Experimental Determination of Mode II Fracture Resistance in Asphalt Concretes

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Abstract This paper presents a test set-up using semi-circular bend (SCB) specimen for measuring pure mode-II fracture toughness of asphalt concretes. Three-point bend fracture tests were performed on the SCB specimens at low temperature. The results showed that this set-up could be used for conducting mode-II fracture tests on hot mix asphalt (HMA) specimens. Linear elastic fracture mechanics (LEFM) concept was used to study the fracture behavior of cracked asphalt concrete. Mode-II critical stress intensity factor, K_{IIc}, was calculated using the fracture load measured from the three-point bend tests. In addition to pure mode-II tests, similar tests were carried out for pure mode-I loading. Results showed that mode-II critical stress intensity factor was higher than that of pure mode-I loading.

Keywords Asphalt concrete, Critical stress intensity factor, Low temperature, Pure mode-II fracture.

1. Introduction

Cracking at low temperatures is one of the major sources of deterioration in asphalt concretes imposing significant costs on the pavement rehabilitation agencies annually. There are many causes for crack nucleation on asphalt pavement surface such as the temperature fluctuation and the traffic load induced from vehicle wheels. Good understanding of cracking mechanism could be helpful for reducing those costs.

Asphalt concrete is a temperature dependant material that may fall within a category of materials that are defined as brittle or quasi-brittle at low temperatures. Many researchers have studied fracture behavior of hot mix asphalt (HMA) mixtures at low temperatures (e.g. see [1-3]). 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 characterizing the fracture phenomenon from the crack tip. This parameter has been used by many researchers (e.g. see [4-6]) for cracks in asphalt concrete mixtures.

In the recent decades, many researchers have studied the fracture behavior of asphalt concretes under pure mode-I (opening mode) loading (see e.g. [4-7]). The temperature cycling is one of the main causes of mode-I cracking in asphalt pavements. In some cases such as reflective cracks, the crack extension is known to take place under a combination of mode-I and mode-II loading. Similarly, according to the research performed by Ameri et. al. [8], the traffic load induced by vehicle wheels at top down cracks (TDC) also results in mixed mode I-II loading. Therefore, it is important to investigate the behavior of cracked asphalt concretes under pure mode-I, pure mode-II, and mixed mode I-II loading conditions. In particular, pure mode-II fracture in asphalt concretes has been rarely studied in the past.

In this research, the semi-circular bend (SCB) specimens, prepared from the cylindrical samples were utilized for conducting three-point fracture tests under pure mode-II loading. In addition to the mode-II tests, fracture tests were performed for mode-I loading as well and the critical stress intensity factors were calculated and compared.

2. Specimen geometry and material

While HMA behavior is strongly affected by temperature, at subzero temperatures, its mechanical behavior is often considered to be brittle or quasi-brittle. Hence, linear elastic fracture mechanics (LEFM) concept is adoptable for investigating the fracture behavior of HMA mixtures at low temperatures. Generally, the cracked asphalt concrete pavement may experience three main modes of fracture, mode-I, mod-II, and mode-III. Among these three modes, mode-I and mode-II are predominant modes of crack propagation in asphalt concrete pavements containing reflective or top-down cracks.

Several test specimens such as single edge notched beam (SENB), disk-shaped compact tension (DC-T), semi-circular bend (SCB) and so on, have been used in the past by many researchers to study the fracture behavior of asphalt concretes. In this research, an improved SCB specimen was employed to conduct the experiments. For this purpose, first several cylindrical samples (130 mm in height, 150 mm in diameter) were prepared using superpave gyratory compactor (SGC) in the laboratory. These samples were sliced into several disks of 32 mm thick by means of a water-cooled masonry sawing machine. Each disk was then halved to obtain semi-circular shaped specimens. At the next stage, an artificial edge crack (20 mm in length) was generated within the specimen utilizing a water-cooled cutting machine with a very thin blade. The width of generated crack was 0.3 mm.

According to the finite element simulations performed by Ayatollahi [9], in a SCB specimen of radius 75 mm containing an edge crack of length 20 mm, pure mode-II loading is achieved when the edge crack distance is 16 mm from the middle of the specimen (see Fig. 1). S_1 and S_2 are the left and right hand side distances of the lower fixtures from the middle of the specimen, respectively. For pure mode-II loading, the values of S_1 and S_2 were found from the FE analysis to be 50mm and 20 mm respectively.

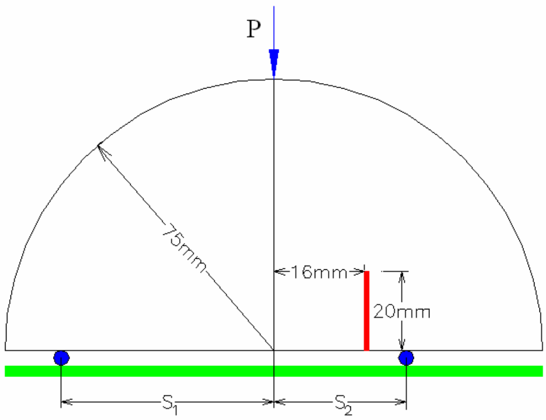

Figure 1. Test specimen used for pure mode-II fracture tests

The asphalt concrete used to prepare the cylindrical samples was similar to the one which is widely used in Iran pavement systems. Aggregate gradation of the HMA mixtures used in this study (as described in Table 1) is within the range of the recommendations by Iran Highway Asphalt Paving

Code (IHAPC). The air void of all mixtures was 4 percent. Asphalt binder with penetration grade of 60/70 was utilized for preparation of the cylindrical samples.

Table 1. HMA aggregate gradation

Sieve size (mm)	Requirements		Percent passing
	Min	Max	
19	100	100	100
12.5	90	100	95
9	67	87	77
4.75	44	74	59
2.36	28	58	43
1.18	20	46	33
0.5	13	34	23
0.3	5	21	13
0.15	4	16	9.5
0.075	2	10	8.4

3. Fracture tests and results

Three-point bend fracture tests were conducted on the SCB specimens under pure mode-II loading at -20°C. To achieve this temperature, the SCB specimens were first put into a freezer with the fixed temperature of -20°C for 4 hours. Then the tests were immediately carried out using a universal testing machine and a three-point bend fixture (as shown in Fig. 2). The displacement rate of the upper fixture was set to a constant value of 3 mm/min. In the first stage, the conventional round-tip supports were used to load the specimens. However, some of the tests were not successful. Because, the crack growth initiated from the lower and right hand side fixture and not from the crack tip (see Fig. 3).

To avoid crack initiation from undesirable locations, the lower fixtures were modified such that instead of applying the bottom loads in the concentrated points (as was the case in the first set-up) the loads were applied as distributed forces. Several finite element analyses were performed to find the width of distributed load (i.e. the magnitude of b in Fig. 4) in order to provide pure mode-II loading. Fig. 5 shows a typical mesh used in the finite element analyses. The appropriate value for the parameter b was eventually found to be 4 mm. The conventional fixtures used in the first set-up were replaced with the second set-up, and the mode-II fracture tests were repeated. By this modification, the crack extension in all the specimens took place from the crack tip (see Fig. 6). Therefore, the pure mode-II fracture test was successfully simulated experimentally using the SCB specimen. The fracture tests were also performed under pure mode-I loading and at -20°C using the same three-point test set-up. However, for this type of loading, the crack was generated in the middle of the specimen with symmetric loading supports of S_1=S_2=50 mm (see Fig. 1). Fig. 7 shows sample of the load-load line displacement curves recorded from the mode-I and mode-II fracture tests. In order to increase the reliability of the experimental results, four SCB specimens were tested for each mode of loading. As shown in Fig. 7, the load increases linearly and then suddenly drops to zero. Therefore, one may suggest that the asphalt concrete failure was due to brittle fracture with negligible nonlinear deformation. Considering the area under the load-load line displacement curve, Fig. 7 shows that the asphalt mixture needs higher energy to fracture under mode-II loading than under mode-I loading.

Figure 2. Three point test set-up

Figure 3. Fracture test using first set-up

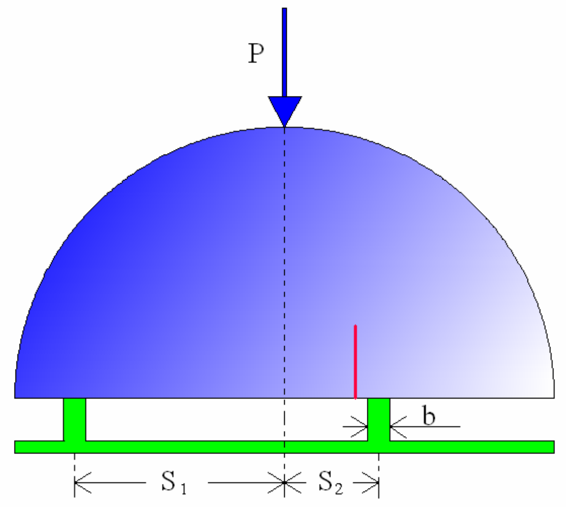

Figure 4. Three-point test (second set-up)

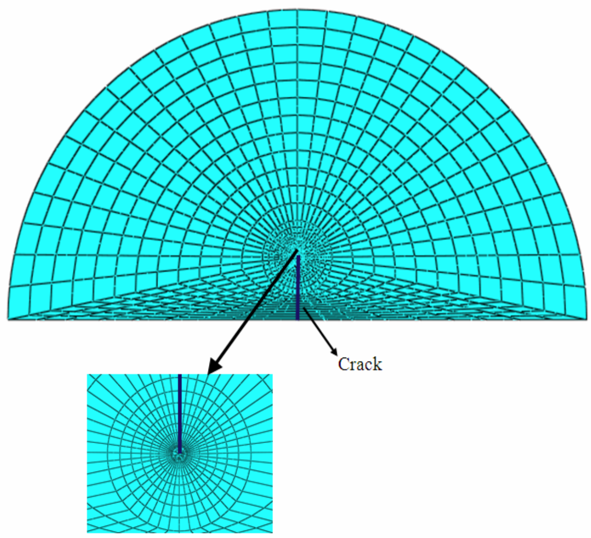

Figure 5. The finite element mesh

The fracture resistance in cracked specimens is often described by the values of critical stress intensity factors. The mode-I and mode-II critical stress intensity factors, K_{Ic} and K_{IIc} can be written for the SCB specimen in terms of the experimentally obtained fracture load P_{cr} as:

$$K_{Ic} = Y_I \frac{P_{I_{cr}}}{2Rt}\sqrt{\pi a}$$
$$K_{IIc} = Y_{II} \frac{P_{II_{cr}}}{2Rt}\sqrt{\pi a} \tag{1}$$

The fracture load P_{cr} is obtained for each mode of loading from the maximum load recorded in the fracture tests. Y_I and Y_{II} are mode-I and mode-II geometry factors which were obtained from finite element analyses as 3.73 and 2.25, respectively. The specimen radius and thickness R, t, and the crack length *a* are 75 mm, 32 mm, and 20 mm respectively.

Figure 6. Fracture test using second set-up

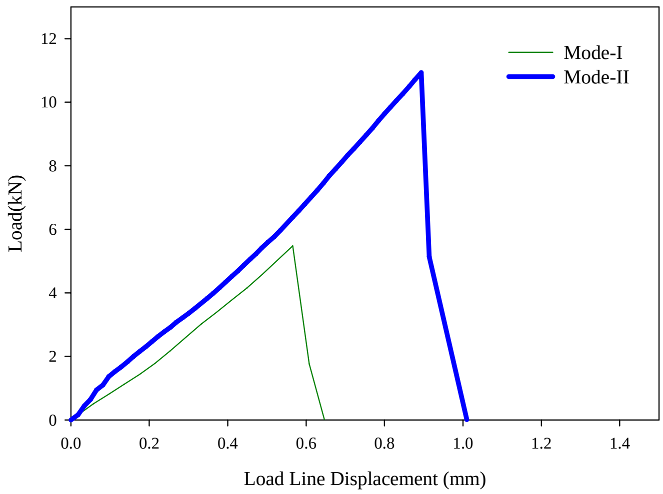

Figure 7. Load vs LLD at -20^{o}C

Table 2. Average experimental results for mode-I and mode-II loading

Mode of loading	$P_{cr}\,(kN)$	Critical stress intensity factor $(MPa.\sqrt{m})$
Pure mode-I	5.3	1.03
Pure mode-II	11.2	1.3

The critical stress intensity factors (K_{Ic} and K_{IIc}) were calculated from Eq. 1 for each test conducted under mode-I or mode-II loading conditions. Table 2 shows the average values of P_{cr}, K_{Ic} and K_{IIc} obtained for asphalt samples. According to this Table, the critical stress intensity factor under pure mode-II loading is about 26% higher than that under pure mode-I loading. In other words, when a cracked asphalt concrete is under pure mode-II loading, its resistance against brittle fracture at low temperatures is more than that of mode-I loading. Moreover, the mode-II fracture load in the asphalt SCB specimens is more than twice the mode-I fracture load (see Table 2). While the crack extension in mode-I fracture tests took place along the pre-crack direction, all the mode-II cracks kinked out of the initial plane (see Fig. 6). This is mainly because the maximum tensile stress around the crack tip is no longer along the crack line when a cracked specimen like SCB is subjected to pure mode-II loading conditions [10].

4. Conclusion

In this paper, a suitable procedure was suggested for conducting fracture experiments on cracked asphalt concretes under pure mode-II loading and at low temperatures. The modified SCB specimens used for the experiments can be produced conveniently by a gyratory compactor or by coring from an existing asphalt pavement. The specimen can be used both for pure mode-I tests and for pure mode-II tests. The mode-I and mode-II tests were performed successfully on an asphalt mixture sample at -20^{o}C. The results showed that both the fracture load and the critical stress intensity factor obtained from the mode-II experiments were considerably higher than those obtained from the mode-I experiments.

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