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Characterization of bitumen fracture using tensile tests incorporated with viscoelastic cohesive zone model

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HIGHLIGHTS

- This study presents an experimental test method for ductile bitumen fracture.
- A viscoelastic cohesive zone model was used to characterize fracture damage of bitumen.
- Test results and subsequent cohesive zone parameters identified were material-sensitive.
- Component material properties were used for microstructure modeling of mixtures.
- Fundamental properties of components were related to overall performance of mixtures.

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ABSTRACT

This paper presents an experimental test method incorporated with a cohesive zone model to characterize viscoelastic fracture damage of asphalt binders and mastics. The testing presented herein is specifically aimed at identifying rate-dependent, non-constant fracture characteristics of ductile asphalt binders and mastics. Test results that are dependent on materials and specimen geometry such as the film thickness of asphalt binder/mastic are presented. The testing results were then incorporated with a viscoelastic cohesive zone model to identify the material-specific damage evolution characteristics and its mechanical impacts on the overall performance of asphalt mixtures by conducting computational microstructure model simulations. Test results and subsequent microstructure model simulations clearly indicate the significance of component-level material properties and their linkage to mixture performance. The experimental protocol incorporated with the cohesive zone model presented in this paper are expected to provide an efficient tool to evaluate damage-induced mechanical performance of mixtures with small-scale material properties.

1. Introduction

Fracture damage due to cracking is a primary cause of failure in asphalt mixtures and pavements. A precise understanding of the fracture behavior of asphalt materials is required to improve pavement thickness design and mixture performance. However, the accurate characterization and evaluation of the fracture damage in asphalt mixtures is challenging because of the complex nature of the damage evolution phenomena. Asphalt mixtures typically exhibit highly inelastic constitutive behavior and are composed of irregularly shaped and randomly oriented aggregate particles in a wide range of sizes, as shown in Fig. 1. In addition to the geometric complexity and inelasticity, asphalt mixtures have been shown to develop literally thousands of instances of micro- and macro-scale damage per cubic meter in various forms before failure, thus rendering an exact solution untenable.

Many researchers have attempted to use computational microstructure modeling [1–10] to characterize and predict the structural degradation of asphalt mixtures arising due to fracture damage. The computational microstructure modeling approach has been receiving increasing attention from the asphaltic materials/mechanics community, because it can separately account for numerous damage modes by considering individual mixture constituents and mixture heterogeneity. Many computational

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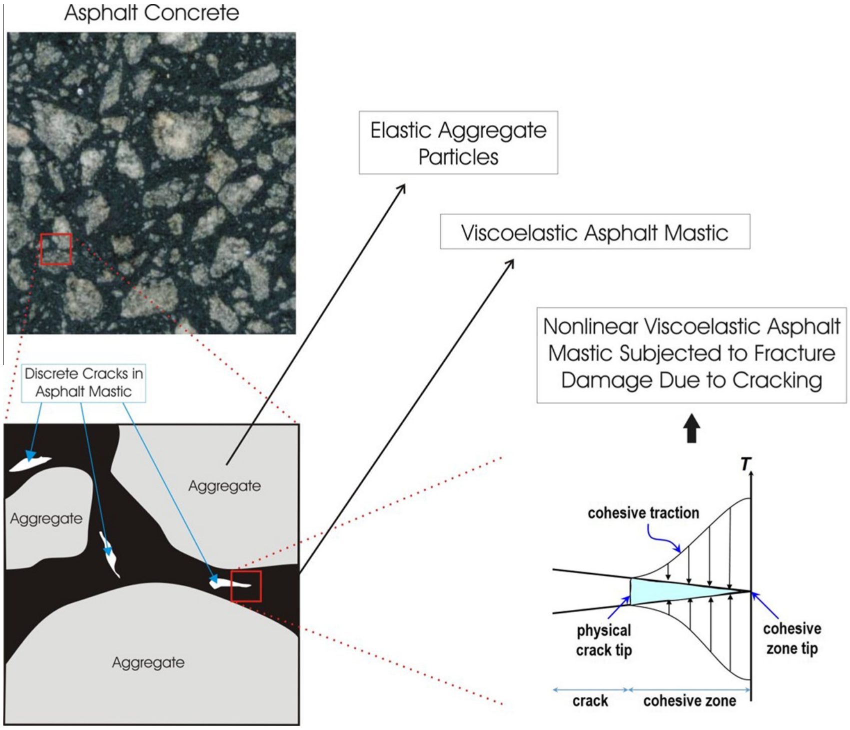

Fig. 1. Asphalt concrete microstructure consisting of elastic aggregates and viscoelastic asphalt mastic subjected to nonlinear fracture and damage.

microstructure modeling approaches have successfully simulated geometric heterogeneity (i.e., random orientation of irregularly shaped aggregates) and predicted the stiffness reduction due to the damage and fracture of asphaltic media; however, most of them, to the best of the authors' knowledge, are limited to successfully characterize the asphalt sample by separating the constituent-level energy dissipation due to a crack extension from the strain energy dissipated by the inelastic bulk material. Many approaches [4–8] typically characterize fracture-damage behavior either by using arbitrary values for simulation purposes only or by *a posteriori* matching of damage evolution characteristics with the laboratory performance test results from macroscopic asphalt mixture samples. Since the fracture properties are fundamental properties of mixture constituents such as asphalt binder/mastic, they should be directly identifiable *a priori* by conducting appropriate tests that can properly characterize microscale damage events in asphalt mixtures; this is required so that the time-, rate-, temperature-, and material-dependent asphalt damage can be successfully represented to improve various design and analysis tools.

The aforementioned limitations are mainly due to a lack of appropriate constituent-level fracture toughness tests particularly for materials such as asphalt mixtures that frequently show ductile fracture behavior. The standard fracture toughness testing protocol based on linear elastic fracture mechanics (LEFM) and/or elastic–plastic fracture mechanics (EPFM) may not be suitable for asphaltic materials in many cases since the fracture behavior is significantly complicated due to ductile and time-dependent characteristics; in other words, the total energy dissipated has contributions from multiple sources. Several attempts [11–16] have been made to improve the identification of fracture parameters; however, most approaches took into account fracture properties of asphaltic materials by performing LEFM-based fracture tests by either assuming that the material simply follows brittle fracture behavior or conducting tests in low-temperature conditions. The time-dependent ductile energy dissipation may not be accurately characterized by these aforementioned approaches.

2. Study objective and scope

This study is to characterize time-dependent ductile fracture behavior of asphalt binder/mastic where most nonlinear damage occurs in the asphalt mixture. Toward that end, a simple test method was first explored, and the resulting test data were incorporated with a viscoelastic cohesive zone model and computational microstructure simulations of mixtures. At the current stage of this research, a limited scope was attempted: one neat binder and its four filled mastics designed with different fillers were subjected at a representative temperature condition (24 °C), while varying film thicknesses of the binder and mastics.

3. Fracture testing system

To characterize the ductile fracture damage behavior of asphalt binder/mastic, a tensile testing method was developed. The tensile testing device, presented in Fig. 2, is composed of four main parts: (i) a drive system; (ii) a motion system; (iii) a data acquisition system; and (iv) a sample block. A stepping motor connected to a gear box generates a torque to turn the side screws that drive the translation stages in opposite directions. A load cell reads the time-dependent resisting force during the test and sends the electric signals to a data acquisition system, where these signals are translated into engineering values (e.g., time, opening displacement, and resisting force). The test is performed under a displacement-controlled static mode. Asphaltic samples (binder or mastic) are fabricated in a form of film between two metal plates (a sample block). To control film thickness, the sample block was designed so that a consistent asphaltic film could be formed between the two plates. First, approximate amount of asphalt binder (a little bit more than being necessary to make a target film thickness) is applied between the two plates, and the two plates are slowly moved inward by controlling the number of revolutions the stepping motor generates, which can control precisely the target gap (i.e., film thickness) between the two plates. After reaching the