PREDICTION OF REFLECTION CRACKING IN PAVEMENT OVERLAYS

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This paper deals with the problem of predicting the rate at which cracks in an underlying layer of a pavement will reflect through a bituminous overlay. It is an application of the principles of fracture mechanics to the problem of the initiation and growth of reflection cracks under the combined influence of repeated vehicular loading and changes in temperature. Both the theory of linear elastic fracture mechanics and that of delayed fracture in viscoelastic materials are used to formulate a method of solution. A brief discussion of the basic concepts, principles, and mathematical formulation is given. Finally, a few simplifying assumptions that lessen the amount of numerical computations required are made, and the applicability of the theory is illustrated by an example. Certain conclusions are drawn, and the need for future research in this area is outlined.

•THE PRESENT state of the art of designing overlays for pavements is to a large degree based on experience gained by trial and error and empirical relations developed from in-service highways and airport runways. As long as the designer is dealing with foundation soils, material properties, environmental factors, traffic loading, and construction techniques that are similar to those from which the relations were developed, the performance can be reasonably well predicted. However, because that is not usually the case, a need exists for a more rational approach to pavement design and pavement rehabilitation.

The present methods of designing overlays are based on some tolerable level of deflection (1, 2); those for overlays on portland cement concrete are based on the stress in the concrete slab at the base (1). If the pavement on which the overlay is to be constructed is cracked or jointed, there will be a substantial amount of reflection cracking through the overlay. Such reflection cracking can ruin the performance of an otherwise good overlay, for it will permit the entry of water through the cracks, leading to softening of the subgrade, pumping, and transverse faulting. Thus, reflection cracking can indeed control the design of an overlay.

Existing methods of analysis and design of overlays do not consider the problem of reflection cracking directly. However, certain construction techniques, such as breaking up the cracked or jointed pavement slabs into small pieces or small blocks, are used to minimize or delay the occurrence of reflection cracking. The disadvantages of those techniques are, of course, the tremendous loss in load-carrying capacity, caused by breaking up the pavement slabs, and the costs involved. A better solution is required—one in which the inherent strength of the slab can be used as much as possible. It is believed that the development of a basic theory that considers the mechanism of the formation and development of the reflection cracking and that describes the processes involved in terms of the invariant material properties of the pavement system, the traffic, and the environment is the best approach to finding a better practical solution to the problem.

The development of a rational method of overlay design not only will enable the prediction of the service lives of pavements carrying more modern aircrafts and

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automobiles with higher wheel loads, wider tires, and different configurations but also will provide a basis for evaluating the advantages of using new materials, new construction techniques, new types of equipment, and better quality control. Such a design method will remove the factors inhibiting innovative design and lead to superior design concepts and pavement rehabilitation techniques.

BASIC THEORETICAL APPROACH

Overlays may develop all types of distress: rutting, disintegration, and cracking. For rigid or flexible overlays on concrete pavements, reflection cracking is the most prevalent form of distress.

The methodology for the analysis of cracking in flexible pavements due to the effects of repeated vehicular wheel loading has been presented in another report (3). It is assumed that a "starter" crack c_o initiates (i.e., begins to grow) from the first loading cycle from inherent flaws in the material. The rate of crack propagation dc/dN is proportional to the fourth power of the stress-intensity factor K, which measures the general transmission of load to the vicinity of the crack tip in accordance with the loading, geometrical, and boundary conditions (4):

$$\frac{dc}{dN} = A[(\Delta K)^4 - K_0^4] \qquad (1)$$

where

c = crack length,
N = number of cycles,
A = materials property,
K_0 = endurance limit ($\simeq 0$ for asphaltic concrete), and
ΔK = increment in K due to the passage of a wheel load.

As the crack continues to grow, the value of K increases correspondingly until K reaches its critical value K_c, when rapid crack propagation occurs. K_c is a property of the material and is a function of the temperature and rate of loading.

For reflection cracking in an overlay, the same principles apply. The discontinuity in the underlying pavement slab produces bending and shear stress concentration at inherent flaws in the overlay along the line of the crack or joint. That causes nucleation of the flaws into microscopic starter cracks. The cracks grow under the influence of both traffic loading and the stresses produced by temperature and moisture changes.

The analysis of crack propagation is considerably simplified by the fact that the line of cracking is already known. In general, the crack will propagate in 2 modes: the opening mode and the in-plane sliding mode (Fig. 1). Usually the opening mode is much more important. The problem is, therefore, reduced to a simple application of fracture mechanics. Once the range and distribution of the starter flaws in the overlay along the potential line of cracking and the properties of the component layers of the pavement as outlined in an earlier report (3) have been determined experimentally, the rate of crack propagation can be obtained from the crack growth law:

$$\frac{dc}{dN} \; A_1(\Delta K_1)^4 + A_2(K_2)^4 \qquad (2)$$

where K_1 and K_2 are the stress-intensity factors for the 2 modes of cracking, under the stresses produced by traffic loading. Equation 2 is applicable when the mean load is constant. For a variable mean load, Roberts and Erodogan (5) give the following formula:

$$\frac{dc}{dN} \; A'(1 + \beta)^2(\Delta K)^4 \qquad (3)$$

for $K < K_c$, where $\beta = (K_{max} + K_{min})/2\Delta K$.

In general the overlay will be subjected to 2 types of loading: (a) repeated traffic loading, which produces pulses of short duration, and (b) stresses due to changes in temperature, which are usually sustained over long periods.

The response of the pavement due to the passage of wheel loads may be considered to be elastic if the speed of the vehicle is greater than about 15 mph, so that linear elastic fracture mechanics is applicable and the crack growth will follow Eq. 3. However, the response of the pavement due to stresses produced by slowly varying temperatures is essentially viscoelastic in nature, and therefore a viscoelastic analysis is needed to obtain the rate of crack propagation. Such an analysis has been presented by Wnuk (6) and is described briefly below.

According to Wnuk, a crack in a viscoelastic material initiates after a time

$$t_* = \Psi^{-1}(n) \tag{4}$$

where

$n = (K_{1c}/K_1)^2$,
$\Psi(t)$ = compliance function = $J(t)/J(0)$,
$J(t)$ = compliance at time t, and
$\Psi^{-1}(t)$ = inverse compliance function.

The crack then grows at a finite rate until eventually at time t_{**}, when the stress-intensity factor reaches its critical value K_{1c}, catastrophic failure occurs. The rate at which the subcritical crack grows is given by

$$\Psi(\Delta/\dot{c}) = (K_{1c}/K_1)^2 \tag{5}$$

for $t_* < t < t_{**}$, where

$$\Delta = \frac{\pi}{8(1 - \nu^2)} (K_1/\sigma_y)^2, \text{ and}$$

$$\dot{c} = \frac{dc}{dt} = \text{rate of crack growth.}$$

Equation 5 may be rewritten as

$$\dot{c} = \Delta/\Psi^{-1}(K_{1c}/K_1)^2 \tag{6}$$

If the wheel loads pass over the crack at regular intervals at the rate of n per day, i.e., N = nt, then the total rate of crack growth $\dot{c}_t$ due to both vehicular loading and temperature stresses will be given by

$$c_t = nA_1'(1 + \beta)^2(\Delta K_1)^4 + nA_2'(1 + \beta)^2(\Delta K_2)^4 + \Delta/\Psi^{-1}(K_{1c}/K_1)^2 \tag{7}$$

for $t_* < t < t_{**}$, and

$$\dot{c}_t = nA_1'(1 + \beta)^2(\Delta K_1)^4 + nA_2'(1 + \beta)^2(\Delta K_2)^4 \tag{8}$$

for $t < t_*$.

Equations 7 and 8 are sufficient to completely describe the rate of growth of the reflection crack at any time during the loading history.

The stress-intensity factor K is the dominant parameter controlling the rate of crack growth. Unfortunately, the K value of a crack in an overlay over a joint in a concrete slab with dowel bars or steel reinforcement bars across the joint is difficult to determine and requires a 3-dimensional finite-element analysis. Such computer programs are available but are rather expensive to operate. Perhaps in the near future some simpler numerical method for obtaining the stress distribution for 3-dimensional crack problems may become available.

However, in order to illustrate the potential applicability of the method, a number of simplifications will be introduced to minimize the amount of numerical computation.

ILLUSTRATIVE EXAMPLE

Consider a 2-dimensional simplification of a pavement system consisting of a 3-in. asphaltic concrete overlay on an 8-in. jointed concrete slab without load transfer dowels, as shown in Figure 2. Under the influence of vehicular loading, an inherent starter crack in the asphaltic overlay directly above the joint in the concrete slab begins to grow with the first loading cycle and propagates in accordance with the crack growth laws previously discussed. Assume also that the asphalt concrete overlay was constructed on a day when the temperature was 110 F, and at that time the joint in the concrete slab was completely closed. If the temperature drops to 60 F, say, a tensile stress will be induced in the overlay because of the contraction of the pavement layers between the contraction joints. Under that sustained stress, the crack grows continuously but not before an initiation period $t_* = \Psi^{-1}(n)$.

Experience has shown that the resistance to cracking in the in-plane sliding mode K_2 is generally much greater than the resistance in the opening mode K_1. As a further simplification, mainly because of the lack of sufficient experimental data, the crack is considered to propagate only in the opening mode.

Based on experimental data, the following material properties are assumed:

Property	Value
Asphalt concrete	
Complex modulus E_1, psi	250,000
Poisson's ratio	0.4
Critical stress-intensity factor K_{1c}, lb-in.$^{-3/2}$	400
Yield stress in tension σ_y, psi	250
Thermal coefficient of expansion, in./in./F (low)	7.0×10^{-6}
Crack propagation constant A_1'	1.0×10^{-13}
Concrete	
Young's modulus E_2, psi	3×10^6
Poisson's ratio	0.3
Thermal coefficient of expansion, in./in./F	7.0×10^{-6}
Subgrade	
Young's modulus E_3, psi	4,500
Poisson's ratio	0.4

In addition, the asphalt is assumed to behave as a standard linear solid as represented by the model shown in Figure 3. The creep compliance function $\Psi(t)$ is, therefore, given by

$$\Psi(t) = 1 + \frac{E'}{E''}\left(1 - e^{-(E''/\lambda)t}\right) = 1 + 2\left(1 - e^{-2.0 \times 10^{-4} t}\right) \tag{9}$$

Stress-Intensity Factor K Due to Vehicular Loading

The K_1 value was calculated as a function of the crack depth c for the vehicular loading shown in Figure 2; a 2-dimensional finite-element program was used. The graph of K_1 versus c is shown in Figure 4. The shape of the K_1 versus c curve is rather unusual; the value of K_1 decreases as crack length increases. That is because the modulus of the concrete slab is very much greater than the modulus of the asphalt concrete overlay, so that the behavior of the composite pavement is controlled to a large extent by the concrete slab.

Stress-Intensity Factor K_1 Due to Temperature Drop

The tensile stress σ in the asphalt concrete section (α for asphalt concrete and concrete are assumed to be equal) is given by

$$\sigma = \alpha E \Delta T \tag{10}$$

where

E = long-term viscoelastic modulus, and

ΔT = drop in temperature of 50 F (assumed for duration of 300 days).

Therefore, $\sigma = 7.0 \times 10^{-6} \times \frac{250{,}000}{3} \times 50$ psi = 37.2 psi.

The value of K_1 for that state of stress is given in another report (7) and is shown as a function of the crack length c in Figure 4.

The value of K_1 versus c for the combined loading is also shown in Figure 4.

Elastic Crack Growth Rate Due to Vehicular Loading and Temperature Stresses

The crack propagation law is

$$\frac{dc}{dt} = nA_1'(1 + \beta)^2(\Delta K_1)^4 \tag{11}$$

where

$A_1' = 1.0 \times 10^{-13}$,

$\beta = (K_{1\,max} + K_{1\,min})/2\Delta K_1$, and

t = time in days.

If the vehicular traffic consists of 1 million equivalent 18-kip axle loads in 20 years, then the value of $n = N/t = 137$ axle loads per day. Thus, all the quantities in Eq. 11 are known, and the rate of crack propagation can be calculated. The results are shown in Figure 5. Evidently the rate of crack growth is considerably increased by the presence of the temperature stresses.

Viscoelastic Crack Growth Rate Due to Temperature Stresses

From Eq. 6,

$$\dot{c} = \Delta/\Psi^{-1}(K_{1c}/K_1)^2 \tag{12}$$

for $t_* < t < t_{**}$.

The graphs of $\Psi(t)$ and $\Psi^{-1}(n)$ are shown in Figure 3. Thus, the values of $\dot{c}$ as a function of the actual crack length can be easily obtained. That is shown in Figure 5.

The initiation time for viscoelastic crack growth is given by $t_* = \Psi^{-1}(K_{1c}/K_1)^2$, where K_1 corresponds to the initial crack length. The graph of t_* versus c is shown in Figure 6. Evidently initiation occurs when the crack length is approximately 1.55 in.

Reflection Crack Growth as a Function of Time

Assuming that the "starter flaw" in asphalt concrete $\simeq$ 0.05 in., the actual growth of the reflection crack due to the combined effects of vehicular loading and temperature change can now be obtained. That is shown in Figure 7. The reflection crack will propagate completely through the asphalt concrete overlay in about 280 days.

CONCLUSION

A method of predicting the rate of growth of reflection cracking in overlays has been presented. The method is quite general and permits the evaluation of the relative and combined effects on the growth of reflection cracking of both vehicular loading and temperature-induced stresses.

Certain simplifying assumptions were made in order to present an illustrative example. Because some of the assumptions were oversimplified, it is not appropriate to make any firm conclusions from the results. Nevertheless, it appears that the

Figure 1. Modes of deformation of reflection crack.

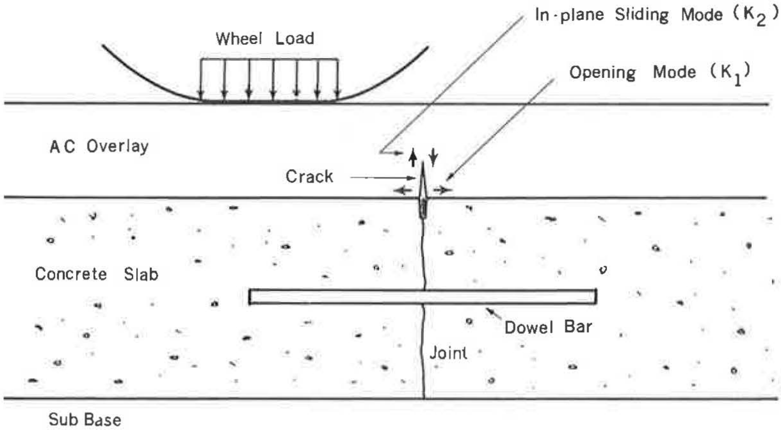


Figure 2. Two-dimensional simplification of problem.

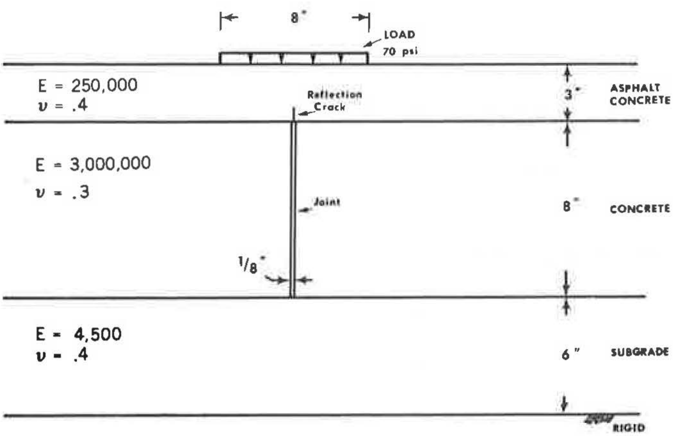


Figure 3. Asphalt concrete model and graphs of $\psi(t)$ and $\psi^{-1}(n)$.

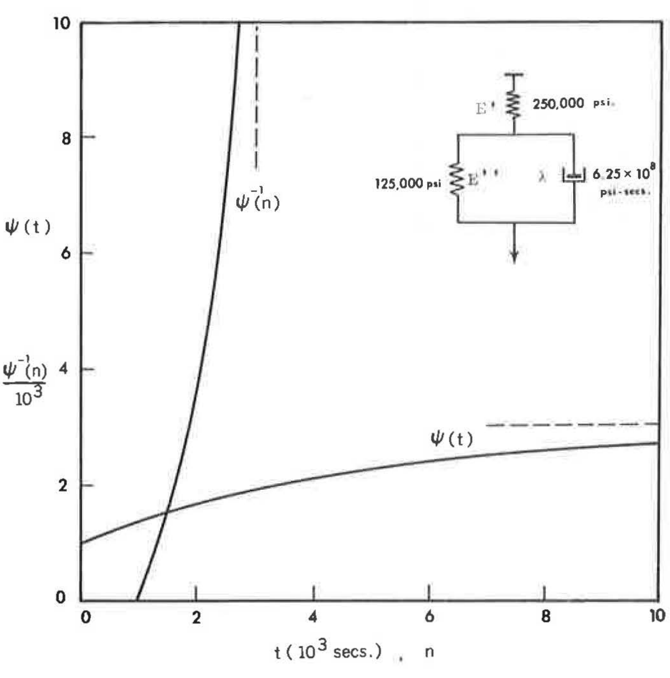


Figure 4. K_1 for vehicular loading and temperature stresses.

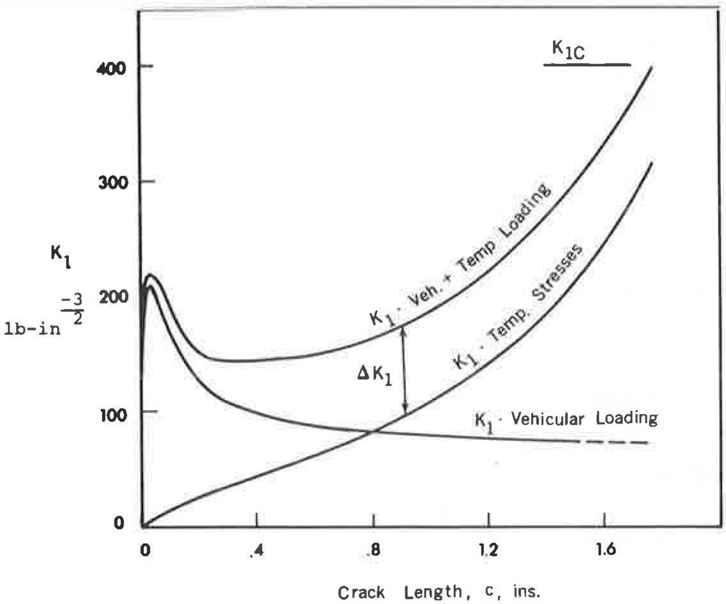


Figure 5. Growth rate of elastic and viscoelastic reflection crack.

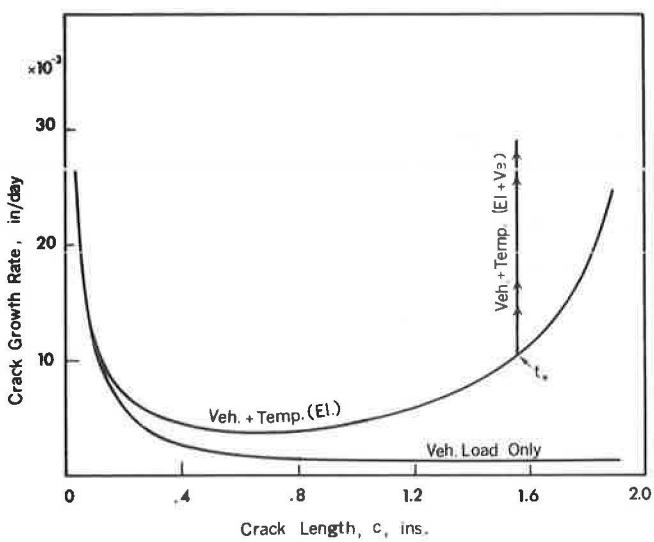


Figure 6. Initiation time for viscoelastic crack growth.

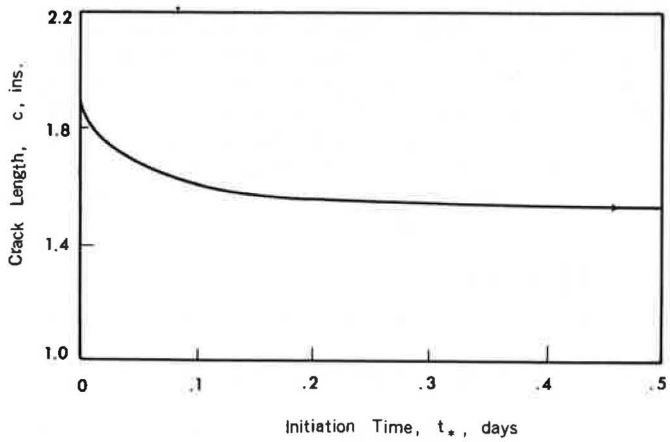
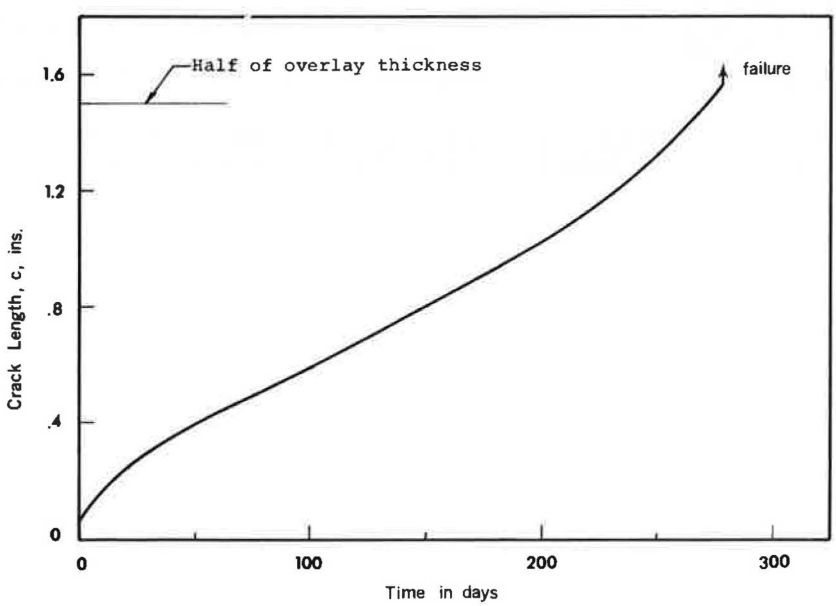


Figure 7. Growth of reflection crack under vehicular loading and temperature stresses.



method yields realistic results and that the effect of temperature change on the growth of the reflection cracking is rather substantial.

In this paper, it has been assumed that the resistance to cracking in the in-plane sliding mode is very much greater than that in the opening mode, and the former has been neglected. That assumption may not be true and should be checked experimentally. It is also recommended that the method be completely verified experimentally. The validity of this method for predicting reflection cracking means that a powerful tool is available that will make the task of minimizing the occurrence of reflection cracking much simpler, will remove those factors inhibiting innovative design, and will thus lead to superior design concepts and pavement rehabilitation techniques.

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