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Study on the rubber-modified asphalt mixtures' cracking propagation using the extended finite element method

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HIGHLIGHTS

- Cracking of SCB asphalt mixture sample was characterized by FEM.
- Microstructure of asphalt mixture was considered in the simulation.
- The crack propagation of rubberized asphalt mixtures was similar to Griffith I style.
- The rubber concentration had a significant influence on the cracking performance.

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ABSTRACT

Crumb rubber modified (CRM) asphalt mixtures have been widely used in highway asphalt pavement due to its environmental advantages and enhancement of mechanical performance. Numerical simulation analysis on rubber-modified asphalt mixtures' crack propagation has attracted more attention when characterizing the low temperature performance of asphalt pavement in recent years. However, in past numerical simulation processing, most researchers took the rubber-modified asphalt mixtures as a linear elastic material, which is incompatible with the viscoelastic characteristics of the rubber-modified asphalt mixtures. Thus, it cannot fundamentally evaluate the fracture characteristics of the rubber-modified asphalt mixtures. Based on this, viscoelastic mechanism of the rubber-modified asphalt mixtures are considered in this paper. The paper studied simulation of the rubber-modified asphalt mixtures crack growth using Extended Finite Element Method (XFEM), based on the notched semi-circular bending (SCB) test. This study investigated the stress distribution characteristics during the crack growth, the path of the crack growth, and the effect on the rubber-modified asphalt mixtures' fracture characteristics using the different rubber content. Thus, it can provide a theoretical guide for the forecast and control of the fracture damage caused by crack growth, which is one of the main early distresses of rubber-modified asphalt pavements.

1. Introduction

As a kind of traditional asphalt pavement material, the rubber-modified asphalt mixtures are also multiphase composite materials, where there are many flaws such as voids, tiny cracks inside aggregates and weak contact points and surfaces. These flaws inside asphalt mixtures and the initial cracks of the asphalt mixtures generate microcosmic cracks, which gradually develop into macroscopic cracks under the repeated vehicle loading and long term environmental influence. The crack growth is caused by tensile stress, shearing stress and the combined action of the two stresses under traffic loadings and low temperature thermal stresses. The development of the cracks lowers the highway service ability, worsens the highway performance and gradually damages rubber-modified asphalt mixtures. Therefore, the fracture problem caused by the growth of the initial crack plays an important role to characterize low temperature performance of asphalt mixture, and has attracted road researchers' attention in the past several decades.

In recent years, the XFEM method was adopted based on the notched semi-circular bending (SCB) test to study the simulation of the rubber-modified asphalt mixtures crack growth. It has drawn more attention since it was introduced to the asphalt community in the US by European and South African researchers [1–3]. It was also

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used to characterize HMA mixtures tensile strength properties by [4,5], and the SCB tests on notched specimens were applied to evaluate the fracture resistance of asphalt mixtures through the *J*-integral [6,7]. The SCB testing is practically attractive even if it has some limitations, such as the existence of an arching effect [8]. The XFEM and image analysis techniques were incorporated to investigate fracture behavior numerically within infrastructure materials [9]. The extended form of the finite element method (XFEM) was applied to study crack initiation, growth and life prediction analysis of non-cylinder pipe [10]. The XFEM can model the pipe without explicitly meshing the crack surfaces, and hence crack growth simulations can be carried out without the need for re-meshing. It is very simple to perform, and multiple test specimens can be easily prepared through mixing and Superpave gyratory compacting of asphalt mixtures. Furthermore, the SCB testing method is easy to conduct considering the fracture characteristics of field cores. SCB testing method can be used to carry out computer simulation. Virtual loading tests can reduce laboratory experiments work of long cycle, huge workload and repetitive tests, and it can save cost in the development and conducting on the test equipment. This study involves scanning the SCB specimens of rubber-modified asphalt mixtures through X-ray CT scanning techniques. Gradation of the SCB specimens was Texas AC-16. After image processing, SCB mode was prepared through XFEM. Notched semi-circular bending (SCB) testing was used to accomplish the study of numerical simulation for the rubber-modified asphalt mixture crack growth. This paper investigates the stress distribution characteristics during crack growth, the path of crack growth, and the effect on the rubber-modified asphalt mixtures fracture characteristics due to the different rubber content.

2. Theoretical background

Extend Finite Element Method (XFEM) was originally proposed by [11,12] and later modified and applied to various crack analysis problems by [13,14]. A numerical XFEM model is constructed by dividing the model into two parts; the first part is to generate a mesh for the domain geometry (neglecting the existence of any crack or other discontinuities) and the second part is to enrich finite element approximation by appropriate functions for modeling any imperfections. The XFEM has been demonstrated to be a very effective numerical simulation method to characterize the discontinuous mechanical problems such as fractures.

The enriched interpolation function of the displacement is described in the following equation:

$$u(x) = \sum_{i \in N} N_i(x) u_i + \sum_{j \in N^{dis}} N_j H(x) a_j + \sum_{k \in N^{asy}} N_k \sum_{a=1}^{4} \Phi_a(x) B_k^a \quad (1)$$

where *i* is the node set of all nodes in the mesh, *j* is the node set of the elements penetrated by the crack, *k* is the node set of the elements containing the crack-tip, which are shown in Fig. 1. N_i, N_j, and N_k are shape functions of corresponding element nodes, and, a_j and B_k^a are the Degree of Freedoms (DOFs) associated with the Heaviside step function H(x) and the crack-tip functions $\Phi_a(x)$. The discontinuous function $H(x)$ considers the value of +1 above the crack and −1 below the crack, and it reflects the discontinuity of displacement of crack surface in crack propagation, which is defined by the following equation:

$$H(x) = \begin{cases} +1 & \text{above the crack} \\ -1 & \text{below the crack} \end{cases} \quad (2)$$

The crack-tip functions $\Phi_a(x)$ provide improved accuracy and is required if the crack-tip terminates inside an element. These functions are defined in the following equation:

$$B_k^a = \left(\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\theta\sin\frac{\theta}{2}, \sqrt{r}\sin\theta\cos\frac{\theta}{2} \right) \quad (3)$$

where θ and rare local polar coordinates defined at the crack tip.

Compared with the traditional FEM, XFEM has the feature which does not need to create special meshes in the areas with initial cracks as the element edge and the set of crack-tip as the node. XFEM considers the mesh and the cracks independently, and does not create dense meshes nearby the crack tip. During the crack propagation, there is no need to create new meshes along with the crack growth. Therefore, the XFEM can be applied to simulate the crack propagation process of the rubber-modified asphalt mixture samples.

3. Experimental method

3.1. Materials

The base asphalt selected in this paper is KRY 70# Asphalt Binder which penetration grade is between 60 and 80 (unit is 0.1 mm), and its properties are shown in Table 1. The crumb rubber with the 40 mesh rubber fineness was chosen to produce rubber asphalt by wet method. The engineering properties of rubber-modified asphalt binders are shown in Table 2.

In this study, Dolerite and limestone were used as the coarse aggregate (greater than 2.36 mm) and fine aggregate (smaller than 2.36 mm), respectively, to get a clear image through computer tomography scanning. Asphalt mixtures were designed using Superpave mixture design method. The continuous gradation, AC-16 with the 16 mm nominal maximum aggregate size, was chosen as the mix graduation. Fig. 2 shows the mix gradation curve of AC-16.

In Superpave design specifications, the optimal asphalt content is designed based on the target air void of 4.0%. The 4.6% asphalt-aggregate ratio was obtained as the optimal design asphalt content based on gyration compaction test. The experimental results is shown in Table 3.

3.2. Specimen preparation and test equipment

Superpave Gyratory Compactor was used to compact the asphalt specimens considering the actual pavement compaction and the design method of asphalt mixtures. Cylindrical AC-16 specimens of 135 mm in height and 150 mm in diameter were prepared using a Superpave Gyratory Compactor (SGC). Then, the specimen was cut into slices with 25 mm thickness using a high precision double diamond blade, and then the specimens were cut into semi-circular specimens with a 25 mm depth notch located at the center. The notch was treated as a pre-crack, as shown in Fig. 3. The equipment used for the notched SCB test is shown in Fig. 4. Fig. 4 shows that the distance between the two fulcrums is 0.8 times of the specimen diameter and the SCB samples were tested at −15 °C and 15 °C

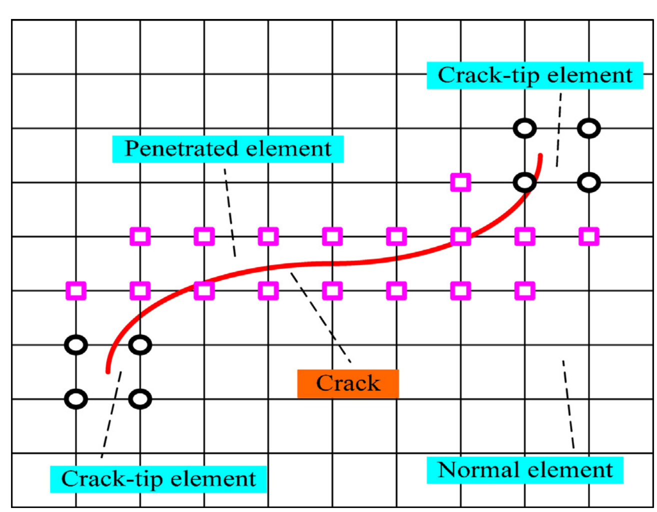

Fig. 1. Enriched nodes in the XFEM.