Simulation of Damage and Crack Propagation in Three-Point Bending Asphalt Concrete Beam

Guowei Zeng[1,2,*], Xinhua Yang[1], Fan Bai[1] Anyi Yin[1]

[1] School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, 430074, China
[2] Hubei Province Key Laboratory of Systems Science in Metallurgical Process, Wuhan University of Science and Technology, 430065, China
* Corresponding author: zengguow@126.com

Abstract A brittle damage-based constitutive model is proposed to characterize the crack initiation and propagation behavior of asphalt mastic under low temperature. The fracture criterion is regarded as a dominant of damage. For asphalt concrete combining aggregate and asphalt mastic, a 2D finite element model including the aggregate generation and packing algorithm and Usermat subroutine technique is developed to perform the crack initiation and propagation. A series of FE simulations are performed to evaluate effects of crack location on crack propagation of asphalt concrete. The numerical results are validated by comparison with the corresponding experiments and other result which based on fracture criterion of maximum circumferential tensile stress. The model and method are proved to be rational and capable of describing the cracking behavior of asphalt concrete with different crack location.

Keywords Asphalt concrete, Three-Point Bending Beam, Numerical Simulation, Brittle Damage, Crack

1. Introduction

Crack is the one of most common distresses of asphalt materials and reduces the road service capacity. Furthermore it also allow for the infiltration of moisture, which result in a rapid deterioration of the pavement structure. It can be suggested that heterogeneity of composites affected its fracture behavior and leading to a significant complexity in crack propagation analysis [1]. The mechanism of crack growth and evaluation of the characterization of fractured pavement structure generally are the fundamental problems in the pavement engineering. They have been more widely focused and studied by the researchers and engineers in recently years [2-5]. The fracture resistance of asphalt concrete significantly influences the service life of asphalt pavements and consequently the maintenance of the pavement network.

Numerous researchers [6-8] proved that the mechanical properties of asphalt concrete are significantly affected by micro structural details and some material parameters, including asphalt content, aggregate type, gradation of aggregate particles, distribution and orientation of aggregates, void ratio, and so on. According to combination of the micromechanical properties of asphalt concrete and heterogeneity, the mechanism cracking behavior for asphalt concrete can be simulated more accurately by construct the micromechanical model containing information about its components and microstructures. For this aim, the current study presents an approach based on the CDM, which considers the concrete heterogeneity.

Asphalt concrete can be described as a multiphase material containing coarse aggregates, mastic cement(including asphalt binder and fine aggregates), and air voids. In this method, the numerical sample model is constructed by replacing the irregular aggregate geometry to resemble real polygon, circle, elliptical and so on. The aggregate content, gradation and some structural parameters, aggregates are generated and randomly located in a prescribed region. Then the generations are assigned to coarse aggregates and the rest region to the mastic. With this method the mechanical properties and fracture of asphalt concrete were evaluated by Xu et al. in[9], Yang et al. in[10] and Yin et al. in[11, 12]. Especially Yin et al. [11, 12] successfully applied the numerical sample model method to investigate the gestation and propagation of the crack in two-dimensional models including three-point bending asphalt mixture beam with pre-crack and uniaxial tensile beam.

Accurate failure predictions can only be obtained if microstructural damage is taken into account in the fracture modelling. This requirement has led to the development of the so-called local or continuum approaches to fracture, in which fracture is regarded as the ultimate consequence of the material degradation process. This paper employ the user defined material technique in FEM directly, a constitute equations of damage model which cover the all potential failure area are developed. The damage model allows damage assessments at every point of a structure for any geometry or loading, as long as the damage mechanisms and stress-strain curve are known. This paper is an attempt to advance our understanding of relationship between crack path and microstructure features as they apply to damage evolution in three point bending asphalt bending beam.

The objective of this paper is to propose a fracture criteria based on damage model for investing cracking behaviors of the three point bending test of asphalt concrete beam. The proposed damage model is implemented in the commercial finite element analysis software Ansys via the user defined subroutine UPFs .The numerical simulation compared with the experimental results to validate our present criterion. The results show that the proposed criterion reasonably predicts the crack growth initiation in different pre-crack locations and aggregate distributions.

2. Random heterogeneous modeling for asphalt concrete

2.1. Brittle damage model for asphalt mastic

For the case of isotropic damage evolution，continuum damage mechanics（CDM）introduces a field variable to represent the damage in a continuum sense. In this paper, this concept has later been used to model the initiation and growth of cracks. By assuming homogeneous distribution of micro voids and the hypothesis of strain equivalence, which states that the strain behavior of a damaged material is represented by constitutive equations of the virgin material (without damage) in the potential of which the stress is simply replaced by the effective stress

$$\tilde{\sigma} = \frac{\sigma}{1-D} \tag{1}$$

where σ is the stress tensor for the undamaged material. And the corresponding scalar damage variable $D = 1 - E_D / E_0$, in which E_D is the effective elastic modulus of the damaged materials, E_0 is the elastic constant of the virgin material and D has a range from 0 to 1, D=0 means that material is intact ,while D=1 means that material is damaged completely.

The another form of the effective stress can be given by

$$\sigma = E_0(1-D)\varepsilon \tag{2}$$

Extended the model to three-dimensional form, such that:

$$\sigma_{ij} = E_{ijkl}(1-D)\varepsilon_{kl} + \frac{D}{3}\delta_{ij}E_{\rho\rho kl}\varepsilon_{kl} \tag{3}$$

Written it to the form of matrix, the constitute law is

$$\boldsymbol{\sigma} = \tilde{\mathbf{D}}\boldsymbol{\varepsilon} \tag{4}$$

where $\tilde{\mathbf{D}}$ is elastic damage stiffness matrix which is relative to the elastic modulus E, poisson ratio v and scalar damage variable D which is expressed as

$$\tilde{\mathbf{D}} = \frac{E}{1+\mu}\begin{bmatrix} B & A & A & 0 & 0 & 0 \\ A & B & A & 0 & 0 & 0 \\ A & A & B & 0 & 0 & 0 \\ 0 & 0 & 0 & C & 0 & 0 \\ 0 & 0 & 0 & 0 & C & 0 \\ 0 & 0 & 0 & 0 & 0 & C \end{bmatrix} \tag{5}$$

where

$$A = \frac{\mu}{1-2\mu} + \frac{D}{3} \tag{6}$$

$$B = \frac{1-\mu}{1-2\mu} - \frac{2D}{3} \tag{7}$$

$$C = \frac{1-D}{2} \tag{8}$$

The Mazars and Pijaudier-cabot[13] had described the damage behavior of quasi-brittle materials like concrete and rock by equal strain, this paper follows their suggestion and the definition of equal total strain is

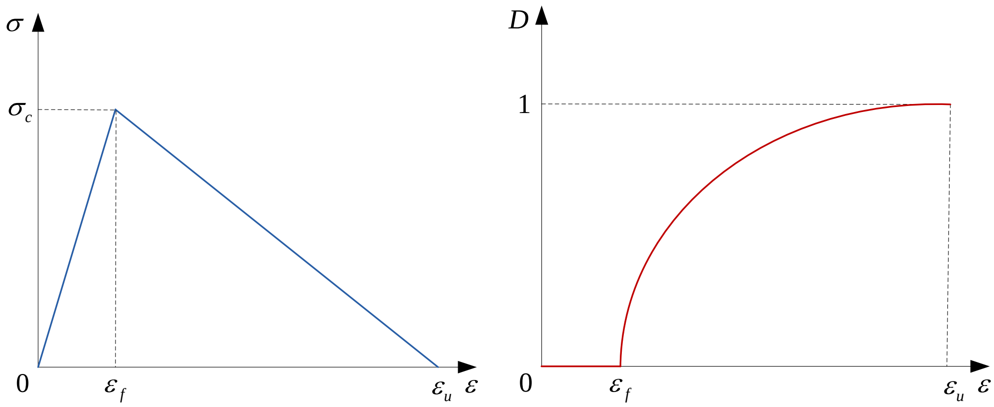
$$\varepsilon = \sqrt{\sum_{i}^{3}\left(\langle \varepsilon_i \rangle\right)^2} \tag{9}$$

where ε_i are the principal strains. For bituminous material the damage is only related to the tensile strain, so it is supposed that the damage is induced only by tensile strains in this paper. Then specify strain $\langle \varepsilon_i \rangle = \varepsilon_i$ if $\varepsilon_i > 0$ and $\langle \varepsilon_i \rangle = 0$ otherwise.

The damage parameter D starts at a damage threshold level $\varepsilon = \varepsilon_f$ and is updated during damage growth which occurs according to an evolution law such that $D = D(\varepsilon)$, which can be determined from the uniaxial tests. a linear elastic behavior has been sustained up to a peak tensile strength point $\sigma_t = E\varepsilon_f$ which is illustrated in Fig. 2(a), then the stress-strain curve followed by descending branch up to a strain ε_u at which the load-carrying capacity is exhausted(and thus $D=1$), so the proposed damage evolution law reads:

$$D(\varepsilon) = \begin{cases} 0 & 0 < \varepsilon \le \varepsilon_f \\ \dfrac{\varepsilon_u(\varepsilon - \varepsilon_f)}{\varepsilon(\varepsilon_u - \varepsilon_f)} & \varepsilon_f < \varepsilon < \varepsilon_u \end{cases} \tag{10}$$

where ε_f, ε_u represent strain for threshold of damage and strain for critical of damage respectively. Fig. 2(b) illustrates the damage evolution curve.



(a)curve of stress-strain (b)curve of damage evolution
Fig. 2 curves of the proposed damage model

2.2. Aggregate generation and packing algorithm

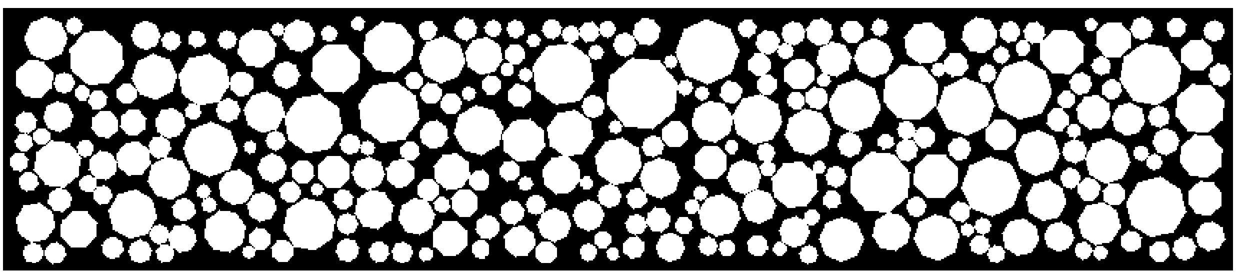
Utilizing a self-compiled algorithm, all spheric aggregates (or round aggregates for 2D) are converted into their corresponding inscribed polyhedra (or regular polygons). The detail of the algorithm was described in the work of Yin et al. [11, 12]. For convenience, the somplete aggregate gradation listed in Table 1 was treated as a simplified aggregate gradation listed Table 2.
Two 2D mesostructural asphalt concrete specimens of different coarse aggregate distributions with the gradation simplified aggregate are created by the generation and packing algorithm, shown in Fig.1 (a) and (b), respectively. In those two figures, the black region represents asphalt mastic and the white regular octagons are graded coarse aggregates.

Table 1. Complete aggregate gradation

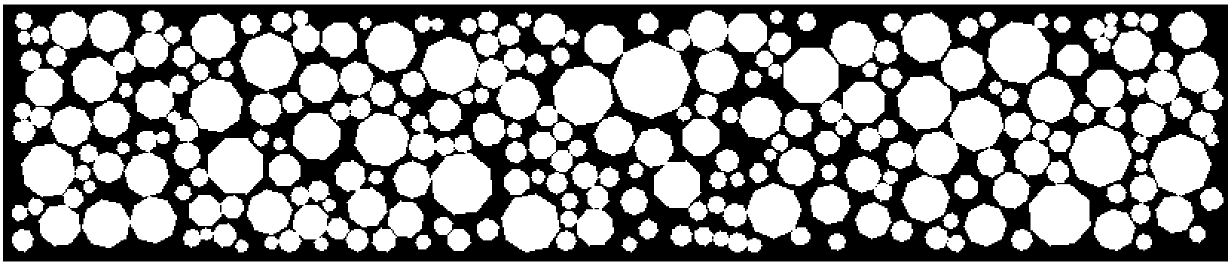
Sieve size (mm)	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing rate (%)	100	98.1	80.8	52.2	34.1	27.5	20.6	14.1	9.9	7.7

Table 2. Simplified aggregate gradation

Sieve size (mm)	16.0	13.2	9.5	4.75	2.36
Passing rate (%)	100	98.1	80.8	52.2	34.1



(a)



（b）
Figure. 1 Two 2D numerical specimens of asphalt concrete

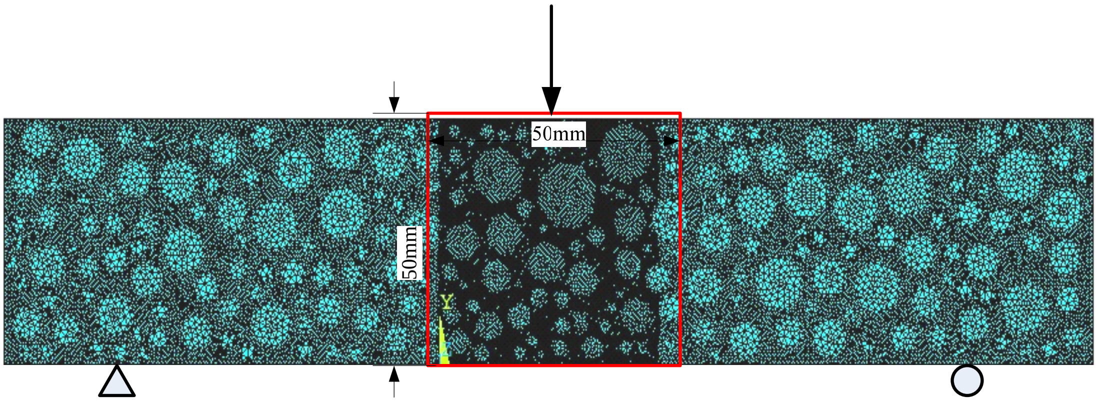
2.3. The finite analysis using damage mechanics for asphalt concrete

The asphalt mastic is assigned to obey an elastic damage constitute law which implemented into the FEM software. A USERMAT subroutine defining the damage elastic material property is coded using the FORTRAN language. Then it is compiled and integrated into the main program by a user defined variable can save the value of damage.

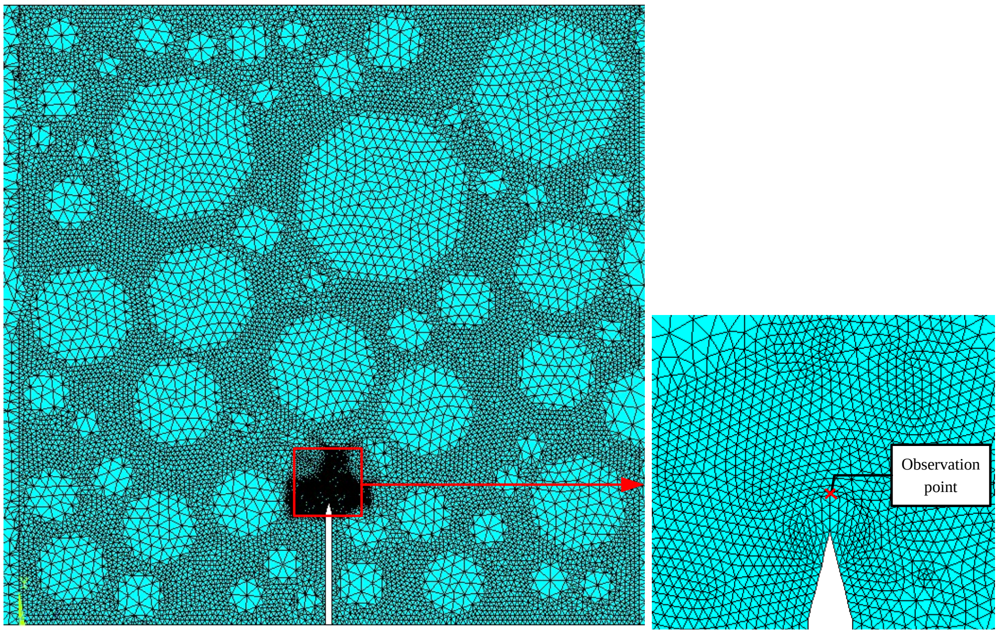
A series of 2D asphalt concrete samples with the dimensions of 150mm×50mm and coarse aggregate gradation shown in Table 2 are modeled. The element we used is 8-node plane183 and the asphalt concretes are treated as composite materials in which component of coarse aggregates which is assigned to elastic material property and asphalt mastic which is assumed to be elastic damage material. The aggregate generation and packing algorithm is used to create its micromechanical asphalt concrete with coarse aggregate, the rest region is modeled as the asphalt mastic. Three point bending experiments are virtually performed. The material properties of coarse aggregate and asphalt mastic are needed to assign independent material parameters. In general, aggregates are linearly elastic, but asphalt mastic is effected by the temperature. In the current paper the asphalt mastic is assumed to be elastic and brittle damaged since temperature is enough low [12], although viscoelasticity in the matrix has been considered in higher temperature. Therefore the detailed parameters of asphalt mastic and coarse aggregates are listed in the Table 3.

Table 3. List of material parameters at T=5℃

Elastic damage model for asphalt mastic			
$E(GPa)$	ν	ε_f	ε_u
0.612	0.35	0.002	0.07
Elastic model for coarse aggregate			
$E(GPa)$		ν	
40		0.15	



(a) Mesh configuration of the whole beam



(b) Mesh in the mesoscale region (c) Mesh near the crack tip

Figure 2. Mesh configuration of the three-point bending beam specimen with a central crack

The fracture of asphalt concrete is mainly due to accumulation and coalescence of microscopic cracks existing or induced by load. One of the features of fracture investigation is the proposed criterion for crack growth initiation. By introducing a damage variable in the constitutive relation, the element fractures and a crack occurs when the fracture threshold within the elements is reached in the numerical simulation. Namely the propagation of crack is the migration of damage zone where are equal to the critical damage value gradually for the material of around crack tip. In this paper, the crack is assumed to only grow in asphalt mastic since mastic stiffness weaker than coarse aggregates several quantities and fracture criterion is given based on damage value as follows:

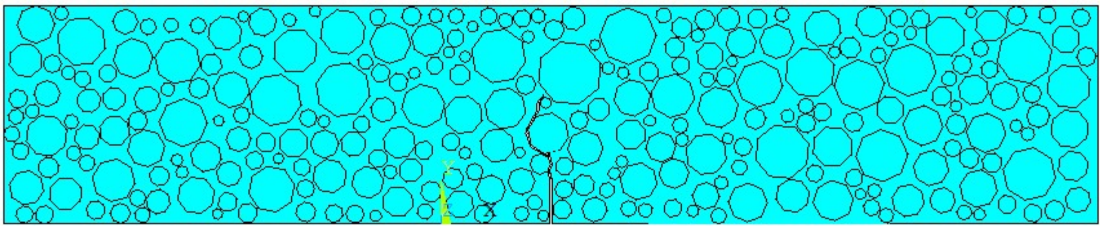
$$D = D_c \tag{11}$$

Once the damage value near the crack tip reaches its critical value D_c, the fracture occurs and propagates. D_c =0.85, which is referred to the results given by Sun et al. [14].

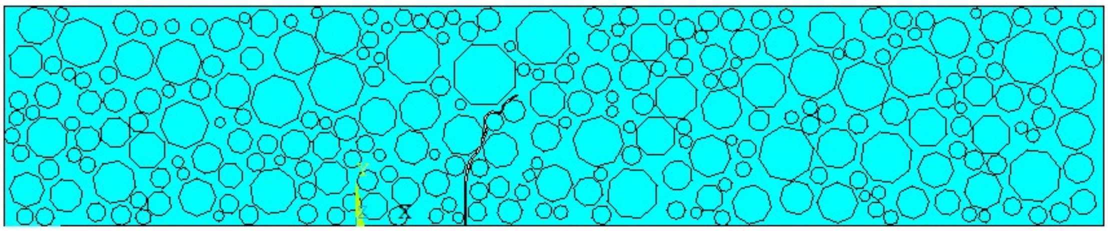
3. Results and discussion

In order to investigate the effect of crack location, several RVEs with three different crack locations were cut from the actual size model: a center crack, a 20mm off-center crack and a 40mm off-center crack are plotted in Fig. 9. By increasing the loading step, the damage around the crack tip will grow until eventually the first element will reach to the critical damage parameter, D_c. At this stage the new crack tip coordinates will be determine by a self-compiled searching program and the crack will advance as much as the new crack tip point. This progress continues until final failure of the specimen.

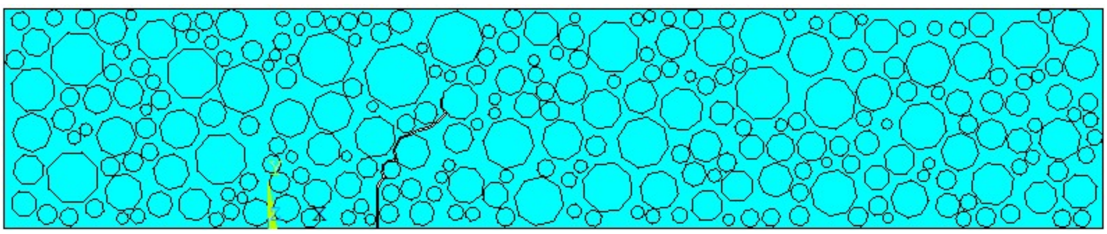
The experimental [12] and numerical crack paths of three crack locations are plotted in Fig.3 and Fig. 4, the simulation results showed good agreement with the experimental paths. Due to the similar coarse aggregate distribution, the simulation results were similar to the results computed by the fracture criterion based on the maximum circumferential tensile stress especially. The damage-based fracture criterion is validated to feasible by the comparison. Furthermore, the paths of this paper predicted showed agreement with the experimental paths more closely than the curves given by Yin et al. [12] in some regions. Then it can be proved the effect of aggregate is more significant to the damage evolution. Form total comparison it can be seen the father the crack is away from the beam center, the larger its kinking angle is. But the crack trends to grow towards to the beam top midspan.



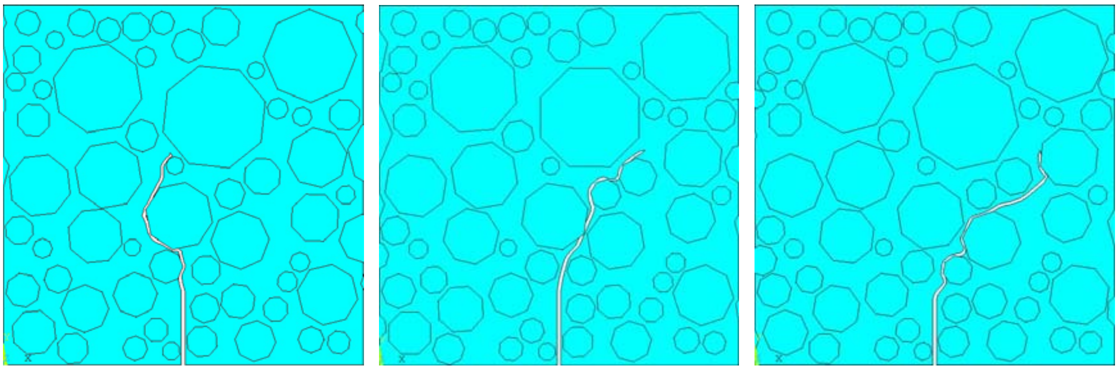
(a) Actual size FEM model for crack location 0mm



(b) Actual size FEM model for crack location 20mm

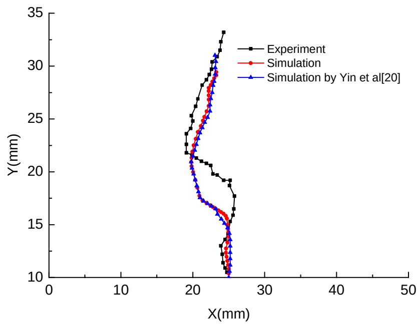


(c) Actual size FEM model for crack location 40mm

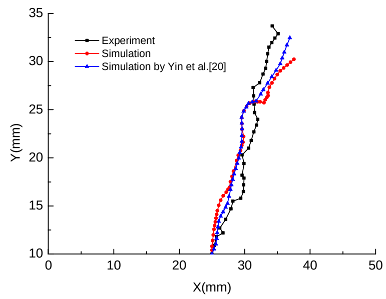


(d) RVEs for 0mm (e) RVEs for 20mm (f) RVEs for 40mm

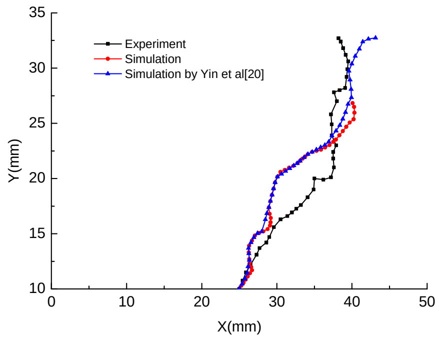
Figure 3. Crack paths for different crack location



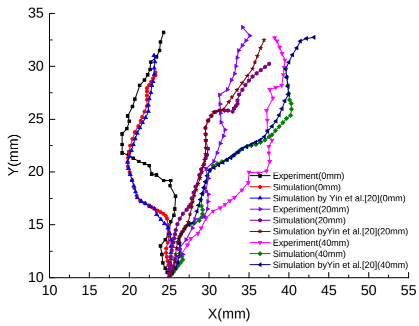
(a) 0mm off-center crack



(b) 20mm off-center crack



40mm off-center crack



Total merged plot for three crack locations

Figure 4. Experimental and numerical crack paths of three kinds of crack

A numerical two-dimensional micromechanical modeling frame considering the heterogeneity feature has been developed to simulate the cracking behavior of asphalt concrete based on the aggregate generation and packing algorithm. Incorporating a damage mechanics approach with this solution allowed the development of a softening model capable of predicting typical global inelastic behavior found in asphalt materials, the proposed model used to compare between the computer simulated results and experimental data of the cracked three-point bending beam, the results showed that the overall agreement is satisfactory.

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