DETERMINATION AND PREDICTION OF CRACK PATTERNS IN ASPHALT MIXTURE UNDER STATIC LOADING

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ABSTRACT. *This paper presents a comparison between predicted and measured crack patterns developing in asphalt mixtures during static loading. Two different state configuration were investigated performing the Indirect Tensile Test (IDT) and the Semi-Circular Bending Test (SCB). A Digital Image Correlation System was applied to obtain a dense and accurate displacement/strain field of asphalt mixtures and for describing the cracking behavior. The resulting fracture behavior in the tests was predicted using a displacement discontinuity boundary element method to explicitly model the microstructure of asphalt mixtures. The predicted crack initiation and crack propagation patterns are consistent with observed cracking behavior. The results also imply that fracture in mixtures can be modeled effectively using a micromechanical approach that allows for crack growth both along aggregate surfaces, as well as through aggregates.*

INTRODUCTION

Cracking has long been accepted as a major mode of premature failure in asphalt concrete pavements. Understanding the cracking mechanisms of asphalt mixtures is key to improving the cracking resistance of mixtures. Unfortunately, the complexity of crack propagation in hot mix asphalt mixtures has been an obstacle to the incorporation of fracture mechanics-based approaches in the bituminous pavement area.

Various models for cracks in granular material have received considerable attention among researchers. Bazant (1) provided a good review of existing cracking models that have been used to analyze brittle materials such as rock and concrete. The analysis of cracks is commonly carried out by either a fracture mechanics approach or a smeared crack approach. The former assumes that a crack can be represented as a series of connected single line segments, which initiate from one or more pre-existing flaws and which propagates through the material according to certain crack growth criteria, such as maximum energy release rate. Alternatively, the smeared crack approach assumes that cracks are distributed over a finite region such that an average tensile strain adequately represents the physical presence of the cracks. With appropriate material models for compression and tension, the smeared crack approach can reasonably predict the cracking behavior of materials. Nevertheless, both methods cannot fully capture the nature of cracks in granular materials, where cracks randomly initiate along weak planes, coalesce to form a major crack band and propagate through the material.

Explicit fracture modeling using random assemblies of displacement discontinuity boundary elements provides a more realistic approach in the simulation of discrete cracks in granular materials (2). The method employs known stress and displacement field influence functions due to defined displacement discontinuity elements that are distributed through the region of interest. The change in geometry due to crack propagation is easily handled by allowing cracks to grow only along the predefined crack paths, which can be assumed to be along aggregate boundaries or to follow internally defined fracture paths within the aggregates.

This paper presents an investigation of the cracking mechanism of an Asphalt Mixture subjected to two different static test configuration: Indirect Tensile Test (IDT) and Semi-Circular Bending Test (SCB). Both test were performed and then simulated using the displacement discontinuity method (DDM) to explicit model the microstructure of asphalt mixtures and predict crack initiation and propagation.

Experimental analyses were enhanced by a Digital Image Correlation System capable of providing a dense and accurate displacement/strain field of composite materials and suitable for detecting the cracking behavior of materials at each instant of interest (3).

The predicted crack initiation and crack propagation patterns are consistent with the cracking behavior observed from Image Correlation analysis. The results imply that fracture in mixtures can be modeled effectively using the displacement discontinuity method. Finally, the results presented showed that crack initiation and crack growth can be easily detected using the Digital Image Correlation System, as well as strain values next to crack boundaries.

STATIC TEST DESCRIPTION

Two different stress conditions of the mixtures were investigated performing the Indirect Tensile Test (IDT) and the Semi-Circular Bending Test (SCB). The tests were performed at 10° C applying a static load occurring with a displacement control system, where the top loading device drops with a 0.08mm/sec speed.

The IDT is an indirect tensile test performed on circular specimens (150 mm diameter). Two strain gauges with a length of 38.1 mm were placed at the centre of the specimen to measure vertical and horizontal deformations during loading. The horizontal stress occurring at the centre of the specimen was computed using the following IDT plane stress equation, according to the SHRP Indirect Tension test procedure:

$$\sigma_h = 2P/\pi Dt \qquad (1)$$

where P is the total applied load, D is the diameter and t the thickness of the IDT specimen.

The SCB is a three point bending fracture test performed using semi-circular shape specimens (150mm in length, 75mm in height). One strain gauge with a length of 20mm is placed on the surface of the specimen in the centre bottom area to measure horizontal deformations. The SCB horizontal stress measurements were computed by means of an equation based on the three point bending moment formula for linear elastic materials, adapted, by means of a finite element study conducted by Molenaar (4), to asphalt mixtures:

$$\sigma_h = 4.8P/Dt \qquad (2)$$

which measures the tensile stress occurred at the bottom edge of the specimen. It must be noted that the equation is valid only if the distance between the supports is equal to 0.8 D.

DISCPLACEMENT DISCONTINUITY METHOD

The modelling of crack growth and localization was performed with a Displacement Discontinuity Boundary Element Method (DDM), recently adopted by Birgisson et al. (5) to model the microstructure and the cracking behaviour in IDT specimens during strength tests.

The DDM is an indirect boundary element method (6). The method assumes displacements in a body are continuous everywhere except at a line of discontinuity. The displacement vector components u_i on each side of the discontinuity can be expressed as:

$$D_i(y_q) = u_i(y_q, 0_-) - u_i(y_q, 0_+) \qquad i = y, z; \qquad -b < y_q < b \qquad (3)$$

where $z = 0_+$ is the positive side and $z = 0_-$ is the negative side of the discontinuity element. Further details on the formulation are discussed by Napier (7) and Birgisson, et al. (5).

A linear variation of displacement discontinuity elements was assumed for the displacement discontinuities. The numerical model consists of two types of elements: exterior boundary elements and potential crack elements. These represent respectively, the boundary surface of the specimen and internal sites where potential crack elements are selected for mobilization (slip or tensile opening modes). A Voronoi tessellation approach was adopted to account for the presence of aggregates (5,7), in which displacement discontinuity elements were randomly placed inside the specimen forming Voronoi patterns of predefined paths.

At each load step, stresses are computed at collocation points inside the potential crack elements; these stresses are then checked against a failure limit to determine whether or not a crack has been activated. A nonlinear failure law, shown in Figure 1, is adopted for the cracking criterion.

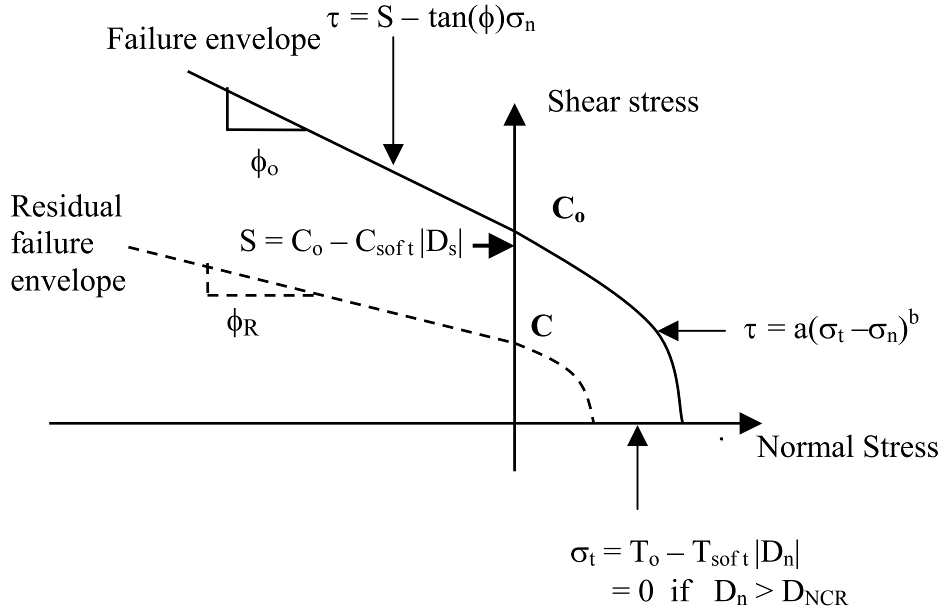


Figure 1. Mohr Coulomb type of failure criterion for determining crack mobilization.

The failure law comprises a linear portion in the compression region that changes over to a power law curve in the tension region, with a continuous slope at $\sigma_n = 0$. The linear portion has the following form:

$$\tau = S - \tan(\phi)\sigma_n \quad when\ \sigma_n < 0 \qquad (4)$$

where S is the cohesion, Φ is the friction angle and σ_n is the normal stress across the discontinuity that is assumed to be negative when compressive. The power law curve is defined by:

$$\tau = a(\sigma_t - \sigma_n)^b \ when\ 0 < \sigma_n < \sigma_t \qquad (5)$$

where σ_t is the tensile strength and the two constants a and b are chosen to match the value and the slope of the linear portion of the failure envelope when $\sigma_n = 0$.

For every load step, a crack search algorithm is performed to detect cracks that may occur in the specimen. At the end of each search step, the detected cracks are added to the system and resolved for determining new cracks in the next search step, until no more cracks are found. When a potential crack element is mobilized, the cohesion S is assumed to weaken as a linear function of the slip D_s,

$$S = C_o - C_{soft} \mid D_s \mid \tag{6}$$

where C_o is the original cohesion intercept and C_{soft} is the rate of cohesion softening. Similarly, the tensile strength σ_t is also assumed to weaken as a linear function of the opening displacement D_n,

$$\sigma_t = T_o - T_{soft} \mid D_n \mid \tag{7}$$

where T_o is the tension cutoff and T_{soft} is the rate of tension softening. When crack slip occurs, the tensile strength is implicitly degraded as the cohesion softens, congruently with the extent of cohesion softening.

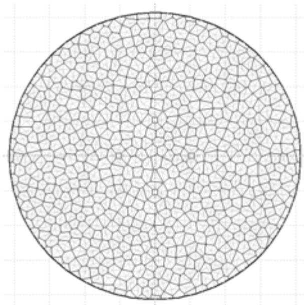
ANALYSES AND RESULTS

Experimental analyses were enhanced by a Digital Image Correlation System capable of providing a dense and accurate displacement/strain field of composite materials and suitable for detecting the cracking behavior of materials at each instant of interest. The DIC System consists in a photogrametric-based method which applies the *Least Square Matching* image matching technique to an image sequence recorded during specimen conditioning. Further details on the system setup, image processing and data extraction are discussed by Roncella and Romeo (3).

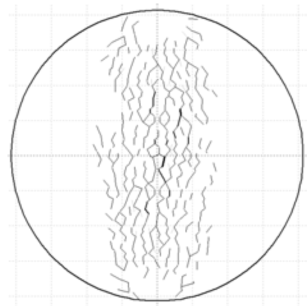
A total of 12 specimens (6 IDT, 6 SCB) were tested at 10° C. For each testing setup three replicates were performed monitoring strains with both strain gauge and DIC analyses, while other three replicates were monitored by the only image sequence processing.

The two tests were also modeled and simulated by means of the Displacement Discontinuity Method. Input parameters for SCB test simulations were obtained from Superpave IDT testing, followed by the interpretation approach developed by Birgisson et al. (8) for obtaining a suitable set of material parameters for the micromechanical displacement discontinuity modeling of mixtures. In order to evaluate the quality of the input parameters, the Superpave IDT stress-strain test results for the mixture tested were simulated with the micromechanical displacement discontinuity method.

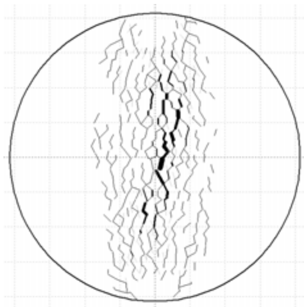
Figures 2,3 show the simulated crack patterns for the mixture during IDT and SCB tests respectively at representative load steps ranging from crack initiation to major crack opening. In the IDT test simulation a huge number of small cracks are clearly visible within the center area of the specimen where high tensile stress is concentrated. In the following load steps, these small cracks coalesce into larger and visible cracks until failure. In the SCB test simulation, small cracks are visible within the center-bottom area of the specimen, which is the area of highest bending moment. In the following load steps the central crack growth region extends along the bottom edge of the specimen, coalescing into a single larger macro-crack along the vertical plane.



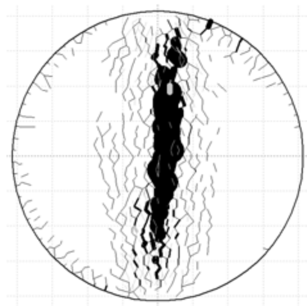
(a) Indirect Tensile Test model



(b) Crack pattern at fracture point

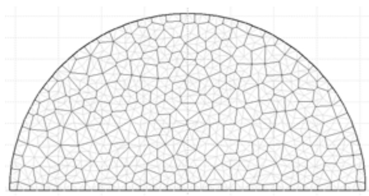


(c) Crack pattern at visible macro-crack

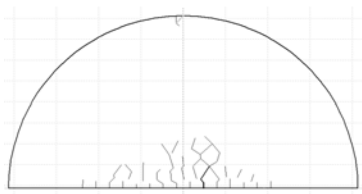


(d) Crack at final load step

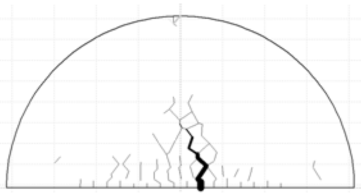
Figure 2. Predicted crack patterns for the mixture during the IDT test



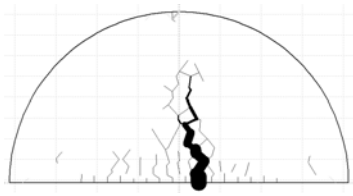
(a) Indirect Tensile Test model



(b) Crack pattern at fracture point



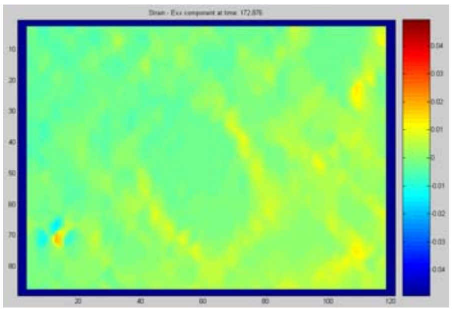
(c) Crack pattern at visible macro-crack

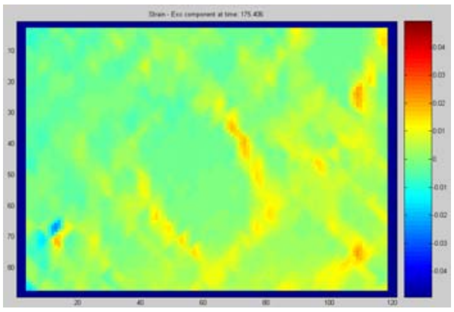


(d) Crack at final load step

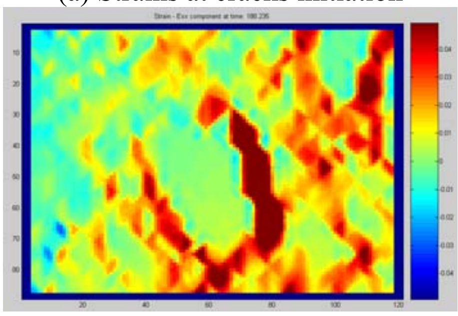
Figure 3. Predicted crack patterns for the mixture during the SCB test

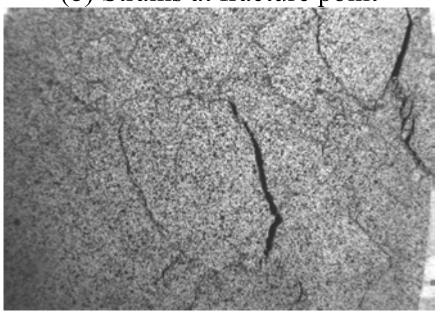
Figures 4,5 show the measured horizontal strain map for the mixture during IDT and SCB tests respectively from crack initiation to major crack opening. The strain maps agree well with the numerical results: high strain values develop within the whole centre area of the IDT specimen, while in SCB specimens, the highest strain results only in a restricted zone located at the bottom edge of the specimens.





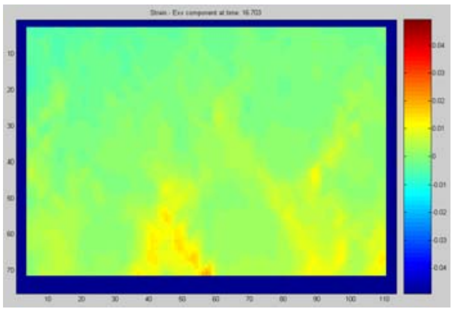
(a) Strains at cracks initiation (b) Strains at fracture point

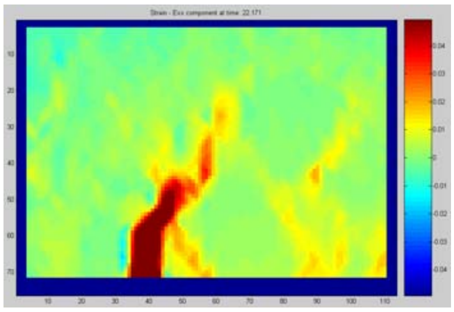




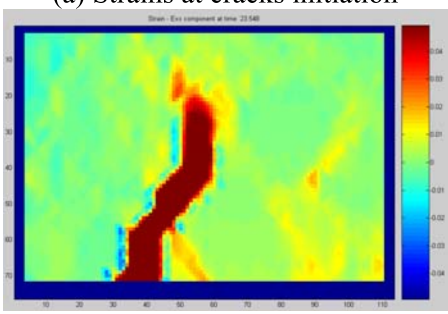
(c) Strains at failure (d) Visible experimental cracks

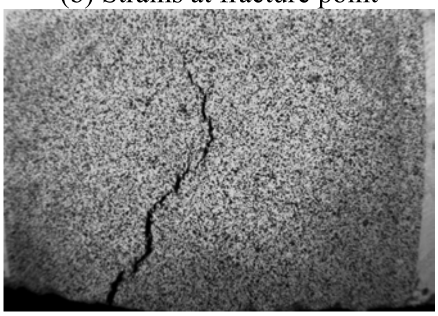
Figure 4. Full field strain maps during the IDT test





(a) Strains at cracks initiation (b) Strains at fracture point





(c) Strains at failure (d) Visible experimental cracks

Figure 5. Full field strain maps during the SCB test

CONCLUSIONS

This paper presented a comparison between predicted and measured crack patterns developing in asphalt mixtures during static loading. Experimental analyses were enhanced by a Digital Image Correlation System capable to provide a dense and accurate displacement/strain field of composite materials at the microstructural level. The resulting fracture behavior in the tests was predicted using a displacement discontinuity boundary element method that models the microstructure of asphalt mixtures. The resulting predicted crack initiation and crack propagation patterns are consistent with observed experimental cracking behavior. The results imply that fracture in mixtures can be modeled effectively using the displacement discontinuity method with Voronoi tessellations. The results presented also showed that the crack propagation patterns can be easily captured using the Digital Image Correlation System. The Image Correlation System appears to be a powerful tool in the analysis of a full two-dimensional displacement/strain full-field during HMA fracture testing.

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