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Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements and Committee on Soil-Bituminous Stabilization.

Abridgment

Practical Method for Evaluating Fatigue and Fracture Toughness of Pavement Materials

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One of the most frequently occurring modes of distress in asphalt highway pavements is the fatigue cracking that results from traffic loads. Few theories have been suggested by researchers for approaching the problem of fatigue in materials in general and in pavement materials in particular. Linear fracture mechanics is one of the methods that has been used to analyze fatigue. Recent studies such as that by Majidzadeh and Kauffmann (1) show that the method is applicable to asphaltic pavement materials.

Crack behavior can be classified into three distinct modes: (a) opening, (b) in-plane sliding, and (c) tearing (Figure 1). Each crack-mode movement is associated with a stress field in the vicinity of the crack tip. The distribution of stress in the vicinity of the crack tip is a problem related to the mathematical theory of elasticity, in which it can be shown that all stress fields at the crack tip exhibit inverse square root singularities. Thus, the stress field can be expressed for the opening mode as follows:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = (K_1/\sqrt{2\pi r})\cos(\theta/2) \times \begin{Bmatrix} 1 - \sin(\theta/2)\sin(3\theta/2) \\ 1 + \sin(\theta/2)\sin(3\theta/2) \\ \sin(\theta/2)\cos(3\theta/2) \end{Bmatrix} \quad (1)$$

The parameter K_1, called the stress-intensity factor, governs the magnitude of the local stresses in the vicinity of the crack tip.

Paris, Gomez, and Anderson (2) first introduced the idea of relating the stress-intensity factor to rates of fatigue crack propagation. Experimental data show that the rate of crack propagation (dc/dN) is proportional to some power of the stress intensity factor; i.e., $dc/dN = AK^n$, where A and n can be characterized as material constants.

The purpose of this paper is to introduce a new method of testing for fatigue and fracture in asphaltic pavement material, a method that is believed to be superior to current procedures. Current methods are discussed and compared with the proposed one.

COMPARISON OF CURRENT AND PROPOSED TEST METHODS

Simplicity of specimen preparation, testing, and analysis of results is the basic advantage of the new method over current procedures. Currently, the determination of fatigue parameters A and n in the fatigue model $dc/dN = AK^n$ is done experimentally by testing beams placed on an elastic foundation and loaded with a cyclic load. Fracture toughness is determined by testing beams that have larger dimensions than the fatigue beams under three-point loading conditions. In the proposed new method, both fatigue testing and fracture testing use an identical experimental setup and identical specimens of discs cut from cylindrical specimens with a triangular notch (Figure 2).

Current Method

To test for fatigue, parameters A and n in the equation $dc/dN = AK^n$ are determined experimentally by testing beam specimens placed on an elastic foundation. The progress of crack growth and the corresponding number of load applications are visually observed and recorded. The steps are

1. Obtain experimental crack minus cycled (c - N) data;
2. Use either a polynomial or nonlinear exponential equation, obtain the best fit to the available experimental c - N data, and develop an analytical expression;
3. Differentiate the analytical (predicted) c - N equation to obtain the dc/dN - N relation;
4. Use the analytical expression available between the stress-intensity factor K and crack length c to develop a set of stress-intensity factor values and their corresponding dc/dN values; and
5. Find the fatigue parameter by using the information in step 4.

For the determination of fracture toughness of asphaltic materials, beam specimens 10.16 by 7.62 by 40.64 cm (4 by 3 by 16 in) are tested. The beams are notched to a depth of 1.524 cm (0.6 in) to produce a c/d ratio of 0.15. They are tested under three-point loading conditions—i.e., a simply supported beam with a central load. Fracture toughness is determined by using the maximum load that the beam can withstand before fracture. This load is used to determine the moment that is used in the calculation of K_{Ic}. A number of investigators have used the K/P-c relations developed for simply supported beams. The best recognized form of such a relation is the Winne and Wundt equation (4).

Proposed Method

Specimens

The specimens are prepared for cylindrical samples. The samples can be manufactured in the laboratory or obtained from existing pavements by coring. Marshall size

Figure 1. Modes of crack deformation.

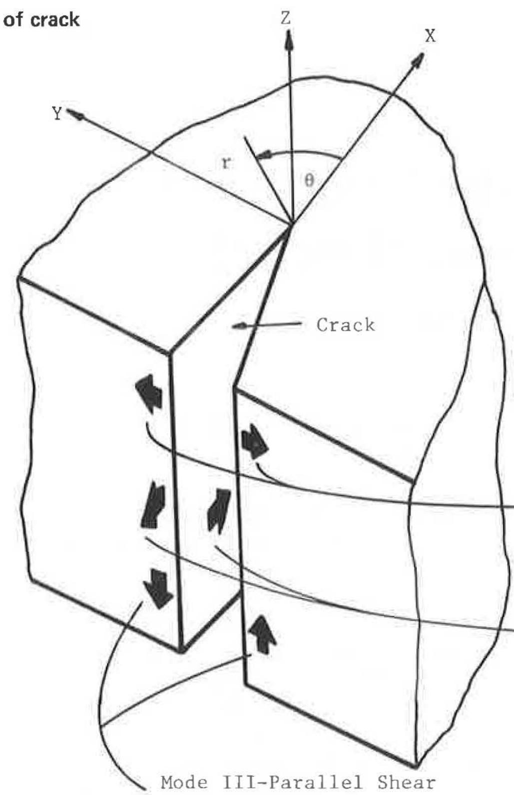
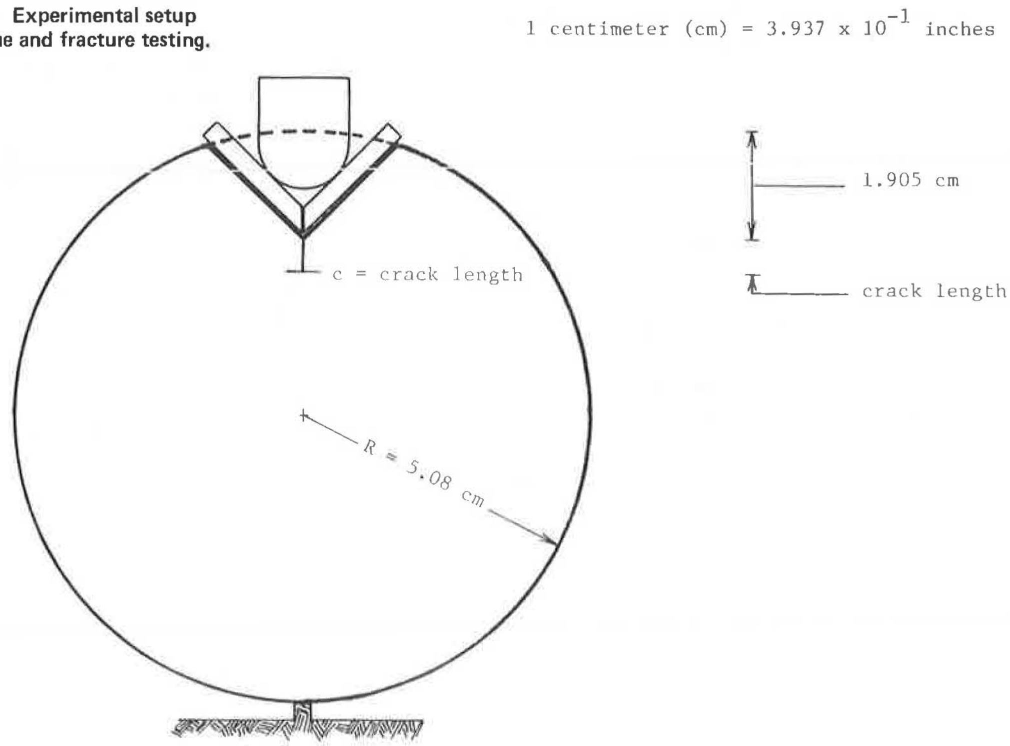


Figure 2. Experimental setup for fatigue and fracture testing.



specimens could also be used. The diameter of the cylinder can vary, but in this study cylinders 10.16 cm (4 in) in diameter were used. Discs of predetermined thickness are cut from the cylinders. The required thickness of the discs is such that the plane strain condition is achieved, a condition assumed in the theoretical modeling of the experiment. A right-angled wedge is cut into the disc specimen to accommodate the loading device. The dimensions of the wedge for the 10.16-cm (4-in) diameter specimen are shown in Figure 2.

Extreme care should be taken in cutting the sample to specifications to ensure symmetry about the vertical axis and smoothness of the loaded surface to avoid stress concentrations not accounted for in the model. Cracks of various lengths can be introduced by extending them from the tip of the wedge by mechanical means such as sawing. Cyclic loading can also induce similar cracks and lead to the eventual fatigue failure of the specimen, which is the main objective of the fatigue and fracture study of pavement materials.

Experimental Setup

The specimen is set on a base so that the wedge points vertically upwards. A three-piece device is used to transmit the vertical force applied by a Material Testing System loading machine. A semicircular piece of rod of sufficient length and rigidity is used to transmit the vertical load to two plates placed on the wedge of the specimen. The plates are rigid enough to transmit the load uniformly to the two surfaces of the wedge. The dimensions of the wedge, the plates, and the semicircular rod are such that symmetry of loading is maintained (Figure 2).

Linear Fracture Mechanics Analysis

Dimensional analysis of Equation 1 indicates that the stress-intensity factor must be linearly related to stress and must be directly related to the square root of a characteristic length. Based on Griffith's original analysis of glass members with cracks and the subsequent extension of that work to more ductile materials, the characteristic length is the crack length in a structural member. Consequently, the magnitude of the stress-intensity factor must be directly related to the magnitude of the applied nominal stress and the square root of crack length c. In any case, the general form of the stress-intensity factor can be written

$$K = f(g) \cdot \sigma \cdot \sqrt{c} \qquad (2)$$

where f(g) is a parameter that depends on the specimen and crack geometry and has been subjected to extensive investigation and research.

Buranarom (5) has developed a general finite element computer program that calculates stress-intensity factors for any given geometry, crack length, and loading condition. The analysis is two-dimensional and assumes the existence of plane strain conditions. Normalized stress-intensity factors were related to normalized crack lengths. Before the factors are defined, it should be mentioned that the relations are valid for all thicknesses and all diameter sizes of specimens as long as the ratio of the wedge depth to the radius of the specimen is 3 to 8 (1.905 to 5.08 cm).

The terms in the relation are defined as follows:

$$K = (F_{stress})(F_{geom})(\sqrt{c})(P/tR) \qquad (3)$$

where

F_{stress} = stress factor,
F_{geom} = geometry factor,
P = vertically applied load,
t = thickness of sample, and
R = radius of sample.

$$F_{stress} = 6.153\,078 \exp[4.305\,77(c/R)^{2.475}] \qquad (4)$$

$$F_{geom} = 3.950\,373 \exp[-3.071\,03(c/R)^{0.25}] \qquad (5)$$

So, given c, R, t, and P, the stress-intensity factor K is calculated. The recommended range for c/R to be used in Equations 4 and 5 is $0 \leq c/R \leq 1$. This range is a practical one for almost all conditions of testing.

Experimental Verification of New Method

Different tests were performed to investigate the validity of the new test method, and the results were compared with those obtained through tests of beams on elastic foundations. Each test is described below, and the results are discussed.

Fracture Toughness Testing

Tests were conducted on specimens that had different thicknesses but a uniform crack length of 0.254 cm (0.1 in). Figure 3 summarizes the results. The tests were conducted so that the rate of stress application at the crack tip was maintained at a constant value for all specimen sizes. This was intentionally done so as to have a common basis of comparison for the results.

From Figure 3, it is reasonable to assume that the K_{Ic} values maintain a constant value for a specimen thickness of about 5.08 cm (2 in) and above. Since fracture toughness is a material property and is supposed to be constant at a given temperature and rate of stress, it can be concluded that tests conducted on samples 5.08 cm thick and thicker simulate the theoretical model assumed in the analysis. Specimens with thicknesses of 5.08 cm or more represent plane strain conditions assumed in the analysis. This is an important conclusion since it sets a lower limit of specimen thickness where the fracture toughness tests are valid.

Figure 4 summarizes the results of tests of the effect of loading rate. The tests were conducted on specimens 5.08 cm (2 in) thick that had an original crack length of 0.254 cm (0.1 in). The comparison of these results with the results obtained on beam tests is excellent. As expected, the results show that fracture toughness is a rate-dependent parameter. The stress rates are calculated based on the stress values in the vicinity of the crack tip.

Fatigue Testing

Two sets of fatigue tests were performed, the first to establish the sensitivity of fatigue life to the level of loads and the second to determine the fatigue parameters A and n in the fatigue model.

The first set of tests was performed at room temperature on specimens 5.08 cm (2 in) thick. Each specimen was subjected to a different load level until failure, and the number of cycles of load application to failure was noted. As expected, the fatigue life increased as the magnitude of the cyclic load decreased. The results, which

Figure 3. Variation of fracture toughness with thickness of specimen.

1 centimeter (cm) = 3.937×10^{-1} inches (in.)
1 pascal $\sqrt{M}$ = 9.1×10^{-4} psi $\sqrt{in.}$

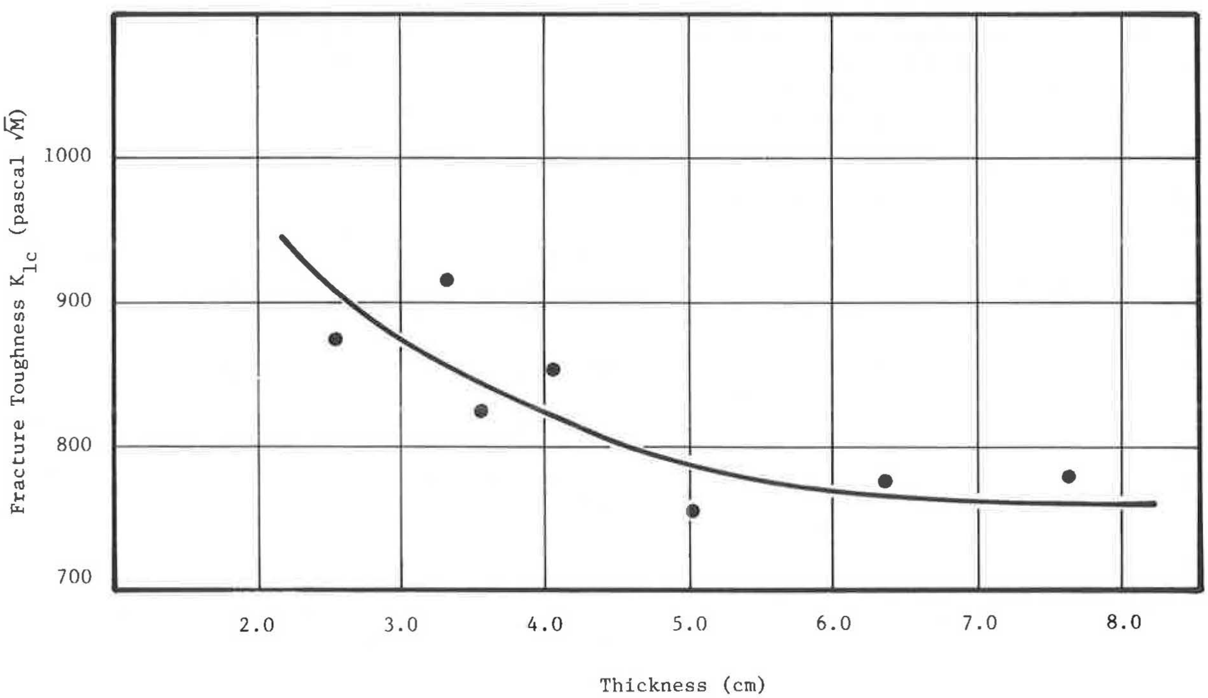


Figure 4. Variation of fracture toughness with rate of stress.

1 pascal/second = 1.45×10^{-4} psi/second
1 pascal $\sqrt{M}$ = 9.1×10^{-4} psi $\sqrt{in.}$

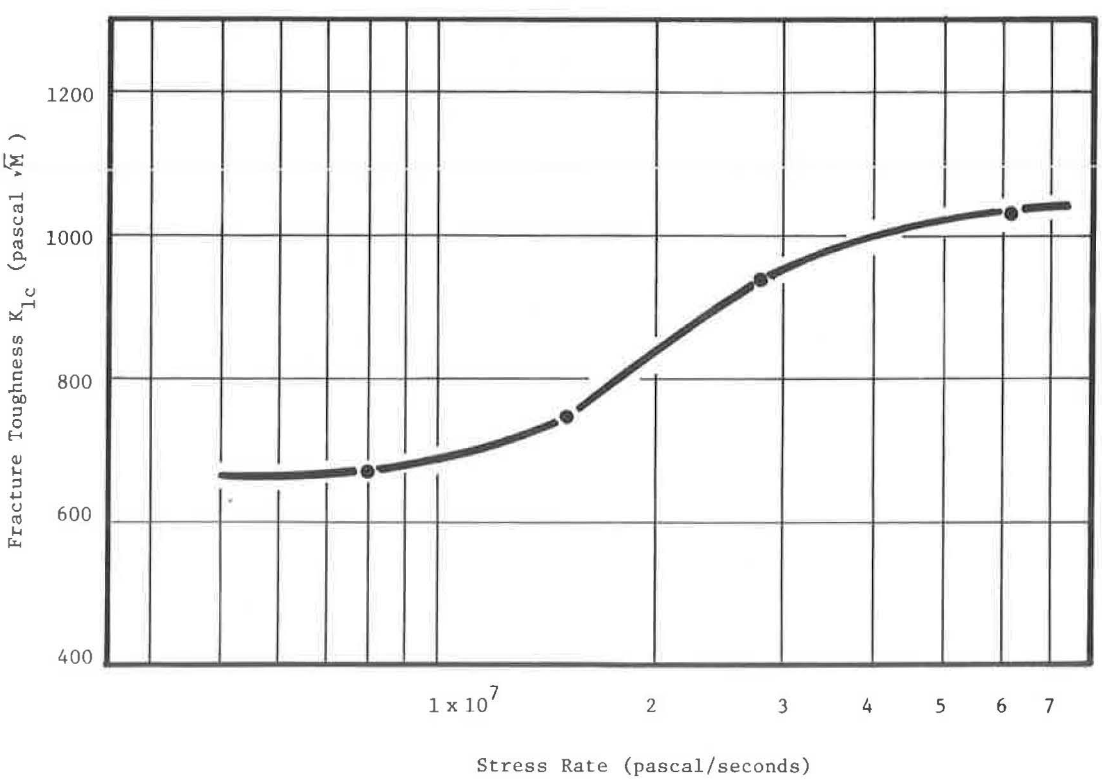


Figure 5. Load versus cycles to failure.

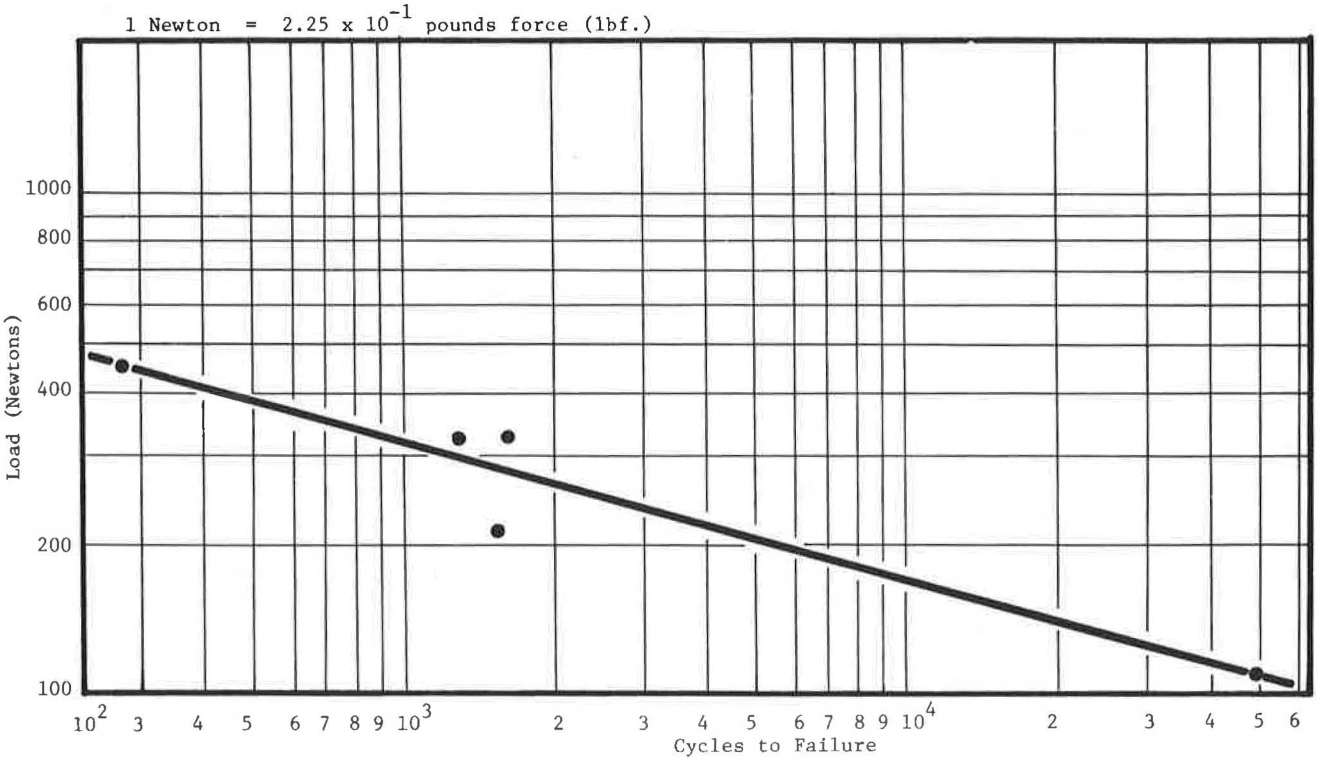
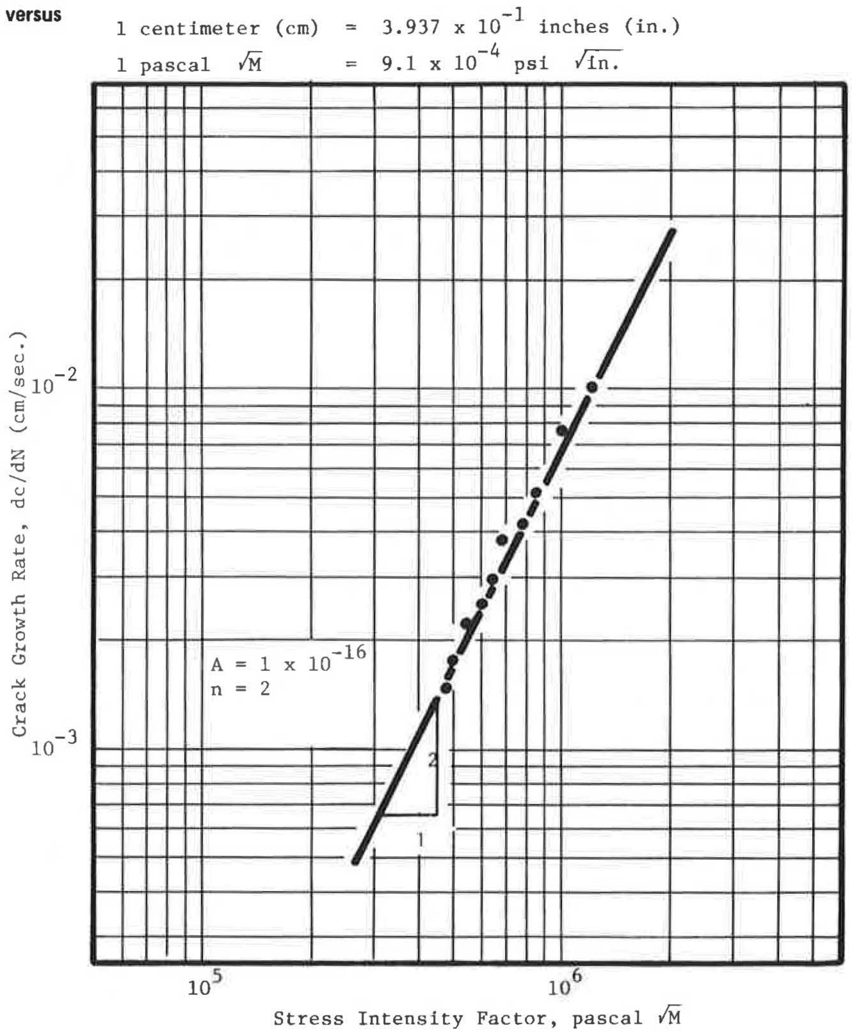


Figure 6. Crack growth rate: dc/dN versus stress-intensity factor.



are shown graphically in Figure 5, confirm known relations of load to life.

Tests for fatigue parameters A and n were also performed at room temperature on samples 5.08 cm (2 in) thick. An original crack of 0.254 cm (0.1 in) was introduced in the specimen before testing. For the specific specimen in question, the c - N data were analyzed by following the procedure described earlier. For a value of n = 2.0, the value of A was 3.4×10^{-7}. These values compare well with those previously obtained by testing, on elastic foundation, beam specimens that had the same asphalt mix properties. Figure 6 shows the graphical analysis of the data.

CONCLUSIONS AND RECOMMENDATIONS

It is obvious that the new method for testing fatigue and fracture toughness is an applicable and feasible one that has certain advantages over the old one. The following conclusions and recommendations can be made:

1. The new method makes it feasible for actual cores taken from highways to be tested for fatigue and fracture in the laboratory, whereas the method that used beams on elastic foundations required a beam cut from the pavement, a task too difficult to be done properly.
2. The theoretical analysis of the specimen geometry and the experimental setup are much simpler in the new method than in the old one. The stress-intensity factor K is independent of the elastic modulus E of the material.

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Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements.

Petrographic Insights Into the Susceptibility of Aggregates to Wear and Polishing

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Results from three studies confirm that a strong relation exists between the petrographic properties of an aggregate and its susceptibility to wear and polishing. Constituent mineral composition; hardness; differential hardness; porosity; grain shape, size, and distribution; and bonding between grains or crystals and matrix are all important properties that contribute to aggregate wear resistance and polish resistance. Hard, well-bonded minerals will resist wear but will eventually polish though at a slower rate than softer minerals. Loosely bonded materials will resist polishing but will wear at a rate that may render them not durable. Two subtasks in the studies revealed that an inverse relation exists between the rate of wear of an aggregate and its susceptibility to polishing. To resist both polishing and wear, an aggregate should ideally contain a high percentage of hard, coarse, angular crystals well bonded into a matrix of softer, finer grains, or the hard crystals should be well bonded together in a porous structure so that slow, gradual, irregular fracture of the crystals will occur. Based on the findings from the three studies and other research, a table has been prepared that includes suggestions for aggregate property values that will result in high resistance to both wear and polishing.

It is generally conceded by those concerned with pavement surface skid resistance and wear resistance that these properties are largely a function of aggregate performance, particularly in bituminous surfaces in which the coarse aggregate constitutes the major portion of the surface that comes in contact with vehicle tires. Other factors such as particle size, shape, and gradation; mix design; binder properties; and construction practices are also important, but these factors play a lesser role.

In the past two decades, several studies have been done by concerned agencies and interested researchers to predict the skid-resistance performance of surface aggregates by laboratory tests before the aggregates are used in field construction, particularly in bituminous surfaces. Most of the methods used in these studies were laboratory polishing procedures intended to simulate aggregate polishing by traffic (1, 2, 3, 4). Other studies involved the testing of field installations to obtain a history of skid-resistance performance on the aggregates that were used in these installations (4, 5, 6). Results of both field and laboratory tests often showed significant performance variations, not only between one general group of aggregates and another—for example, between limestone and granite—but also between aggregates of the same group that come from different sources—for example, between one limestone and another or between one granite and another (7, 8, 9, 10). These variations aroused an interest among several researchers in investigating basic factors that influence the skid-resistance performance of various aggregates. Accordingly, several petrographic studies were undertaken