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Three-dimensional heterogeneous fracture simulation of asphalt mixture under uniaxial tension with cohesive crack model

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HIGHLIGHTS

- Model heterogeneous asphalt mixture with aggregate generation and packing algorithm.
- Conduct 3D tensile fracture simulations.
- Observe microcrack initiation and coalescence and macrocrack gestation.
- Evaluate effects of aggregate distribution and fracture parameters on fracture.

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ABSTRACT

A three-dimensional (3D) heterogeneous fracture modeling technology is presented to simulate complex crack evolution in quasi-brittle asphalt mixture. In this technology, the random aggregate generation and packing algorithm is employed to create 3D heterogeneous numerical model of asphalt mixture, and the cohesive elements with the tension/shear softening laws are inserted into both the mastic matrix and the aggregate–mastic interfaces as potential cracks. The nucleation and coalescence of microcracks, and inception and propagation of main macrocracks are carefully studied under uniaxial tension and temperature of −10 °C. The effects of the averaged coarse aggregate size and the cohesive fracture parameters on performance of asphalt mixture are also evaluated.

1. Introduction

Cracking is a major source of deterioration of asphalt materials and asphalt pavements. Cracks in asphalt pavements result in irreversible structural and functional deficiencies which increase maintenance costs and decrease the lifespan. Accordingly, understanding fundamental mechanisms behind initiation and propagation of cracks is an important issue for accurate design, construction and maintenance of pavements. There were various efforts to investigate the fracture mechanism of asphalt mixture during the past several decades [1–3].

However, there are some challenges which need to be tackled when studying the fracture mechanism of asphalt mixture. Because asphalt mixture is a complicated material composed of randomly distributed solid inclusions (coarse and fine aggregates), viscous matrix (asphalt) and voids, its physical properties and mechanical performance are affected by a series of mesostructural factors, such as asphalt content and property, aggregate type, gradation of aggregate particles, distribution and orientation of aggregates, and void ratio [4–6]. The heterogeneous feature of asphalt mixture is not suitable to be homogenized in fracture simulation because the homogeneous fracture model often predict unrealistically smooth or wrong crack paths [7]. A typical fracture pattern observed nowadays in some multi-phase materials, such as asphalt mixture, fiber reinforced composite and toughened alloy, often consists of a main crack, branches, tortuosities, and a number of microcracks [8,9]. Some researches [10–12] attributed the fracture mechanism of these multi-phase composites to the complex morphological features and heterogeneous properties caused by random spatial distribution of reinforced phase at the mesoscale. So analysis in the mesoscale level should be an extremely powerful and necessary tool for understanding and prediction of the macroscopic behavior of asphalt mixture.

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Recently, a number of researches were concentrated in the mesostructure and microstructure characteristics of cement like materials [8,13–16] and a variety of numerical heterogeneous asphalt mixture and concrete models were also created through tackling the challenge of numerical representation of random heterogeneity of aggregates in different ways, including direct and indirect approaches. Instead of modeling material phases explicitly, the indirect approaches simplify heterogeneous material properties into random fields, which satisfy a certain distribution, and assign them to the regular lattice model. Accordingly, effects of some mesostructural factors on mechanical properties of asphalt mixture can be numerically evaluated. These approaches are suitable for both two-dimensional (2D) and three-dimensional (3D) models.

Two popular direct approaches, i.e. the numerical image processing technique and the parameterization modeling technique, were developed in recent years to explicitly model the different material phases in asphalt mixture. In the first method, a high-resolution camera or computed tomography (CT) scanner is used to capture a 2D digital image of asphalt mixture, and then the image is transferred into a geometrical model involving numerical aggregates with the shape, gradation and distribution near to nature with the help of the image boundary recognition technique. This method was used to simulate the 2D fracture of asphalt mixture combined with the discrete element method by You and Buttlar [17] and Dai and You [18] and with finite element method by Kim et al. [19]. Recently, a 3D microstructure model was developed by You et al. [15] through using a 3D reconstruction technique based on a series of parallel 2D images to predict the mixture modulus. However, the laboratory dependency is a major limitation of such an image-based model because it is time-consuming and very expensive to fabricate and cut specimens and then to deal with the scanned images. In the second method, randomly distributed aggregates are generated by some numerical algorithms according to given aggregate gradation and content. Yang et al. [20] presented a 3D lattice model, in which the numerical specimen was meshed into homogeneous lattice elements with the same shape and size, and some elements were assigned as aggregates but the others as asphalt mastic according to a given aggregate content, in order to predict the rheological behavior of asphalt mixtures. Kristiansen et al. [21] and Al-Raoush and Alsaleh [22] used random ellipses with different shape and dimensions to model aggregates or polydisperse material for the evaluation of mechanical properties of concrete and polydisperse particle materials. Xu et al. [23] proposed a novel aggregate generation and packing algorithm, in which coarse aggregates were modeled as convex polyhedron, more approximate to the reality, extended from triangular fundaments. But it has a limitation that the created model could not coincide with the prescribed aggregate content precisely. Instead, Yang et al. [16] presented an advanced efficient algorithm, in which graded aggregates were modeled as regular convex polyhedrons with different sizes, and Yin et al. [24] successfully applied it to create 2D multiscale models of three-point bending asphalt mixture beam with a pre-crack. The parameterization modeling technique need not be based on real specimens, but it requires amounts, geometries, and physical and mechanical properties of mixture constituents as input conditions. It is well known that air void is a very important factor affecting the physical properties of asphalt mixture. In the above mentioned approaches, air voids are generally combined with fine aggregates and asphalt binder into asphalt mastic, so that the air void effect can be contained. Because of their random generation in asphalt mixture and finer sizes than those of most aggregates, they are always ‘missing’ in the 2D images captured by a high-resolution scanner [25]. Due to currently limited modeling technique and huge computational cost, it is still a challenge to represent air voids explicitly in the parameterization modeling approaches.

The meso-mechanical model provides explicit account for arbitrary mesostructural morphologies, different properties and content of various constituents, and mesoscopic fracture patterns, so that it becomes easier to identify and design mesostructural configurations of asphalt mixture. Some very realistic results, such as crack pattern, localization process happening in a spontaneous manner, average stress–strain specimen curves, and material failure mechanism, were obtained from 2D studies. But the 2D mesostructural model is too simple to represent the complex morphological characteristics of asphalt mixture, and many loading cases cannot be simulated by 2D models. In addition, the crack surfaces of asphalt mixture in experimental tests are mostly rough and uneven due to the existence of coarse aggregates or strong inclusions, and the larger area of rough crack surface may have effects on the structural load-carrying capacity as well as the reliability. So the 2D analysis is intrinsically limited. However, due to the difficulty in modeling and high computational costs, most of current fracture studies are based on the 2D modeling technology.

Several typical fracture tests, such as the disk-shaped compact tension and the three-point bending, proved that asphalt materials behave evident postpeak softening response in the fracture process [26,27]. Li and Marasteanu [28] used the acoustic emission method in the semi-circular bending tests to capture the microscopic fracture characters in asphalt material and found that numerous discrete microcracks occurred and developed before the macrocrack formed. The analogous fracture phenomenon was also observed in the aggregate reinforced materials like cement materials [29]. The traditional fracture mechanics approaches are limited in simulations of discrete cracks and cracks along biomaterial interfaces, as well as damage evolution caused by crack growth. As an alternative, the cohesive crack modeling approach has received increased attention in modeling crack propagation in asphaltic materials and pavement mechanics community due to its simple formulation, easy implementation in various computational methods, such as finite element and discrete element methods (FEM and DEM), and ability to model crack along biomaterial interfaces (such as aggregate–mastic interface), which are often considered as weak zones susceptible to cracking, and to adequately capture energy dissipation in the fracture process zone. Nowadays, however, the cohesive crack modeling approach is mainly used in 2D studies of asphalt mixture.

The present study aims at developing a 3D mesostructural fracture simulation approach for asphalt mixture by extending our previous 2D algorithm [30]. The 3D heterogeneous mesostructural specimens are created by using the aggregate generation and packing algorithm based on the given aggregate gradation. After the specimens are meshed with the solid elements, the zero-thickness cohesive interface elements equipped with the tension and shear softening laws are inserted into both mastic and aggregate–mastic interfaces as potential cracks in advance to simulate 3D crack initiation and propagation. And then the virtual uniaxial tension tests are performed at $-10\,^{\circ}\mathrm{C}$ to observe the mesoscale fracture phenomena in the numerical specimens and to evaluate the influences of some mesostructural factors on fracture behaviors.

2. Modeling methodology

2.1. Random aggregate generation and packing algorithm

AC-16 is a continuous dense gradation for hot mixed asphalt mixture defined in Chinese asphalt mixture specification and widely adopted in Chinese asphalt pavement engineering. Table 1 lists its complete aggregate gradation with aggregate sizes ranging from 16.0 mm to 0.075 mm. Because the amount of fine aggregates is thousand times or even more that of coarse aggregates, it is impossible to construct a micromechanical model of asphalt mixture with complete aggregate gradation, which would greatly increase the element number and go against the computational efficiency. Accordingly, as an unevadable issue, the simplicity needs to be given for the mesostructure modeling before the algorithm is implemented, in