Construction and Building Materials 160 (2018) 10–18

Contents lists available at ScienceDirect

Construction and Building Materials

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

Simulation of bending fracture test process for asphalt concrete beam based on heterogeneous state

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HIGHLIGHTS

- A detailed analysis of the influence of the homogeneity degree on the crack propagation behavior.
- Graphical presentation of the crack propagation path and stress distribution.
- Obtaining the distance between the crack initiation point and the midspan.
- Verifying the deflection of the three-point bending beam by laboratory test and numerical calculations.
- Analysis of the influence of the tensile strength on the crack propagation path.

ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 1 November 2017
Accepted 7 November 2017

Keywords:
Pavement
Asphalt
Fracture
Crack
Homogeneous degree

ABSTRACT

To analyze the crack propagation behavior of bending fracture of asphalt concrete beam, RFPA (Realistic Failure Process Analysis) was selected to conduct a numerical simulation of bending fracture test of asphalt concrete beam specimens under the heterogeneous state. Physical tests were performed on AC-13C to simulate the process of bending fracture. Research results showed that the direction of crack extended along the stochastic distributed 'basic element,' the heterogeneity of 'basic element' only changes the direction of crack growth locally, it will not change the trend of crack propagation. Affected by the stochastic distribution of heterogeneous element, the stress distribution presents multiple peaks in specimen split process. The crack propagation gradually changed from the initial mode I–II to mode I. At the beginning of the loading procedure, tensile, compressive, and shear stresses reached the minimum at about 65 mm away from the middle of the beam. Once the distribution process completed and no element fracture happened, the tensile and shear stresses increased rapidly to 1.4–1.6 times. When element fracture occurred, the stress at the initial point of crack quickly dropped to 0. The location of fracture starting point deviated from midspan by about 3–5 mm. The crack distribution tends to discrete with the decrease of the homogeneity degree, but when the homogeneity degree is high, the crack distribution will be relatively straight and regular. The deflection analyzed under different conditions is about 1.9 mm, which is consistent with the deflection 1.7 mm tested in the laboratory. With lower tensile strength under the same homogeneous degree, the crack in specimen has multiple paths extending from the bottom to upward, as long as the tensile strength grows, the crack extends upward while only one path occurs.

1. Introduction

Crack is caused by fatigue failure of the asphalt surface or stabilized base under either repeated traffic loading or resulting from thermal stresses. Analyzing failure mechanism of asphalt mixture is the foundation for understanding asphalt pavement distress pattern, simulation, and analysis of pavement structure, optimization of asphalt mixture design and repair techniques. The test procedures for measuring failure response can be grouped into the following categories: simple flexure, supported flexure, direct axial, diametric, triaxial, fracture mechanics, and wheel-track testing. The primary methods are considered to be simple flexure, diametric fatigue, and test based on fracture mechanics principles. Bending fracture test is one of the primary methods used in asphalt mixture and pavement structural design process, along with failure mechanism studying. From the bending fracture test, stress distribution and corresponding crack extension state of the beam under loading procedure can be observed and analyzed, which is greatly

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https://doi.org/10.1016/j.conbuildmat.2017.11.014

significant for studying strength and crack mechanism of the asphalt mixture.

2. Background and objectives

With ever-increasing traffic growth in China, pavement distress resulting from repeated loading or fatigue of asphalt pavements has been a well-recognized problem. Consequently, research on the crack mechanism and crack treatment have become an important subject.

There are several modes of asphalt pavement crack, such as low-temperature crack, reflection crack, fatigue crack, which are affected by numerous factors and their interactions. Several key mix properties such as asphalt type, asphalt content, aggregate gradation and air-void content influence crack. Other factors such as temperature, loading frequency, and test periods of the applied load also exert influence on crack. It can be suggested that homogeneity of composites affects their crack behavior and leads to a significant complexity in crack propagation analysis. The mechanism of crack growth and evaluation of the fractured pavement structure behavior are the fundamental problems in pavement engineering, and they have been widely studied by the researchers in recent years [1–4].

The stages of crack growth are known as crack initiation, propagation, and unstable fracture. Crack prediction is normally based on the cumulative damage concept given by Miner's [5]. The damage is calculated as the ratio of the predicted number of traffic repetitions to the allowable number of load repetitions. The most commonly used fatigue crack models are those developed by Shell Oil [6] and the Asphalt Institute (MS-1) [7].

Numerical simulation was applied to investigate the propagation of the crack in two-dimensional models including three-point bending test of asphalt concrete beam with pre-crack and uniaxial tensile beam [8]. As a result, a fracture criterion based on damage model for investigating crack behaviors of the three-point bending test of asphalt concrete beam was proposed [9]. CZM (cohesive zone model) concept was used to study the fracture behavior of asphalt concrete and to simulate crack initiation and propagation of both Mode I and mixed-mode crack [10].

According to the micromechanical properties and homogeneity of asphalt concrete, the mechanism of crack behavior for asphalt concrete can be simulated more accurate by constructing the micromechanical model containing information about its components and microstructures. The current study presents an approach based on the CDM (continuum damage mechanics) which considers the concrete homogeneity [9,11].

The bending fracture test is popular in studying the propagation of crack and resistance of asphalt mixture [12–14]. However, this test renders limited information on deformation and stress distribution in asphalt mixture specimens due to its relatively simple operation, and limited literature was focused on the stress distribution and failure mechanism performed by this test.

With simulation of bending fracture test of asphalt concrete beam and considering the effect of heterogeneous state, this study aims to analyze the stress distribution, crack state and varying pattern, and study the damage mechanism of the asphalt mixture deeply. The results of the study hope to lay the groundwork for better understanding of the pavement performance properties.

3. Bending test of asphalt concrete beam

Bending test of asphalt concrete beam is used to measure the mechanical property in bending failure under specific temperature and loading rate. The beam length is 250 ± 2.0 mm with a cross-section of 35 ± 2.0 mm in width and 35 ± 2.0 mm in height. The uniformly distributed load is applied to the middle of the beam by universal testing machine until fracture. Test data were collected to calculate the bending strength at the maximum load and obtain the flexural tensile strain from the midspan deflection when the specimen is failed.

4. Principle of bending test

4.1. Principle of RFPA

Realistic Failure Process Analysis (RFPA) is widely used to process finite element analysis in the geotechnical material. The advantage of RFPA over the tradition analysis tool lies in the fact that it directly shows the analysis results in the figure. RFPA includes loading system, data collection, and analysis system. Parameters of a heterogeneous material, such as elastic modulus, Poisson's ratio, and intensity parameter are assigned according to Weibull distribution. Modified Mohr-Coulomb is employed to analyze the damage of unit under compression or shear.

At the same time, the 'basic element' which is the basic micro-scale unit that constitutes a media was introduced into the element partition of heterogeneous media. It is the smallest units that represent the characteristics of media regarding physical properties. The 'basic element' is the most basic unit of rupture of media. Here, comparing with macro-scale, 'basic element is small enough to ignore its mechanical parameter affection. On the other hand, comparing with micro-scale, 'basic element' is big enough to contain mineral crystal, cement crystal, and micro-defect. Also, its mechanical property is the average value of this composition (Fig. 1).

4.2. Heterogeneous material

Weibull firstly applied a statistical method in 1939 to describe heterogeneity of material and power function to state extreme strength distribution. This method is essential to scale effect and strength theory; RFPA is based on this method as well. In RFPA, a mechanical parameter of model material like elastic modulus, Poisson's ratio, or intensity parameter is assigned according to Weibull distribution to describe material heterogeneity:

$$\phi(\alpha) = \frac{m}{\alpha_0} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{m-1} \cdot e^{-\left(\frac{\alpha}{\alpha_0}\right)^m} \tag{1}$$

where: α—mechanical parameter of the 'basic unit' of materials (modulus of elasticity, etc.); α_0—an average of 'α'; m—The shape function of the distribution function, and the physical meaning reflects the heterogeneous of the material, which is defined as the homogeneous coefficient of the material, that is homogeneous degree; $\phi(\alpha)$—Statistical distribution density of 'α' (unit: MPa^{-1}).

Formula (1) reflects the distribution of microheterogeneity of materials. With increasing homogeneous degree (m), the mechanical properties of 'basic element' will be concentrated in a narrow range, which indicates that material is homogeneous. However, with decreasing homogeneous degree, the distribution of mechanical properties of 'basic element' will become wider, which indicates that material property tends to be discrete.

In this manuscript, elastic modulus is taken as an example to introduce the assignment of mechanical parameters of the 'basic element' in RFPA. It is assumed that 'E_0' represents the elastic modulus of all elements. '$\varphi(E)$' is the statistical quantity of 'basic element' with elastic modulus 'E', the integral of Weibull distribution function of elastic modulus base on formula (1) is:

$$\varphi(E) = \int_0^e \phi(x)dx = \int_0^e \left(\frac{m}{\alpha_0} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{m-1} \cdot e^{-\left(\frac{\alpha}{\alpha_0}\right)^m}\right)dx = 1 - e^{-\left(\frac{E}{E_0}\right)^m} \tag{2}$$