Construction and Building Materials 65 (2014) 232–242

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Fracture simulation of pre-cracked heterogeneous asphalt mixture beam with movable three-point bending load

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HIGHLIGHTS

- Experiment and heterogeneous simulation are combined to investigate fracture behavior.
- Aggregate generation and packing algorithm is for creating a mesostructural model.
- Characterize microcrack initiation and coalescence and macrocrack gestation.
- Mode I and mixed mode cracking behaviors are investigated.

ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form 20 March 2014
Accepted 23 April 2014
Available online 21 May 2014

Keywords:
Asphalt mixture
Heterogeneity
Three-point bending
Fracture
Cohesive elements

ABSTRACT

The random aggregate generation and packing algorithm is employed to model pre-cracked three-point bending beams of asphalt mixture which is treated as a two-phase material comprising randomly distributed coarse aggregates and asphalt mastic, and the cohesive elements are inserted inside mastic and into aggregate-mastic interfaces to simulate crack initiation and propagation. The mode I and mixed mode cracking behaviors are simulated through changing the beam location in the loading setup. The predicted results compare very well with the experimental ones, and then the influences of crack location and coarse aggregate distribution on cracking behavior are evaluated.

1. Introduction

Cracking in asphalt layers is a major distress source in roadway engineering especially in cold regions. As a pavement material, asphalt mixture is a typical heterogeneous composite comprising asphalt matrix, voids, and coarse and fine aggregates with irregular shape, random orientation and distribution. The complex morphological features at the meso-scale directly determine its mechanical properties including fracture performance [1–3]. The homogenized model often used in design is too simple to predict realistic crack path and load-carrying capacity, because a typical fracture pattern in asphalt mixture often contains a main crack and some microcracks as well as some branches and tortuosities [4,5]. Li and Marasteanu [6] used the acoustic emission method in the semi-circular bending test to capture the microscopic fracture characters in asphalt mixture and found that numerous microcracks occurred and developed before the macrocrack formed. In order to understand fundamental fracture mechanisms of asphalt mixture, therefore, it is necessary to construct a heterogeneous model involving constituents and microstructures.

Nowadays, a number of researchers have paid their attention to the meso-scope and microscope characteristics of heterogeneous materials like cement concrete and a variety of numerical heterogeneous models are built for representation of random heterogeneity in different ways [7–12]. Among them, the numerical image processing technique and the parameterization modeling technique are the most popular in explicitly modeling different material phases in asphalt mixture. In the first method, some two-dimensional (2D) digital images of asphalt mixture are captured by a high-resolution camera or a computed tomography scanner and then transferred into geometrical models involving numerical aggregates with the shape, gradation and distribution near to nature with the help of 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

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http://dx.doi.org/10.1016/j.conbuildmat.2014.04.119
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Buttlar [13] and Dai and You [14] and with the finite element method by Kim et al. [15]. However, it is time-consuming and very expensive to fabricate and cut experimental 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. Kristiansen et al. [16] and Al-Raoush and Alsaleh [17] used random ellipses with different shape and dimensions to model aggregates and disperse particles for evaluation of mechanical properties of concrete and polydisperse particle materials, respectively. Xu et al. [18] proposed a novel aggregate generation and packing algorithm, in which coarse aggregates were modeled as convex polyhedron, more approximate to the reality, extended from some triangular fundaments. But it has a limitation that the created model could not coincide with the prescribed aggregate content precisely. Instead, Yang et al. [19] presented an advanced efficient algorithm, in which graded aggregates were modeled as regular convex polyhedrons with different sizes and aggregate content could be controlled well. Yin et al. [20] successfully applied this algorithm to create 2D meso-scale models of asphalt mixture and further studied the mechanisms of crack initiation and propagation with the employment of cohesive zone model, which is one of the most promising models currently in simulating crack propagation in quasi-brittle materials. In pavement mechanics community, the cohesive zone modeling approach has received increasing attention in modeling crack initiation and propagation due to its simple formulation, easy implementation in the form of cohesive interface elements and ability to adequately capture energy dissipation in the fracture process zone [21].

In recent years, numerous experiments were performed as powerful tools to investigate the fracture behavior of asphalt mixture as well as to provide some required material properties for numerical analysis. Wagoner and his coworkers developed a single-edge notched beam test [22] and a disk-shaped compact tension test [23] to study the crack behavior of asphalt mixture and to obtain the fracture energy. Tabakovic et al. [24] investigated applicability of the cohesive zone model for simulating the performance of bituminous material subjected to quasi-static loading with the constitutive parameters obtained from a uniaxial tensile test at different loading rates and the fracture parameters from a three-point bending test. Ameri et al. [25] measured the critical load in the semi-circular bend test to calculate the fracture resistance of asphalt mixture. After reviewing several different test configurations, the single-edge notched beam test is selected as a promising fracture test by Wagoner et al. [22] to provide an estimate of the fracture energy for asphalt mixture due to its simplicity and ability to induce mix-mode fracture by simply offsetting the mechanical notch from the beam centerline. Kim et al. [26] also employed the single-edge notched beam test to determine the fracture energy and to characterize mixed-mode fracture characteristics. Mixed-mode fracture is very usual in asphalt pavement engineering since the critical loading most often involves a combination of thermal loading (tension) and wheel loading (bending tension and shear) [22].

In this paper, the aggregate generation and packing algorithm proposed by the authors [12,19] is used to create a pre-cracked heterogeneous asphalt mixture beam model, and the cohesive zone model with tension/shear softening laws is used to characterize the post-peak softening behavior of asphalt mastic. Both experiments and numerical simulations of Mode I and mixed-mode fracture are performed at 5 °C by moving the beam on the three-point bend loading setup. After comparison validation, the effects of crack relative location and coarse aggregate distribution on cracking behavior of asphalt mixture are evaluated.

Table 2
Simplified coarse aggregate gradation.

Size range (mm)	2.36–4.75	4.75–9.5	9.5–13.2	13.2–16
By weight (%)	27.4	43.4	26.3	2.9

2. Modeling frame for heterogeneous asphalt mixture

2.1. Random aggregate generation and packing algorithm

The random aggregate generation and packing algorithm proposed by the authors [12,19] is used here to create geometrical models of random heterogeneous asphalt mixture. Table 1 lists a complete aggregate gradation of asphalt mixture AC-13, in which the aggregate size ranges from 0.075 to 16 mm. It can be seen that the fine aggregates with diameters less than 2.36 mm have low volume fraction but huge amount, so that it is impossible to construct a micromechanical model of asphalt mixture with complete aggregate gradation. For simplicity, the aggregates are divided into two types: coarse and fine aggregates, according to their sizes. Numerous fine aggregates and asphalt binder are put together to form asphalt mastic, whose mechanical properties are assumed to be uniform. As a result, asphalt mixture is treated as a two-phase composite with coarse aggregates embedded in the matrix of asphalt mastic. Referring to Ref. [27], 2.36 mm is considered as the cut-off size between coarse and fine aggregates to reduce the computational cost in the prerequisite of acceptable modeling fidelity. After the simplification, only the coarse aggregate gradation shown in Table 2 needs to be considered in modeling.

The main algorithm procedure is illustrated as follow.

(1) Conversion from full to coarse aggregate gradation

The volume content of coarse aggregates $\varphi^{(1)}$ in asphalt mixture and the mass percent of the *i*-th group $g_i^{(1)}$ in coarse aggregate gradation can be expressed as

$$\varphi^{(1)} = \varphi\sum_{i=1}^{N} g_i, \quad g_i^{(1)} = g_i \Big/ \sum_{i=1}^{N} g_i \tag{1}$$

where φ is the volume content of all aggregates in asphalt mixture, g_i is mass percent of the *i*-th group of aggregates in the full aggregate gradation and $\sum_{i=1}^{n} g_i = 1$, *n* is the group number of aggregates in the full aggregate gradation, and *N* is the group number of coarse aggregates with particle diameters larger than 2.36 mm, respectively.

Aggregates in engineering are often processed into convex polyhedrons so as to form a stable internal skeleton structure in pavement. Some researches [28] proved that aggregate shape greatly affects mechanical behaviors of asphalt mixture. However, it is very difficult in the algorithm to implement generation and packing of polyhedral aggregates directly. For convenience, spherical

Table 1
Complete aggregate gradation of AC-13.

Sieve size (mm)	16	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