ASPHALT
PAVING
TECHNOLOGY
[illegible]

AAPT

Journal of the
Association of Asphalt Paving
Technologists

Volume [illegible]

Determination of Crack Growth Rate Parameters Of Asphalt Mixtures Using the Superpave IDT

Reynaldo Roque[1]. Zhiwang Zhang[2] and Bhavani Sankar[3]

Abstract

Mixture resistance to crack propagation will have a direct effect on the cracking performance of asphalt pavements. Therefore, it would be useful to have a practical and reliable system to determine crack growth rate parameters (fracture parameters) of asphalt mixtures. Given the advent and continuing implementation of the Superpave volumetric mixture design procedure, it would be particularly useful if the system were compatible with specimens produced with the Superpave Gyratory compactor. Fracture parameters could be used to optimize mixture designs and would also provide the fundamental properties needed to accurately predict pavement performance.

A complete testing, data acquisition, reduction, and analysis system was developed in this study to determine fracture parameters using the Superpave IDT (indirect tension test). The theoretical relationships and data reduction procedures developed preclude the need to measure crack growth rate directly during testing, or the need to obtain or estimate asphalt mixture stiffness or any other property to analyze the fracture test data. These two features not only make fracture testing easier to perform, but it may also be argued that better consistency can be achieved, since the variability introduced by using properties determined from independent tests, as well as the inherent inaccuracies involved in measuring crack growth rate directly, are eliminated. It also eliminates the need to produce and test another set of specimens.

Based on tests performed on two Superpave mixtures, the system developed was shown to provide rational and consistent fracture test results that compared favorably with fracture parameters published in the literature for similar mixtures. Therefore, the system appears to provide a viable approach for determining fracture resistance of asphalt mixtures produced with the Superpave Gyratory compactor or of field cores obtained from pavements in the field.

---

[1]Associate Professor, [2]Graduate Research Assistant, and [3]Professor, respectively University of Florida, Gainesville FL

The oral presentation was made by Professor Roque

Key Words: Bituminous Mixture, Crack Growth, Indirect Tension Test, Gyratory Compactor, Field Cores

Introduction

Mixture resistance to crack propagation will have a direct effect on the cracking performance of asphalt pavements. Therefore, it would be useful to have a practical and reliable system to determine crack growth rate parameters (fracture parameters) of asphalt mixtures. Given the advent and continuing implementation of the Superpave volumetric mixture design procedure, it would be particularly useful if the system were compatible with specimens produced with the Superpave Gyratory compactor. Fracture parameters could be used to optimize mixture designs and would also provide the fundamental properties needed to accurately predict pavement performance.

The use of mechanics is necessary to fundamentally and accurately account for the different factors that affect the development and propagation of cracks in asphalt pavements. In recent years, fracture mechanics (1) and continuum damage mechanics (2,3,4) have found increasing use in the analysis and evaluation of asphalt mixtures and pavements. Each approach offers advantages and disadvantages with respect to the type of failure mechanism that can be considered. Continuum damage mechanics offers a much more fundamental explanation of damage than conventional fatigue approaches. However, given the fact that only a continuum can be modeled, continuum damage mechanics is incapable of properly addressing the mechanism of crack propagation (i.e., once a crack is introduced, the system is no longer a continuum). In addition, damage mechanics does not provide a true physical interpretation of damage; damage may be any change in the material micro- or macro-structure that results in a reduction in the material stiffness.

Conversely, fracture mechanics begins with the assumption that there are inherent flaws or cracks in the material. Therefore, fracture mechanics by itself is incapable of properly addressing the mechanism of crack initiation. Initial crack sites must generally be selected for analysis and evaluation. However, fracture mechanics does provide a physical interpretation of damage (i.e., a crack length has physical meaning). Ideally, a combination of continuum damage mechanics and fracture mechanics should be used to properly address the mechanism of cracking in pavements. However, the approach eventually selected by the pavement community will probably be the subject of debate for many years to come.

It may be argued that fracture mechanics may be applied in a conservative manner without the need to address crack initiation. If it can be determined that a mixture will not propagate cracks, then whether or not cracks initiate becomes a moot point. There is no need to predict crack initiation if it can be determined that the cracks will not propagate even if they initiate. Regardless of the approach taken, a rational argument can be made for the need to determine fracture parameters of asphalt mixtures.

Unfortunately, there is no way to directly determine fracture parameters in the Superpave system. The two primary mixture tests developed to support Superpave, the simple shear test (SST) and the Superpave IDT, are not suitable for this purpose in their present form. Furthermore, the determination of fracture parameters has been relatively difficult to achieve for several reasons. First, direct tension tests have generally been used to obtain fracture parameters because they result in relatively simple stress states that are easy to interpret. Unfortunately, direct tension tests are relatively difficult to perform because they involve gluing the loading platens onto the specimen. In addition, precise alignment is difficult, if at all possible to attain with a material like asphalt concrete, especially if the test temperature is different than the temperature at which the platens were glued to the specimen. Finally, specimen geometries suitable for direct tension testing are difficult to obtain from the cylindrical specimens produced with the Superpave Gyratory Compactor.

Another difficulty associated with fracture testing is the measurement of crack growth rate during the test. Cracks are difficult to see in asphalt mixtures. Use of crack foils or coatings can help, but it may be difficult to match the properties of these materials exactly with those of different asphalt mixtures at different temperatures. Therefore, the crack length determined from these systems is an estimate. In addition, measurement of crack growth rate is tedious and makes the test more difficult to perform.

Based on the discussion presented above, it would clearly be beneficial to develop a testing and data reduction system to determine crack growth rate parameters that overcomes the difficulties and deficiencies identified. In addition, the system should be compatible with specimens produced using the Superpave Gyratory Compactor. The development of a system based on the Superpave Indirect Tension Test (IDT) would suit these purposes well. It would be possible to obtain two to three indirect tension specimens for determination of fracture parameters from each Gyratory compacted specimen.

Objectives

The primary objective of this study was to develop and evaluate a testing and data acquisition, reduction, and analysis system to determine crack growth rate parameters of asphalt mixtures using the Superpave IDT. Furthermore, the system to be developed was to meet the following criteria:

- The system should not require the direct measurement of crack growth during testing.
- The system should be a stand-alone system. In other words, the interpretation of the test data should not require the use of properties (e.g., stiffness or Poisson's ratio) that have to be determined independently from other tests on the mixture. Introduction of properties from other tests would not only introduce additional variability in the fracture test results, but would also obviously require the production of additional specimens for testing.

Scope

This paper and the testing system presented deals with the determination of parameters that represent mixture resistance to crack propagation. The concept of effective crack length, which is widely used in the area of fracture mechanics, was used throughout. Simply stated, the effective crack length is determined as the crack length that results in a specified change in material response. The use of the effective crack length concept assumes that all damage is a result of crack growth. In reality, the change in mixture response results not only from crack growth, but also from heat, and from damage in the form of micro-cracking. A procedure was developed in this study that separates the effect of heat, and the effects of micro-cracking induced during crack initiation, from the determination of effective crack length and associated fracture parameters. However, it should be noted that except for perfectly brittle materials, some micro-cracking is probably always occurring concurrently with crack growth. This micro-cracking is interpreted as crack growth in the effective crack length concept.

This is analogous to the use of continuum damage mechanics, where crack growth and micro-cracking are both interpreted as damage.

It should be noted that it may be possible to obtain crack initiation parameters from data obtained from the testing system developed in this study. In fact, it will be shown that the occurrence of damage can be inferred from the test data. However, this will be the study of future work.

Research Approach

The development of the system to determine crack growth rate parameters from the Superpave IDT involved the following steps:

- Determination of the best specimen geometry, including specimen thickness and proper notching procedures for the most accurate determination of fracture parameters.
- Development of the theoretical relationships needed to determine crack length and stress intensity factor from load and deformation measurements obtained from the Superpave IDT.
- Establishment of proper data acquisition procedures to assure that sufficient data are obtained to define crack growth rate precisely enough to determine fracture parameters.
- Establishment of proper data reduction procedures to consistently and reliably determine fracture parameters.
- Evaluation of fracture test data to determine the reasonableness of the results. This was accomplished in several ways: a) by determining whether the crack lengths determined from the test data were reasonable; b) by comparing the measured fracture parameters to values published in the literature for similar mixtures; c) by evaluating the repeatability of the results; and d) by evaluating the reasonableness of the trends in the fracture test results.

Specimen Geometry and Notching

The Superpave IDT is shown in Figure 1. The testing system and associated analysis procedures are described in detail by Roque and Buttlar (5), and Buttlar and Roque (6). These authors and others (7,8,9) have clearly shown that the stress state within cylindrical specimens loaded along the diametral axis cannot be represented using plane stress analysis. In other words, the stress state varies significantly between one side of the specimen and another. This poses a significant problem for determining fracture parameters, because variable stresses result in variable stress intensity factors, which makes it difficult, if not impossible to interpret the data properly.

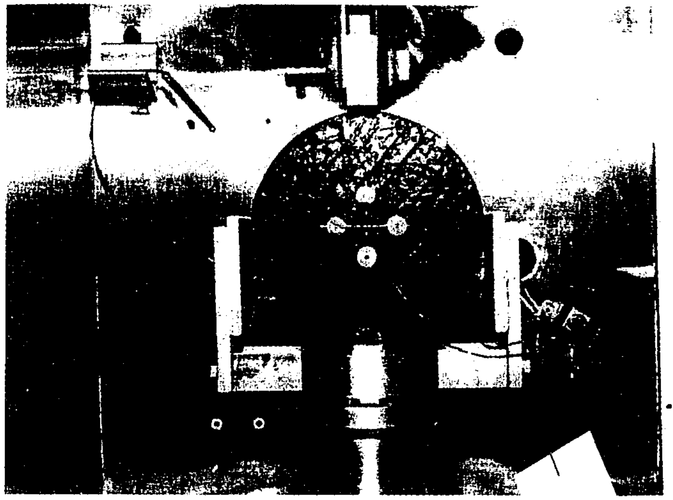

Figure 1. The Superpave Indirect Tensile Test (IDT)

Roque and Buttlar (5) and Hugo (10) showed that plane stress conditions are approximated fairly closely if a relatively thin (approximately 25 mm) specimen thickness is used for indirect tension tests. Therefore, a uniform stress intensity factor can be achieved by using a specimen thickness of approximately 25 mm. Approximately three 25-mm specimens can be obtained by slicing a standard specimen produced with the Superpave Gyratory Compactor.

Fracture tests are generally performed on notched specimens. The notch serves to concentrate the stress so that the crack initiates and propagates along a predetermined path. This allows for deformation or crack length measurements to be obtained along the path of the crack. The size and shape of the notch may have a significant influence on the test results. Therefore, several preliminary tests were conducted to identify the simplest and most effective notching procedures for use with the Superpave IDT.

There are two considerations that need to be made in selecting notch size and shape: 1) the notch must be large enough to assure the crack will initiate and propagate along the desired path; and 2) the effect of the notch must be interpretable such that stress intensity factors can be accurately determined. This latter requirement can be achieved in one of two ways: 1) the notch can be produced with such a sharp instrument that it essentially represents a true crack and its effect can be ignored; or 2) a notch of well-defined shape can be produced, such that the effects of the shape can be analyzed theoretically. After numerous unsuccessful attempts to produce a sharp notch in the center of the specimen, the latter approach was selected in this investigation. Even the use of a special tool developed using a carbide-coated hacksaw blade resulted in relatively dull crack tips. A circular hole was first drilled in the center of the specimen through which the blade was inserted and a notch was made. Further attempts at notching were abandoned, because it was difficult to accomplish and provided little, if any, benefit over the use of a simple hole. Based on these preliminary tests, the decision was made to use a circular hole at the center of the specimen and to theoretically evaluate the effects of the hole on the determination of stress intensity factor. After several trials, an 8-mm diameter hole was determined to sufficiently weaken the 150-mm diameter specimens to assure cracks to initiate and propagate at the center of the specimens. As shown in the following section, two analysis procedures were developed: one that assumed the hole to be a crack; and a more rigorous analysis that considered the stress states in the vicinity of the hole in the determination of stress intensity factors. A comparison of the two approaches allowed for an evaluation and illustration of the effects of ignoring notch geometry in the determination of stress intensity factors and fracture parameters. This work is presented later in the paper.

Determination of Crack Length and Stress Intensity Factor

As mentioned earlier, crack length is difficult, if at all possible, to measure accurately and reliably for asphalt mixtures, such that any measurement of crack length is approximate. Therefore, one of the objectives of this study was to develop a system where the measurement of crack length would not be required during testing. This objective implies that the crack length would need to be determined using the measured response(s), load, and dimensions of the specimen. Two theoretical approaches were developed to accomplish this:

- An energy-based approach.
- A compliance-based approach.

A summary of the theoretical developments and results obtained with each approach is presented in the following sections.

Energy-Based Approach

Crack length, or change in crack length, was determined by equating the total energy dissipated by the specimen to the energy used to create new crack surface. The total energy dissipated by the specimen was determined from the externally applied load and the external deformation measurement (i.e., the load and deformation measured at the loading platens). The energy used to create new crack surface was determined from measurements of the crack opening after a specified number of load cycles were applied. The horizontal measurement obtained from the Superpave IDT was used for this purpose, since the measurement is made at the center of the specimen in the vicinity of the crack. The difference in deformation before and after the specified number of load cycles was used to compute the energy associated with crack growth using the stress distributions at the crack tip corresponding to the crack lengths before and after the specified number of load cycles. Since the crack length was unknown (the goal of this exercise was to solve for crack length), an iterative procedure was developed to solve for crack length. In this procedure, the crack length was varied until the dissipated energy associated with the creation of new crack surface was equal to the total energy dissipated by the specimen.

It was anticipated that a significant amount of damage, and consequently, energy dissipation, would occur in the vicinity of the steel loading platens. Therefore, it was determined that the external energy should be estimated from the internal vertical deformation measurements obtained from the Superpave IDT. Theoretical relationships were developed between the internal measurement and the platen-to-platen measurement.

In spite of the great deal of time and care that was taken to set up this energy-based system and associated software, the results were generally poor. Crack lengths determined from this system were not considered to be reasonable. Sensitivity analyses indicated that the system was excessively sensitive to the stress distributions predicted near the crack tip. In addition, the fact that external energy must be estimated from internal measurements may have resulted in significant inaccuracy.

Based on these preliminary results and observations, the decision was made to not pursue this approach any further. In addition, a detailed description of the system and the calculations involved was deemed not to be warranted for presentation in this paper.

Compliance-Based Approach

The basic premise behind the compliance-based approach to determining crack length is simple: the specimen will become more compliant as the crack length increases. The key is to establish a definitive relationship between crack length and measured deformation for the specified specimen geometry and measurement system being used. Obviously, solutions were not available for the case of the indirect tensile specimen with a vertical crack at its center and the measurement system used with the Superpave IDT. Therefore, the first task associated with the development of a compliance-based approach was to develop these relationships.

Approximate Method As a first approximation, the system was modeled as shown in Figure 2, which shows the indirect tensile specimen with a vertical crack of total length c (=2a). This particular development does not consider the presence of the 8-mm diameter hole that is drilled to concentrate stresses at the center of the specimen. The following relationship was developed between crack length and the horizontal measurement obtained from the Superpave IDT:

$$\frac{\delta}{\delta_o} = 2\sqrt{1+\frac{c^2}{L^2}} - \frac{(1+\nu)}{\sqrt{1+\frac{c^2}{L^2}}} + \nu \qquad (1)$$

where, δ = resilient horizontal deformation across the crack length
δ_0 = resilient horizontal deformation of the uncracked specimen (this corresponds to the deformation measured on the first cycle of loading).
L = gage length of which deformation is measured
c = 2a = crack length
ν = Poisson's ratio

Note that the equation was set up in dimensionless terms by dividing the measured deformation (δ) for any crack length by the deformation measured at the start of the test before any crack growth has occurred (δ_0). This is a very powerful technique because it had the effect of eliminating the stiffness of the mixture as a variable in the equation (i.e., stiffness dropped out in the development and does not appear in the equation above). The implication is that mixture stiffness does not need to be measured or even estimated to determine crack length and crack growth rate parameters.

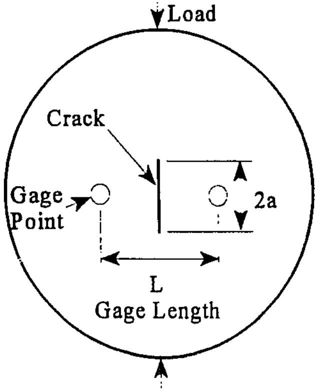

Figure 2. Model of Superpave IDT with Vertical Crack

Unfortunately, Poisson's ratio did not drop out of the equation. However, the sensitivity analysis presented in Figure 3 shows that varying Poisson's ratio from 0.0 to 0.5 (the range typically encountered for asphalt mixtures) had a relatively small effect on the relationship between normalized deformation (δ/δ_0) and normalized crack length (c/L). In fact, for a crack length of 40 mm, assuming a Poisson's ratio of 0.25 would result in maximum error of 2 percent in the predicted crack length, regardless of the actual Poisson's ratio of the mixture being tested (assuming its Poisson's ratio is between 0.0 and 0.5). This precludes the need to measure Poisson's ratio to interpret fracture tests.

It is well known that horizontal tensile stresses are highly uniform along the vertical axis of a diametrically loaded cylindrical specimen. For a relatively thin specimen, where plane stress conditions are approximated, the magnitude of the tensile stress may calculated as follows:

$$\sigma = \frac{2P}{\pi t d} \qquad (2)$$

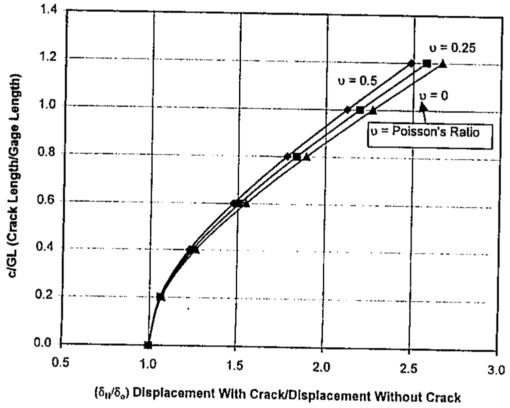

Figure 3. Effect of Poisson's Ratio on Predicted Crack Length Using Displacement From Superpave IDT

where,

σ = horizontal stress along the vertical axis
P = total load applied to the diametrally loaded specimen
t = specimen thickness
d = specimen diameter

The stress intensity factor (*K*) for the crack and specimen geometry illustrated in Figure 2 can be approximated with the following equation:

$$K = \sigma\sqrt{\pi a} \qquad (3)$$

Although this is the solution for a crack of length 2a within an infinitely large body subjected to a uniform stress, comparisons to the rigorous solutions presented later in the paper indicated that this equation reasonably approximates *K* for this problem. This approximate approach was used to make an initial evaluation to determine the viability of the system. It did not make sense to spend an enormous amount of time on more rigorous solutions involving finite element analyses, etc., until it could be shown that viable results could be obtained with the approximate system.

It was found that reasonable results could be obtained using this approximate system. However, in the interest of space, all test results will be presented later in the paper. This will allow for a comparison between the approximate and the rigorous solutions to determine the importance of properly modeling the notch conditions when evaluating fracture test results.

Rigorous Solution (FEM Analysis) More rigorous solutions were also developed for the relationship between crack length and horizontal deformations measured with the Superpave IDT, and for the stress intensity factor of the specific geometry of the specimen being tested. The obvious limitation of the approximate solution presented above is that it does not account for the effect of the hole at the center of the specimen. Although the approximate solution does represent the opening created by the hole as a crack, a round hole distributes stress much differently than a crack. Therefore, it was deemed necessary to develop a more accurate solution and determine the effect on determining fracture parameters. Once again, there was no available solution to this problem, so the solution had to be developed.

The finite element computer program ABAQUS was used to model the diametrally- loaded specimen with an 8-mm diameter hole at its center. Numerous finite element meshes were generated to represent specimens with different crack length, including the case of a specimen without a crack (i.e., only an 8-mm diameter hole). The goal was to obtain a matrix of solutions from which relationships could be developed to determine crack lengths from measured deformation and stress intensity factor for known crack length, load, and specimen dimensions. This would preclude the need to perform finite element analyses to analyze data in the future.

A preliminary evaluation was conducted to determine the most accurate method of determining stress intensity factor from the ABAQUS code. Two methods of determining stress intensity factor were evaluated. The first makes use of the definition of stress intensity factor:

$$K = \lim_{r \to 0} (\sigma_r\sqrt{2\pi r}) \qquad (4)$$

where,

K = stress intensity factor
r = distance from the crack tip
σ_r = stress at distance *r* from the crack tip

Therefore, *K* can be determined in practice by plotting as $\sigma_r\sqrt{2\pi r}$a function of *r* and determining the intercept of the relation at *r* = 0. An example of this approach is shown in Figure 4, which was determined for the case of a rectangular specimen with a crack on one edge subjected to uniaxial tension (this case was run because the solution for K is readily available). An evaluation of this approach to determine K revealed that use of very refined finite element meshes was required to achieve solutions that were within 10 percent of published closed-form solutions for which K is well known.

Stress intensity factor can also be determined by using the J-integral approach, since:

$$K = \sqrt{JE} \tag{5}$$

where,

K = stress intensity factor
J = potential energy in the entire specimen, which is the definition of the J-integral
E = Young's modulus

It should be noted that although the J-integral method theoretically requires knowledge of Young's modulus for determination of K, it can be easily shown that K is practically independent of Young's modulus. The reason is that the J-integral is also a function of Young's modulus, such that the effect of Young's modulus cancels in the determination of K.

The ABAQUS computer program has an automated routine that can be used to determine the J-integral and K. A typical finite element mesh used for the analyses of the Superpave IDT is shown in Figure 5. Given the symmetrical nature of this problem it was only necessary to model one quarter of the specimen for analysis. It is important to note that ABAQUS will apparently not calculate the J-integral if there are any triangular elements anywhere in the finite element mesh. The "isomesh" feature in ABAQUS, which automatically generates a mesh composed strictly of quadratic elements near the crack tip, was found to be very useful in this regard. An evaluation of stress intensity factors determined using the J-integral approach revealed that solutions that are within 2 percent of published closed-form solutions for which K is well known, can be achieved with fairly rough finite element meshes. Therefore, the J-integral method was used in the development of the relationships presented in this paper.

A matrix of finite element analyses were conducted to develop the relationship between horizontal displacement measured with the Superpave IDT and crack length. The relationship is shown in Figure 6, which also shows the relationship based on the approximate solution which did not consider the presence of a circular hole in the analysis. As explained earlier, the relationship was developed in dimensionless terms, which eliminates the effect of mixture stiffness. It is clear from Figure 6 that the approximate solution would lead to significant errors in the determination of crack length and fracture parameters.

Figure 7 shows the relationship developed between crack length and stress intensity factor based on the results of the finite element analyses. This relationship was also developed in dimensionless terms,

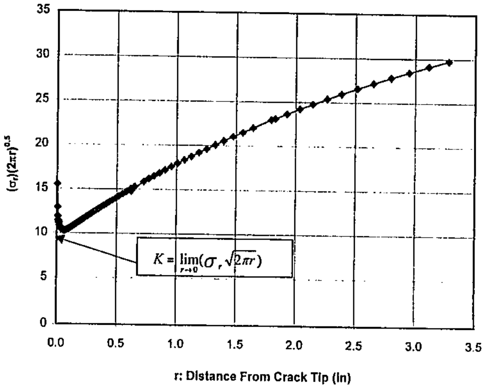

Figure 4. Determination of Stress Intensity Factor from Predicted Stresses

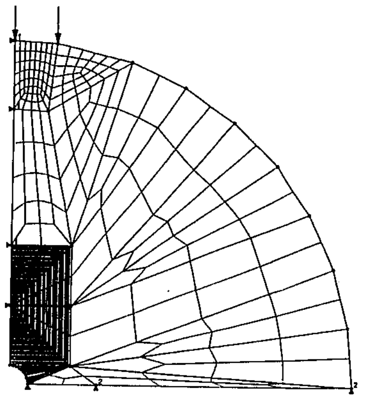

Figure 5. Finite Element Mesh of Superpave IDT with Hole and Vertical Crack

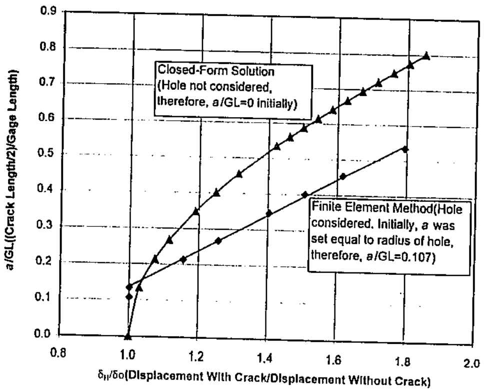

Figure 6. Theoretical Relationship Between Normalized Crack Length and Normalized Horizontal Displacement from Superpave IDT

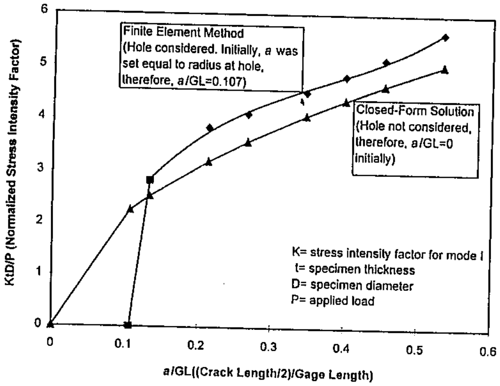

Figure 7. Relations Between Normalized Stress Intensity Factor and Normalized Crack Length

such that *K* can be obtained for specimens of different diameter, thickness, load or gage length. Of course, as mentioned early in the paper, relatively thin specimens should be used to maintain conditions that approximate plane stress. Figure 7 also shows that there is a significant difference between the stress intensity factor determined with the approximate solution and the one from the more rigorous solution.

Materials and Testing Procedures

Two Superpave mixtures were tested as part of this investigation: one designed on the fine side of the restricted zone, the other designed on the coarse side of the restricted zone. Both mixtures were 12.5-mm nominal maximum size mixtures produced with oolitic limerock obtained from South Florida. Specimens were compacted using a Superpave Gyratory compactor to produce 4500-g, 150-mm diameter specimens, to an air void content of 7 percent (± 0.5 percent). Both mixtures met all Superpave requirements, including all aggregate and volumetric requirements. Given that the focus of this paper is the development and evaluation of a system to determine fracture parameters for asphalt mixtures, and not the evaluation of the fracture resistance of the mixtures themselves, no additional details on the materials and mixtures tested will be given in the paper.

Gyratory compacted specimens were sliced to obtain test specimens that were approximately 25 mm thick. Up to three 25-mm thick specimens can be obtained from each Gyratory-compacted specimen.

A masonry bit was used to drill an 8-mm diameter hole at the center of each specimen. The specimens were placed on a specially designed template that assured that the hole was drilled at the exact center of the specimen. The template was composed of two aluminum plates that were used to hold the specimen securely on the drill press. The specimens were positioned with the help of a series of concentric circles inscribed on the surface of the bottom plate. It is important to drill the hole with the specimen's center positioned on a hole on the support plate (bottom plate) that is just slightly greater than 8 mm. This prevents damage from occurring when the drill bit exits the specimen. All tests were performed at 10C. Specimens were placed in an environmental chamber and allowed to reach temperature stability overnight. In addition, the specimens were allowed to dry for at least 24 hr after sawing. Gage points were attached to the specimen surfaces as per the requirements of the Superpave IDT (5,6,11) prior to placement in the environmental chamber. LVDTs were attached to the gage points immediately prior to testing. All fracture tests were conducted by applying repeated load cycles consisting of a 0.1-second haversine load followed by a 0.9-second rest period.

Interpretation of fracture test results according to the theory developed and presented earlier in this paper requires determination of resilient deformations as a function of loading cycles. Therefore, data must be acquired at a sufficiently rapid rate to allow for accurate determination of peak deformations and load during testing. In order to accomplish this for the 0.1-sec haversine loading used in this investigation, data must be acquired at a rate of 150 points per second (pps). Unfortunately, excessively large and unmanageable data files would result if data for four LVDTs and load were obtained at this rate over several thousand cycles. Therefore, data acquisition software was developed to take "snapshots" of the load and deformation response of the specimen at specified intervals. For example, for fracture tests performed at higher stress levels, detailed data (i.e., 150 pps) were obtained at intervals of 250 load repetitions. For tests performed at lower stress levels, detailed data were recorded at intervals of 500 load repetitions.

Data Interpretation Methods

As with most tests, proper interpretation of data is critical to obtaining valid and consistent results. However, careful interpretation of fracture tests on asphalt mixtures is particularly critical to obtaining good results. The procedures described below were determined to provide good results when used with the testing and analysis procedures presented in this paper. It should be noted that these procedures are preliminary and additional work and experience with fracture data obtained from the test may lead to standard procedures that may include additional details that may improve the data interpretation process.

Overview

Determination of fracture parameters from repeated load tests using the Superpave IDT involves the following steps:

- Obtain and plot resilient horizontal deformations as a function of loading repetitions. An example is shown in Figure 8 for tests performed on the fine-graded Superpave mixture.
- Determine the initial resilient horizontal deformation (δ_0) that corresponds to the response of the specimen in the undamaged state. This value is used to normalize all subsequent deformations to determine change in crack length according to the relationships described in Figures 3 and 6 (approximate and rigorous solution, respectively). Additional discussion relating to the determination of this value is presented below.
- Determine and plot crack length as a function of load repetitions using the data obtained in Steps 1 and 2 and the relationships presented in Figure 3 or Figure 6. The resulting plot corresponding to the test results presented in Figure 8, is presented in Figure 9, which shows both the rigorous (finite element) and the approximate (closed-form) solutions.

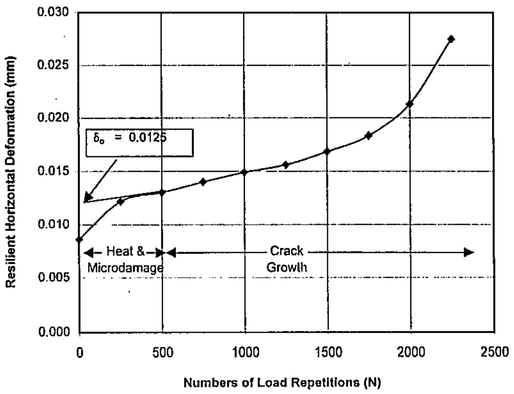

Figure 8. Resilient Horizontal Deformation During Repeated Load Fracture Test

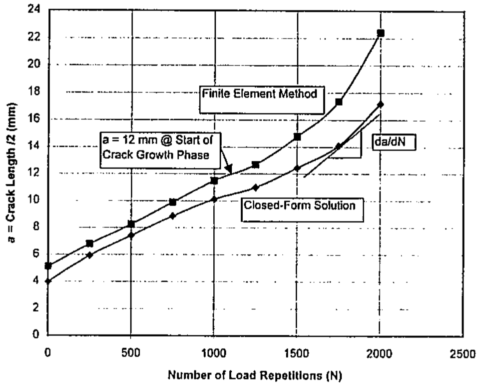

Figure 9. Effective Crack Length During Repeated Load Fracture Test

- Determine the rate of crack growth (da/dN) at several points (number of load repetitions) during the test by determining the slope of the relationship between crack length (a) and number of load repetitions (N), as illustrated in Figure 9. This was accomplished in practice by fitting a third order polynomial to the a vs N relationship and taking its derivative at the desired number of load repetitions.
- The stress intensity factor (*K*) is then obtained for the

corresponding number of load repetitions by using the relationships presented in Figure 7.

- Steps 4 and 5 result in a series of crack growth rates (da/dN) and corresponding stress intensity factors (*K*) that can be used to obtain the relationship between da/dN and *K*. Figure 10 shows this relationship corresponding to the example test data presented in Figures 8 and 9. The Figure is generally plotted using a log-log scale, which reflects the power law nature of the Paris law (i.e., $da/dN = A(K)^n$)
- The fracture parameters A and n for the Paris law are obtained by regression analysis to determine the intercept and slope of the log-log relationship between da/dN and *K*. Their determination is illustrated in Figure 11, which show that only the linear portion of the relationship is used in their determination.

Additional details relating to the data reduction procedures established in this investigation and the significance and physical interpretation of some of the trends observed in the data are presented in the following sections.

Determination of Resilient Deformations

As indicated in the previous section, detailed data (150 pps) were obtained every 250 or 500 cycles, depending on the stress level used to conduct the tests. Specifically, five full loading cycles were recorded at these intervals. Resilient horizontal deformations for use in the interpretation of fracture data were obtained by averaging the resilient horizontal deformations of three consecutive load cycles. Additional details regarding the determination of resilient deformations from the Superpave IDT may be found in Roque et al. (11) and Roque et al. (12).

Determination of Initial Deformation (δ_0)

The trend between resilient horizontal deformation (δ) and number of load repetitions (N) shown in Figure 8 was fairly typical of all fracture tests conducted in this investigation. Initially, there was a relatively rapid increase in resilient deformation, but the rate of increase reduced within the first few hundred load repetitions. This behavior makes no physical sense from the standpoint of crack growth or damage: the rate of damage cannot decrease under constant stress conditions if the crack or the damage zone is getting larger (which is the implication of larger resilient deformations). Therefore, it was concluded that there was another reason for this initial rapid increase in resilient horizontal deformation.

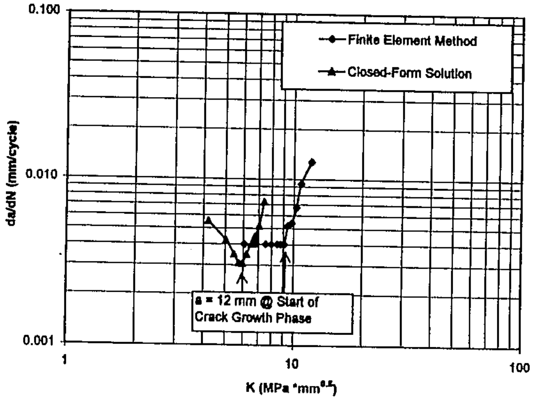

Figure 10. Relation Between Crack Growth Rate and Stress Intensity Factor

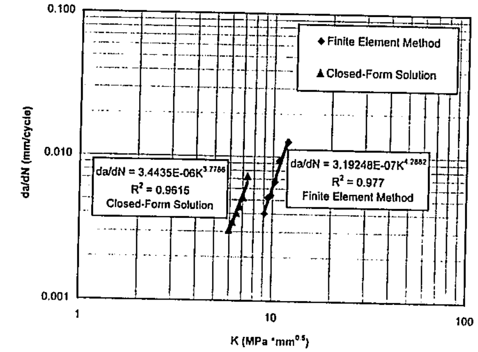

Figure 11. Determination of Fracture Parameters A and n, where $da/dN = A\,(K)^n$

Work by Di Bennedetto (13) showed that significant increases in temperature could occur during the early part of repeated load tests on asphalt mixtures. The temperature increase reduces the stiffness of the asphalt mixture, which would explain the increase in resilient deformation. This is consistent with the observations in this study and provides a rational physical explanation for the data obtained. Therefore, as shown in Figure 8, increases in resilient deformation during the early part of the fracture test may be attributed to heat and damage. It may be further deducted that the temperature in the specimen has stabilized once the rate of increase of resilient deformation stabilizes.

This phenomenon has an effect on the interpretation and determination of the initial deformation (δ_0). In theory, δ_0 represents the resilient horizontal deformation corresponding to the undamaged specimen. In the relationships developed in this paper, the value is used to normalize deformations obtained during the course of the fracture test such that the effect of stiffness is eliminated from the determination of crack length. Therefore, δ_0 should be obtained at conditions corresponding to the conditions after the specimen has reached temperature stability.

Given the argument presented above, the proper way to obtain δ_0 is shown in Figure 8, which shows that an extrapolation of the δ_0 vs N relation from the point where the rate of increase in resilient horizontal deformation stabilizes. The initial deformation (δ_0) is determined as the intercept of the straight-line extrapolation at $N=0$. At this time, the extrapolation is performed by visually determining the location when the rate of deformation has stabilized. More standardized procedures need to be developed to determine this value, which is critical to the accurate determination of fracture parameters using this method.

Further Discussion on Determination of Fracture Parameters

Figures 9 through 11 show that the approximate (closed-form) solution resulted in significantly different predicted crack lengths and fracture parameters than the more rigorous solution that accounted more precisely for the presence of the hole in the test specimen. The approximate solution significantly overestimated the rate of crack growth for a given level of stress intensity (i.e., it significantly underestimated the fracture resistance of the mixture). These results clearly emphasize the importance of precisely controlling and/or accounting for notch geometry in the interpretation of fracture tests.

Perhaps more importantly, the trends in the data presented in Figures 9 through 11, which were typical of all fracture tests performed in this investigation, supports the validity of the more rigorous solution, and of the testing system in general. The shape of the da/dN relationship for the approximate solution shown in Figure 10 is typical of fracture test results presented in the literature (1). During the initial part of the test, da/dN is shown to decrease as the stress intensity factor (*K*) increases. This behavior has no physical meaning. In fact, this response makes no sense, as it would imply that higher stresses and stress intensities would result in less crack growth. The fact is that if a crack grows, then the stress intensity increases and da/dN must increase for a constant stress test. Consequently, most researchers have simply ignored these data in their interpretation of fracture test results.

The authors believe that this response is an artifact caused by improper data interpretation: specifically, not accounting for the effects of the notch during the early part of the test. Figure 10 shows that when the more rigorous solution was used, da/dN did not decrease, but instead remained constant, during the early part of the test. Therefore, accounting for the notch effects eliminated this unreasonable response. One may argue that da/dN should in fact begin to increase from the very beginning of the test. However, one must recognize that a notch is essentially a hole, and a hole is not a crack. It takes time (or load repetitions) for the hole to develop into a true crack. Micro-damage is occurring during this time, which results in higher resilient horizontal deformations, but da/dN should not increase until a crack actually forms (i.e., the rate of damage should not increase until the geometry of the specimen changes). This is consistent with the results presented in Figure 10 for the rigorous solution.

It should be noted that these issues are not as critical in traditional approaches used to determine fracture parameters, where crack growth is measured directly and is then empirically related to stress intensity. However, the goal of this investigation was to develop a method that does not require direct measurement of crack growth, so proper theoretical interpretation is critical to determining crack length and stress intensity accurately.

The magnitudes of the crack lengths determined offer further evidence of the validity of the system developed in this investigation. Results presented in Figure 9 indicate that specimen failure (da/dN began to increase very rapidly) when the predicted crack length was about 45-mm (2 times *a*). This is a very reasonable result, since a 45 mm crack length within a 150-mm diameter specimen would cause substantial weakening such that overall specimen failure should be imminent. The crack length associated with the point when da/dN began to increase (i.e., the start of crack growth) was also reasonable. As shown in Figure 10, crack growth was determined to start at a crack length of 24 mm, such that half the crack length (*a*) was 12 mm. Given that the radius of the hole was 4 mm, this implies that the length of the crack in front of the hole immediately after crack initiation was about 8 mm. It is interesting to note that for all tests performed in this investigation, *a* was consistently determined to be between 11 and 13 mm at the beginning of crack propagation.

Test Results and Evaluation

Five fracture tests were performed on the Superpave coarse-graded mixture: two at a relatively high stress level; two at an intermediate stress level; and one at a low stress level. Two tests were conducted on the Superpave fine-graded mixture: one at a high stress level, the other at an intermediate stress level. As indicated earlier, all tests were performed at 10C. The results of these tests are summarized in Figure 12 and Tables 1 and 2.

Figure 12 shows that all five test results for the Superpave coarse-graded mixtures appear to group rather nicely. This is consistent with the notion that fracture parameters are fundamental material properties that should be independent of the stress level or other experimental variables. The two results for the Superpave fine-graded mixtures also appeared to line up well with each other.

On the other hand, the values of A and n for individual specimens presented in Tables 1 and 2, exhibited a significant amount of variability. This appears to imply, that as with most tests performed on asphalt mixtures, some replicate testing would be required to determine A and n reliably. Perhaps A and n determined using the composite results of all tests performed (see Tables 1 and 2) may provide the best estimate of the true A and n for these mixtures. It should be noted that the n based on the composite results was less than the n for any individual tests. It appears that this effect is caused by the results obtained at lower stress levels, which appeared to result in da/dN values that were high relative to those obtained at higher stress levels. The reason for this is unclear at this time, but may be related to the fact that micro-damage may play more of a role in the lower stress tests than in the higher stress tests. Additional work will be required to investigate the effects of stress levels on the determination of fracture parameters.

Other researchers have also reported a broad range in A and n determined from fracture tests. Researchers in the Netherlands (1) have reported that A and n are inversely related (i.e., higher A's are associated with lower n's). The magnitude of A and n agreed well with values published in the literature for dense-graded asphalt mixtures. Results obtained in the Netherlands (1) indicated that for dense-graded mixtures tested at 15C, the range in n was from 3.5 to 6.8, where most values were between 3.5 and 4.5. For the same mixtures, A ranged from 4 x 10^{-11} to 5 x 10^{-7}, where most values were

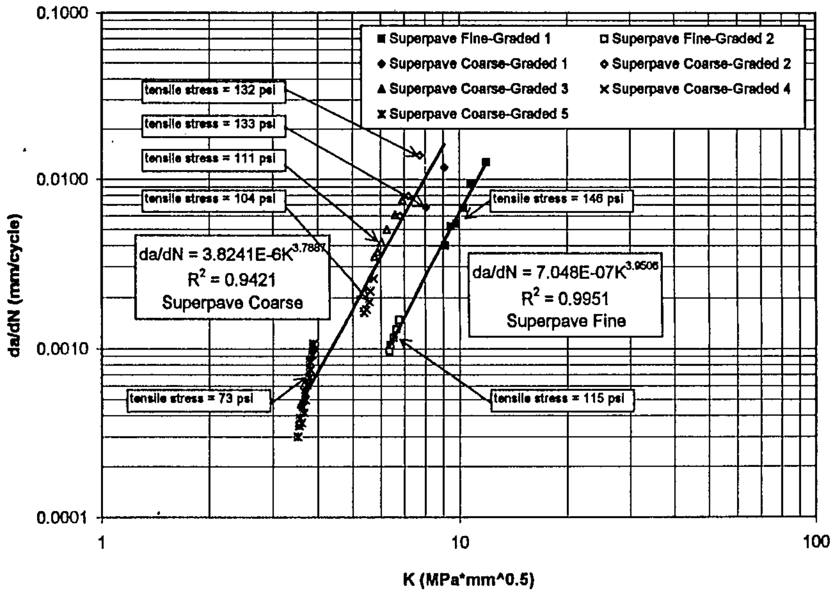

Figure 12. Fracture Test Results for Superpave Coarse and Fine-Graded Mixtures

Table 1. Fracture Test Results for Superpave Coarse-Graded Mixture @10C

Specimen No.	Stress Condition	Number of Cycles of Failure	A	n
1	High	1750	1.586×10^{-8}	6.6736
2	High	2750	3.687×10^{-7}	4.7088
3	Intermediate	5500	1.762×10^{-6}	4.3261
4	Intermediate	7750	1.670×10^{-8}	6.8151
5	Low	25000	4.886×10^{-11}	12.41
Composite of all Tests	--	--	3.824×10^{-6}	3.7887

Table 2. Fracture Test Results for Superpave Fine-Graded Mixture @10C

Specimen No.	Stress Condition	Number of Cycles to Failure	A	n
1	High	2750	3.192×10^{-7}	4.2882
2	Intermediate	12250	6.075×10^{-9}	6.4897
Composite of all Tess	--	--	7.048×10^{-7}	3.9506

between 1×10^{-7} and 7×10^{-8}. The composite values for A and n shown in Tables 1 and 2 are within this range, except that A for the coarse-graded mixture is slightly above the range. However, this is consistent with the fact that tests were performed at 10 C in this investigation. Fracture resistance is expected to be lower as temperature decreases and the mixture becomes more brittle.

Given the apparent variability in A and n determined for single specimens, it may be argued that it would be best to specify da/dN at a specified stress intensity factor (instead of A and n) for mixture design and specification purposes. It is obvious, from the data presented in Figure 12 that da/dN from individual specimens is much less variable than A and n. The potential problem in specifying a single value of da/dN is that depending on the characteristics of the mixtures, the relationship between da/dN and K may cross, such that the selection of the most relevant K value would be critical.

Finally, the data presented in Figure 12 clearly show that the fine-graded Superpave mixture has better fracture resistance than the coarse-graded Superpave mixture, even though the mixtures were produced with the same aggregates and asphalt cement, and were compacted to the same air void content. This appears to imply that aggregate structure may have an important effect on mixture fracture resistance. Although the void content of these mixtures was the same, the void structure was probably not the same. Some coarse-graded Superpave mixtures have been found to have relatively high permeability, indicating the presence of fairly large and interconnected voids. These larger voids create larger stress concentrations that reduce the mixture resistance to fracture. It appears that the finer-graded mixture had smaller voids that were more dispersed throughout the mixture.

Summary and Conclusions

A complete testing, data acquisition, reduction, and analysis system was developed in this study to determine fracture parameters using the Superpave IDT (indirect tension test). The theoretical relationships and data reduction procedures developed preclude the need to measure crack growth rate directly during testing, or the need to obtain or estimate asphalt mixture stiffness or any other property to analyze the fracture test data. These two features not only make fracture testing easier to perform, but it may also be argued that better consistency can be achieved, since the variability introduced by using properties determined from independent tests, as well as the inherent inaccuracies involved in measuring crack growth rate directly, are eliminated. It also eliminates the need to produce and test another set of specimens.

Based on tests performed on two Superpave mixtures, the system developed appeared to provide rational and consistent fracture test results that compared favorably with fracture parameters published in the literature for similar mixtures. Therefore, the system appears to provide a viable approach for determining fracture resistance of asphalt mixtures produced with the Superpave Gyratory compactor or of field cores obtained from pavements in the field.

Fracture tests performed on Superpave mixtures indicated that the mixture graded on the coarse side of the restricted zone had significantly lower fracture resistance than the mixture graded on the fine side of the restricted zone. Both mixtures were produced with the same aggregate and asphalt cement and compacted to the same air void content. Therefore, it appears that the resulting void structure of these two mixtures may be significantly different, where the coarser-graded mixtures had larger voids that increased stress concentrations and reduced the mixture resistance to crack propagation.

As a final note it must emphasized that great care must be taken in analyzing and reducing fracture data to obtain good results. In addition, it appears that as with most properties determined for asphalt mixtures, multiple tests are required to determine A and n reliably. However, less variability was observed in da/dN determined within the range of the data than for the parameters A and n. Additional work will be required to address these and other issues before fracture test data from the tests can be put into practice.

References

1 M.M.J. Jacobs, P.C. Hopman. and A.A.A. Molenaar, "Application of Fracture Mechanics Principles to Analyze Cracking in Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists*, Vol. 65, pp.1-39, 1996.

2 D.N. Little, R.L. Lytton, D. Williams, and Y.R. Kim, "Propagation and Healing of Microcracks in Asphalt Concrete and Their Contributions to Fatigue," *Asphalt Science and Technology*, pp. 149-195, 1997.

3 Y.R. Kim, H-J. Lee And D. N. Little, "Fatigue Characterization of Asphalt Concrete using Viscoelasticity and Continuum Damage Theory," *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, pp.520-569, 1997.

4 Y.R. Kim, H-J. Lee And D. N. Little, "Mechanistic Evaluation of Fatigue Damage Growth and Healing of Asphalt Concrete: Laboratory and Field Experiments," *Eighth International Conference on Asphalt Pavements*, Seattle, Washington, pp. 1089-1107, 1997.

5 R. Roque, and W.G. Buttlar, "The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties using the Indirect Tensile Mode," *Journal of the Association of Asphalt Paving Technologists*, Vol. 61, pp.304-332, 1992.

6 W.G. Buttlar, R. Roque, "Experimental Development and Evaluation of the New SHRP Measurement and Analysis System for Indirect Tensile Testing at Low Temperature," *Transportation Research Record*, national Academy Press, Washington, D.C., No. 1454, pp.163-171, 1994.

7 M.S. Mamlouk, and Sarofim, "The Modulus of Asphalt Mixtures-An Unresolved Dilemma." *Presented at the 67th Annual Meeting of the Transportation Research Board*, 1988.

8 J.J. Heiniche, and T.S. Vinson, "Effect of Test Condition Parameters on IRM_r." *Journal of Transportation Engineering*, ASCE, Vol. 114, No. 2 (March 1988), pp. 153-172.

9 J>B. Sousa, R.. Taylor, and A..J. Tanco, "Analysis of Some laboratory Testing System for Asphalt-Aggregate Mixtures," *Presented at the 70th Annual Meeting of the Transportation Research Board*, 1991.

10 F. Hugo, and W.J. Schreuder, "Effect of Sample Length on Indirect Tensile Test Parameters," *Journal of the Association of Asphalt Paving Technologists*, Vol. 62, pp.422-449, 1993.

11 R. Roque, W.G. Buttlar, B.E. Ruth, M. Tia, S.W. Dickison, and B. Reid, "Evaluation of SHRP Indirect Tension Tester to Mitigate Cracking in Asphalt Pavements and Overlays," *Final Report to the Florida Department of Transportation*, August 1997, 364pp.

12 H. Di Benedetto, A. A. Soltani, and P. Chaverot. "Fatigue Damage for Bituminous Mixtures: A Pertinent Approach," *Journal of the Association of Asphalt Paving Technologists*, Vol. 65, pp.142-158, 1996.

Discussions

MR. DALE DECKER: Looking at the data that you had comparing coarse graded and fine graded mixes, clearly that is the same

conclusion initially that WesTrack also came up with. Have you had any opportunity to look at any of those WesTrack mixes? There are performance data there and you could compare laboratory to performance. Any thought about possibly doing that?

PROFESSOR REYNALDO ROQUE: I would love to do that. We are doing that with a number of Florida sections. We have eight sections to this point where we have very detailed performance data and we have very detailed mixture data. Since we developed the tests then we have gone ahead and measured these fracture parameters to see how they relate. We are right now looking at all of that to try to make sense of the data. Of course, WesTrack is a much more controlled experiment. That would certainly help us.

MR. DALE DECKER. That might be a good tie to performance.

PROF. ROQUE: Yes, it would be. I would welcome that.

DR. RAJ DONGRÉ: I did some tests on binder to determine fracture toughness by putting notches in the direct tension specimen. What I found was that as the crack length increased your intensity factor also changed. Meaning the stress intensity factor of crack length relationship was non-linear, which would indicate that you would need some kind of an elastic plastic analysis. You indicated that you only saw 2 percent difference between the K which is the linear elastic and J which is elastic plastic. Or you did not do the elastic plastic analysis. Meaning how do you account for what happens in front of the crack when you have such intense stresses? That is what I am wondering.

PROF. ROQUE: I think there are a lot of issues raised by your question. The 2 percent difference was between the finite element solution and published close form solutions. You can use the J-integral with elastic or you can use it with plastic. The J integral is not really a function of the material model that you use, it is basically an energy calculation around the crack. So I think what you are saying is right but we have accounted for that, I think, in the analysis that we have done.

DR. DONGRÉ: Normally when you do fracture testing, for example in a direct tension test mode, the crack front always is perpendicular to your stress. And you also use direct tension and try to get far field stresses meaning where you are applying stress should be far from where the crack is. In this case, maybe this has no effect, but what is curious is your crack front approaches your loading. So at some point the crack front is approaching the load that is coming the opposite direction. I wonder what impact that would have in the fracture parameters that you are measuring. Do you have to worry about the fact that your stresses no longer remain far field as your crack front approaches to failure and if you have a way of accounting for that?

PROF. ROQUE: The J integral takes into account the complex stress states in the vicinity of the crack. So you are accounting for the fact that you have bi-axial stresses. You are right in saying that this is not a pure tension test. It is not pure tension. You have compression. But assuming we are in the diametral axis you don't have shear. So it is still a mode 1 cracking problem. The calculation of K becomes a simple calculation when you have a simple stress state like a pure tensile stress state. The calculation of K just goes through the J integral when you have a more complex stress state. It does not affect the K that you do get.

DR. DONGRÉ: Perhaps. But I would think that as your crack front approaches the loading platen that your far field stress assumption would be violated. I don't think any analysis method right now will allow you to account for that.

PROF. ROQUE: That is an excellent point. I think that if you look in theory the far field stresses are actually highly uniform in this test. In reality they are not. I think what happens is that you have the end effects. That is what I am really concerned about. What we have really found is this goes back to how you interpret the data. This test is not a production test by any means. We haven't nailed down every single detail of the interpretation but one of the things we found that helped us tremendously in getting proper interpretation of the test is we have to limit the length of crack over which we interpret the data. I think it is related to the fact that once you get beyond a certain length you are starting to get into a zone where the stresses are not what you think they are any longer. You are getting end effects up there which is the very reason we went to the middle of the specimen with the indirect tension test. The other thing is, just from a practical point of view, once the crack gets to about 50 mm the specimen fails. So you can't get any more data. These tests are progressing and bang they go. You are not going to be measuring crack growth with the crack getting within an inch of the loading head because it will never get there. It just simply will never get there. Actually that all comes out very nicely when you plot that DaDn versus K curve you will start seeing that the curve starts to become non-linear and flatten out once we start getting those results. We have established sort of a rule right now. At this point we are using a rule of about a maximum of 25 to 28 mm for half the length of the crack which would make it about a 50 to 60 mm crack maximum as far as the data that we can analyze to still get reasonable results from the test. I think that relates to the very issues you are talking about. You are limited to what you can interpret and you should not interpret data coming from cracks that get into that zone.