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Micromechanical analysis of asphalt mixture fracture with adhesive and cohesive failure

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ABSTRACT

This paper investigated the fracture behavior of asphalt mixture using randomly generated two-dimensional (2-D) microstructure models. Asphalt mixture was modeled as a multi-phase heterogeneous material with both adhesive and cohesive failure potential. Viscoelastic properties were assigned to asphalt binder. Two different fracture models, cohesive zone model (CZM) and extended finite element model (XFEM), were adopted to simulate the fracture damage within the Fine Aggregate Matrix (FAM) (cohesive failure) and at the FAM–aggregate interface (adhesive failure), respectively. The numerical simulation offers both qualitative and quantitative results to understand the fracture behavior of asphalt mixture considering the interaction between cohesive and adhesive failure. Parametric studies were conducted to evaluate the effect of loading rate, FAM modulus, and fracture parameters on fracture potential of asphalt mixture. This study provides an effective method to study the fracture mechanism of heterogeneous material by considering different fracture mechanisms for matrix material and bi-material interface.

1. Introduction

Cracking is one of the major causes of asphalt pavement deterioration at low and intermediate temperatures. Cracks significantly reduce the lifespan of pavements and increase maintenance and repair costs. Understanding cracking mechanism of asphalt mixtures is crucial for developing a mechanistic-based design method for asphalt pavements. Asphalt mixture is a heterogeneous multi-phase material including aggregate, binder, air void, and other additives. The overall fracture performance of asphalt mixture is dependent on the properties of each component, such as the moduli of asphalt binder and aggregate, binder viscosity, and the bonding condition between aggregate and asphalt. Other factors like the gradation, shape, angularity, and texture of aggregates also affect the fracture behavior of asphalt mixture [1,2]. Therefore, a fracture model that can consider the microstructure of asphalt mixture is needed to accurately predict the fracture behavior of asphalt mixture and evaluate the effect of each mixture component on the overall performance of asphalt mixture.

Currently, two types of methods are available to generate the microstructure of asphalt mixture: digital image processing and random microstructure generation. For digital image processing, a high-resolution camera or X-ray computed tomography (CT) scanner is used to obtain the internal structure of asphalt mixtures (two-dimensional or three-dimensional). Post-processing of image is required to build the microstructure using the boundary recognition technique. This method has been used to generate numerical models for discrete element and finite element analysis of asphalt mixtures [3–7]. The numerical

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Nomenclature

a_I	nodal enriched degree of freedom vector of the crack interior
b_I^α	nodal enriched degree of freedom vector of the crack tip
F_α	elastic asymptotic crack tip function
G_0	instantaneous modulus
G_∞	long-term equilibrium modulus
G_i	spring constants in the generalized Maxwell model
G_n	work done by the traction force in the normal direction
G_s	work done by the traction force in the first shear direction
G_t	work done by the traction force in the second shear direction
G_n^C	critical fracture energy in the normal direction
G_s^C	critical fracture energy in the first shear direction
G_t^C	critical fracture energy in the second shear direction
G_I	strain energy release rate in the normal direction
G_{Ic}	critical strain energy release rate in the normal direction
G_{II}	strain energy release rate in the first shear direction
G_{IIc}	critical strain energy release rate in the first shear direction
G_{III}	strain energy release rate in the second shear direction
G_{IIIc}	critical strain energy release rate in the second shear direction
H	discontinuous jump function across the crack surface
r	radius in the polar coordinate system
N_I	usual nodal shape function
t_n	nominal traction stress in the normal direction
t_n^o	peak values of the nominal stress in the normal direction
t_s	nominal traction stress in the first shear direction
t_s^o	peak values of the nominal stress in the first shear direction
t_t	nominal traction stress in the second shear direction
t_t^o	peak values of the nominal stress in the second shear direction
$\bar{t}$	stress component when there is no damage within the cohesive element
u_I	usual nodal displacement vector

Greek symbols

α	power index in the power law
θ	angle in the polar coordinate system
ρ_i	relaxation time

model generated through this method has the same aggregate gradation and spatial distribution as the physical sample. Therefore, multiple specimens need to be scanned to reflect the variation of microstructure that is inherent for constructional materials such as asphalt mixture. This requires extensive labor work to prepare and test the specimens in the laboratory.

On the other hand, random generation method generates microstructure models of asphalt mixtures according to a certain algorithm that considers the gradation and shape of aggregates. For example, an elliptical particle model was used in analyzing the fracture behavior of random asphalt mixtures without considering the aggregate angularity effect [8]. However, the elliptical model cannot simulate the stress concentration near the aggregate tip. A recent study was conducted to simulate the tension-induced fracture behavior of heterogeneous asphalt mixture using equilateral convex polyhedron to represent coarse aggregates, which simplified the geometry of aggregates by assuming the same length for the edges of aggregates [9].

Besides the heterogeneous microstructure, damage characterization is another challenging issue in computational fracture simulation of asphalt mixture. The traditional linear elastic fracture mechanics (LEFM) theory is not competent to solve the fracture problem in heterogeneous materials due to a large amount of re-meshing work. The modeling difficulty increases as the rate-dependent material properties are taken into consideration, such as the viscoelasticity of asphalt binder. Cohesive zone models (CZM) have been used by many researchers to model fracture of asphalt mixtures at micro-scale. It is compatible with existing numerical methods such as finite element method and discrete element method. Most importantly, it is a powerful tool to model bi-material interface especially when the material interface can be pre-defined. In the asphalt mixture, the weak areas that are most prone to cracking are usually the binder–aggregate interface. Previous studies have successfully utilized CZM to predict the fracture behavior along the mastic–aggregate interface [10–13]. However, it has been reported that convergence difficulty is usually accoutered when the crack path is not pre-defined and a large amount of CZM elements need to be embedded in the potential fracture area.