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Mixed-mode fracture characterization of fine aggregate mixtures using semicircular bend fracture test and extended finite element modeling

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HIGHLIGHTS

- Integrated experimental-computational effort to characterize mixed-mode fracture.
- Semicircular bend fracture tests integrated with the extended finite element model.
- The extended finite element model with a mode-dependent cohesive zone fracture.
- Much larger fracture toughness of in-plane shear mode-II than opening mode-I.
- A power relationship between the total fracture toughness and involvement of in-plane shear mode-II fracture in the total.

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ABSTRACT

This paper presents integrated experimental-computational efforts to characterize the mixed-mode fracture of a fine aggregate matrix mixture which is the primary phase of cracks around stiffer coarse aggregates when typical asphalt concrete mixtures are subjected to intermediate service temperatures. Experimentally, semicircular bend fracture tests were conducted by varying the geometric-loading configurations with different initial notch inclination angles and supporting spans to achieve different fracture modes (opening mode-I, in-plane shear mode-II, and mixed). The semicircular bend fracture test results were then integrated with the extended finite element model which is also incorporated with mode-dependent cohesive zone fracture to properly identify the mode-dependent fracture properties. The test and model simulation results indicated that the cohesive zone fracture toughness of in-plane shear mode-II is quite different (approximately three times greater) from opening mode-I fracture toughness. The critical fracture energy was related to the mixed-mode ratio, which presented a power relationship between the total fracture toughness and involvement of in-plane shear mode-II fracture in the total. Findings and observations from this study, although they are limited at this stage, imply that the mixed-mode fracture characteristics are significant and need to be considered in the structural design of asphalt pavements with which multi-axial cracking is usually associated.

1. Introduction

Various asphalt pavement distresses are at least partially induced by fracture, including fatigue cracking, thermal cracking, and reflective cracking of the asphalt layer. Cracking in asphaltic pavement layers causes primary failure of the roadway structure and leads to long-term durability issues that are often related to moisture damage. In particular, asphaltic materials are subjected to multi-axial damage and mixed-mode fracture in the pavement structure due to complicated traffic loads and layered pavement geometry. The fracture resistance of asphalt materials significantly influences the entire performance of asphalt pavements and consequently, the maintenance and management of the pavement network. Therefore, a better understanding of the fracture process is considered a necessary step for the continued development of design-analysis procedures for asphaltic mixtures and pavement structures.

Due to the significance of fracture characterization, many researchers have studied the fracture behavior of asphalt mixtures by attempting different fracture tests such as the single-edge

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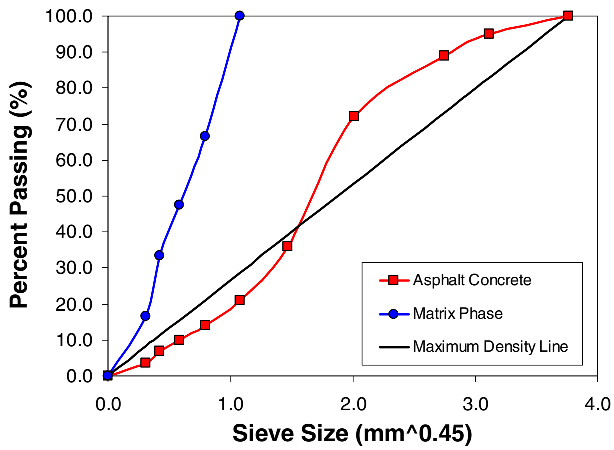

Fig. 1. Aggregate gradation curves: asphalt concrete mixture and its FAM phase.

notched beam test, the disk-shaped compact tension test, and the semicircular bend test. However, most studies have been conducted under low-temperature conditions and considered only opening mode-I fracture [1–3] due to various technical challenges involved both in performing mixed-mode fracture tests and in the resulting data analyses. Asphalt fracture, such as fatigue cracking, often occurs at intermediate service temperatures, and most fractures are associated with complex loading states, which usually involve a combination of opening and shearing displacement (so-called mixed-mode).

To characterize the mixed-mode fracture of asphalt materials, a few recent studies [2,4,5] have attempted fracture tests and relevant data analyses. Braham [5] conducted the single-edge notched beam test with an offset notch to analyze the mixed-mode fracture characteristics of different asphalt concrete mixtures. He showed that the fracture is mixture-specific and that fracture energy increases as the level of mode-II increases. However, the physical identification and quantification of the mode-II fracture toughness in the mixed-mode test were not fully estimated. More recently, the authors of this study conducted semicircular bend (SCB) fracture tests with a fine aggregate matrix (FAM) mixture to identify mode-I, mode-II, and mixed-mode fracture characteristics [6–8]. To explore mode-dependent fracture, the SCB tests were performed by varying the geometric-loading configurations with different initial notch inclination angles and supporting spans [8]. The test results were then analyzed to characterize the mixed-mode fracture by simply calculating the area under the load-displacement curves up to peak force. The simple experimental characterization was then elucidated in another study [7] by integrating the SCB test results with the extended finite element model (XFEM), which was also incorporated with mode-dependent cohesive zone fracture. In the study, the authors could identify opening mode-I and in-plane shear mode-II fracture properties separately, but remained a further study to the overall characterization of mixed-mode fracture behavior with different mixed-mode ratios.

2. Study objectives and scope

This study extends the authors' previous efforts [6–8] to reach a more comprehensive understanding to the mode-dependent fracture characteristics of asphalt mixtures. Thus, the same SCB test results presented in the previous study [7] are used herein, but the entire test results are integrated with the XFEM and the mode-dependent cohesive zone model to find overall mode-dependent fracture characteristics (i.e., opening mode-I, in-plane shear mode-II, and mixed-mode with different ratios). At the current stage of our efforts, only one asphalt mixture in a form of FAM was attempted to study the mode-dependent fracture with a

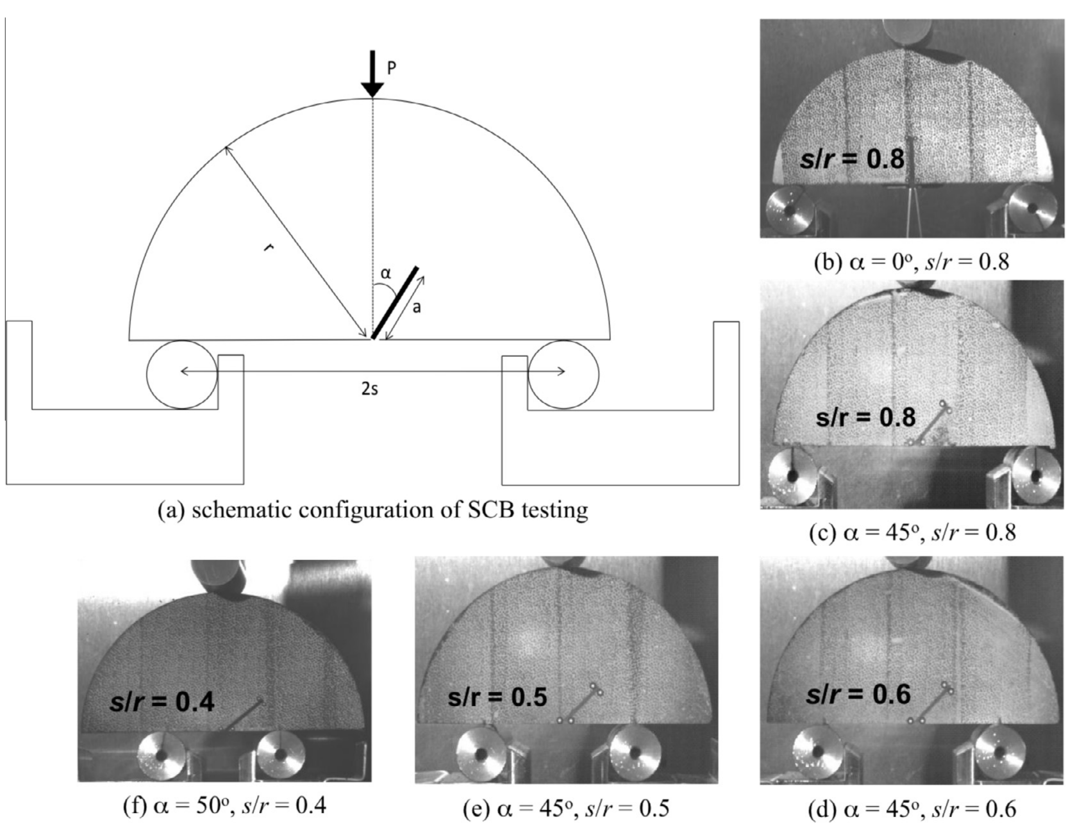

Fig. 2. Geometry and loading conditions of the SCB specimen.