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Simulation of damage evolution and crack propagation in three-point bending pre-cracked asphalt mixture beam

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HIGHLIGHTS

- The damage evolution and crack propagation of asphalt mixture are simulated.
- Asphalt mastic in fracture processes is described by the damage constitutive model.
- The heterogeneous asphalt mixture models are created with a parameterization method.
- Effects of pre-crack location and aggregate distribution are evaluated.

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ABSTRACT

A numerical simulation framework is proposed to analyze damage evolution and crack propagation behaviors of heterogeneous asphalt mixture under low temperature. In this framework, asphalt mixture is considered as a two-phase composite consisting of coarse aggregates and asphalt mastic (namely a mix of fine aggregates and asphalt binder). The heterogeneous and random geometrical models of asphalt mixture are created with the parameterization method and the physical degeneration of asphalt mastic in fracture processes is characterized with the damage constitutive model with some experimentally determined parameters. The framework is validated by good agreement between the predictions and the experiments in crack path. Finally, the effects of crack location and coarse aggregate distribution on crack propagation and damage evolution in a pre-cracked three-point bending asphalt mixture beam are evaluated.

1. Introduction

As one of main building materials widely used in modern highway and pavement construction, asphalt mixture is a complex heterogeneous material composed of aggregates, asphalt matrix and voids and exhibits complex mechanical behaviors [1]. Microcrack or damage is a significant source of premature degradation of asphalt pavement especially in cold regions and can largely reduce the road service capacity, so that fracture is a main type of distresses. As fundamental problems in pavement engineering, consequently, the cracking mechanism and fracture characteristics of asphalt mixture have attracted more and more attention in recent years [2–5].

The mechanical properties of asphalt mixture are significantly affected by microstructural details and component parameters, including asphalt content, aggregate type, gradation, distribution and orientation, void ratio, and so on [6–8]. Homogeneous models tend to neglect heterogeneity of asphalt mixture, so they always give some predictions of unrealistically smooth crack paths and unreliable load-carrying capacities. In order to simulate cracking behaviors of asphalt mixture more accurately, it is necessary to construct its micromechanical model with the component and microstructure information.

Due to irregular microstructural configurations and random particle distribution, accurate micromechanical modeling is generally very complicated. Many efforts have been made to develop heterogeneous modeling methods which treat asphalt mixture as a two-phase material with coarse aggregate particles embedded in asphalt mastic matrix [9–11], namely a mix of fine aggregates and asphalt paste. These modeling methods can generally divided into two types: the numerical image processing method [12] and the parameterization modeling method. Utilizing the numerical image processing method, a geometric model of asphalt mixture with realistic aggregate shape, gradation and distribution can be

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generated from a high-resolution digital camera (DC) or computed tomography (CT) scanner photo with the numerical image processing technology. Based on this method, the 2D and 3D fracture simulations of asphalt mixture were performed by Dai and You [9] and You and Buttlar [13], respectively. However, it is time-consuming and very expensive to fabricate and cut experimental specimens and then to deal with the scanned images. In the parameterization modeling method, asphalt mixture is treated as a mix of coarse aggregates and asphalt mastic, and graded coarse aggregates are modeled as particles with different shape and size. Consequently, a heterogeneous numerical model of asphalt mixture can be rapidly created without material loss. Xu et al. [14] proposed a three-dimensional aggregate generation and packing algorithm, in which arbitrary-shaped polyhedra are created by extending triangular fundaments as visualized aggregates and saved in the aggregate base and later taken out one by one and randomly packed in a given cylindrical or cubical region equiprobably. Yang et al. [15] developed a 3D random modeling frame for asphalt mixture, in which graded spherical particles were firstly packed in a given region and then converted into inscribed polyhedra. It can largely reduce time cost in modeling. Yin and his coworkers applied this modeling frame to simulate crack propagation in a pre-cracked three-point bending asphalt mixture beam [16] and nucleation and coalescence of microcracks, and gestation and propagation of macrocracks in a uniaxial tensile specimen [17].

On the other hand, some experimental studies, such as the edge cracked beam subjected to three- or four-point bending [18,19], the disc-shaped specimen in compact tension [20] and the semicircular bend (SCB) specimen subjected to three-point bend loading [21,22], were done in the recent decades. The postpeak softening phenomenon was observed in these tests and considered to originate from material degradation in the fracture process. It was often characterized by the cohesive zone model [23,24]. But the damage degree and distribution cannot be given for different stages of crack growth. Fracture can be regarded as the ultimate consequence of material degradation in the viewpoint of continuum damage mechanics [25,26]. In recent years, continuum damage mechanics began to be used in description of nonlinear behavior of asphalt mixture, such as Zhao [27], Uzan [28], Underwood and Kim [29], and so on. However, the proposed damage constitutive models are too complicated to simulate fracture problems of asphalt mixture.

In this paper, asphalt mixture is considered as a two-phase composite consisting of coarse aggregates and asphalt mastic. A heterogeneous geometrical model of pre-cracked three-point bending asphalt mixture beam is constructed with the parameterization modeling method proposed by Yang et al. [15]. The softening behavior of asphalt mastic is characterized with the damage constitutive model with a scalar damage variable. The damage constitutive model parameters are determined based on the direct tensile test performed on asphalt mastic. And then the crack initiation and propagation process is numerically simulated. The effects of crack location and coarse aggregate distribution on damage distribution near the crack tip and the crack path are analyzed and evaluated.

2. Basic models for asphalt mastic

2.1. Damage constitutive relation

Material damage has various physical visions, such as a micro-crack, and a micro-void, but can be mathematically characterized by a damage variable according to continuum damage mechanics [30]. Although damage is inherently an anisotropic phenomenon, an isotropic damage formulation with a single scalar variable is often used due to its simplicity and capability to overcome the convergence problems involved in numerical computational implementation.

With the hypothesis of strain equivalence, considering damage is only relative to the deviatoric stress, the effective stress tensor in a damaged material is defined as

$$\sigma_{ij} = (1-D)\tilde{\sigma}_{ij} + \frac{D}{3}\delta_{ij}\tilde{\sigma}_{kk} \tag{1}$$

where σ_{ij} is the real stress tensor, $\tilde{\sigma}_{ij}$ is the effective stress tensor, $\tilde{\sigma}_{kk}$ is the effective volumetric stress, δ_{ij} is the Kronecker delta and D is the scalar damage variable with a range from 0 to 1. $D = 0$ means that material is intact, while $D = 1$ means that material is fully damaged.

Replacing the real stress tensor with the effective stress in the elastic constitutive relation, the damage constitutive equation can be given as follows:

$$\sigma_{ij} = E_{ijkl}(1-D)\varepsilon_{kl} + \frac{D}{3}\delta_{ij}E_{\rho\rho kl}\varepsilon_{kl} \tag{2}$$

where ε_{kl} is the real strain tensor and E_{ijkl} is the elastic tensor.

Eq. (2) can also be rewritten in the form of matrix as follows:

$$\{\sigma\} = [\widetilde{E}]\{\varepsilon\} \tag{3}$$

where $[\widetilde{E}]$ is the effective elastic matrix which is connected with the elastic modulus E, Poisson's ratio ν and damage variable D.

$$[\widetilde{E}] = \frac{E}{1+\nu}\begin{bmatrix} B & A & A & 0 & 0 & 0 \\ A & B & A & 0 & 0 & 0 \\ A & A & B & 0 & 0 & 0 \\ 0 & 0 & 0 & C & 0 & 0 \\ 0 & 0 & 0 & 0 & C & 0 \\ 0 & 0 & 0 & 0 & 0 & C \end{bmatrix} \tag{4}$$

where

$$A = \frac{\nu}{1-2\nu} + \frac{D}{3}, \quad B = \frac{1-\nu}{1-2\nu} - \frac{2D}{3}, \quad C = \frac{1-D}{2} \tag{5}$$

Analogous to the damage definition in concrete-like materials by Mazars and Pijaudier-cabot [31], the damage variable can be connected with the equivalent strain.

$$D = \begin{cases} 0 & 0 < \varepsilon \leqslant \varepsilon_f \\ \frac{\varepsilon_u(\varepsilon-\varepsilon_f)}{\varepsilon(\varepsilon_u-\varepsilon_f)} & \varepsilon_f < \varepsilon < \varepsilon_u \end{cases} \tag{6}$$

where ε_f and ε_u the threshold strain at damage initiation and the critical strain at crack initiation or growth, respectively. The equivalent strain is defined as

$$\varepsilon = \sqrt{\sum_i^3 (\langle\varepsilon_i\rangle)^2} \tag{7}$$

where ε_i is the ith principal strain component and $\langle\ \rangle$ is the Macaulay bracket. $\langle\varepsilon_i\rangle = \varepsilon_i$ if $\varepsilon_i > 0$, otherwise $\langle\varepsilon_i\rangle = 0$. For bituminous material at low temperature, it is assumed that the damage is induced only by tensile strain.

2.2. Damage-based fracture criterion

From the viewpoint of continuum damage mechanics, fracture is mainly due to damage accumulation. The fracture criterion is defined as follows [32]:

$$D \geqslant D_c \tag{8}$$

where D_c is the critical damage. It means that once the damage near the crack tip is larger or equal to the critical value D_c, the crack will