COHESIVE FRACTURE MODELING OF ASPHALT CONCRETE USING THE THREE-POINT BENDING

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Abstract. *The discrete element method represents a convenient and powerful tool for studying effects of material microstructure on fracture mechanisms in asphalt concrete. Cracks in asphalt pavements create irreversible structural and functional deficiencies that increase maintenance costs and decrease lifespan. Therefore, it is important to understand the fracture behavior of asphalt mixtures and, for this purpose, single-edge-notched beams are usually tested with the three-point bending technique in order to evaluate the fracture energy of asphalt concrete. Homogeneous and heterogeneous models are employed to investigate the fracture behavior in fracture mode I. User-defined geometric models were used to represent irregular shapes of the aggregate by clumps. A cohesive softening model was adopted as an intrinsic constitutive law governing the mechanical behavior of the asphalt concrete to simulate fracture propagation. The 2D numerical predictions were compared to the experimental measurements taken in asphalt concrete beam tests.*

Keywords: *Granular materials, Asphalt Concrete, Discrete Element Method, Fracture, Cohesive Softening Model*

1 INTRODUCTION

There are a variety of numerical methods available for calculating approximate solutions of engineering problems. The finite element method (FEM) and boundary element method (BEM) are currently in a very advanced stage of development and may be considered as traditional methods for solving boundary value problems. Comparatively, the method of discrete elements (DEM) is at an earlier stage, but since the pioneering work by Cundall and Strack (1979) several improvements in mathematical formulation, as well as many applications to different engineering problems, were presented, discussed and published in journals and conferences that contributed to the growing use of DEM as a powerful numerical method.

For a better understanding of the behaviour of asphalt pavement concrete, Abbas et al. (2005) used DEM to simulate the dynamic response of asphalt mastics (dispersion of aggregate fillers within a medium of asphalt binder), You et al. (2011) considered a 3D viscoelastic model for microstructural-based discrete element simulation of asphalt mixture behaviour and Kim et al. (2009) investigated the micromechanical fracture modelling of asphalt concrete using a single-edge notched beam to predict asphalt mixture stiffness and fracture propagation. In this research, both homogeneous and heterogeneous models are employed to study the fracture behavior of asphalt concrete using a single-edge notched beam SE(B) test through DEM simulation using the computer program PFC2D – Particle Flow Code v.4 (Itasca, 2012) and user-defined geometric models in order to represent irregular shapes of the aggregate by clumps, assemblies of disks acting as rigid bodies.

2 COHESIVE ZONE MODEL

The cohesive zone model (CZM) has been receiving increasing attention from the asphaltic materials and pavement mechanics community as a mechanistic approach to model crack initiation and propagation in materials and structures. The cohesive zone model is not limited to modeling a single crack tip, but it is also able to describe crack nucleation and pervasive cracking through various time and length scales. The model provides a powerful and efficient tool that can be easily implemented in existing computational methods for brittle, quasi-brittle and ductile failure, all of which are frequently observed in asphaltic materials. As a result, currently the CZM approach is widely accepted as a computationally convenient fracture analysis tool.

Three material parameters are needed for its complete definition, namely: the cohesive energy (Φ), the cohesive strength ($\sigma_{\max}$) and the separation displacement (δ_{sep}). These three parameters are related through the cohesive energy potential, written as:

$$\Phi = \int_0^{\delta_{sep}} \sigma(\delta) d\delta \tag{1}$$

According to Eq. (1) only two of the three parameters are independent. The cohesive energy, taken to be equivalent to the work of fracture, and the cohesive strength are usually obtained from experiments, while the separation displacement is a more difficult parameter to be measured. The stress softening $\sigma(\delta)$ can be described by various functions, such as exponential, polynomial, bilinear or trilinear forms. For instance, Geubelle and Baylor (1998) utilized a bilinear CZM to simulate spontaneous initiation and propagation of transverse matrix cracks and delamination fronts in thin composite plates subjected to low-velocity impact.

The implementation of a bilinear CZM in DEM is shown in Fig. 1. The contact strength force F_{max} is calculated from two strength parameters (normal force F_c^n and shear force F_c^s) and is assumed to vary linearly as a function of the contact angle α.

$$F_{max} = (1 - \frac{2\alpha}{\pi})\, F_c^n + \frac{2\alpha}{\pi}\, F_c^s \tag{2}$$

where α is the angle between the direction of the contact force and the segment connecting the particle centers.

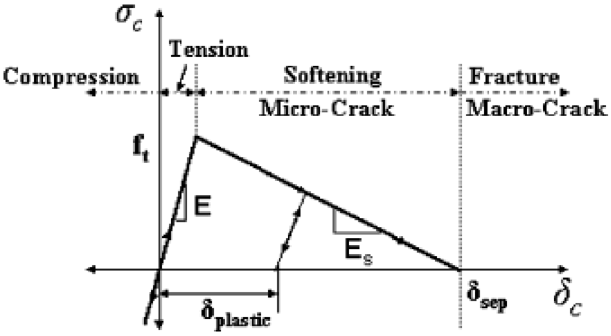


Figure 1: Concept of a bilinear cohesive softening model (Kim, 2009)

The contact force between two particles, calculated by Eq. (3), is compared to the contact strength force

$$F = \sqrt{\left(\left(F^n\right)^2 + \left(F^S\right)^2\right)} \tag{3}$$

When the contact force exceeds the strength force, then the contact will begin to yield or "soften", manifested by a decaying traction between particles. The increment of contact displacements ΔU^k can be decomposed into elastic and plastic contact displacement increments

$$\Delta U^K = \Delta U_e^k + \Delta U_p^k \tag{4}$$

The force increment ΔF^k is a function of the increment of the elastic displacement only

$$\Delta F^K = K^K \Delta U_e^k \tag{5}$$

The elastic (or plastic) displacement increment can be determined using the consistency condition $F - F_{\max} = 0$. The contact strength is a function of the accumulated plastic deformation, described by

$$F_c^k\left(U_p / U_{p\max}\right) = F_c^k\left(1 - \frac{U_p}{U_{p\max}}\right) \tag{6}$$

where

$$U_p = \sum \left|\Delta U_p\right| \tag{7}$$

3 SINGLE-EDGE NOTCHED BEAM TEST

According to Kim et al. (2009), the selection of the specimen geometry is the first step in developing a fracture test for asphalt concrete. The single edge notched beam SE(B) – Fig. 2 -

can be readily fabricated from laboratory compacted beams or slabs. The loading configuration (three-point bend) allows for simple stress states and it is easy to control the test with closed-loop servo-hydraulic equipment. Moreover, by simply offsetting the mechanical notch location (Fig. 3), the notched beam test can be used to characterize mixed-mode fracture characteristics.

Figure 2: SE(B) test fixture and clip gage (Wagoner et al., 2005).

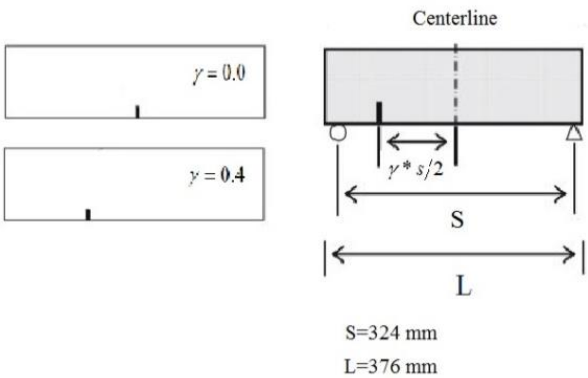


Figure 3: SE(B) with various notch offsets.

The asphalt concrete mixture used in this study was a mixture consisting of an asphalt binder and a 9.5 mm maximum aggregate size, whose gradation curve is shown in Fig. 4. This particular mixture has been extensively characterized by Wagoner et al. (2005), including the bulk material properties required as material inputs in the numerical model.

The test setup is shown schematically in Fig. 5, with specimen length (L) of 376 mm, height (h) of 100 mm, thickness of 75 mm, notch depth of 19 mm and a notch to depth (a/h) ratio of 0.19. The depth of the notch was selected to be long enough to ensure adequate stress intensity at the notch tip to initiate a crack, but short enough to ensure a ligament of adequate length for test repeatability and to prevent crack initiation under self-weight. The tensile strength and the resilient modulus were experimentally determined as 3.56 MPa and 14.2 GPa, respectively. The Poisson’s ratio was assumed equal to 0.35.

4 NUMERICAL SIMULATION OF MODE I FRACTURE

4.1 Homogeneous discrete element model

Figure 6 shows a discrete element configuration for the small region around the crack tip along the middle of the specimen length. The bulk material is modeled as an elastic, homogeneous and isotropic medium with a face-centered arrangement of particles (0.1mm radius) and a two-dimensional cohesive contact model is considered along the center of the specimen only, represented in Fig. 7 as the red region. A constant velocity boundary condition is imposed at the center of the top edge of the model (Figs. 7 and 8) in order to predict stable fracture behavior. The calibrated fracture energy was 241 J/m2.

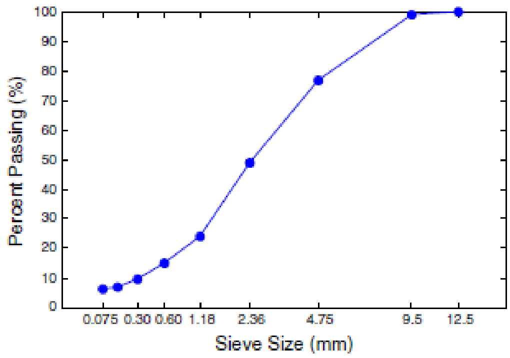


Figure 4: Gradation plot of asphalt mixture (Wagoner et al., 2005)

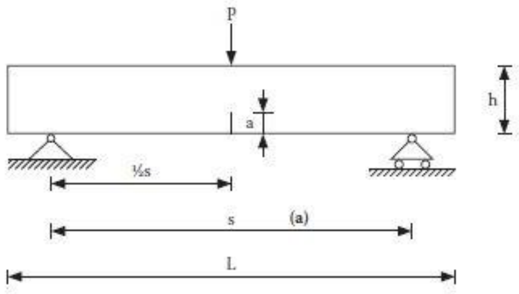


Figure 5: Specimen dimensions in SE(B) tests (Kim et al., 2009)

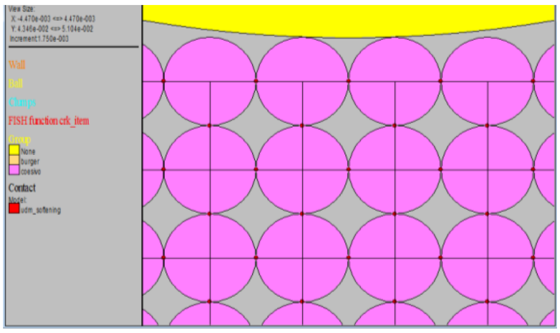


Figure 6: Discrete element configuration for the small region around the crack tip along the middle of the specimen.

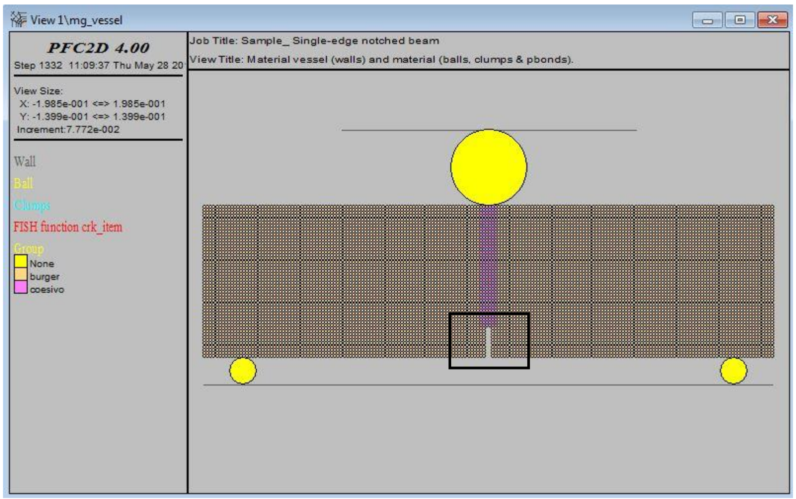


Figure 7: DEM model geometry and boundary conditions.

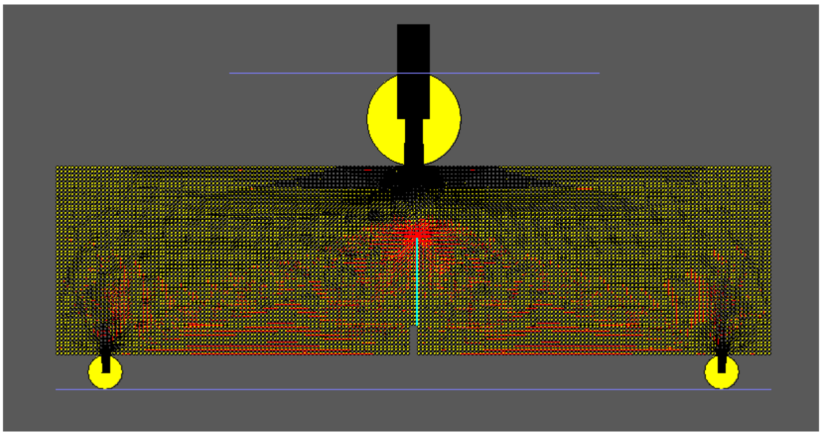


Figure 8: Load was imposed in terms of a constant velocity boundary condition at the center of the top edge of the model.

Figure 9 compares experimental results obtained by Wagoner et al. (2005) with numerical results, obtained with the discrete element method, by Song et al. (2006), Kim et al. (2009) and in the present investigation. Results are shown in terms of force versus crack mouth opening displacement (CMOD).

4.2 Heterogeneous discrete element model

For the heterogeneous analysis, two kinds of geometric models may be used to rebuild the asphalt concrete mixture microstructure, namely image-based model and user-defined model. An image-based model is built from real images of an asphalt mixture. With current imaging techniques, such as X-ray Computed Tomography (X-ray CT), most of the real micro-structural features of the mixture could be characterized (Abbas et al., 2007; Masad, 2004). The disadvantage is the laboratory dependency, which gives users limited options to choose different microstructures unless the images are redone. On the other hand compared with the imaged based models, a major advantage of the user-defined models is its lab-independency. For example, when researchers try to investigate the effects of aggregate shapes on mixture performances, it is possible to minimize the influences of other factors such as aggregate orientation, gradation, air voids and asphalt properties.

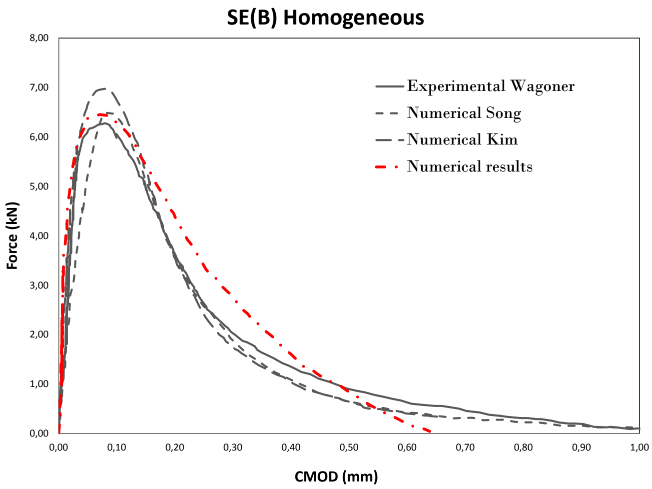


Figure 9: Comparison between experimental and numerical results.

Clump technique is a common method to model irregular shaped particles in DEM simulations. A clump is made of a group of disks and behaves as a rigid body. The motion of a clump is determined by the resultant force and moment vectors acting on it. The contact forces only exist between clumps and the internal contacts within the clump are skipped during the calculation to save computer time. In this study, non-spherical shape particles were generated by using the clump technique available in the PFC2D v.4 software (Itasca, 2012).

Figure 10 shows a beam model with offset parameter γ=0.4, as defined in Fig. 3, equivalent to a notch situated 65mm from the middle of the specimen. The fracture initiates propagation in mode I but its path quickly deviates towards the loading point, as shown in Fig. 11.

Figure 12 compares experimental results obtained by Wagoner et al. (2005) with numerical results, obtained with the discrete element method, by Kim et al. (2009) and in the present investigation. Results are shown in terms of force versus crack mouth opening displacement (CMOD).

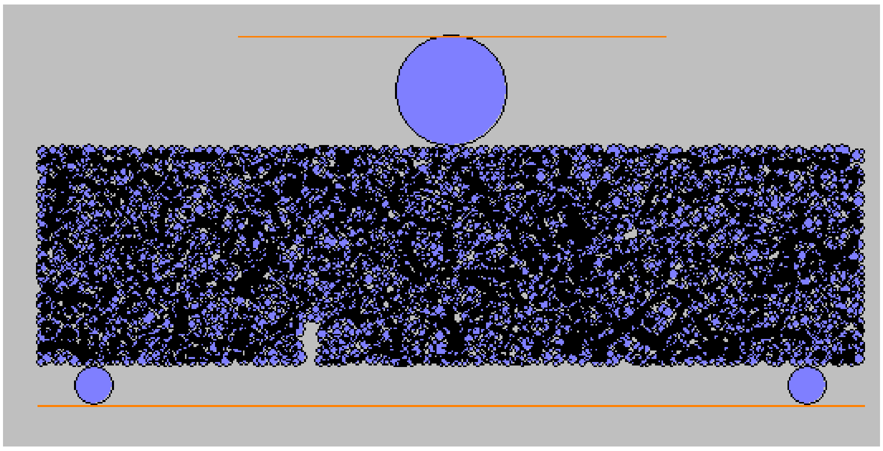
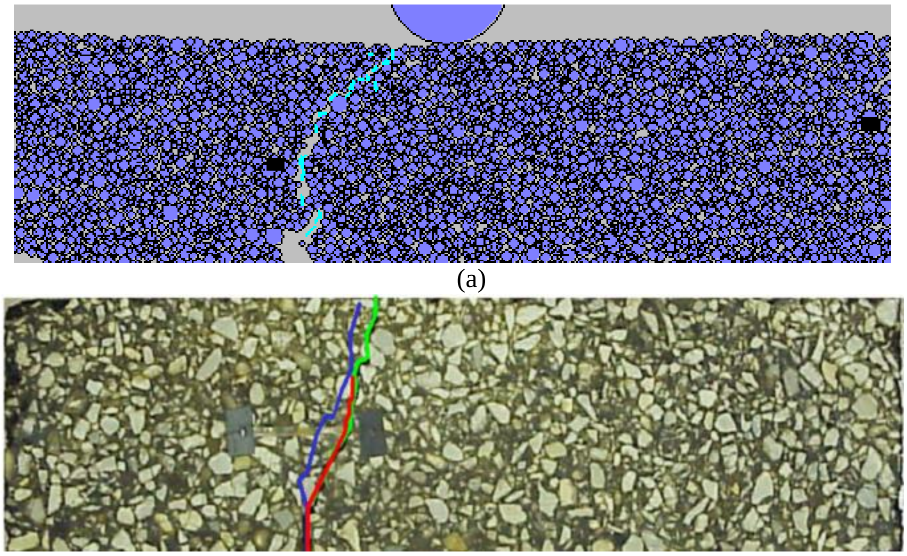


Figure 10: Heterogeneous DEM model with γ=0.4



(a)

(b)

Figure 11: (a) DEM fracture trajectory obtained in the present study; (b) Green and blue lines indicate experimental results from Wagoner et al. (2005) and red line represents DEM trajectory from Song et al. (2006).

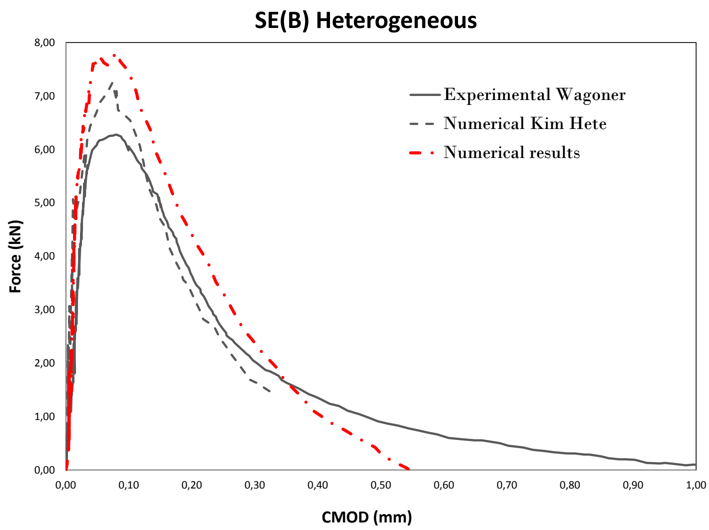


Figure 12: Comparison between experimental and numerical results.

5 CONCLUSION

In this research the discrete element method was applied to investigate the fracture behavior of asphalt mixtures by testing single-edge-notched beams with the three-point bending technique. Homogeneous and heterogeneous models were employed considering the fracture mode I (opening mode). In order to represent the irregular shapes of the aggregate in the heterogeneous model the clump technique was used, consisting of a group of disks that behaves as a rigid body. To simulate fracture propagation the cohesive softening model was adopted as the intrinsic constitutive law, while the bulk material was modeled as an elastic, homogeneous and isotropic medium. Numerical results computed for both models were compared with those obtained by other authors, through laboratory tests or discrete element analysis, with good agreement in terms of fracture trajectory (Fig. 11) and crack mouth opening displacement (Figs. 9 and 12).

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