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Impact of temperature cycling on fracture resistance of asphalt concretes

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Abstract. Asphalt pavements are exposed to complex weather conditions and vehicle traffic loads leading to crack initiation and crack propagation in asphalt pavements. This paper presents the impact of weather conditions on fracture toughness of an asphalt concrete, prevalently employed in Ardabil road networks, under tensile (mode I) and shear (mode II) loading. An improved semi-circular bend (SCB) specimen was employed to carry out the fracture experiments. These experiments were performed in two different weather conditions namely fixed and cyclic temperatures. The results showed that consideration of the impact of temperature cycling resulted in decreasing the fracture toughness of asphalt concrete significantly. Furthermore, the fracture toughness was highly affected by loading mode for the both fixed and cyclic temperature conditions studied in this paper. In addition, it was found that the MTS criterion correctly predicts the onset of fracture initiation although this prediction was slightly conservative.

Keywords: fracture toughness; SCB specimen; weather conditions; asphalt concrete; low temperature

1. Introduction

Many distresses such as rutting, corrugation and cracking influence the asphalt pavement performance. Among these distresses, the most crucial factors of deterioration in asphalt overlays is the crack formation at low temperatures. Damages resulting from the crack formation decrease the service life of asphalt pavements and impose significant costs to the road agencies. Having the proper and complete knowledge on the fracture mechanisms can be a reasonable way to reduce the rehabilitation and maintenance costs.

Hot mix asphalt (HMA) mixtures are temperature dependent behaving in a brittle manner at low temperatures, while they behave as visco-elastic at high temperatures. Linear elastic fracture mechanics (LEFM) approach works very well for brittle materials to predict the onset of crack growth. In LEFM, the critical stress intensity factor K_f is a fundamental parameter for characterizing the fracture phenomenon at the crack tip. Many researchers have employed this parameter (K_f) for studding fracture behavior of asphalt concretes at low temperatures (see e.g, Li and Marasteanu 2004, Dongre *et al.* 1989, Anderson *et al.* 1990). Meanwhile, it is remided that

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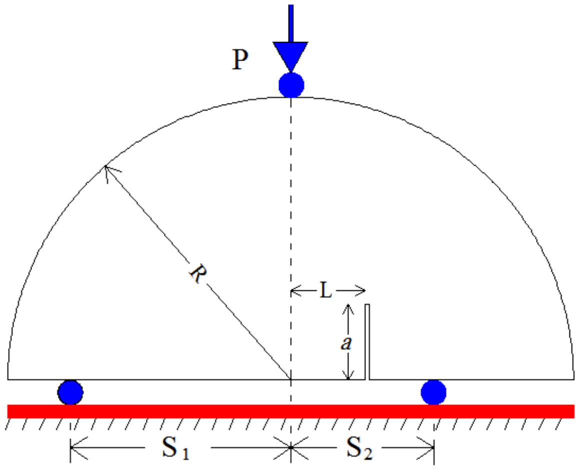


Fig. 1 SCB specimen loaded by a three-point bend fixture.

Majidzadeh *et al.* (1971) were the first to apply fracture mechanics methodology for considering the crack growth in HMA mixtures.

Fracture in HMA mixtures are occurred by many reasons like weather conditions and traffic loads induced from the vehicle wheels. Based on an investigation done by Ayatollahi *et al.* (2014), as the vehicle approaches to a crack within the asphalt overlay, both mode I and mode II loading occur at the crack tip. Similarly, the crack extension in reflective cracks is also known to take place under a combination of mode I and mode II loading (see e.g, Graf and Werner 1993, Molenaar 1993).

Previous studies published in the literature reveals that all experimental investigations on asphalt concretes have been performed in constant weather conditions (see e.g, Khattak *et al.* 2007, Kim and El-Hussein 1995, Wagoner *et al.* 2005). While, the real road structures made of asphalt concretes are subjected to repeated weather loadings during their service life that can be simulated by thermal cycle. Therefore, there is a great need to investigate the impact of temperature cycling on the fracture toughness of HMA mixture. The effect of temperature cycling has been investigated in the past for some other temperature-dependent materials such as polymer concretes (Shokrieh *et al.* 2011); while, this issue received no attention to investigate fracture behavior of the asphalt concretes. Hence, in order to realistic designing of the road structures, its impact on the fracture toughness of the asphalt concretes should be studied.

In the present paper, the impact of temperature cycling on the fracture toughness of an asphalt concrete is studied via performing fracture tests using an improved SCB specimen. In order to compare the results, the fracture tests were also repeated for a fixed temperature of -15°C. Mode I and mode II fracture toughness of the asphalt concrete were finally computed using the fracture load obtained from the fracture experiments.

2. Test specimen

In order to perform fracture experiments in the present work, an improved semi-circular bend

Table 1 Finite element results for SCB specimens

Mode of loading	M^e	S&L (mm)	K_I $(MPa\sqrt{m})$	K_{II} $(MPa\sqrt{m})$	Y_I	Y_{II}
Pure mode I	1	(S_1,S_2)=(60,60)&L=0	0.267	0	5.105	0
Mixed mode I/II	0.8	(S_1,S_2)=(50,20)&L=-2	0.086	0.029	1.655	0.546
Mixed mode I/II	0.5	(S_1,S_2)=(50,20)&L=5	0.061	0.059	1.171	1.131
Mixed mode I/II	0.2	(S_1,S_2)=(50,20)&L=11	0.031	0.094	0.599	1.792
Pure mode II	0	(S_1,S_2)=(50,20)&L=16&b=4mm	0	0.120	0	2.298

(SCB) specimen shown in Fig. 1 was chosen. It is worth mentioning that this geometry was chosen because the gyratory compactor machine (that is employed for producing samples made of asphalt concretes) was only able to produce cylindrical samples. Unlike the conventional SCB specimen (Lim and Johnston 1994), the crack in the improved SCB specimen is always perpendicular to the flat part. The radius and the crack length of the SCB specimen shown in Fig. 1 were assumed to be R=75 mm and *a*=20 mm, respectively. This specimen was simply loaded using a three-point bend fixture. Moreover, L and S state the position of crack and lower supports, respectively. Loading modes from pure mode I to pure mode II can be created at the crack tip of the SCB specimen through changing the values of L and S. For describing the relative contributions of mode I and mode II, a mixity parameter M^e is used here as

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

where M^e is 1 for pure mode I and zero for pure mode II. For any other mixed mode loading conditions, M^e varies between 0 and 1. A large number of finite element analyses were performed to obtain the appropriate values of S and L for simulating pure mode I, pure mode II and various mixed mode I/II loading. In the simulations done by the finite element method, values of the specimen radius R, crack length *a*, specimen thickness t and the applied load P were assumed to be 75 mm, 20mm, 32mm and 1000N, respectively. To accurately find the crack parameters, the mesh adjacent to the crack tip were built fine enough and those far away from the crack tip were modeled relatively coarse. J-integral technic was used in the finite element analyses to find stress intensity factors namely K_{I} and K_{II}. Values of L and S for the specified loading mode along with the computed values of the stress intensity factors (K_{I} and K_{II}) have been given in Table 1. The geometry factors were finally obtained by taking the stress intensity factors extracted from the finite element into the below equations as follow

$$Y_I = \frac{K_I}{\sqrt{\pi a}}\frac{2Rt}{P} \tag{2a}$$

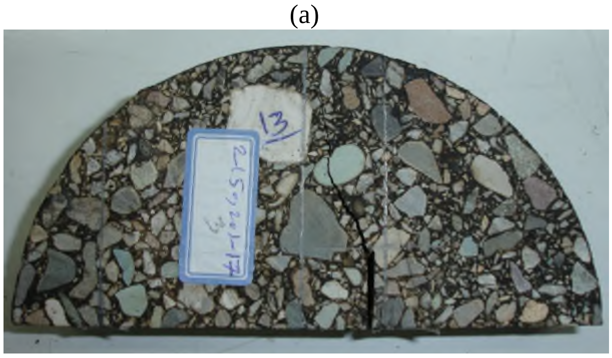
$$Y_{II} = \frac{K_{II}}{\sqrt{\pi a}}\frac{2Rt}{P} \tag{2b}$$

where Y_I and Y_{II} are known as the mode I and mode II geometry factors, respectively. Their values have been presented in Table 1. These values would be used later to calculate fracture toughness of the asphalt concrete.

Table 2 HMA aggregate gradation No. 4

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

(a)



(b)

Fig. 2(a) Cutting processes to produce SCB specimen, (b) cracked SCB specimen

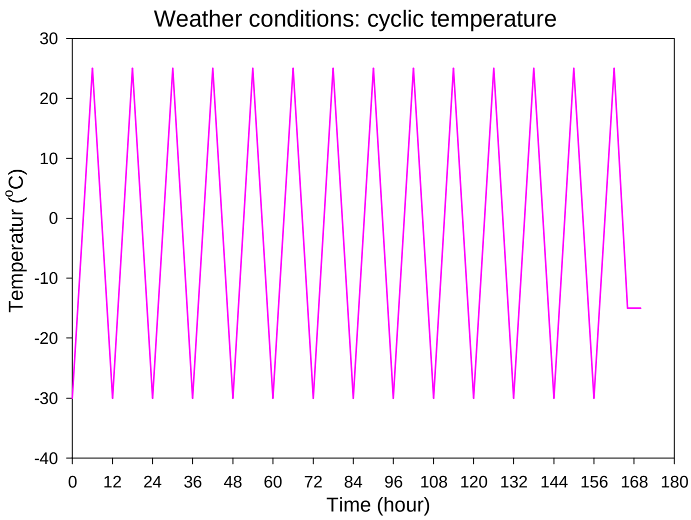


Fig. 3 Temperature variations for the weather conditions of cyclic temperature

3. Experimental program

3.1 Material and test specimen provision

HMA mixtures are such composite materials. Aggregate gradation of the asphalt concretes used in this study was selected as Table 2 which was within the range of the recommendations by Iran Highway Asphalt Paving Code. Air void of all mixtures was 4 percent, and binder with penetration grade of 60 was used for preparing asphalt concretes.

In order to manufacture the SCB specimens from HMA mixture, cylindrical samples with radius of 75 mm were made using superpave gyratory compactor. The cylindrical samples were then sliced into several discs of thickness 32 mm by means of a water-cooled masonry sawing machine. Finally, the discs were halved to prepare the SCB specimens and a pre-crack was generated in each specimen using a water-cooled cutting machine with a very thin blade. The specimen radius R, the thickness t and the pre-crack length a were 75 mm, 32 mm and 20 mm respectively. The cutting processes together with and a sample of produced cracked SCB specimen is shown in Fig. 2.

3.2 Fracture experiments

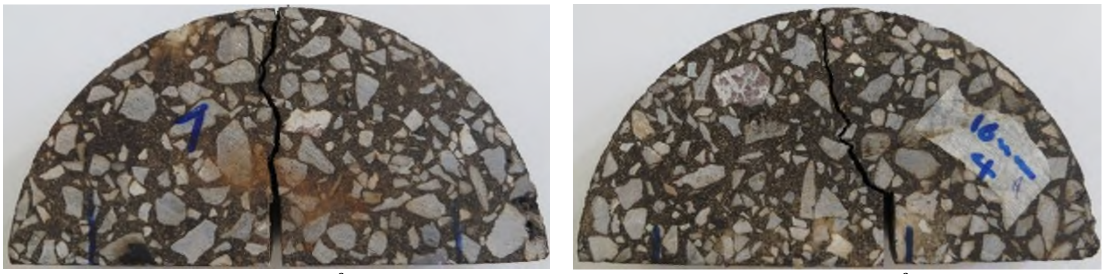
Three-point bend fracture tests were conducted on the SCB specimens under either pure mode I or pure mode II loading in two different weather conditions explained as: 1) the produced cracked SCB specimens were kept in a freezer fixed at the constant temperature of -15°C for 4 hours to ensure that all parts of the specimen have the same temperature. 2) the produced cracked SCB specimens were kept in a freezer providing the cyclic temperature according to the weather profile shown in Fig. 3. Indeed, this profile presents Iran weather conditions (Shokrieh *et al.* 2011). Based on Fig. 3, the temperature goes down from 25°C to -30°C, and again goes up to 25°C. In the

Fig. 4 Three-point bend set-up to carry out fracture experiments

mentioned cooling and warming processes, the temperate was varied gently such that each half cycle was taken 6 hours. Moreover, the SCB specimens experienced the mentioned thermal cycle for 7 days, and as is clear from Fig. 3, they generally experienced 14 temperature cycles.

In order to compare the fracture test results between the weather conditions of fixed and cyclic temperatures, the temperature for the SCB specimens exposed at the cyclic temperature was finally fixed at -15°C for 4 hours similar to the first weather conditions explained above. Once the SCB specimens were conditioned at the fixed or cyclic temperatures mentioned above, the fracture experiments were performed immediately using the three-point bend set-up shown in Fig. 4. In this fracture test set-up, the two lower supports were fixed and the upper support moved downwards with a constant speed of 3mm/min. To perform mode I fracture tests, the crack was generated in the middle of the SCB specimen and the lower supports were adjusted at S_1=S_2=60 mm based on Table 1. Similarly, the crack in pure mode II specimen was positioned at L=16mm, and the lower supports were adjusted at S_1=50 mm & S_2=20 (see Table 1). Fig. 5 shows samples of the SCB specimens after the fracture tests under pure mode I and pure mode II loading. As is seen in this figure for mode I loading, the path of crack growth was straight and along the initial crack; while, for pure mode II loading, crack progressed along a curvilinear path. 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 (Erdogan and Sih 1963). Furthermore, the fracture angle for the pure mode II was larger than that for the pure mode I loading.

Four replicates for each one of loading mode in a certain weather conditions were tested to ensure that the results were reliable. An example of load-load line displacement curves recorded directly from the experiments has been given in Fig. 6. It is evident from Fig. 6 that the load initially enhanced linearly to gain a peak value, and once the fracture took place, it dramatically decreased to reach the value of zero. These variations of the load versus load line displacement



Pure mode I (M^e=1) Pure mode II (M^e=0)

Fig. 5 Samples of the SCB specimens after fracture tests

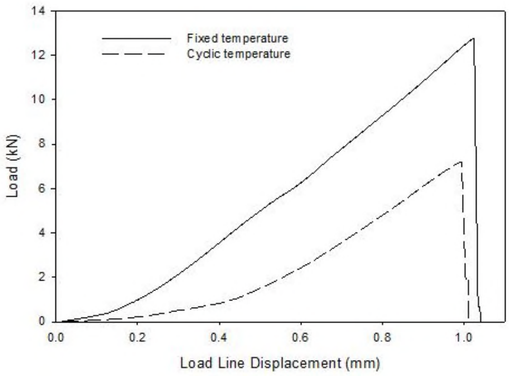


Fig. 6 Sample of load-load line displacement curves

connoted the brittle fracture of the asphalt concrete studied in the current paper. Consequently, as mentioned earlier, LEFM seems to be a reasonable and applicable approach to analyze the fracture test results. The fracture resistance in the cracked bodies is often stated with critical stress intensity factors known as fracture toughness. The mode I and mode II fracture toughness (K_{If} and K_{IIf}) for the SCB specimen can be calculated by below equations

$$K_{If} = Y_I \frac{P_{cr}}{2Rt}\sqrt{\pi a} \tag{3a}$$

$$K_{IIf} = Y_{II} \frac{P_{cr}}{2Rt}\sqrt{\pi a} \tag{3b}$$

The values of Y_I and Y_{II} were already calculated and given in Table 1. P_{cr} in the above equations refers to the peak load which is taken into the Eq. (3) for calculating the critical stress intensity factors.

4. Results and discussion

It is reminded that the fracture experiments in the present research were carried out in two various weather conditions namely fixed and cyclic temperatures. For each temperature conditions

Table 3 Fracture loads recorded from the experiments together with the averaged mode I and mode II fracture toughnesses.

Weather Conditions	Loading mode	Replicate No.	P_{cr} (kN)	Averaged K_{If} $(MPa\sqrt{m})$	Averaged K_{IIf} $(MPa\sqrt{m})$
Fixed temperature	Pure mode I	1	5.18	1.38	0
		2	5.03		
		3	5.34		
		4	5.15		
	Pure mode II	1	11.56	0	1.39
		2	11.41		
		3	11.62		
		4	11.66		
Cyclic temperature	Pure mode I	1	4.52	1.20	0
		2	4.58		
		3	4.52		
		4	4.46		
	Pure mode II	1	11.20	0	1.37
		2	11.24		
		3	11.26		
		4	11.30		

and loading modes, four SCB specimens were tested which the fracture loads (P_{cr}) together with the corresponding calculated critical stress intensity factors K_{If} and K_{IIf} using the Eqs. 3(a) and 3(b) have been presented in Table 3. It is also reminded that asphalt concretes are practically subjected to weather conditions of cyclic temperature rather than to those of fixed temperature. For comparison purposes, critical stress intensity factors for different weather conditions are given in Fig. 7. It includes error bars representing the variation of experimental data. As is clear from Fig. 7, mode I and mode II fracture toughness (K_{If} and K_{IIf}) of the asphalt concrete were lower in weather conditions of the cyclic temperature than in weather conditions of the fixed temperature.

This signifies that the asphalt concrete in weather conditions of cyclic temperature resisted against crack progress worse than that in weather conditions of fixed temperature. As a result, based on these results, it can be said that the thermal cycle weakens the asphalt concretes against fracture for any loading mode. Hence, neglecting the impact of temperature cycling would result in overestimating the measured fracture toughness of asphalt concretes. One may suggest that reduction in the fracture resistance of asphalt concretes due to temperature cycling must be considered when the road structures are designed. On the other hand, Fig. 7 indicates the effect of loading mode on the fracture resistance of the asphalt concrete in the both weather conditions. According to this figure, the fracture resistance was affected by loading mode. Another result derived from Fig. 7 is that the loading mode did not equally affect the values of fracture toughness for the two studied weather conditions. It seems that as the proportion of shear loads increased, the influence of temperature cycling reduced so that a negligible influence was observed for pure mode II loading.

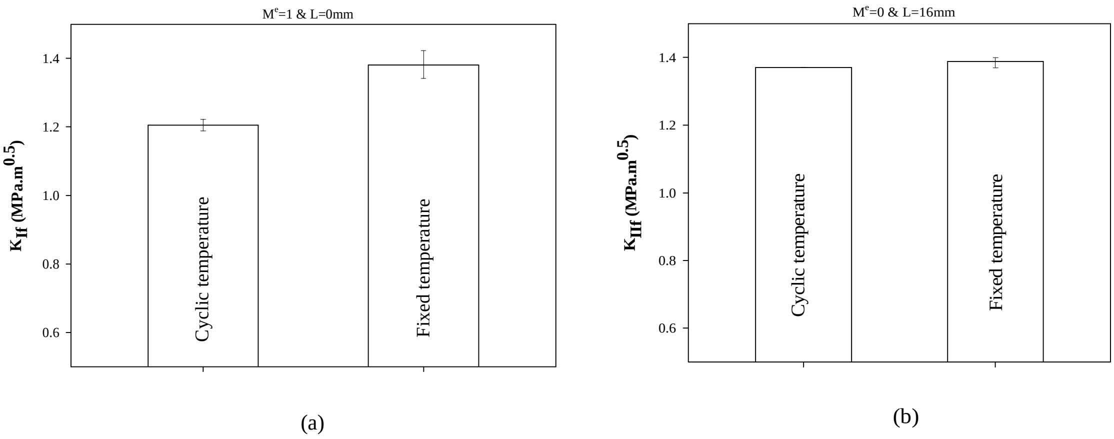


Fig. 7 Critical stress intensity factors for different weather conditions and loading modes

Numerous fracture criteria have been introduced in the past. Some of which are listed below

- *Maximum tangential stress* (suggested by Erdogan and Sih 1963)
- *Generalized maximum tangential stress* (suggested by *Smith et al.* 2001)
- *Maximum energy release rate* (suggested by *Irwin* 1957)
- *Strain energy density* (suggested by *Sih* 1974)

In the present work, MTS criterion was chosen to predict the onset of crack growth in the asphalt concrete. A brief description of the criterion is presented b herein. Stress distribution at the crack tip in a cracked body can be written as

$$\sigma_{rr} = \frac{1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_{\mathrm{I}}\left(1+\sin^2\frac{\theta}{2}\right)+\frac{3}{2}K_{\mathrm{II}}\sin\theta - 2K_{\mathrm{II}}\tan\frac{\theta}{2}\right] \tag{4}$$

$$\sigma_{\theta\theta} = \frac{1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_{\mathrm{I}}\cos^2\frac{\theta}{2}-\frac{3}{2}K_{\mathrm{II}}\sin\theta\right] \tag{5}$$

$$\sigma_{r\theta} = \frac{1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_{\mathrm{I}}\sin\theta + K_{\mathrm{II}}\left(3\cos\theta - 1\right)\right] \tag{6}$$

where r and θ are the crack tip co-ordinates and σ_{rr}, $\sigma_{\theta\theta}$ and $\sigma_{r\theta}$ are the stress components in the polar co-ordinate system. According to the MTS criterion, the direction of fracture initiation angle θ_0 can be determined from

$$\frac{\partial\sigma_{\theta\theta}}{\partial\theta}\Big|_{\theta=\theta_0} = 0 \Rightarrow \left[K_{\mathrm{I}}\sin\theta_0 + K_{\mathrm{II}}\left(3\cos\theta_0 - 1\right)\right] = 0 \tag{7}$$

Brittle fracture also occurs once the right hand side of the following equation reaches the mode I fracture toughness, $K_{\mathrm{I}c}$

$$K_{\mathrm{I}c} = \cos\frac{\theta_0}{2}\left[K_{\mathrm{I}}\cos^2\frac{\theta_0}{2} - \frac{3}{2}K_{\mathrm{II}}\sin\theta_0\right] \quad (8)$$

From the Eqs. (7) and (8), MTS criterion predicts the fracture initiation at $K_{\mathrm{II}}/K_{\mathrm{I}c}$=0.866 for pure mode II loading. Based on the fracture results presented in Table 3, K_{IIf}/K_{If} is calculated as 1.0 and 1.1 for cyclic and fixed temperature conditions, respectively. By comparing these values for both of the fracture results with the value of MTS criterion (namely 0.866), it can be concluded that the MTS criterion correctly predicts the onset of fracture initiation although this prediction is slightly conservative.

5. Conclusions

• Fracture experiments were successfully carried out on the asphalt concrete using an improved SCB specimen under pure mode I and pure mode II in two different weather conditions of cyclic and fixed temperatures.

• The results demonstrated that the weather conditions significantly affect the fracture toughness of asphalt concrete. In other words, asphalt concrete resist less in a real weather conditions namely cyclic temperature than the fixed temperature. Hence, neglecting the impact of temperature cycling would result in overestimating the measured fracture toughness of asphalt concrete.

• For mode I loading, the path of crack growth was straight and along the initial crack; while, for pure mode II loading, crack progressed along a curvilinear path.

• The fracture resistance was affected by loading mode. Moreover, the loading mode did not equally affect the values of fracture toughness for the two studied weather conditions.

• The maximum tangential stress (MTS) criterion was used to predict the fracture initiation. The comparisons were made with the fracture results, and it was found that the MTS criterion correctly predicts the onset of fracture initiation although this prediction was slightly conservative.

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