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Crack and crack growth behavior analysis of asphalt mixtures based on the digital speckle correlation method

Li Chao, Wang Lan *, Wang Xiao-xiao

School of Civil Engineering, Inner Mongolia University of Technology, Hohhot 010051, China

HIGHLIGHTS

- We report the results of analyzing asphalt crack initiation and propagation rules using semi-circular bending (SCB) tests and the DSCM on the microscopic level.
- The strain field (Exx) and the rate of change displacement field (dU/dt) are well suited to study the properties of crack and fracture characteristics of asphalt mixtures.
- Analysis of the differences in the deformation properties of asphalt binder, stone, interface, and crack-tip; comparative analysis of the cracking rules of CR-and SBS-modified asphalt mixtures.

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ABSTRACT

Cracking is one of the main reasons for asphalt pavement damage. Because of the anisotropism of asphalt mixtures, traditional experimental methods cannot analyze displacement and strain fields accurately. A full-field, noncontact measurement technology—the digital speckle correlation method (DSCM)—is a good method to analyze the deformation characteristics of asphalt mixtures. By using DSCM and a semi-circular bending (SCB) test, the crack initiation and propagation rules can be tested experimentally; the full-field displacement and strain can be analyzed by vic-3D software. The results show that the strain field (Exx) and the rate of change displacement field (dU/dt) are well suited to study the properties of crack and fracture characteristics of asphalt mixtures. The interface between asphalt binder and stone is the weakest part of the entire structure, and comparing the crack growth rate and load displacement curve of a crumb-rubber (CR) modified asphalt mixtures and a styrene-butadienestyrene (SBS) modified asphalt mixtures, it is found that the carrying capacity of a CR modified asphalt mixtures is stronger than that of a SBS modified asphalt mixtures.

1. Introduction

With asphalt mixtures widely applied in road engineering, it is essential to determine the mechanical and deformation properties of asphalt mixtures accurately [1–3].Asphalt mixtures cracking is one of the main reasons for asphalt pavement damage, and researchers have focused on numerical simulation analysis [4–8] and macrostructure examination to study asphalt mixtures cracking behavior. Lee and Kuai developed a fatigue crack propagation model of asphalt mixtures on the basis of viscoelasticity and fracture mechanics, and found that the model could provide a reasonable prediction of fatigue crack propagation of asphalt mixtures under various load and temperature conditions [9]. Kim, Lee, and Lutif presented a model using the finite-element method and a cohesive zone fracture model to predict crack propagation in asphalt mixtures [10]. However, since models often use ideal parameters (material parameters and test conditions), model results are different from true results. Current approaches to macrostructural examination of the interface between asphalt binder and stone involve boiling, immersion, electrophotometric, colorimetric, as well as other methods. Kim, Pinto, and Park studied the interface performance changes with moisture damage in asphalt mixtures using a boiling method [11]. As the method judged the extent of stripping based on visual inspection, many artificial factors are involved; thus, such methods cannot be used in measuring and researching the course of asphalt destruction under real conditions, which is a disadvantage.

It is essential to determine the actual strain field distribution of an asphalt mixtures to evaluate its macro-cracking behavior

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* Corresponding author.
E-mail address: wanglan661018@163.com (L. Wang).

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[12,13].A traditional experimental technique for determining test specimen strain characteristics is the application of strain gauges; however, strain gauges only provide small-area strain information, and cannot capture true peak strain or high-resolution information when applied in regions having large strain gradients. Thus, it is necessary to limit the analysis to asphalt mixtures deformation fields. In recent years, a full-field noncontact measurement technology—the digital speckle correlation method (DSCM) has become increasingly popular in detecting and analyzing local heterogeneities in composite materials [14–18]. The DSCM was first proposed in the 1980s [19–21], and was then applied to determine strains in specimens of resin films and fiber-reinforced polymer composites [22,23]. Kim and Wen first proposed using the DSCM technique as a possible displacement/strain measurement method for asphalt mixtures [24]. Bjorn, Antonio, Elena, and Gabriele evaluated the use of the DSCM to characterize hot mixtures asphalt (HMA) cracking behavior, and obtained full-field strain maps; their analysis stood on the merit and demerits of the DSCM [23]. Tan, Hou, and Zhang analyzed the strain field of asphalt mixtures using the DSCM and other tests, and found that DSCM was superior [25]. She obtained the strain field for crack growth in asphalt mixtures, and found that the DSCM is well suited to determining the strain of asphalt mixtures. Since the DSCM has only recently been used in investigations of asphalt mixtures, and is a relatively new optical measure, its use is still being tested and perfected. Most of the current research has focused on its feasibility of DSCM, and thus it is rare to find studies of the laws of crack spreading in asphalt mixtures using it.

Based on the above analysis, in this paper, we report the results of analyzing asphalt crack initiation and propagation rules using semi-circular bending (SCB) tests and the DSCM on the microscopic level. Specifically, we present the following: (1) calculation and analysis of the full-field horizontal displacement (U), horizontal strain (Exx), horizontal displacement rate of change (dU/dt), and horizontal strain rate of change (dExx/dt) measured during the initial asphalt loading process; (2) analysis of the differences in the deformation properties of asphalt binder, stone, interface, and crack-tip; and (3) comparative analysis of the cracking rules of CR-and SBS-modified asphalt mixtures.

2. Experimental details

2.1. Materials

1. Asphalt: CR-modified asphalt, which consists of asphalt and fine rubber particles, was used. Based on the asphalt penetration test, the base asphalt used in the study is 90#. The crumb-rubber particle size is 30 mesh and its fineness is 0.600 mm. The CR-modified asphalt was made using a wet process; the mixture proportions were 80% base asphalt and 20% crumb rubber powder by weight. The proportions for SBS-modified asphalt were 4% SBS modifiers and 96% base asphalt.
2. Aggregate and mineral powder: Basalt (10–20 mm and 3–5 mm) was used as the coarse aggregate, as well as for the fine aggregate (0–3 mm); limestone fines were used as the mineral powder Table 1.
3. Asphalt mixtures gradation: Two types of mixture (CR-modified asphalt mixtures AC-16 and SBS-modified asphalt mixtures AC-16) were used. Aggregate gradation is shown in Table 2.
4. Test specimens: The samples were formed using a Superpave Gyratory Compactor (Model 5850). The compactor parameters were as follows: rotation angle, 1.16°; vertical pressure, 600 kPa; speed of rotation, 30 rpm; compaction times, 125 s; specimen diameter, 100 mm. Semicircular specimens were cut by special equipment (IPC-Global). The diameter and thickness of the semicircular specimen were 100 and 25 mm, respectively. Owing to the fact that asphalt mixtures do not exhibit a well-contrasted natural texture, the speckle pattern is usually artificially made by applying thin white paint, which with the specimen's contrasting pattern of black, forms a homogeneous, randomly oriented texture (in order to improve the accuracy of calculations, the distribution of gray level at the surface of the specimen should be random).

2.2. Experimental methods

1. SCB test: The SCB test system is shown in Fig. 1. The load system used a MTS-810 testing machine. The standard size test specimen had a diameter 2R = 100 mm and a thickness B = 25 mm. The specimen was placed on the load system for the three-point bending test. The support distance of the two poles was 0.8 times the specimen diameter (support distance 80 mm) and its loading position was at the top of specimen. The loading rate was 1 mm/min and the test temperature 10 °C.
2. DSCM: The DSCM is a digital imaging method based on an optical measurement system; the test system is shown in Fig. 2. The system comprised light sources, a CCD camera, an image acquisition system, and vic-3D software. The measured planar object was placed in the loading device, and white light was shined on its surface. Sampling frequency and resolution were controlled by the image acquisition system, and then the load and image acquisition systems were activated and images collected by the CCD camera, which in turn, were imported into a computer. The calculations were performed by vic-3D software, from which two- (2D) and three-dimensional (3D) full-field measurements of U, Exx, dU/dt, and dExx/dt were obtained.

The DSCM device was calculated using the sub-pixel calculation method. The sub-pixel was used in the analysis with a system that did not require the scale and resolution to be set. Moreover, the resolution had nothing to do with the calculation precision. The resolution improvements on the image acquisition device resulted in a closer data acquisition point closer to the interface, which is a more realistic response to the strain changes on the interface. (In this paper, the resolution is 2 million pixels, which meets the requirements of the interface analysis.)

3. Theoretical principles

The basic principle of DSCM is the tracking of the same points between two consecutive images. The unreformed image is defined as the reference image, a subset of $(2M+1)\times(2M+1)$ pixels with a

Table 1
Properties of 90 # base asphalt, CR-modified asphalt, and SBS-modified asphalt.

Test properties	90# base asphalt	SBS-modified asphalt	CR-modified asphalt	Standards and criteria
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	90	62	60	JTG E20 T0604-2011
Softening point (°C)	51	70	73.9	JTG E20 T0606-2011
Ductility (cm)	150/(15 °C)	38.5/(5 °C)	32.2/(5 °C)	JTG E20 T0605-2011
Flashpoint (°C)	290	269	277	JTG E20 T0611-2011