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Experimental and numerical investigation of fracture behavior of asphalt mixture under direct shear loading

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HIGHLIGHTS

- Experiment and heterogeneous simulation are combined to investigate shear fracture.
- A direct shear test setup fit for asphalt mixture is designed.
- Asphalt mixture exhibits obvious different fracture behaviors at different temperature.
- Some internal shear fracture mechanisms are analyzed.

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ABSTRACT

Experiments and heterogeneous simulations are combined to investigate cracking behavior of sheared asphalt mixture. A series of direct shear tests are performed at different temperatures with a self-manufactured direct shear test setup, and then a heterogeneous fracture modeling approach based on the random aggregate generation and packing algorithm and the bilinear cohesive crack model is utilized to simulate shear fracture processes. Two kinds of fracture, the single crack type for −20 and −10 °C, and the double crack type for 0 and 5 °C, are observed. Some internal mechanisms are analyzed based on numerical simulations.

1. Introduction

Asphalt mixture is widely used in high-grade highways and airport pavement constructions due to its high strength, lower noise, easy construction and maintenance and comfortable driving. However, with the increase of traffic volume and the number of heavy vehicles in recent years, asphalt pavements often fail before reaching its design life due to low temperature cracks. As a major source of distress in roadways, the cracks lead to roughness, spalling and moisture infiltration, and significantly reduce the service capacity of asphalt pavements and considerably increase the maintenance and management cost of pavement network. Therefore, understanding the fundamental mechanisms behind initiation and propagation of cracks is very important for improving pavement construction design and life prediction [1].

As the most complicated material in flexible pavement system, asphalt mixture is a typical heterogeneous composite material comprising coarse and fine aggregates with irregular shape and random distribution, asphalt matrix and voids at mesoscale. Aggregates usually take up about 85% of the volume of asphalt mixture and are generally brittle. Asphalt matrix is very sensitive to the temperature. It is viscous at high temperature and considered to be linear elastic at low temperature. Numerous studies [2–4] proved that the physical properties and mechanical performance of asphalt mixture are directly governed by the complex morphological features at the mesoscale, such as shapes, gradations, distribution and orientation of aggregates, asphalt content and void ratio. The complex cracking behaviors of asphalt mixture are intrinsically intertwined with heterogeneity and randomness, so that various fracture mechanisms including microcracking, cracking branching, crack deflection, crack face sliding, aggregate bridging, crack tip blunting, and cleavage of aggregates, can be involved in them [5,6]. Accordingly, a new challenge is thrown out in experimentally and analytically characterizing fracture performance of asphalt mixture with the heterogeneity and randomness nature.

Numerous experimental tests were performed to investigate the fracture resistance of asphalt mixture and evaluate the effect

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of heterogeneity on fracture performance in recent years. Tabakovic et al. [7] employed a uniaxial tensile test and a three-point bending test to obtain the tensile strength and the fracture energy at different test rates. Molenaar et al. [8] conducted the semi-circular bend test to investigate crack growth resistance of various asphalt mixtures. Wagoner and his coworkers developed a single-edge notched beam test [9] and a disk-shaped compact tension test [10] to study the crack behavior of asphalt mixture and to evaluate the effects of aggregate gradation and temperature on fracture resistance. Li and Marasteanu [11] used the acoustic emission method in the semi-circular bend test to capture the microscopic fracture characters in asphalt material and evaluated the influence of air voids, aggregate type and asphalt content on the size of fracture process zone. By using the disk-shaped compact tension test, Kim and Buttlar [12] discussed the effects of nominal maximum aggregate size, temperature and aggregate type on the fracture behavior of asphalt mixture and found that the peak load, the fracture energy and even the microscopic fracture mechanism at mesoscale would be varied with these factors. Most of the abovementioned researches only explored the mode I fracture behavior of asphalt concrete, but the mixed-mode and mode II fractures are often popular in a pavement system due to continuous traffic loads and environmental conditions including temperature and moisture [5]. For a pavement layer with a top-down transverse crack, shear mode loading sometimes plays an important role in the crack deformation when a vehicle passes near the crack [13]. However, less attention was paid to the experimental characterization of mode II, namely shear-type cracking, which may be caused by heavy vehicular loads. Braham and Buttlar [14] studied the pure mode II crack growth resistance of asphalt mixture experimentally using the prismatic beam specimens with two opposite vertical edge cracks on both the sides of beam subjected to a nonsymmetrical four-point bending load. Amrei et al. [15] investigated the critical stress intensity factor of pure mode II crack of asphalt mixture using a modified semi-circular bend test. Nevertheless, both of them treated asphalt mixture as a uniform material. At present, there are few researchers paying their attention to the mesoscopic fracture mechanism of asphalt mixture under pure mode II loading as well as the influence of heterogeneity and randomness on the fracture behavior.

Laboratory test is a powerful tool in characterizing the fracture behavior of asphalt mixture, but it is too time-consuming and expensive to capture the micro-fracture mechanisms only using experimental techniques. Moreover, the complexity of material microstructure makes it difficult to capture some comprehensive fracture information on the scale of observation even with some advanced measurement technologies, such as acoustic emission and X-ray tomography. Nowadays, some numerical mesoscale fracture modeling techniques are developed in combination with experimental tests to investigate crack growth in asphalt mixture. Some researchers have been attracted to the meso and microstructure characteristics investigation of cement like materials and a variety of numerical heterogeneous models are built for numerical representation of randomly distributed aggregates with different sizes and irregular shape in different ways. The mesoscale model provides explicit account for arbitrary mesostructural morphologies, constituent properties and contents, and mesoscopic fracture patterns, so that it becomes easy to identify and design mesostructural configurations of asphalt mixture. The numerical image processing technique [16,17] and the parameterization modeling technique [18,19] are two most popular approaches in explicitly modeling different material phases in asphalt mixture. In the first method, the 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 information with the help of image boundary recognition technique. This method was used for simulating the fracture of asphalt mixture combined with the discrete element method by Kim and Buttlar [20] and with the finite element method by Kim et al. [21]. However, it is time-consuming and 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. Yang et al. [19] presented an advanced efficient algorithm, in which graded aggregates were modeled as regular convex polyhedra with different sizes and aggregate content can be controlled well. Yin et al. [22] successfully applied this algorithm to create 2D mesoscale models of asphalt mixture and further studied the mechanisms of crack initiation and propagation in combination with the cohesive zone model which is currently one of the most promising models in simulating crack propagation in quasi-brittle materials [23,24]. In the asphaltic pavement mechanics community, the cohesive zone model is receiving 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 [25]. Although much progress has been made toward understanding various mechanisms involved in the Mode I and mixed fracture process based on the numerical simulations at mesoscale, some significant work, such as pure mode II fracture mechanism investigation, needs to be done.

This paper seeks to investigate the pure Mode II cracking behavior and the fracture mechanism of asphalt mixture through experimental test and numerical simulation. A direct shear test device is designed to investigate fracture behavior and obtain the shear strength of asphalt mixture at different temperature. At the same time, the mesostructural fracture modeling approach based on the random aggregate generation and packing algorithm and the bilinear cohesive crack model is used for predicting the cracking process and analyzing the fracture mechanism in asphalt mixture under shear.

2. Direct shear test

2.1. Materials and specimens

As a continuous dense gradation, the densely-graded asphalt concrete (AC) gradation shown in Table 1 was defined in the Chinese asphalt mixture specification and widely adopted in Chinese asphalt pavement engineering. AC-16 hot mixed asphalt mixture (HMA) with AC gradation and bitumen content of 5.1% is used in the present direct shear test. The specimens are fabricated with the same batch of raw materials, including 70-penetration bitumen with the physical properties shown in Table 2 and limestone aggregates.

Some asphalt mixture slabs with 305 mm length, 305 mm width and 50 mm thickness are compacted with an automatic steel roller compactor. And then the cuboidal specimens with 100 mm length, 50 mm width and 40 mm thickness are machined by cutting these slabs in water cooling with a diamond blade. Finally, the specimens are dried in air for 24 h and stored at subzero temperature.

2.2. Test setup

The direct shear test setup, shown in Fig. 1, is designed to match a microcomputer control electronic universal testing machine (WDW-100). It consists of a clamping device, a loading block and a guide rail. The guide rail supporting the clamping device is fixed on the base of WDW-100, while the loading block is fastened to the loading head of WDW-100. The clamping device can be moved along the guide rail according to the test request. In general, the gap between the right end face of the upper clamp and the left side face of the loading block is about 1 mm. The left half of specimen is fixed by the clamping device with a constant distance of 49.8 mm between its upper and lower pawls in order to ensure consistency in the clamping force for all specimens, but the right half of specimen remains suspended. The side face of specimen is asked not to be sheltered during test in order that the crack path in it can be shot clearly by a digital camera.