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Study on affecting factors of interface crack for asphalt mixture based on microstructure

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HIGHLIGHTS

- The present study combined the results of the digital speckle correlation method and the numerical simulation to accurately analyze the law and influence factor for the production and development of the interface crack.
- The full-field and non-contact measurement technology, namely DSCM, is well-suited for the heterogeneous strain of the asphalt mixture.
- A cohesive zone model of the semi-circular specimen was established by the finite element analysis software ABAQUS, which was employed for the execution of the numerical simulations.

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ABSTRACT

A crumb rubber (CR) asphalt mixture was tested using a combination of semi-circular bending (SCB) and the digital speckle correlation method (DSCM) to analyze the change of the displacement and strain fields during loading. The two-dimensional (2D) cohesive zone model (CZM) of the CR asphalt mixture semi-circular specimen was established by the finite element analysis software ABAQUS, which was used to carry out numerical simulations. The reliability of the simulation results were tested using the DSCM results. The DSCM and CZM numerical simulation were combined to study the affecting factors of the asphalt mixture interface crack in terms of its microcosmic view. The results show that the finite element simulation results highly inosculated the DSCM test result. The results of the finite element cohesive zone model simulation indicate that the interface crack of the asphalt mixture was mainly effected by critical stress, interface angle of inclination, interface length, and interface location. The stress intensity factor calculated by the finite element shows that the asphalt mixture crack expansion was mainly affected by the crack length, crack angle of inclination, and crack location.

1. Introduction

Scholars aim to thoroughly understand the cracking characteristics of asphalt mixture with relation to early crack damage in asphalt pavements [1–3]. Sutton indicated that asphalt mixture is a heterogeneous composite material because of the anisotropy of the different materials (aggregate and asphalt) and the stress concentration of the internal defects, wherein the interface between the aggregate and asphalt becomes the weakest link in strength in the asphalt mixture. Therefore, it is significant to study the crack located at the mixture interface [4]. Kim studied crack damage from interfacial adhesion degenerate of the asphalt mixture based on the boiling method and the immersion method test. However, the subjective factors of these methods can easily result in test result errors, which suggest the existence of more defects [5].

Some scholars have studied the interface cracking characteristics of asphalt mixture by using a conventional macroscopic test. Studies show that the macroscopic test based on phenomenological theory can only establish a link between the macroscopic characteristics of the asphalt mixture and pavement performance. Moreover, the generation of macroscopic cracks is a result of microscopic damage, thus the macroscopic test is hard to ultimately explore the mechanism of cracking generation and the rule of cracking propagation [6–8]. Wittmann suggested the study of mechanical properties of certain scale materials to focus on a lower level of scales for structural characteristics, thereby explaining and furthering the study of the interface crack of the asphalt mixture from a mesoscopic point of view [9].

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A full-field and non-contact measurement technology, namely the digital speckle correlation method (DSCM), is well-suited for the strain of heterogeneity of the asphalt mixture. In recent years, DSCM has been widely used for deformation tests of the asphalt mixture [10]. Kim and Wen first proposed the DSCM technique as a possible displacement/strain measurement method for the asphalt mixture. Kim measured the displacement of the compression specimen by DSCM. The results confirmed the application of DSCM to study asphalt mixture as compared to the results of linear variable differential transformers (LVDT) [11]. To investigate the stretching rate of the asphalt mixture beam, Tan used DSCM to research the stretching strain rate of the asphalt mixture under different stress levels by third-point loading. The accuracy of the DSCM test result was verified by the shear rate under the shear status [12].

Recent studies focused mainly on simple microscopic experiments or numerical simulations. However, the asphalt mixture is anisotropic. It is difficult to build a constitutive relation using a simple microscopic experiment as this only establishes a link between the macroscopic characteristics of the asphalt mixture and the pavement performance, and ignores the essential mechanical properties that should be analyzed by numerically simulating the cracking properties of the asphalt mixture [13–15]. Seong discussed the feasibilities and principles of application using a bilinear cohesive zone model (CZM) in asphalt mixture experiments. The cohesive parameters were calibrated using a simulation of the mode I disk-shaped compact tension (DCT) results, and the predicted mixed-mode crack trajectory was in close agreement with experimental results [16]. Hyunwook used a bilinear CZM implemented in the finite element method (FEM) to investigate the low-temperature fracture behavior of pavements, and found the finite element pavement fracture models could successfully predict the progressive crack behavior of asphalt pavements under the critical temperature and heavy aircraft gear loading conditions [17]. Dai used CZM to analyze the cohesive properties of asphalt mixture interface, which was combined with the results of the Scanning Electron Microscope (SEM) to discuss the validity of the CZM [18]. Huang used a bilinear CZM to simulate the indirect tension test on the asphalt mixture and analyzed the damage mechanism of the asphalt mixture. A comparison of the numerical simulation and test results validated the consistency between the two results, thereby suggesting the applicability of the CZM to simulate the crack behavior of the asphalt mixture [19].

The present study obtained the deformation characteristics of the interface crack and established the two-dimensional CZM of the asphalt mixture based on the microstructure test (DSCM). The results of the DSCM and numerical simulation were compared and mutually authenticated to accurately analyze the law and influence factor for the production and development of the asphalt mixture interface crack.

2. Experimental program

2.1. Test materials

(a) Asphalt: The 90# virgin or base asphalt (PetroChina Liaohe Petrochemical Company Panjin City, China) used in this investigation was the same for all the test samples and derived from the same crude oil graded as PG 60/80 according to strategic highway research program (SHRP). The CR modified asphalt contained 20 wt% (percent by weight) crumb rubber powder with a 30 mesh size, which was made from discarded rubber tires. The properties of the CR modified asphalt are shown in Table 1.

(b) Asphalt mixture: The present study used an AC-16 type of CR modified asphalt mixture. The gradation (by mass) of the asphalt mixture is shown in Table 2.

2.2. Test procedures

2.2.1. Semi-circular bending (SCB)

Fig. 1 illustrates the loading method for SCB with a specified sample size [diameter ($2R = 100$ mm); thickness ($B = 25$ mm); depth of pre-notch (1 cm, 2 cm, and 3 cm)], two fulcrum distances ($2D = 80$ mm), a loading rate of 1 mm/min, and a test temperature is 10 °C.

2.2.2. Digital speckle correlation method (DSCM)

The DSCM is a digital image method based on the optical measurement system. The test system is shown in Fig. 2. The system was composed of light sources, a Charge Coupled Device (CCD) camera, an image acquisition system, and Vic-3D software. For the experiment, the measured plane object was placed in the loading device and the white light was shone on the sample surface. The sampling frequency and resolution were controlled by an image acquisition system. The load system and image acquisition system were turned on to allow the CCD camera to collect the images and store them on a computer. The calculations were performed using Vic-3D software, from which the 2D and 3D full-field U (horizontal displacement) and E_{xx} (horizontal strain) values (dU/dt and dE_{xx}/dt) were obtained.

3. Cohesive zone model (CZM)

Dugdale et al. and Barenblatt et al. first proposed the idea of the CZM. They believed that there is a small area near the crack tip that can resist separation of the interface and provide cohesion of the interface separation [20,21]. The schematic diagram of the CZM is shown in Fig. 3. The laws of attraction and separation in the cohesion area define the constitutive relation of the CZM, where in the relative displacement relationship of two surfaces is defined by the cohesion of the interface and the single-directional thickness. In terms of fracture characters, the CZM includes a bilinear CZM and an exponential CZM. Previous studies suggest that a bilinear CZM is more suitable than an exponential CZM in simulating the crack behavior of an asphalt mixture [22]. Fig. 4 is the curve of t and δ, which was provided by the finite element method using the commercial software ABAQUS, where t is cohesion and δ is the relative displacement of fracture surface.

Table 1
Properties of CR modified asphalt.

Test properties	CR modified asphalt	Standard	Criteria
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	60	>40	JTG E20 T0604-2011
Softening point/°C	73.9	≥55	JTG E20 T0606-2011
Ductility/cm	32.2/(5 °C)	≥10	JTG E20 T0605-2011
Flash point/°C	297	≥280	JTG E20 T0611-2011

Table 2
Passing percent (by mass) of asphalt mixture.

Passing percent /mm	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-16	100	100	97.5	88.8	70.8	45.7	35.6	24.4	18.1	13.1	8.7	6.8