The displacement discontinuity method for modeling fracture in the semi-circular bending test

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Abstract

This paper investigates the capability of a displacement discontinuity boundary element method, which was already used to assess the mechanics of fracture in the SuperPave™ Indirect Tension Test, to model the microstructure of asphalt mixtures. The paper presents a semicircular bending test simulation in order to verify the independence of the method from the testing setup application. The predicted stress–strain curves were shown to compare well to the experimental results, as well as the cracking behaviour. The results imply that the method is able to characterize asphalt mixtures properties regardless of the particular testing setup used in the investigation. It has also shown promise as a tool for studying the mechanism of crack growth and propagation in hot mix asphalt (HMA) during every kind of testing setup.

Keywords: Displacement discontinuity method; Hot mix asphalt; Semi-circular bending test

1. Introduction

The improvement of cracking resistance of hot mix asphalt (HMA) is one of the main issues in asphalt pavement design. Lately many research programs have been initiated that are based on fracture mechanics approaches, aimed at a better understanding of the mechanism of crack growth and propagation in HMA mixtures.

The main obstacle to the comprehension of fracture mechanics-based approaches consists in the complexity of modeling crack propagation. The use of traditional numerical methods, such as the finite element method (FEM), to describe the mechanics of crack initiation and crack growth in the bituminous pavement area is at best tedious, as discussed in Birgisson et al. [1]. The FEM requires highly refined meshes around the cracking area in order to simulate the stresses in the vicinity of the crack tip; it also requires elaborate remeshing to simulate the geometry of a growing crack. On the contrary, a boundary element approach needs meshes only on the boundaries of an object or pavement, including cracks, reducing significantly the number of elements required.

Birgisson et al. [1] used a displacement discontinuity boundary element method (DDM) to model the microstructure of asphalt mixtures modelling and SuperPave Indirect Test (IDT) specimen and simulating the cracking behaviour of the IDT test. The method appeared to be a good predictor of crack initiation and fracture growth agreeing with experimental sections both in observations and in stress-strain response. Based on this work, it was determined that the method had the potential to simulate and evaluate cracking behaviour of asphalt mixtures. The study presented in this paper investigates the DDM potential to simulate and evaluate cracking behavior and key material parameters of asphalt mixtures regardless of testing setups (load conditions and sample shape). The implementation of the method is based on the simulation of a semicircular bending (SCB) test since this test has been proposed in the recent past as a possible alternative to the IDT test.

A SCB specimen was modeled using the 2-D version of the boundary element program DIGS (Discontinuity Interaction and Growth Simulation), developed by Napier [2], modeling the micromechanical structure of the mixture with Voronoi tessellations, which have been demonstrated to be representative of the aggregate structure in granular materials as well as in asphalt mixtures. The material properties of the mixture were

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calibrated for use in the numerical model to simulate IDT strength test and applied as input parameters in the simulation of the SCB test. The simulation showed a good agreement with laboratory observations: the predicted crack propagation is consistent with the crack growth observed visually in laboratory; in addition, the stress–strain responses match the experimental results well.

2. Experimental testing

One fine-graded mixture was used to perform the tests for the cracking behavior investigation. The mixture was a 10 mm nominal maximum aggregate size produced with limestone obtained from North Italy with 6.5 percent ($\pm$ 0.5 percent) air void and 5.4% design asphalt content (50/70 PEN bitumen). Specimens 150 mm diameter by 25 mm thick were used to perform resilient modulus, creep compliance, and strength tests at 10 °C, using the Superpave Indirect Tensile test with the system developed by Roque and Buttlar [3]. Some of these specimens were sliced to obtain semicircular specimens of height 75 mm in order to conduct semicircular bending tests at 10 °C.

The SCB is a three point bending fracture test performed using semicircular shape specimens. The SCB experimental setup is shown in Fig. 1(a). A continuously increasing load is applied on the semicircular specimen placed under a loading ring, which drops with a 0.08 mm/sec speed, while the load transmission occurs with a displacement control system. The strain measurements were taken using strain gauges with a length of 20.0 mm placed on the bottom edge of the specimen.

In the IDT strength test the static load is applied on the top and the bottom plates; vertical and horizontal deformations during loading were measured by two strain gauges with a length of 38.1 mm placed at the center of the specimen as shown in Fig. 1(b).

To represent the horizontal and vertical stresses occurring at the centre of the specimen during the IDT test, the following IDT plane stress equations were used:

$$\sigma_h = 2P/\pi Dt \tag{1}$$

$$\sigma_v = P/A \tag{2}$$

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

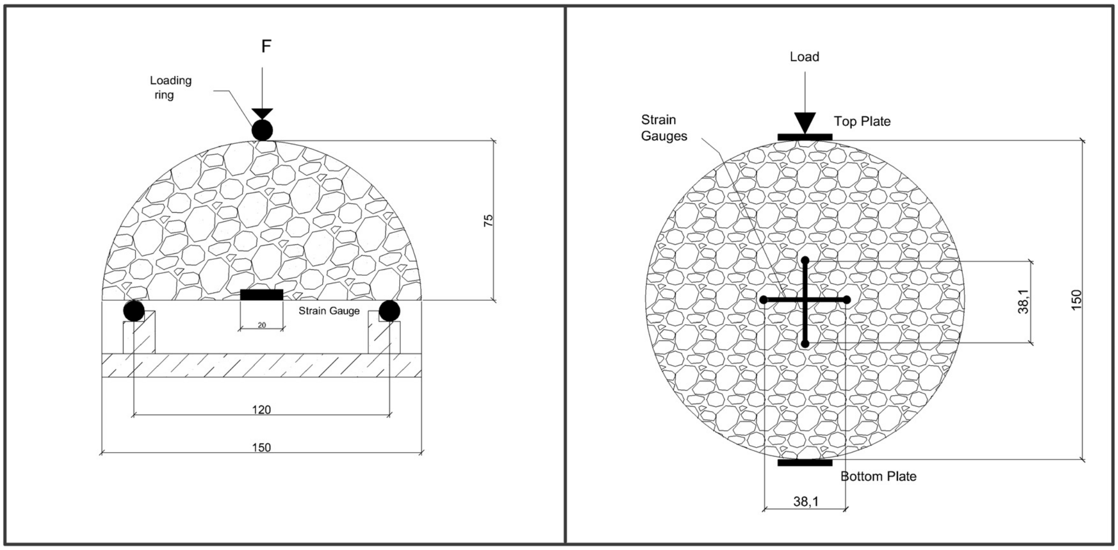
For the SCB test horizontal stress measurement, an equation based on the three point bending moment formula for linear elastic materials was used. Molenaar [4] performed a detailed finite element study to adjust the three point bending moment formula. The resulting formulation represents tensile stress occurred at the bottom edge of the specimen:

$$\sigma_h = 4.8P/Dt \tag{3}$$

It must be noted that the equation is valid if the distance between the supports is equal to 0.8D.

3. Numerical model

The displacement discontinuity boundary element method (DDM) was recently used by Birgisson et al. [1] to model the microstructure and the cracking behaviour



a) SCB experimental setup **b) IDT experimental setup**

Fig. 1. Experimental setups of both tests. (a) SCB experimental setup; (b) IDT experimental setup.

Table 1
Calibrated material parameters for the parametric study of the mixture

Parameters	T_0 (Mpa)	D_{NCR} (mm)	T_{soft} (Mpa/mm)	C_0 (Mpa)	C_R (Mpa)	C_{soft} (Mpa/mm)	ϕ_0 (degree)	ϕ_R (degree)
Mastic	3.60	0.12	10.0	3.60	0.18	1.00	38	32
Internal fracture paths	8.40	0.28	10.0	8.40	0.28	1.00	40	34
			Young Modulus	12200				
			Poisson's ratio	0.36				

of IDT specimens during strength tests. The displacement discontinuity element formulation with Voronoi tessellations was applied to account for the presence of aggregates and material defects.

The numerical model consists of two types of elements: exterior boundary elements and potential crack elements. The exterior boundary elements represent the outer surface of the specimen. The potential crack elements are located at internal Voronoi tessellation sites, so that elements can be selected for mobilization (slip or tensile opening) at critical locations. At each load step, stresses are computed at collocation points inside the potential crack elements; these stresses are then checked against a non-linear material failure criterion (Mohr–Coulomb) to determine whether or not a crack has been activated.

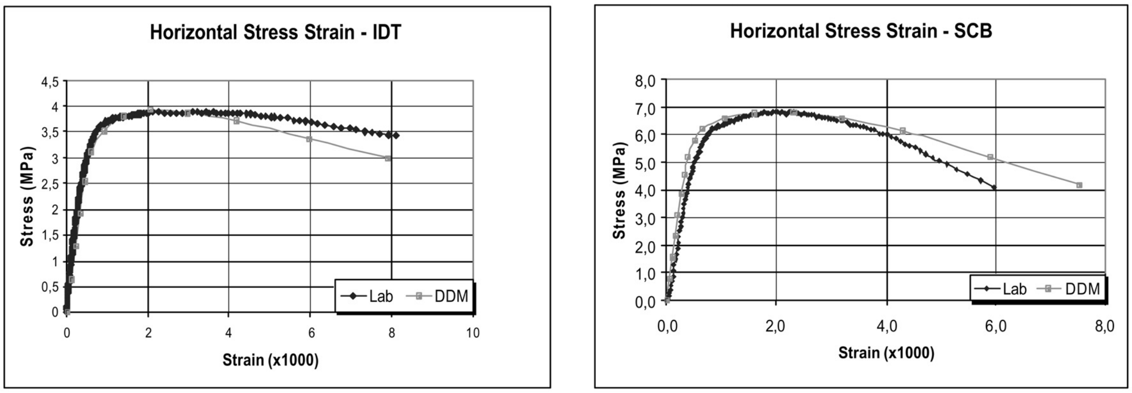
The modeling of the SCB specimen showed some difficulties compared to the IDT modeling, owing to the particular geometry configuration. Actually the IDT sample benefits from the overall radial symmetries, contrary to the SCB sample, which is supported by the single symmetry given from the specimen height. The obstacle was to identify the right boundary condition setting of the elements placed above the support rings, which act as gages in an area without symmetrical properties. For each load step, stresses were computed using Eqs. (1)–(3), while strain values were computed using the following eq:

$$\varepsilon_h = \Delta H / L_{gauge} \tag{4}$$

where ΔH is a horizontal deformation measured at the horizontal strain gauge location and L_{gauge} is the gauge length.

4. Results from numerical simulations

The IDT strength test was simulated, according to the recommendations described by Birgisson et al. [1], in order to identify a suitable set of material parameters for the mastic and fracture paths in the aggregates which were calibrated until the predicted stress-strain curves matched the experimental results (Fig. 2(a)). First the material parameters for the mastic were calibrated; then each of the internal fracture path strength parameters was adjusted to higher and lower values from the calibrated parameters to observe the sensitivity of the predicted stress-strain response. The resulting calibrated



a) IDT stress–strain response **b) SCB stress–strain response**

Fig. 2. Comparison between predicted and measured curves in both tests. (a) IDT stress-strain response; (b) SCB stress–strain response.

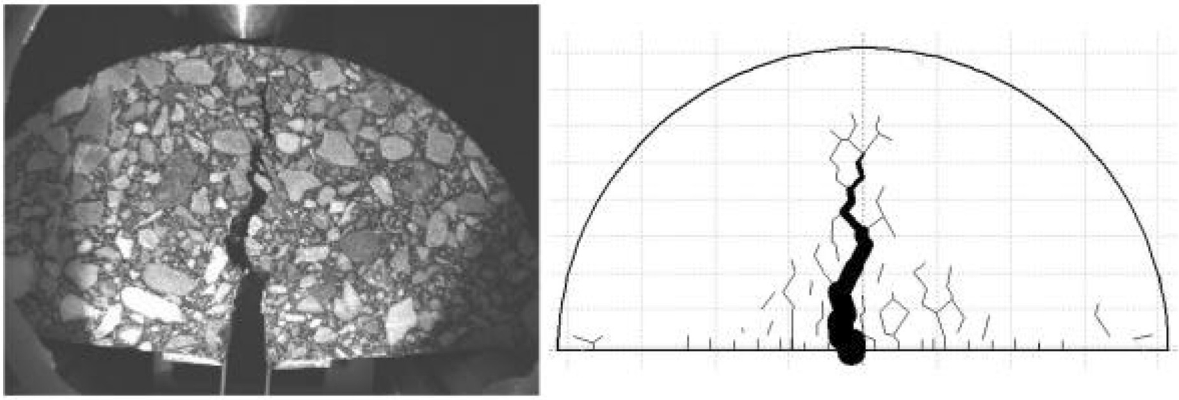


Fig. 3. Comparison between experimental and model crack propagation.

parameters from the IDT simulations, listed in Table 1, were used as input parameters for the simulation of the SCB test. Figure 2(b) shows a comparison between predicted and measured horizontal stress–strain curves: the resulting numerical simulations match the horizontal tensile stress–strain curves up to the ultimate load and partially capture the post peak response, as well. Besides, comparing the SCB simulation result with experimental images, the analogy between predicted and observed fracture growth is evident (Fig. 3).

5. Conclusions

This paper investigated the boundary element method potential to simulate and evaluate cracking behavior and key material parameters of asphalt mixtures. A semicircular bending specimen was modeled using a displacement discontinuity method with Voronoi tessellations. The set of input material parameters was first calibrated from simulations of a SuperPave IDT strength test.

The SCB simulation showed good agreement with the experimental results: measured and predicted horizontal stress–strain curve compared well up to the ultimate load and partially in the post-peak response. In addition, the predicted crack propagation paths showed a vertical crack through the center of the specimen which is consistent with observed cracking behaviour.

It can be concluded that displacement discontinuity method with Voronoi tessellations is an efficient tool for the characterization of asphalt mixture fracture properties regardless of the particular testing setup used in the simulation. It should become a powerful medium in the investigation of the mechanism of crack growth and propagation in HMA subjected to any kind of testing setup and specimen geometry.

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