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Multi-Scale Heterogeneous Fracture Modeling of Asphalt Mixture Using Microfabric Distinct Element Approach

Kim, Hyun Wook*   William G. Buttler*

Abstract

Many experimental and numerical approaches have been developed to evaluate paving materials and to predict pavement response and distress. Micromechanical simulation modeling is a technology that can reduce the number of physical tests required in material formulation and design and that can provide more details, e.g., the internal stress and strain state, and energy evolution and dissipation in simulated specimens with realistic microstructural features. A clustered distinct element modeling (DEM) approach was implemented in the two-dimensional particle flow software package (PFC-2D) to study the complex behavior observed in asphalt mixture fracturing. The relationship between continuous and discontinuous material properties was defined based on the potential energy approach. The theoretical relationship was validated with the uniform axial compression and cantilever beam model using two-dimensional plane strain and plane stress models. A bilinear cohesive displacement-softening model was implemented as an intrinsic interface and applied for both homogeneous and heterogeneous fracture modeling in order to simulate behavior in the fracture process zone and to simulate crack propagation. A disk-shaped compact tension test (DC(T)) with heterogeneous microstructure was simulated and compared with the experimental fracture test results to study Mode I fracture. The realistic arbitrary crack propagation including crack deflection, microcracking, crack face sliding, crack branching, and crack tip blunting could be represented in the fracture models. This micromechanical modeling approach represents the early developmental stages towards *a* "virtual asphalt laboratory," where simulations of laboratory tests and eventually field response and distress predictions can be made to enhance our understanding of pavement distress mechanisms, such as thermal fracture, reflective cracking, and fatigue crack growth.

* Department of Civil and Environmental Engineering University of Illinois

INTRODUCTION

Cracks in asphalt pavements often create irreversible structural and functional deficiencies that increase maintenance costs and decrease lifespan. Asphalt concrete is a quasi-brittle composite material which is composed of brittle inclusions (aggregates) and a viscous matrix (asphalt mastic). The fracture of heterogeneous solids is a difficult problem to handle numerically due to the creation and continuous motion of new surfaces. The use of linear elastic fracture mechanics to analytically describe these mechanisms would be arduous, since the fracture patterns typically consist of a main crack, crack branches, secondary cracks and microcracks.

Numerical modeling of asphalt materials is a useful tool to aid in the understanding of complex phenomena, including: local stress-strain distributions in a heterogeneous microstructure, local and global effects of microstructure, fracture toughening mechanisms, and the interactions between fracture behavior and boundary conditions. There are many different numerical approaches that can be used to study asphalt micromechanical behavior. The finite element method (FEM) is the most widely employed numerical method in computational mechanics problems. However, the discrete element method (DEM) has a potential advantage over the FEM approach in the modeling of fracture in heterogeneous materials, since the material is represented by a discontinuous particle structure without the need for a mesh in the strict sense. The infinite number of material points of the continuum is replaced by a finite number of particles that interact through cohesive contacts and collisions with neighboring particles coming into contact. Most physical materials and systems are discontinuous at some level, especially in the atomic-, micro- and meso-level. For routine design and analysis, materials such as asphalt concrete, cement concrete, and soils are typically treated as continuous even though they consist of discrete grains at the microscopic level. However, the discontinuum approach used in a DEM modeling is a powerful tool that gives the researcher far more insight into the mechanisms of material behavior as compared to traditional analysis methods.

Discontinuities were first introduced into numerical models in the late 1960's by more or less parallel developments in soil and concrete mechanics by Goodman et al [1] and Ngo et al. [2] via modifications of existing continuum methods. After that, an alternative approach termed distinct element method was introduced by Cundall [3]. He designed this method specifically to model a priori discontinua. This type of method is also called the discrete element method. Following the lines of Cundall and Hart [4], the name discrete element method should apply to a method only if: 1) the model allows for finite displacements and rotations of discrete bodies including a complete detachment, and; 2) the model recognizes new contacts automatically as the calculation progresses. There are several different DEM algorithms, including the rigid body-spring method developed by Kawai [5], and the simple deformable polygonal discrete element procedures by Hocking et al. [6], Mustoe [7], Bolander [8], and D'Addetta [9].

The micromechanical modeling approach presented herein is envisaged as an early developmental step towards the "virtual asphalt laboratory," where simulations of laboratory tests and eventually field response and distress predictions can be made to enhance our understanding of pavement distress mechanisms, such as thermal fracture or reflective cracking. The DEM will ultimately be used in multi-scale modeling, where global pavement response and local fracture behavior can be considered in the same model simulation. In this work, the theoretical relationship between the continuum and discontinuum approach is defined and validated with uniform axial compression and cantilever beam tests for the different particle arrangements and a powerful numerical scheme involving cohesive zone modeling is introduced to investigate the fracture behavior of asphalt concrete and to simulate crack nucleation, initiation and propagation in both homogeneous and heterogeneous mode I behavior using a disk compact tension test.

MULTI-SCALE MODELING AND INVERSE ANALYSES

The application range of a numerical model is directly related to the observation scale, as depicted in selected modeling techniques presented in Figure 1. The diagram emphasizes the choice of scale definitions used in the analyses. From the point that localization phenomena like cracks occur, the material cannot be treated as continuous any longer. Therefore, most continuum models, both standard and enhanced ones cannot account for the discrete nature of material failure in a natural way. Alternatively, discrete models like lattice, granular dynamics or discrete element methods (DEM) have been developed. As the name DEM suggests, a solid is replaced by a discontinuous particle composite which allows for a detachment of bonds between particles (if initially present) and the means to handle re-contacting of open surfaces. In contrast to continuum models, discrete or discontinuum models are characterized by the fact that displacements and stresses do not vary continuously in space. The DEM describes a class of dynamically driven computational schemes which are based on the motion of contacting particles. Due to computational limitations, mostly two-dimensional models with circular or polygonal particle shapes are employed. The models of this class are able to predict and simulate the fracture behavior of small scale applications of materials reasonable well. Recently, the increasing availability of computer power has made possible large scale computations of this nature. Based on very simple contact laws and a limited number of arbitrary parameters, discrete element simulations can describe sophisticated material responses [10].

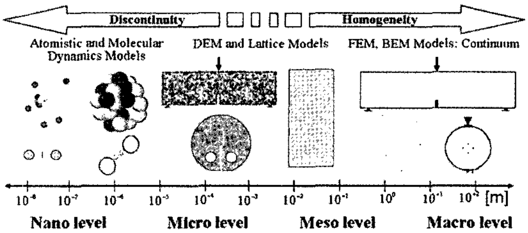


Figure 1. Multi-scale structures and numerical model techniques

Typically, three general approaches can be employed in a research investigation, namely: experimental observations, analytical modeling, and numerical modeling. Experimental measurements can provide material properties and descriptions of material behavior, but the results can often be affected by the boundary conditions, including specimen size, geometry, and characteristics of the testing device. Analytical models can provide 'exact' answers and useful benchmark solutions, but are limited to relatively simple boundary value problems with highly idealized and simplified material properties. Numerical methods can be employed to extend analytical methods to consider more complex boundary conditions and material constitutive models, as has been demonstrated with the finite element method over the past several decades. However, modern numerical analysis techniques have the added advantage of allowing the study of the interaction between material microstructure and boundary conditions. For instance, information about the material structure at the meso-level can be incorporated into the numerical model, as shown in Figure 2.

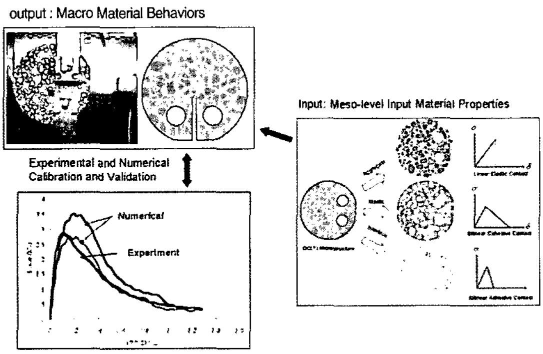


Figure 2. Inverse analyses with experimental and numerical methods

Input data for micromechanical analyses involving multi-phase models with specified morphological features, such as asphalt concrete, include the strength and stiffness of the constituent materials, as well as the properties of the interface between constituents (such as the asphalt-aggregate interface). Such properties must be determined experimentally, or in the case of difficult-to-measure parameters, estimated using inverse analysis techniques. Clearly, many difficulties and challenges remain in the endeavor towards a virtual materials laboratory [11]. The remainder of this paper is devoted to demonstrating how the clustered DEM technique has been used to study fracture in hot-mix asphalt at low temperatures. The basic theory behind the constitutive models in the PFC-2D DEM implementation first presented, followed by some brief verification simulations involving various particle packing arrangements.

DISCRETE ELEMENT METHOD

The distinct element modeling approach implemented in PFC-2D utilizes fixed-size and fixed-shape circular elements that can be used to approximate bulk material stress-strain behavior by assigning "stiffness" to particles, which is activated when particles overlap or when bonded particles separate [12]. The contact models can also be used to simulate material fracture, by assigning more sophisticated bonding models, including softening-type constitutive models. These tools can be used to simulate crack initiation and propagation in a manner similar to the cohesive-zone modeling (CZM) approach. The constitutive models used in the current 2-D clustered DEM application consist of three parts: a contact stiffness model, a slip friction model and a bonding model. The linear contact model is defined by the normal and shear stiffness k_n and k_s (force/displacement) of the two contacting entities (ball-to-ball or ball-to wall) acting in series. The contact normal secant and shear tangent stiffness are given by:

Normal secant stiffness:

$$K^n = \frac{k_n^{[A]} k_n^{[B]}}{k_n^{[A]} + k_n^{[B]}} \tag{1}$$

Shear tangent stiffness:

$$K^s = \frac{k_s^{[A]} k_s^{[B]}}{k_s^{[A]} + k_s^{[B]}} \tag{2}$$

The normal stiffness is secant stiffness and it linearly relates the total normal force to the total normal displacement.

$$F_i^n = K^n U^n n_i \tag{3}$$

The shear stiffness is a tangent stiffness and it relates the increment of shear force to the increment of shear displacement.

$$\Delta F_i^s = -k^s \Delta U_i^s \tag{4}$$

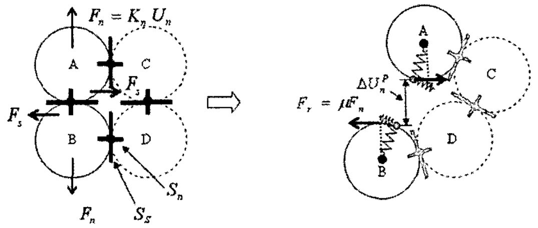


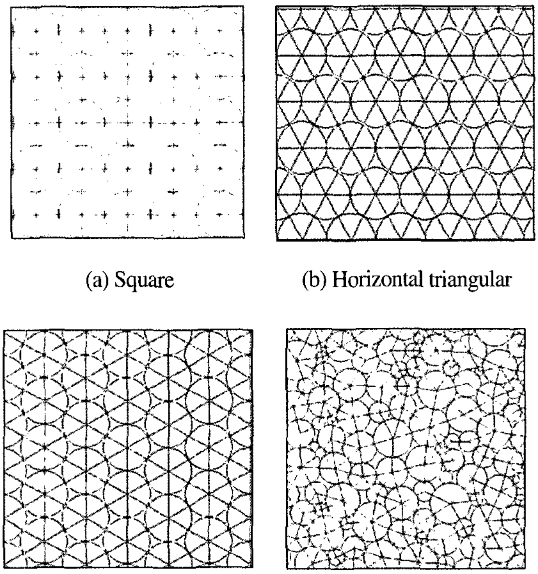
Figure 3. Constitutive contact, slip, and bond model

The slip friction model is an intrinsic property of the two entities in contact (ball-ball or ball-wall) that governs frictional sliding of unbonded or debonded particles. The slip and bond models describe the constitutive behavior governing the response of particle contact points. The slip model is defined by the friction coefficient at the contact. For bonded assemblies, if the applied force becomes larger than the maximum allowable shear contact force, then slip is allowed to occur. The bond model allows particles to be joined at contacts, which activates material stiffness in opening and shear. The constitutive behavior for contact occurring at a point for the normal and shear components are given by Figure 1. S_n and S_s are normal and shear bond strengths; F_r is the frictional force.

RELATIONSHIP BETWEEN CONTINUUM AND DISCONTINUUM

Theoretical Relationship for Particle Arrangements

Possible particle arrangements for 2D DEM modeling with disk-shaped particles are shown in Figure 4 [13, 14]. However, in the random arrangement it is very difficult to assign material properties, particularly for the purposes of fracture modeling, as the particle radius is an important factor in the calculation process.



(a) Square (b) Horizontal triangular

(c) Vertical triangular (d) Random

Figure 4. Different particle arrangements of discrete elements

The theoretical relationship between continuum and discontinuum approaches for these arrangements can be obtained based on the strain energy and two-dimensional Hooke' s law. The relationship between an assemblage of discrete springs and the elastic properties of a plane continua are given by:

Plane strain:

$$k_n = \frac{E}{\sqrt{3}(1+\upsilon)(1-2\upsilon)} \quad (5)$$

$$k_s = \frac{E(1-4\upsilon)}{\sqrt{3}(1+\upsilon)(1-2\upsilon)} \quad (6)$$

Plane stress:

$$k_n = \frac{E}{\sqrt{3}(1-\upsilon)} \quad (7)$$

$$k_s = \frac{E(1-3\upsilon)}{\sqrt{3}(1-\upsilon^2)} \quad (8)$$

These expressions were first described by Morikawa et al. and developed further by Mustoe et al. [15, 16]. It is interesting to note that the triangular particle arrangement used in this formulation limits the value of Poisson' s ratio to a maximum of 0.25 in plane strain from equation (6), and a maximum of 0.33 in plane stress from equation (8) corresponding to a shear spring stiffness of zero.

Model Validation for Hexagonal Arrangements

Herein, equation (5), (6), (7), and (8) are validated by comparison with solid 2-D elasticity solutions. In each case, the discrete element results are compared with analytical solutions from classical elasticity.

Uniform Axial Compression (Plane strain)

In this example, an arrangement of width W=16 and height H=17.32 units for horizontal arrangement and an arrangement of width W=15.29 and height H=17 units for vertical arrangement was subjected to a uniform axial compressive stress of vertical stress = 0.001 unit. As shown in Figure 5, the boundary conditions constrain the arrangement to remain rectangular as it deforms. From the elastic theory, the properties E and Poisson' s ratio that would have resulted in those deformations in plane strain are given by

$$E = \sigma_Y(1-\upsilon^2)\frac{H}{\delta_y} \quad (9)$$

$$\upsilon = \frac{-H/W}{\delta_y/\delta_x - H/W} \quad (10)$$

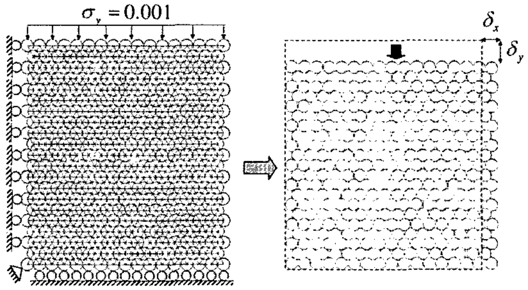


Figure 5. Boundary conditions and deformed uniform axial compression specimen

Table 1. Results from axial compression analyses (Plane strain-Horizontal)

Contact Stiffness		Computed Displacement		Computed Modulus based on Elastic Theory (Equation (9) and (10))		Determined Modulus based on Stiffness (Equation (5) and (6))	
Kn	Ks	y_disp.	X_disp.	E	Poisson' ratio	E	Poisson' ratio
1	1	-0.0102	0.0004	1.703	0.046	1.732	0.000
1	0.5	-0.0116	0.0017	1.465	0.137	1.461	0.125
1	0.001	-0.0147	0.0046	1.101	0.253	1.083	0.250

Table 2. Results from axial compression analyses (Plane strain-vertical)

Contact Stiffness		Computed Displacement		Computed Modulus based on Elastic Theory		Determined Modulus based on Stiffness	
Kn	Ks	y_disp.	X_disp.	E	Poisson' ratio	E	Poisson' ratio
1	1	-0.0099	0.0001	1.722	0.009	1.732	0.000
1	0.5	-0.0113	0.0014	1.479	0.123	1.461	0.125
1	0.001	-0.0142	0.0041	1.129	0.246	1.083	0.250

The results for the horizontal and vertical arrangements summarized in Table 1 and 2. The tables show reasonable agreement between the computed and theoretical elastic constants.

Cantilever Beam (Plane stress)

As a more severe test, this example shows the ability of the discrete element model to reproduce bending effects with much smaller particles. An arrangement of width W=0.0055 and height H=0.03464 units for horizontal arrangement and an arrangement of width W=0.00563 and height H=0.0345 units for vertical arrangement were made. The cantilever shown in Figure 6 is subjected to a unit transverse point load P=0.0001 at its tip under plane stress conditions. The slender beam solution for the tip deflection of a cantilever is given by

$$\delta_x = \frac{PL^3}{3EI} \tag{11}$$

The cantilever shown in Figure 6, however, has a non-uniform section due to the equilateral triangles used in its discretization. An approximate comparison is possible using a beam height H = 0.03464, thickness t = 1 and an average section width of 0.0055. This approximate slender beam solution for the tip deflection using E from equation (7) and (8) is then compared with the computed value of δx using the discrete element approach with different combinations of Kn and Ks in Table 3 and 4.

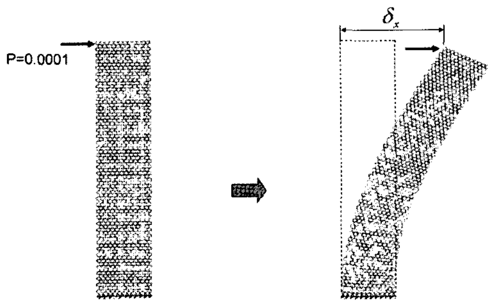


Figure 6. Boundary conditions and deformed cantilever beam

Table 3. Results from cantilever analyses (Plane stress-Horizontal)

Contact Stiffness		Computed Displacement	Determined Modulus based on Stiffness (Equation (7) and (8))		Theoretical Displacement
Kn	Ks	X_displ.	E	Poisson' ratio	X_displ.
5	5	1.100E-02	8.660	0.000	1.054E-02
5	2.5	1.270E-02	7.423	0.143	1.230E-02
5	0.005	1.584E-02	5.777	0.333	1.580E-02

Table 4. Results from cantilever analyses (Plane stress-Vertical)

Contact Stiffness		Computed Displacement	Determined Modulus based on Stiffness (Equation (7) and (8))		Theoretical Displacement
Kn	Ks	X_disp.	E	Poisson' ratio	X_disp.
5	5	9.248E-03	8.660	0.000	8.238E-02
5	2.5	1.046E-02	7.423	0.143	9.611E-02
5	0.005	1.258E-02	5.777	0.333	1.235E-02

Once again, the results from the PFC-2D numerical simulation are in reasonable agreement with the elasticity solution. It should be kept in mind that the desired result of the verification studies were not to obtain an exact correspondence between the elasticity and discrete modeling solutions, rather, only to illustrate that the DEM approach yields reasonable correspondence to the continuum solutions for basic bulk material behavior. The real benefit of the DEM modeling approach is realized when modeling more complex problems, such as crack propagation in a heterogeneous media, where complex localized behavior such as crack deflection, crack branching, microcracking, etc., are simulated. Nevertheless, it is important to first verify that bulk material response can be reasonably predicted, since complex micromechanical simulations involve communication between areas undergoing bulk material response and areas experiencing softening and the creation of new crack surfaces.

COHESIVE FRACTURE MODEL

Dugdale [17] and Barenblatt [18] proposed cohesive models to investigate ductile and brittle material fracture behavior, respectively. The cohesive crack concept was later successfully extended by Hillerborg et al. [19] to study nonlinear fracture process in Portland cement concrete. Furthermore, cohesive zone models (CZMs) have been used to simulate the fracture process in a number of material systems including polymers [20], metallic materials [21], ceramic materials [22], metal matrix composites [23], and fiber reinforced plastic composites [24]. They have been used to simulate fracture under static, dynamic, and cyclic loading conditions. An intrinsic general displacement-softening contact model available in PFC-2D, which is a form of a bilinear cohesive zone model, has been implemented in our clustered DEM fracture simulations. Geubelle et al. utilized a bilinear CZM to simulate spontaneous initiation and propagation of transverse matrix crack and delaminating fronts in thin composite plates subjected to low-velocity impact [25]. The detail explanations can be found in our other paper [26].

HOMOGENEOUS AND HETEROGENEOUS FRACTURE MODELING

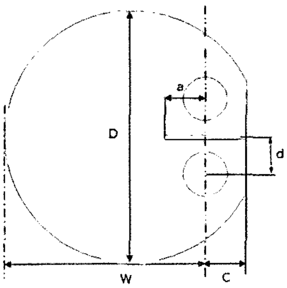
Material Parameters

Two experimental quantities, material strength and fracture energy, are evaluated herein as initial inputs into the CZM, which can later be calibrated through inverse analysis to account for the fact that they are not truly intrinsic material parameters. The first-failure tensile strength determined from the indirect tension (IDT) test at -10℃ and 1 Hz was taken as the material strength. The procedure for determining the first-failure tensile strength is outlined in the AASHTO TP-9 specification (1996). The material tensile strength of 3.56 MPa was obtained in the IDT test for the dense-graded limestone-dolomite asphalt mixture studied herein. The single-edge notched beam (SE (B)) test was used for determining the fracture energy of the mixture under investigation, which is also described in Wagoner et al. [27]. In this experiment, the crack-mouth opening displacement (CMOD) was increased at a linear rate. The fracture energy was then determined by calculating the area under the load-CMOD curve and normalizing by the cross-sectional area of the beam. The fracture energy of 344 J/m^2 was obtained from the SE (B) test. Because the fracture energy obtained in this method does not directly provide the amount of energy associated with the material separation, it is convenient and logical to adjust this parameter for model calibration.

Homogeneous Fracture Prediction Models

A disk-shaped compact tension, or DC(T), specimen and testing procedures have been developed for obtaining the fracture energy of asphalt concrete [28]. The main purpose for the development of this specimen geometry is the ability to test cylindrical cores obtained from in-place asphalt concrete pavements and gyratory-compacted specimens fabricated during the asphalt concrete mixture design process for relevant fracture properties. The dimensions of the specimen were determined by using the ASTM E399 Standard as a guideline. The specimen diameter is 150mm and both cored hole diameters within the specimen are 25mm. the detail model dimension can be found in Figure 7 [29]. General walls were made in the inside of the top and bottom hole in the specimen and the constant velocity or displacement was applied into the walls which also has the normal and shear stiffness.

For the homogenous model, 75,967 particles with 0.35mm radius and 226,266 contacts are used in the microstructural reconstruction and 328 cohesive contacts are inserted along the middle of specimen.



DC(T) Dimension (mm)	
D	150
W	110
a	27.5
d	25
C	35
Ø	25
t	50

Figure 7. DC (T) specimen geometry for asphalt concrete

Figure 8 represents the experimental and numerical global results which are applied force vs. CMOD curves. Based on the plane strain relationship between the stiffness and elastic material properties, different Poisson' s ratios for the bulk material region were analyzed.

The difference between the experimental and numerical results can probably be reduced by further calibration of model parameters, however, due to the computational expense of the iterative, inverse

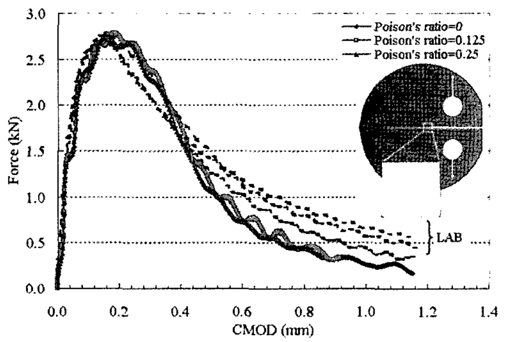


Figure 8. Global responses of homogeneous fracture models

analysis procedure, this has not yet been pursued. Furthermore, the introduction of a more sophisticated softening model, such as a tri-linear or exponential softening model in the local contact constitutive law could also be employed to improve the match of the modeling results to the experiment. Finally, the use of a viscoelastic bulk material model may lead to improved predictions. Nonetheless, the current results suggest that the cohesive zone modeling approach implemented in the PFC-2D clustered DEM simulation is promising method for modeling crack propagation in bench-scale fracture tests.

Fracture Toughening Mechanisms

Heterogeneous fracture modeling is a very challenging area due to the complexity of the asphalt concrete microstructure and the complicated interactions between aggregate, aggregates and asphalt, and the presence of voids. The problem is further complicated by the viscoelastic nature of the binder.

The toughening mechanisms which can be seen in the macro- or meso-level have not been well defined experimentally nor well described theoretically. As shown in Figure 9, there are very different fracture mechanisms due to the nonhomogeneity in the specimen such as microcracking, crack branching and deflection, crack face sliding, crack bridging, and crack tip blunting. During fracture, the high-stress state near the crack tip causes microcracking at flaws such as air voids remaining after material compaction. This microcracking phenomenon consumes a part of the external energy caused by the applied load the microcracks have a variable orientation with respect to the main crack plane. Furthermore, the density of microcracks generally decrease with increasing distance from the face of the main crack (Figure9-(a)).

The macrocrack may propagate into several branches due to heterogeneity of concrete and more energy will be consumed in the formation of new crack branches Figure 9-(b)). Crack deflection occurs when the path of least resistance is around a relatively strong particle or along a weak interface (Figure 9-(c)). Also, during the opening of a tortuous crack, there may be some frictional sliding between the cracked faces. This causes energy dissipation through friction and some bridging across the crack (Figure 9-(d)). One of the important toughening processes in concrete is grain bridging. Bridging occurs when the crack has advanced beyond an aggregate that continues to transmit stresses across the crack until it ruptures or it pulled out (Figure 9-(e)). Asphalt concrete has internal voids which produces a blunt crack tip like in Figure 9-(f). Based on these ideas, heterogeneous fracture modeling was attempted in an effort to gain some insight towards fracture toughening mechanisms in asphalt concrete [30, 31].

Figure 10 shows the specimen microstructure and model responses during heterogeneous fracture simulation. From the simulation results, we can obtain the crack path, location and timing of microcracks, and stress and strain distributions across the entire specimen. Figure 10-(c) represents the microcracks and macrocrack in the entire specimen and the figure

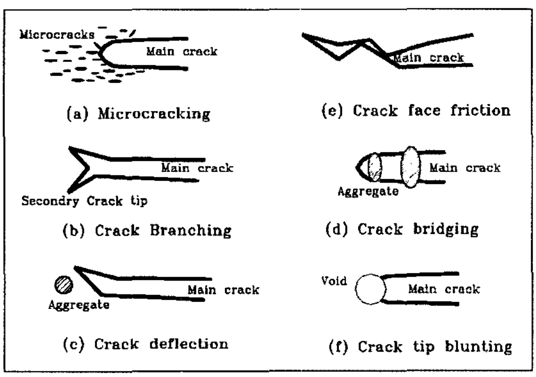


Figure 9. Fracture toughening mechanisms of asphalt concrete

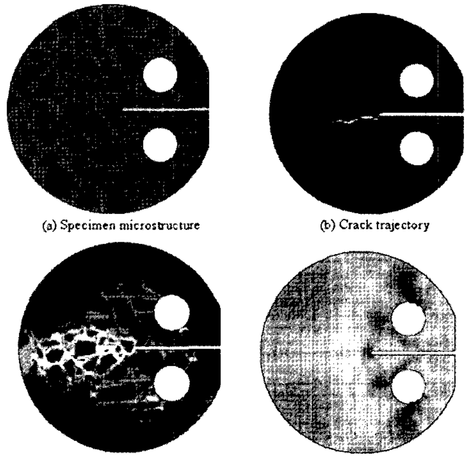


Figure 10. Heterogeneous fracture model results of DC(T) test

illustrates that the majority of cracking has occurred in the expected ligament zone. The white coloring of figure 10-(c) is the area exaggerated by heavy microcracking. In addition, local microcracks can be observed around the internal holes where simulated loading was applied. One of the benefits of fracture simulation is to investigate difficult-to-measure quantities such as crack tip displacement and the size and material behavior in the fracture process zone.

Heterogeneous Fracture Prediction Models

Figure 11 is an example of global response matching as illustrated on force vs. CMOD curves. Case 1 represents the specimen with "0" Poisson's ratio for all materials and case 2 represents the heterogeneous specimen with "0.15" Poisson's ratio for aggregate and with "0.2" Poisson's ratio for mastic and interface based on the plane strain state. The case 3 is the same with case 2 but based on plane stress conditions. Overall the global response shows a reasonable match with experimental results in case 2, although better results could be obtained by employing the strategies discussed earlier (additional iterations in the inverse analysis, more sophisticated softening model, and viscoelastic bulk material). Furthermore, in the not-so-distant future, the ability to model and simulate three-dimensional material microstructure will yield further improvements in model accuracy.

Material strength ratios of 2.85: 1.0: 0.91 for the aggregate, mastic, and material interface were used. In this heterogeneous cohesive fracture model, a total of 38,709 balls with 0.35mm radius and 114,958 contacts were arranged in a face-centered packing. Furthermore, 18,674 balls and 48,749 contacts were used for aggregates, 20,035 balls and 52,674 contacts for mastic, and 13,535 contacts for the interface between aggregates and mastic were used in this simulation. All material properties of the heterogeneous models are shown in Table 5.

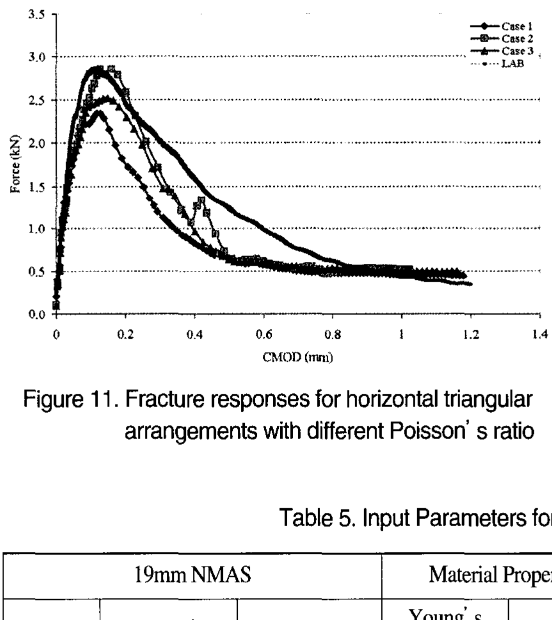


Figure 11. Fracture responses for horizontal triangular arrangements with different Poisson' s ratio

DISCUSSION AND CONCLUSIONS

A multi-scale modeling concept framework was presented from the atomic level to the structural level and inverse analysis was explained for integrating experimental, analytical, and numerical approaches to understand the fracture behavior of asphalt concrete. The relationship between continuum and discontinuum theory was defined with two-dimensional Hooke' s law and strain energy-based derivation for the plane strain and plane stress conditions. In order to validate the relationship, uniform axial compression and cantilever beam models were simulated and compared with the derived equations based on the displacement results and a reasonable match between theoretical and DEM

Table 5. Input Parameters for heterogeneous fracture models

19mm NMAS			Material Properties		MDEM Contact Properties			
	Poisson' s Ratio	Phase	Young' s Modulus (GPa)	Strength (MPa)	Normal Stiffness (GPa)	Shear Stiffness (GPa)	Bond Strength (N)	Strength Ratio
Case 1	0	Aggregate	56.8	6.59	1.64	1.64	133.24	2.85
	0	Mastic	11.4	2.31	0.33	0.33	46.81	1.00
	0	Interface	11.4	2.11	0.33	0.33	42.64	0.91
Case 2	0.15	Aggregate	56.8	6.59	2.04	0.81	133.24	2.85
	0.20	Mastic	11.4	2.31	0.52	0.0021	46.81	1.00
	0.20	Interface	11.4	2.11	0.52	0.0021	42.64	0.91
Case 3	0.15	Aggregate	56.8	6.59	1.93	0.92	133.24	2.85
	0.20	Mastic	11.4	2.31	0.49	0.0037	46.81	1.00
	0.20	Interface	11.4	2.11	0.49	0.0037	42.64	0.91

simulated results were obtained.

A clustered DEM fracture model with a bilinear cohesive contact model was implemented using PFC-2D software and used to simulate crack propagation in asphalt concrete laboratory compact tension specimens. Using tensile strength and fracture energy results obtained from experiments, crack propagation in a disk-shaped compact tension test (DC(T)) was simulated using a homogeneous model. Overall, the trends in initial stiffness, peak load and corresponding CMOD matched well with experimental results. Additionally, a heterogeneous, clustered DEM model was successfully developed and used to simulate fracture in the DC(T) test; yielding promising results.

Although much more work is needed, the heterogeneous fracture simulation demonstrated the potential usefulness of the approach in the investigation of complex fracture mechanisms in asphalt concrete which are observed in the laboratory and field. With the creation of a single heterogeneous model, many mixture tests, such as creep, stiffness, strength, and fracture can be simulated with minor changes to the model. It is believed that this modeling approach can be used soon to reduce the amount of expensive and time-consuming experimental tests required in research and development studies and design and can also provide specific, detailed information which is difficult or even impossible to determine from laboratory measurements. Furthermore, many possible problems in experiments such as imperfect symmetric specimen alignment, unexpected boundary conditions, and specimen size limitations can be addressed through this modeling approach. However, many challenging tasks remain, such as: three-dimensional heterogeneous modeling [32]; large-scale, e.g. pavement system modeling; size effect studies [33]; experimental determination of interface material properties [34]; systematic modeling of material defects and air voids, and; viscoelastic and dynamic fracture modeling.

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