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Fracture resistance of asphalt concrete under different loading modes and temperature conditions

S. Pirmohammad, M.R. Ayatollahi *

Fatigue and Fracture Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran 16846, Iran

HIGHLIGHTS

- Fracture tests were conducted under mixed I/II loading using an improved SCB specimen.
- Both loading mode and temperature affect the fracture behavior of asphalt concretes significantly.
- Depending on loading mode, SBS copolymer improves fracture resistance of asphalt concrete at lower temperatures.
- Asphalt concretes are more vulnerable to fracture under mixed mode I/II loading than pure mode I or II.

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ABSTRACT

This paper deals with the effects of loading mode and temperature on the fracture resistance of asphalt concretes under static loading. Three-point fracture tests were successfully performed on the cracked asphalt concrete samples under different modes of loading including pure mode I, pure mode II and mixed-mode I/II at several subzero temperatures. Improved semi-circular bend (SCB) specimen containing an asymmetric vertical edge crack was employed to provide the desired loading modes. Critical stress intensity factors (K_{If} and K_{IIf}) were then computed using the fracture load obtained from the experiments and the geometry factors determined from the finite element analyses. Furthermore, two different asphalt concrete mixtures (called normal and modified asphalt concretes) were used for specimen preparation. Results showed that both temperature and loading modes influence the fracture resistance of asphalt concrete significantly. For all the fracture tests performed under different modes of loading and decreasing temperature, the fracture resistance of asphalt concretes first increased and then below a certain temperature (−20 °C) decreased. Moreover, the minimum fracture resistance of asphalt concrete occurred under a specific mixed-mode I/II loading that can be considered as an index to assess the onset of crack growth in asphaltic materials. According to the test results, the modified asphalt concretes showed higher resistance against crack growth than the normal asphalt concretes particularly at lower temperatures.

1. Introduction

Asphalt concrete cracking in the cold climate regions is considered as one of the major modes of deterioration in asphalt pavements. Since the rehabilitation of cracked asphalt pavement or performing new asphalt concrete layers is costly and time consuming, it is essential to investigate cracking mechanisms in order to mitigate crack development through the whole asphalt overlay.

Asphalt concrete is a temperature dependant material that may fall within a category of materials defined as brittle or quasi-brittle particularly at subzero temperatures. Linear elastic fracture mechanics (LEFM) is a reliable approach to investigate fracture behavior of brittle materials. In LEFM, the stress intensity factor, *K*, is a fundamental parameter for characterizing the fracture phenomenon from the crack tip. Several researchers have studied the fracture behavior of hot mix asphalt (HMA) mixtures by applying stress intensity factor at subzero temperatures (see e.g. [1–4]).

Many causes have been suggested for crack nucleation in asphalt pavement such as temperature fluctuation and traffic load induced from the vehicle wheels (see e.g. [5]). Cracking due to temperature fluctuation often occurs transverse to the road direction, and its initiation is almost exclusively linked to pure mode I (tensile mode) crack growth mechanism. According to an investigation performed by Ameri et al. [6] on top-down cracks, traffic loads transferred from the vehicle wheels can change the crack growth mechanism from pure mode I to mixed-mode I/II (i.e. tensile and shear modes). Similarly, the crack extension in reflective cracks is

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* Corresponding author. Tel.: +98 21 7724 0201; fax: +98 21 7724 0488.
E-mail address: m.ayat@iust.ac.ir (M.R. Ayatollahi).

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also known to take place under a combination of mode-I and mode-II loading [7,8]. Most of the previous experimental investigations on the cracked asphalt concretes are concentrated on mode I crack growth (e.g. [9–11]) and very limited investigations have been carried out on mixed-mode I/II and pure mode II loading conditions. For example, Artamendi and Al-Khalid [12] used LEFM to investigate the asphalt concrete fracture behavior under a fixed combination of mode I and mode II, and at one temperature. Therefore, it is very useful to conduct a series of experiments in order to explore the fracture behavior of asphalt concretes under pure mode II and mixed-mode I/II loading.

In this research, the effects of ambient temperature and loading mode on the fracture resistance of hot mix asphalt (HMA) mixtures have been investigated under static loading. Extensive three-point fracture tests were performed on the improved SCB specimens under different loading and temperature conditions, and the critical stress intensity factors were then computed from the fracture loads obtained from the experiments.

2. Specimen geometry

Various test specimens such as single edge notched beam (SENB), disk-shaped compact tension (DC-T), semi-circular bend (SCB) have been used in the past by several researchers [3,13,14] to study the fracture behavior of asphalt concretes. In the present work, an improved SCB specimen was employed to conduct the fracture tests (see Fig. 1). Different combinations of mixed mode loading including pure mode I and pure mode II can be simulated using the SCB specimen by changing the crack distance from the middle point of SCB specimen i.e. L, and the support distances S_1 and S_2 as shown in Fig. 1. Experiments in this research study were performed under pure mode I, pure mode II and three different mixed-mode I/II loading conditions. Appropriate values of parameters S_1, S_2 and L were determined (as given in Table 1) by performing finite element analyses for these five different loading conditions. The cracked SCB specimens were modeled using 8-node plane strain elements, and the J-integral technique was used to determine the SIF in the finite element analyses. Moreover, the singular elements with nodes at quarter-point positions, which are highly recommended for crack modeling, were used for the elements around the crack tip. As can be seen from Table 1, pure mode I loading is achieved when the specimen is loaded symmetrically; while, mixed-mode I/II and pure mode II loading are achieved by asymmetric loading of the specimen. In the finite element analyses, crack length a, specimen radius R, specimen thickness t and load P were assumed to be 20 mm, 75 mm, 32 mm and 1000 N, respectively. The values of a, R and t selected here are the same values which are used in the experiments. The stress intensity factors (K_I and K_II) obtained directly from the finite element analyses have been presented in Table 1. These stress intensity factors are required to calculate the geometry factors Y_I and Y_II as follow:

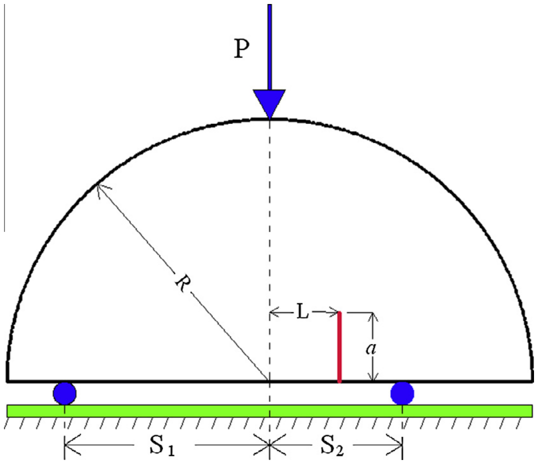

Fig. 1. SCB specimen for conducting fracture tests under different loading modes.

$$Y_\mathrm{I} = \frac{K_\mathrm{I}}{\sqrt{\pi a}}\frac{2Rt}{P} \qquad (1)$$
$$Y_\mathrm{II} = \frac{K_\mathrm{II}}{\sqrt{\pi a}}\frac{2Rt}{P}$$

The mode I and mode II geometry factors Y_I and Y_II which would be used later for calculating asphalt concrete fracture resistance, can be computed by replacing the assumed values of a, R, t, P and the relevant stress intensity factors (from Table 1) in Eq. (1). The computed geometry factors for five different cases of mixed mode loading have been given in Table 1 along with mode mixity parameter M^e which is written as:

$$M^e = \frac{2}{\pi}\tan^{-1}\left(\frac{K_\mathrm{I}}{K_\mathrm{II}}\right) \qquad (2)$$

The parameter M^e is linked to the relative contribution of mode I and mode II. While M^e equals 1 for pure mode I and zero for pure mode II, its value for mixed-mode I/II loading is between them ($0 < M^e < 1$).

3. Specimen preparation and material

In order to manufacture the SCB specimens from HMA mixtures, first cylindrical samples of radius 75 mm were prepared using superpave gyratory compactor. These cylindrical samples were then sliced into several discs of thickness 32 mm by means of a water-cooled masonry sawing machine, and each disc was halved to prepare SCB specimens. Crack was then generated in the SCB specimens utilizing a water-cooled cutting machine with a very thin blade. The specimen radius and thickness R, t, and the crack length a were 75 mm, 32 mm, and 20 mm respectively.

The HMA mixtures are composed of three main components including aggregates, binders and air voids. Aggregates are extracted from natural rocks and constitute about 95% by weight of HMA mixtures. They can be classified by their size which is determined by sieves with standard openings (e.g., 12.5 mm, 9.5 mm, 4.75 mm and so on). Aggregate gradation gives the percentage of these different sizes in a HMA mixture. Binders which constitute about 5% by weight of HMA mixtures stick aggregates together, and are classified by a parameter called "penetration grade" stating softness of the binder. Binders with the penetration grades of 40–50, 60–70 and 85–100 are the common ones which are frequently used in the road pavements, and sometimes modifiers like SBS (Styrene–Butadiene–Styrene) are added to the binder to improve the performance of HMA mixtures. Moreover, the air void percentage affects the density of HMA mixtures such that by increasing the air void percentage, the HMA density decreases.

The HMA mixtures used to produce the cylindrical samples were similar to those widely employed in Iran pavement systems. Two types of HMA mixtures were used in this research study such that one contained binder with penetration grade of 60 and another one contained binder with penetration grade of 85 modified with 3.5% by weight of a co-polymer called SBS (Styrene–Butadiene–Styrene). For brevity, these mixtures are designated as *normal asphalt concrete* and *modified asphalt concrete*, respectively. The aggregate gradation of all HMA mixtures employed in this research (as described in Table 2) was within the range recommended by Iran Highway Asphalt Paving Code (IHAPC). Moreover, all SCB