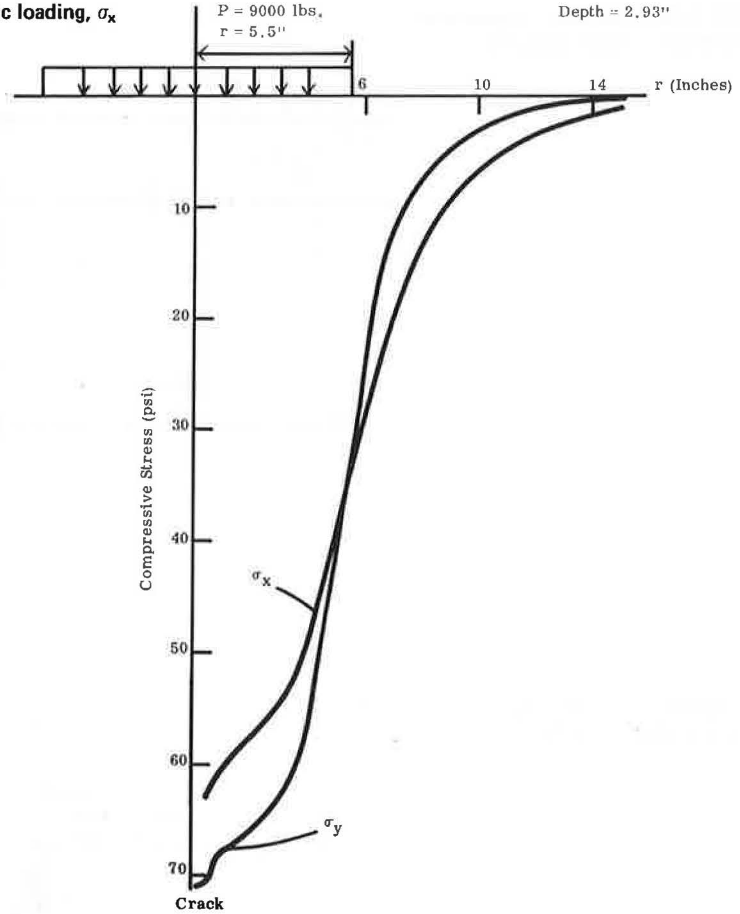


Figure 3. Finite element symmetric loading, σ_x versus r and σ_y versus r.

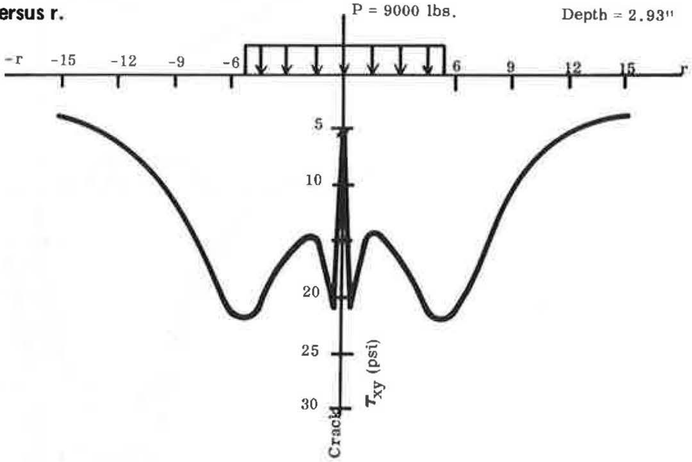


Figure 4. Symmetric loading, τ_{xy} versus r.

Figure 5. Finite element pavement with load offset r from crack.

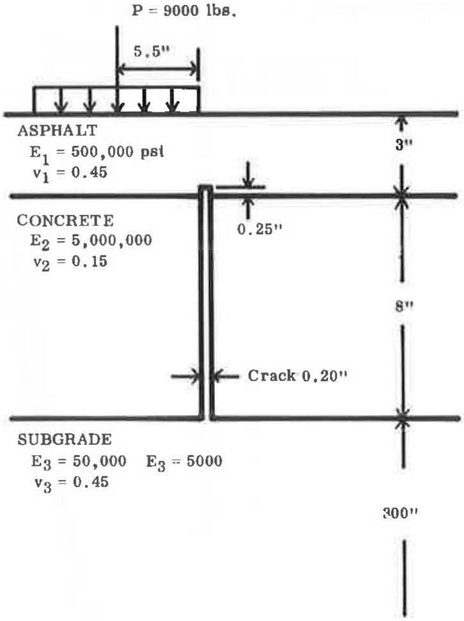
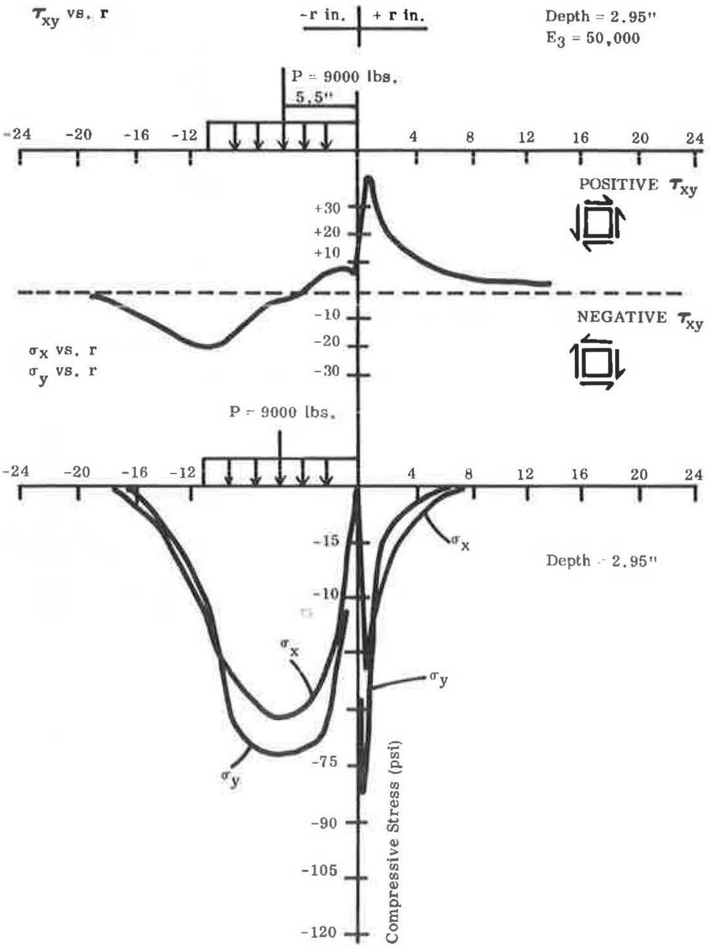


Figure 6. Finite element nonsymmetric loading.



fracture can also be recognized as a contributor to the state of distress. Thus it appears that the analysis of fracture and cracking, in most instances, would require consideration of the interacting effects of various modes of fracture.

Recently Sih (12) has proposed a theoretical approach known as the S_c theory based on the field strength of the local strain energy density (12). The fundamental parameter in the new theory, the strain-energy-density factor S, is direction sensitive, thus permitting the direction of crack growth to be predicted rather than assumed a priori as in the Irwin theory. S is a function of the stress intensity factors k_1, k_2, and k_3 given by

$$s = a_{11}k_1^2 + 2a_{12}k_1k_2 + a_{22}k_2^2 + a_{33}k_3^2 \tag{3}$$

where $k = K\sqrt{\pi}$. The coefficients for plain strain are given by

$$\begin{aligned} a_{11} &= \frac{1}{16G}\{(3 - 4\nu - \cos\theta)(1 + \cos\theta)\} \\ a_{12} &= \frac{1}{16G}\{(2\sin\theta)(\cos\theta) - (1 - 2\nu)\} \\ a_{22} &= \frac{1}{16G}\{4(1 - \nu)(1 - \cos\theta) + (1 + \cos\theta)(3\cos\theta - 1)\} \\ a_{33} &= \frac{1}{4G} \end{aligned} \tag{4}$$

where ν is the Poisson's ratio, and G is the shear modulus of elasticity.

The fundamental hypotheses on unstable crack growth in the Sih theory are as follows:

1. Crack initiation takes place in a direction determined by the stationary value of the strain-energy-density factor, i.e., $\delta S/\delta\theta = 0$ at $\theta = \theta_0$ = crack extension direction; and
2. Crack extension occurs when the strain-energy-density factor reaches a critical value, i.e., $S_c = S(k_1, k_2, k_3)$ for $\theta = \theta_0$.

The important feature of the S_c theory is that the single parameter S_c can simultaneously determine the fracture toughness of the material and the direction of crack initiation in a structure subjected to a general mode of fracture.

With regard to reflection cracking, the first step in applying the above fracture mechanics principles is to identify the fracture mode or modes associated with crack extension. The finite element stress analysis discussed previously predicted that the asphalt overlay subjected to load-associated stress would be in compression on the bottom. This leads to the conclusion that the opening mode (mode I) type of fracture does not occur. Most significantly, the computer analysis predicted that there would be significant relative displacement between the two concrete slabs when loaded at the edge of load over the center of crack position. This relative displacement between the two slabs would lead one to hypothesize that reflection cracking is of the mode II type (in plane sliding). But this hypothesis is questionable because of the high compression σ_x stresses present. In light of these conclusions, it is hypothesized that reflection cracking is a general mode of fracture occurring under the simultaneous interaction of K_1, K_2, and K_3.

Based on the pavement structure in Figure 1, the K_1 and K_2 stress intensity factors are shown in Figure 8 for the previously mentioned two load positions ($K_3 = 0$ at $z = 0$). It is difficult to associate the negative K_1 terms with the physical process of fracture and crack extension. McClintock and Walsh (15) have assumed that cracks close up under compression and develop friction on the sliding crack surfaces, hence requiring much higher compressive stresses to produce fracture. Thus it appears that at load position 1 fracture is much less likely to occur than at position 2 where significant shear stress is present at the crack tip. When a three-dimensional problem is considered, all modes of fracture should be present, and crack growth must be analyzed with the simultaneous interaction of these modes. Sih's theory provides the necessary method to handle this general mode of fracture.

In the application of these concepts to overlay design, mixed-mode fracture under repeated loading should be investigated. To the authors' knowledge, fatigue under predetermined mixed-mode conditions has not been experimentally observed, nor has any damage theory been formulated that uses fracture mechanics principles to predict general mode fracture. Substantial work has been done on mode I fracture in bituminous materials where damage growth can be represented by

$$dc/dN = A K_1^n \tag{5}$$

Recently, Majidzadeh and Ramsamooj (13), investigating the cracking of flexible pavements under moving load, have presented a growth law in the form of

$$dc/dN = A_1 K_1^{n_1} + A_2 K_2^{n_2} \tag{6}$$

where K_1 and K_2 are mode I and II stress intensity factors. According to this damage model, the damage resulting from the action of each fracture mode is additive and independent. However, there are a number of fundamental questions raised with respect to the validity of such assumptions.

EXPERIMENTAL OBSERVATION

Fatigue tests have been conducted to verify the hypothesis that reflection cracking is of mixed-mode fracture (specifically not mode I) and to observe the general propagation and mechanics of crack growth. Model laboratory pavements, 36 in. (91.4 cm) in diameter consisting of a 1⅛-in. (2.86-cm) asphalt overlay over a 3-in. (7.6-cm) rigid concrete based on an elastic foundation, were fatigue tested at a load of 500 lbf (2.2 kPa). The asphalt and concrete layers were bonded by a thin asphalt tack coat with no bond between the foundation and concrete layers. The concrete slab was made in two pieces with testing performed at a ⅛-in. (0.32-cm) separation between the two pieces simulating a joint or crack. A sinusoidal dynamic load of 0.2-sec duration with 1 sec rest period between loads was transmitted to a 4½-in. (11.4-cm) square rigid loading head. The square loading head was used to provide a symmetric distribution of load stress with respect to the underlying crack in the rigid layer. Figure 9 shows the model pavement and test set up.

Similar cracking patterns and fatigue failures were obtained for all the slabs tested. As an example of the crack behavior observed, consider a typical fatigue test with the model pavement shown in Figure 9. This test was conducted with the center of loaded area directly over the center of the underlying crack with the resulting crack pattern shown in Figure 10. The following important observations were made:

1. No crack extended from the center of the loaded area, nor did cracks develop anywhere under the loaded area;
2. Cracks initiated at the edge of the loaded area directly over the underlying crack in the rigid layer;
3. These cracks grew simultaneously and at approximately the same rate outward from the loaded area in the ±z direction, reflecting the underlying crack; and
4. At the end of the test (355,000 cycles), the cracks had grown to almost transverse the slab, and the material next to the cracked zone had generally yielded.

From the observations of five slab tests, the following conclusions can be drawn

Figure 7. Nonsymmetric loading, τ_{xy} versus r for E_3 = 50,000 and E_3 = 5,000.

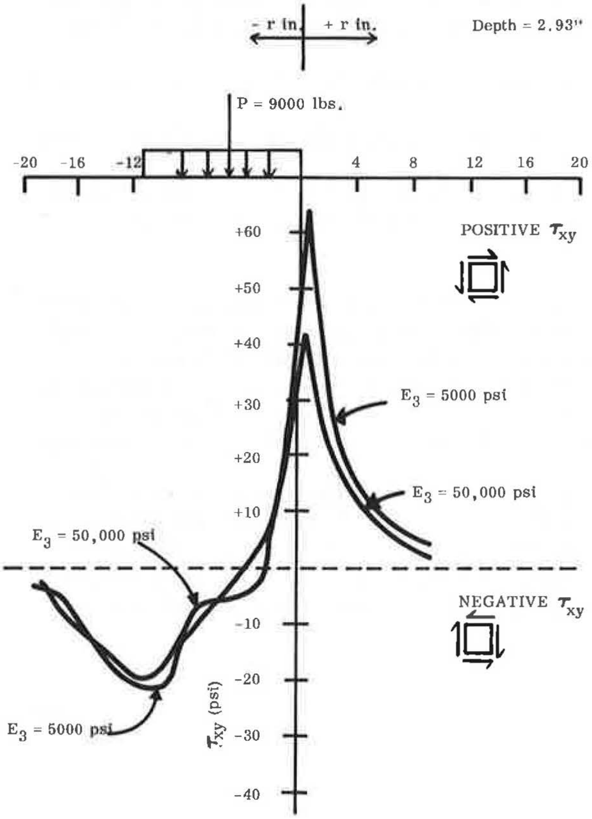


Figure 8. Change in stress intensity factors with position.

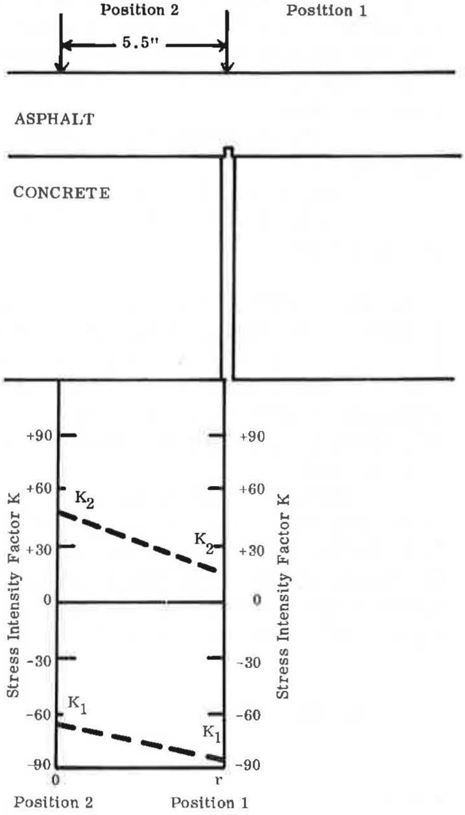


Figure 9. Overlaid pavement model.

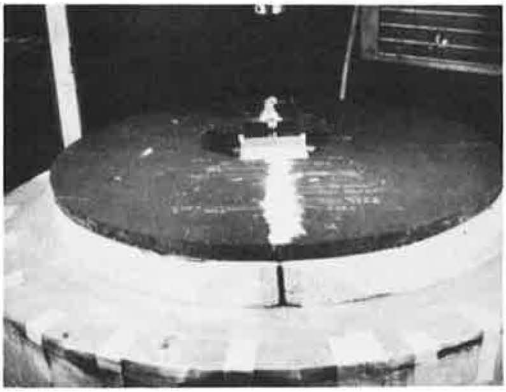
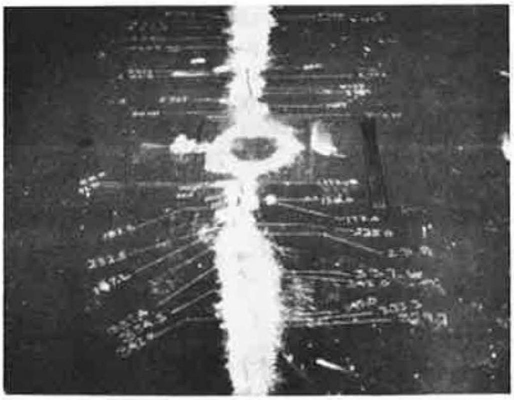


Figure 10. Reflection cracking pattern for symmetric loading.



with regard to the hypotheses concerning the mechanisms of reflection cracking:

1. Mode I type of fracture did not occur because no crack grew from the center of the loaded area (the point of maximum tensile bending stress). This is also evidence that the asphalt layer is in compression.
2. Crack growth initiated at the center edge of the loaded head is proof of the mixed-mode fracture.
3. Crack initiation and gradual growth are evidence that reflection cracking is a fatigue process.
4. General yielding of material is not common to bending type fatigue but rather to characteristics of high shearing stresses. This again quantitatively proves multimodal failure.

Beam models of the overlay structure (shown in Figure 11) were fatigue tested under mixed-mode conditions to analyze the two-dimensional propagation of reflection cracks. It was observed that these cracks propagate from the surface under mixed-mode conditions arising from compressive bending stresses and high shear stresses induced by differential vertical movement in the underlying rigid concrete layer. This theory on mixed-mode fracture was used to develop a growth law and to predict the fracture angle of the cracks.

The finite element method was used to evaluate S_{min} and θ_o for various initial flaw crack lengths of the overlay model shown in Figure 12. The θ_o values were all calculated to be about 12 deg and agreed well with the observed fracture angles obtained during fatigue tests on the models. From the crack length versus cycle data obtained during these fatigue tests dc/dN was obtained, and its relation with S_{min} is shown in Figure 12. The growth is described by

$$dc/dN = A'S_{min}^{n} \tag{7}$$

where

$A' = 6.8 \times 10^{-6}$ in./cycle (17.2×10^{-6} cm/cycle), and
$n = 2.309$.

Equation 7 was derived for the same sand-asphalt material as that used in modeling flexible pavements where crack growth was found to be proportional to the K_I stress-intensity factor to the 4th power. Since K is proportional to $S^{1/2}$, any growth law involving S_{min} for sand asphalt would expect to have an n power of about 2.0.

Therefore, pending further investigation of the constants n and A′, the fatigue life of an asphalt overlay (for load-endured reflection cracking) may be expressed by

$$\int_{c_o}^{c_f} \frac{1}{A'S_{min}^{n}}\, dc \tag{8}$$

where

c_o = initial flaw, and
c_f = crack length at which S_{cr} is reached or the overlay thickness, whichever is less.

Figure 11. Two-dimensional overlay model.

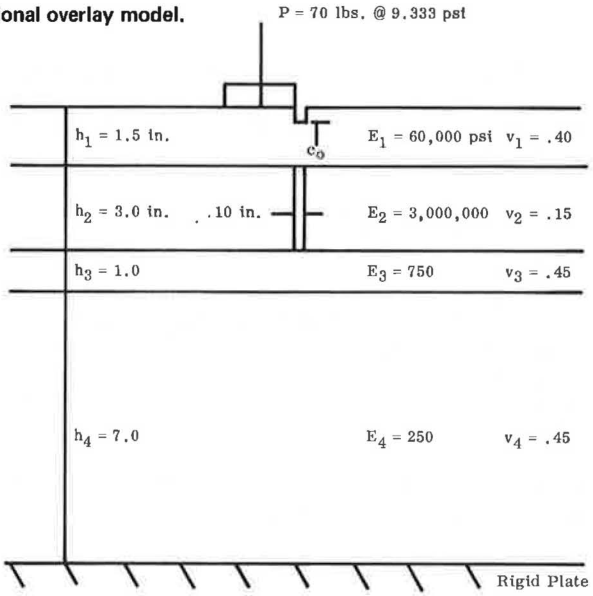
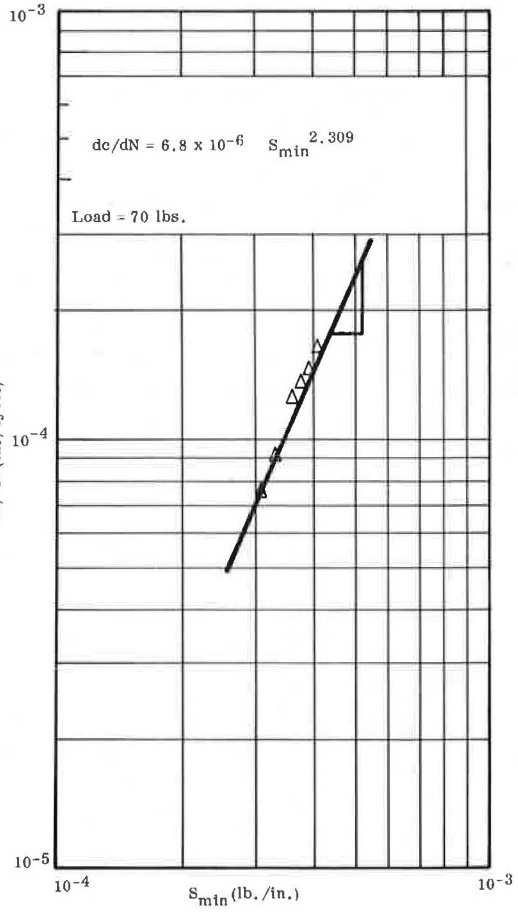


Figure 12. Crack growth rate versus S_{min}.



CONCLUSIONS

This paper is concerned with identifying the mechanisms of load-associated reflection cracking. The general concept of the strain-energy-density factor is presented as a method of analysis for mixed-mode fracture experienced in asphalt overlays. The following conclusions are reached:

1. Reflection cracking is multimodal fatigue fracture of the asphalt material over underlying crack or joints in the rigid base;
2. Typical asphalt overlays are in compression on the bottom and thus do not experience mode I fracture as occurs in flexible pavements;
3. Through the use of energy concepts in fracture mechanics, general mode fracture can be analyzed, and the mechanics associated with the initiation and progressive crack growth can be identified; and
4. Two-dimensional growth rate of reflection cracks can be described by law of the form of equation 7.

This subject is the topic of current research at Ohio State University, and further results will be presented as they become available.

REFERENCES

1. L. L. Smith and W. Gartner, Jr. Welded Wire Fabric Reinforcement for Asphaltic Concrete. HRB Bulletin 322, 1962, pp. 1-10.
2. F. Copple and L. T. Oehler. Michigan Investigation of Soil-Aggregate Cushions and Reinforced Asphaltic Concrete for Preventing or Reducing Reflection Cracking of Resurfaced Pavements. Highway Research Record 239, 1968, pp. 120-131.
3. J. L. Vicelja. Methods to Eliminate Reflection Cracking in Asphalt Concrete Resurfacing Over Portland Cement Concrete Pavements. AAPT, Vol. 32, 1963.
4. F. W. Kimble. Conditioning an Existing Concrete Pavement for Bituminous Resurfacing. HRB Bulletin 123, 1956, pp. 11-18.
5. B. M. Gallaway and B. D. LaGrone. Use of Rubber Aggregate in a Strain Relieving Interlayer for Arresting Reflector Cracks in Pavements. International Symposium on the Use of Rubber in Asphalt Pavements, May 1971.
6. G. R. Korfhage. The Effect of Pavement Breaker-Rolling on the Crack Reflectance of Bituminous Overlays. Highway Research Record 327, 1970, pp. 50-63.
7. J. W. Lyon. Heavy Pneumatic Rolling Prior to Overlaying: A 10-Year Project Report. Highway Research Record 327, 1970, pp. 45-49.
8. Structural Design of Asphalt Concrete Pavement Systems. HRB Special Rept. 126, 1971.
9. D. V. Ramsamooj. The Design and Analysis of the Flexibility of Pavements. Ohio State Univ., PhD dissertation, 1970.
10. E. M. Kauffmann. The Application of Fracture Mechanics Concept to Predict Cracking of Flexible Pavements. Ohio State Univ., PhD dissertation, 1973.
11. P. D. de Verteuil. Fatigue Properties of Asphaltic Concrete Field Specimens. Ohio State Univ., MS thesis, 1973.
12. G. C. Sih. Strain-Energy-Density Factor Applied to Mixed Mode Crack Problems. Institute of Fracture and Solid Mechanics Technical Rept., Lehigh Univ., 1972.
13. K. Majidzadeh and D. V. Ramsamooj. Mechanistic Approach to the Solution of Cracking in Pavements. HRB Special Rept. 140, 1973, pp. 143-157.
14. V. A. Karamians. Effect of Temperature on Fatigue Life of Asphaltic Mixtures. Ohio State Univ., MS thesis, 1973.
15. F. A. McClintock and J. B. Walsh. Proc., 4th U.S. National Congress of Applied Mechanics, 1962, p. 1015.
16. A. J. McEvily, R. C. Boettner, and T. L. Johnston. On Foundation and Growth of Fracture Cracks in Polymers. In Fatigue, An Interdisciplinary Approach. Syracuse Univ. Press, 1964.