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Impact of thickness, void content, temperature and loading rate on tensile fracture toughness and work of fracture of asphalt mixtures- An experimental study using the SCB test

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A B S T R A C T

Asphaltic concrete mixtures are among the most common construction materials for the pavement of roads. As a multi-phase composite mixture with randomly distributed aggregates inside the mastic part, the mechanical properties of such materials can be influenced by different factors. Cracking and induced fracture is among the common degradation and failure modes in these construction mixtures that often takes place in cold regions. In this research, the effects of some influencing parameters including temperature, air void percentage and loading rate are investigated experimentally on the fracture toughness (K_{Ic}) and work of fracture (W_{Ic}) of hot mix asphalt material. Edge notched semi-circular bend (SCB) specimen was employed to conduct mode I fracture experiments. The thickness of SCB samples were considered as variable and the HMA mixtures were tested with two SCB thicknesses of 30 and 60 mm. The experimental results showed that both fracture toughness and fracture work are increased by increasing the thickness. However, the effect of thickness on the fracture work was much more significant than the K_{Ic} value. Also, the fracture and cracking resistance parameters were increased by decreasing the temperature and air void content. Both K_{Ic} and W_{Ic} values were also increased by increasing the loading rate in the investigated range of 1 to 8 mm/min. The most influencing parameters on the change of fracture resistance parameters were the temperature, loading rate, air void content and thickness, respectively.

1. Introduction

Asphaltic mixtures are among the very common construction and building materials for the superstructure paving of the roads. Such materials can be categorized as multi-phase and heterogeneous composites in which their strength and mechanical properties may depend on the mix design and ingredients. A typical asphalt mixture is composed of some main parts such as coarse and fine stone aggregates, binder or bitumen, air void and some additional and optional materials such as fillers, additives, reinforcing fibers, etc. The overall strength and load carrying capacity of the resultant asphalt concrete is a function of the mechanical properties and weight percentage of each part and ingredient. Also as a visco-elastic and temperature dependent behavior that is seen for the bitumen material the overall mechanical performance of asphaltic mixtures or overlays may also be dependent significantly on the environmental conditions such as speed of vehicles, heavy/light traffic, moisture, raining or snowing, daily or seasonal gradient of temperature, freezing-thawing mechanism and etc (Alkofahi & Khedaywi, 2021; Žiliūtė et al., 2016; Watson & Rajapakse 2000; Solaimanian et al., 2003; Karimi et al., 2021; Salour & Erlingsson 2013; Gupta et al., 2014; Yao et al., 2014; Badeli et al., 2018; Aburawi 2022). Therefore, some major failure modes and distress sources such as crack initiation and propagation, rutting, moisture damage, striping, fatigue damage etc. are often observed in the overlays and pavements in real situations as investigated in the aforementioned research works. The failure mode in asphaltic mixtures is mainly controlled by the service temperature such that at low temperature conditions cracking and brittle or rapid fracture of mixture is the dominant loading mode (Marasteanu et al., 2002; Shahryari et al., 2021; Dave et

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al., 2011, 2019; He et al., 2022). By increasing the temperature, failure mode switches to rutting that is not as dangerous as the cracking mode (Das & Singh 2017; Jahangiri et al., 2019; Huang &Wang 2021).

A large number of academic and technical efforts have been done during the last four decades to study and understand the cracking and fracture phenomenon in asphaltic mixtures. These works can be categorized in theoretical studies, numerical analyses and simulations, experimental studies at laboratory scales, real scale and field investigations (Liu et al., 2019; Al-Qudsi et al., 2020, Gao et al., 2015; Ling et al., 2017; Nian et al., 2021; Ahmed et al., 2013; Loizos et al., 2009; Kim et al., 2005; Ziari et al., 2019; 2022; Ameri et al., 2011; Aliha et al., 2021; Yin, 2015; Frigio et al., 2015; Golalipour et al., 2021). From the laboratory scale fracture experiments, a number of test samples and methods have been utilized by different researchers and asphalt research comminutes. Circular and disc shape samples are among the suitable and favorite testing configurations for asphaltic mixtures in the laboratory studies. This is because of convenience of specimen manufacturing and preparation from cylindrical Marshall or Gyratory compacted samples. In this regard, semi-circular bend (SCB), compact tension disc (CTD), edge notched disc bend (ENDB), edge notched compressed disc (ENCD), Brazilian compressed disc (BCD), wedge splitting disc (WSD) are some well-known circular shape test samples (Li et al., 2008; Yang et al., 2021; Kaloush et al., 2010; Mubaraki et al., 2013; Pirmohammad & Bayat 2016; Stewart et al., 2018). Using the aforementioned test samples, the effect of various parameters including the geometry effect, size effect, loading rate effect, temperature effect, environmental effect, mix-design effect have been investigated on cracking response and fracture behavior of asphaltic mixtures (Mandal et al., 2019; He et al., 2021; Shahryari et al., 2021; Zhu et al., 2018; Xiongzhou et al., 2021; Haghighatpour et al., 2018; Fuan et al., 2021). For example, Haghighatpour and coworkers (2018), studied the effect of height of ENDB specimen on mode I fracture toughness of hot mix asphalt (HMA) at low temperature conditions. Similarly, using the ENDB specimen Eghbali et al. (2019) investigated the mode I fracture toughness and fracture energy of stone mastic asphalt (SMA) mixture with different ENDB geometries. Motamedi et al. (2020) also investigated the effect of loading rate and temperature on fracture behavior of fiber reinforced asphalt concrete under mode I loading. Kaloush and coworkers (2010) tested fiber reinforced asphalt mixture using novel wedge splitting disc loaded with a wedge device.

Using different testing configurations and test samples including the ENDC and BD specimens , Yang et al. (2021) and Fuan et al. (2021) compared the influence of specimen geometry on mode I fracture response of asphaltic mixtures. Stewart et al. (2018) tested an asphalt concrete using the DCT specimen to explore the influence of thickness and ligament area on low temperature fracture behavior. Fakhri et al. (2020) and Haghighatpour and Aliha (2022) assessed the impact of freezing and thawing mechanism on the low temperature fracture toughness of asphaltic samples under modes I/II and I/III using the SCB and ENDB specimens. Fakhri and coworkers (2018), Aliha et al. (2018) and Molayem et al. (2021) studied some parameters such as fracture energy and load – CMOD results of hot mix asphalt concrete under intermediate temperatures tested with different loading modes and loading rates. The SCB test was utilized in the mentioned samples. Fatigue and J-integral analyses of cracked SCB specimens made of HMA mixture modified with carbon nanotube additive was also investigated by Ameri et al. (2016). The use of additives (such as poly phosphoric acid (PPA), Styrene Butadiene Styrene (SBS), anti-stripping agent, crumb rubber (CR) and F-T paraffin wax (Sasobit)), waste materials (recycled polyethylene terephthalate (PET) bottles), fibers (such as jute or synthetic forta-ferro), recycled asphalt mixtures (RAP), waste aggregates and etc on the mixture of asphalt concrete and the resultant effect on the mechanical and cracking resistance properties have also investigated widely in the literature (Zarei et al., 2022; Mubaraki et al., 2019; Abdulshafi et al., 2002; Hamedi et al., 2020; Somé et al., 2018; Najjar et al., 2019; Yousefi et al., 2021; Aliha et al., 2017, 2019; Ziari et al., 2020; Moniri et al., 2021; Najjar et al., 2022a,b; Mansourian et al., 2018; Asdollah-Tabar et al., 2021; Tahmoorian et al., 2020, 2022). Although such additives may reduce the strength properties of the resultant asphaltic concrete, such materials have some advantages from economic and environmental aspects and they are called cleaner concrete products. Therefore, the use of such materials has received much attention in the industrial and real construction applications.

Among the available test specimens employed for asphalt cracking resistance study the SCB specimen is the simplest one that has been received more attention by the researchers (Bui et al., 2021; Falchetto et al., 2018; Mirsayar et al., 2017; Mubaraki and Sallam 2020; Zhang et al., 2019; Yuan et al., 2020; Aliha et al., 2020; Behbahani et al., 2013a,b; Cannone Falchetto et al., 2017; Saha and Biligiri 2016; Saed et al., 2022; Ashani et al., 2022; Mohammad et al., 2012; Biligiri et al., 2012; Amirdehi et al., 2019; Chen et al., 2009). This test specimen was suggested by AASHTO and ASTM standards for determining the fracture toughness of hot mix asphalt materials (AASHTO, 2015, 2016). Two common outputs, (i) fracture toughness and (ii) fracture energy indexes, can be obtained from the SCB test for characterizing the cracking behavior of asphaltic mixtures. The first index describes the load bearing capacity and resistance of material against fracture initiation and the later shows the energy required for the failure and breakage of the sample. Based on the literature review of published works some important parameters such as thickness of SCB, test temperature, rate of applied loading and void percentage of HMA mixtures can affect the fracture behavior of such construction materials. However, the importance of such factors on the overall cracking response of asphaltic mixtures has not been investigated deeply and comprehensively in the past. This paper investigates the effects of these four parameters on fracture toughness and work of fracture HMA materials using the SCB specimen. A large number of fracture experiments are conducted on the SCB samples with different thickness under different loading rates and low temperatures. The impact and importance of each parameter on the fracture toughness and fracture work is investigated and discussed.

2. Test specimen for fracture study of HMA mixtures

As stated in the previous section the SCB specimen was selected to conduct the experimental fracture studies of current research. The SCB specimen is a semi-circular shape specimen with diameter *D* and width *B* as shown in Fig. 1 schematically. A vertical notch with length and width of (a and t, respectively) is created in the middle of the flat edge of the semi-disc. At this condition if the specimen is loaded by a three-point bend fixture with symmetric bottom loading span of 2*S*, pure mode I (pure tensile deformation of the crack faces) occurs. In the framework of fracture mechanics a key-parameter characterizing the stress field ahead of the crack tip is called the stress intensity factor (SIF). The SIF for the SCB specimen under mode I loading condition is function of disc radius, disc thickness, notch length and the loading span and can be obtained from the below formulation (Aliha et al., 2015):

$$K_{\mathrm{I}} = \frac{\mathrm{P}}{\mathrm{D.B}}\sqrt{\pi \mathrm{a}}\, f\left(\frac{\mathrm{a}}{\mathrm{D}}, \frac{2\mathrm{S}}{\mathrm{D}}\right) \tag{1}$$

In this formulation, *f* (a/D and 2S/D) is the geometry factor that is the function of crack length ratio (a/D) and span length ratio (2S/D). This geometry factor has already been determined in previous works by numerical analysis of the SCB specimen. Table 1 presents the corresponding values of "*f* " for the SCB specimen under different loading conditions and notch depths.

Table 1. Geometry factor of SCB specimen for different conditions under pure mode I case.

			a/D= 0.15			
2S/D	0.3	0.4	0.5	0.6	0.7	0.8
f (a/D and 2S/D)	0.99	1.81	2.58	3.33	4.08	4.85
			a/D= 0.2			
2S/D	0.3	0.4	0.5	0.6	0.7	0.8
f (a/D and 2S/D)	1.23	2.08	2.93	3.76	4.60	5.47
			a/D= 0.25			
2S/D	0.3	0.4	0.5	0.6	0.7	0.8
f (a/D and 2S/D)	1.67	2.63	3.60	4.57	5.54	6.52
			a/D= 0.3			
2S/D	0.3	0.4	0.5	0.6	0.7	0.8
f (a/D and 2S/D)	2.43	3.65	4.87	6.09	7.32	8.54

The critical value of SIF at the onset of mode I failure is known as the "fracture toughness". Therefore, the fracture toughness of asphaltic mixtures tested with the SCB configuration can be determined by inserting the peak or the maximum load carried by the sample into the Eq. 1.

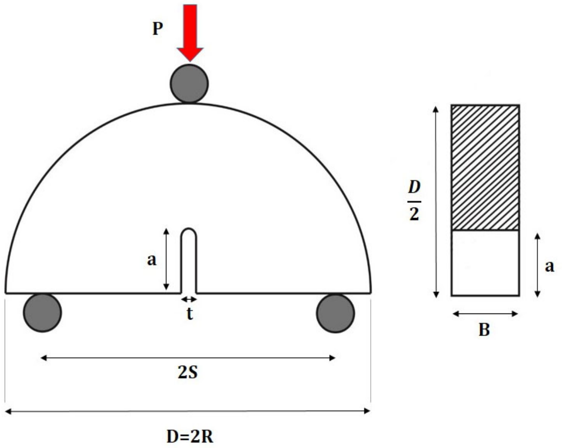

Fig. 1. Configuration of the SCB specimen for mode I fracture study of asphaltic mixtures

3. Mixture design and asphalt sample preparation

For manufacturing of hot mix asphalt samples of this research, siliceous aggregates with gradation No. 4 (according to the Iranian highway and road paving standard known as: code-234) was utilized. The Nominal Maximum Aggregate Size for this gradation is 19 mm. The gradation and weight percentage of aggregates are illustrated in Table 2. The bitumen used for the binder of hot mix asphalt was common bitumen with penetration grade of 60/70 and performance grade of 64-24. This type of bitumen is often used in the construction of roads in many countries with different temperature ranges and environments. Some basic properties of such bitumen material are illustrated in Table 3. After gradation of sieve sizes and stone aggregates, the Marshall standard mix-design method was employed and the aggregates were mixed with binder at 155˚C. The resultant mixture were then poured into the cylindrical molds with diameter of 150 mm and height of 130 mm and compacted using a Superpave Gyratory Compactor with two gyratory rotations of 30 and 100 rotations. This operation was led to final hot mix asphalt mixtures with air void percentages of 3 and 7%, respectively.

Table 2. Gradation of stone aggregates used for mix-design of asphaltic mixture of this research.

Aggregate passing percentage %	aggregate size (mm)
100	19
90-100	12.5
78-82	9
44-74	4.75
28-58	2.36
5-21	0.3
2-10	0.075

Table 3. Properties of 60/70 bitumen used for the mixture of HMA.

Property	Standard	value
Specific Gravity @ 25 °C	ASTM D70	1.03 gr/cm^3
Ductility @ 25 °C	ASTM D113	100 cm
Kinematic Viscosity @ 120 °C	ASTM D2170	811 mm^2/s
Kinematic Viscosity @ 135 °C	ASTM D2170	420 mm^2/s
Kinematic Viscosity @ 150 °C	ASTM D2170	233 mm^2/s
Flash Point	ASTM D92	307°C
Penetration (25 °C)	ASTM D5	63°C
Penetration index (PI)a	–	-1.12

The cylindrical samples were then cut and sliced perpendicular and along the cylinder axis to create semi-circular samples. For investigating the effect of specimen thickness on the fracture behavior the thickness of semi-discs were considered as 30 and 60 mm. A vertical notch with length of 23 mm was created at the middle of each semi-disc using a rotary diamond saw blade. The width of the blade was about 2 mm. Hence the final width of created notches in the manufactured SCB samples was less than 2.5 mm. In order to investigate low temperature cracking resistance of the manufactured hot mix asphaltic samples, half of the samples were stored at 0^{o}C and the rest of them were stored at -20^{o}C for about one day.

4. Cracking resistance study and fracture experiments

Fig. 2 presents the selected variables and input parameters for conducting the experimental study of this research. All the manufactured SCB samples were tested under three-point bending with constant loading span of $2S$ = 120 mm (i.e. $2S/D$ = 0.8). The specimens were loaded monotonically with two cross head speeds of 1 and 8 mm/min with four replicates for each testing condition. The load versus displacement curves (typically shown in Fig. 3 for one of the SCB samples) were obtained for the all test samples. Fig. 4 presents the experimental set up for mode I testing of the SCB sample before and after failure stage. The peak load value was used to calculate the critical SIF or fracture toughness for the tested SCB samples via employing Eq. (1). Also the area below the load-displacement curve (that is equal to the work of fracture) is another characteristic index for cracking study of materials including the hot mix asphalt mixtures. The corresponding values of these two fracture parameters are determined and presented in the next section for different testing conditions in the investigated asphaltic mixtures.

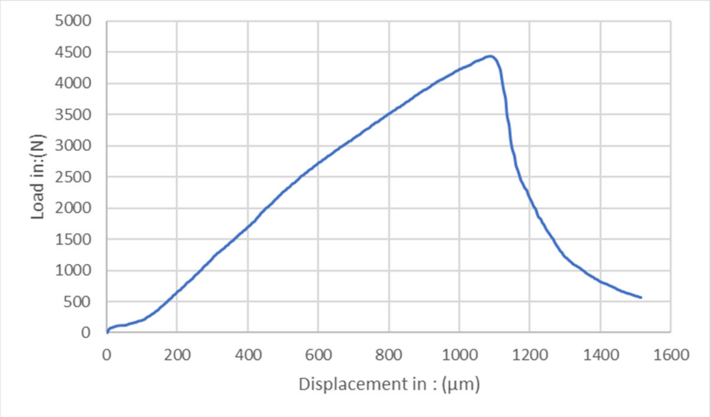

Fig. 3. Sample example of load versus displacement curve obtained from the SCB testing under mode I


(a) (b)

Fig. 4. (a) Experimental test set up utilized for the notched SCB testing, (b) failed specimen after testing.

5. Results and discussion

The experimental results obtained for low temperature cracking resistance of hot mix asphalt mixture using the SCB tests are presented in Table 4. Based on these data it is obviously seen that all the investigated input parameters including the thickness of specimen, air void content, loading rate and test temperature affects the fracture toughness and fracture energy values. Depending on the testing condition, the fracture toughness of tested HMA mixture varies typically in the range of 0.6 and 0.9 MPa.m$^{0.5}$. This range lies well in the reported range for low temperature fracture toughness of similar asphalt mixtures in previous works (Fuan et al., 2021; Haghighatpour et al., 2018; Shahryari et al., 2021; Eghbali et al. (2019); Motamedi et al., 2020; Ziari et al., 2019; Xiongzhou et al., 2021; 2022; Ameri et al., 2011). However, the importance of such parameters on the output parameters is not the same and depends on the given variable. For example, as seen from Fig. 5 that compares the trends of all data set for both fracture toughness and fracture energy indexes, it is seen that the cracking resistance reduces or increases by changing the input variables.

Table 4. Experimental fracture results obtained for the tested SCB specimen under different testing conditions.

Thickness (mm)	Temperature (ºC)	Air void (%)	Loading rate (mm/min)	K_{Ic} (MPa.m$^{0.5}$)	W_{Ic} (J)
30	0	3	1	0.684	1.955
30	0	3	8	0.753	2.189
30	0	7	1	0.524	1.523
30	0	7	8	0.612	1.769
30	-20	3	1	0.761	2.210
30	-20	3	8	0.812	2.503
30	-20	7	1	0.608	1.702
30	-20	7	8	0.668	1.875
60	0	3	1	0.781	4.342
60	0	3	8	0.834	4.679
60	0	7	1	0.625	3.527
60	0	7	8	0.659	3.734
60	-20	3	1	0.852	4.820
60	-20	3	8	0.873	4.932
60	-20	7	1	0.702	3.953
60	-20	7	8	0.726	4.485

The trends obtained from the experiments are presented and discussed further in the following. Fig. 6 illustrates the variations of K_{Ic} (Fracture toughness) and W_{Ic} (work of fracture) for the tested SCB specimen with different thicknesses. It is seen that by increasing the thickness of SCB specimens from 30 mm to 60 mm both fracture toughness and fracture work values are increased. But the increase in the value of W_{Ic} due to increase of thickness is much more significant than the K_{Ic} value. This is mainly because of the larger ligament area ahead of the crack front where the thickness of SCB specimen is increased such that results in higher energy required for the propagation of fracture via the ligament. This fracture may pass from both tight aggregates and softer bitumen or interface of aggregate and binder parts. The change in the K_{Ic} value by increasing the thickness is only about 8% demonstrating that the K_{Ic} parameter is not affected significantly by the thickness of the SCB specimen. But the results obtained from the thicker sample seem more reliable and rational than the thinner one for using in practical and field situations. This is because sufficient numbers of aggregates and volume of mastic material can be located in the ligament area of thicker SCB specimens.

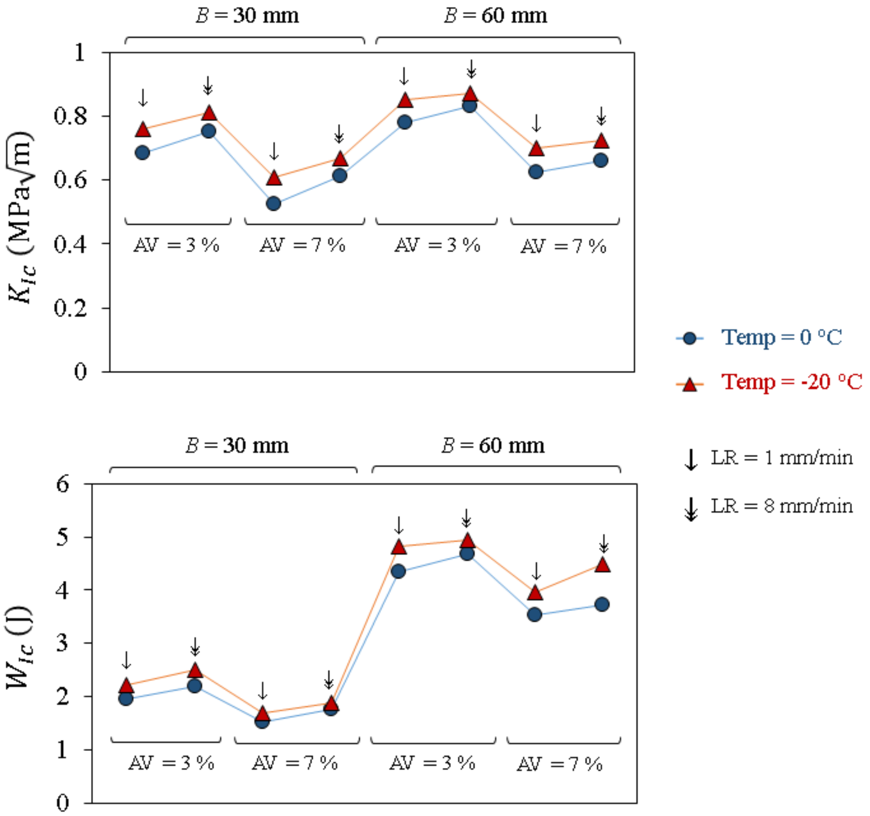

Fig. 5. General trends for the variations of K_{Ic} and W_{Ic} for the tested HMA mixture using the SCB test (*"B"*: represents the thickness of SCB, *"AV"*: represents the air void percentage, *"LR"*: represents the loading rate and *"Temp"*: represents the temperature).

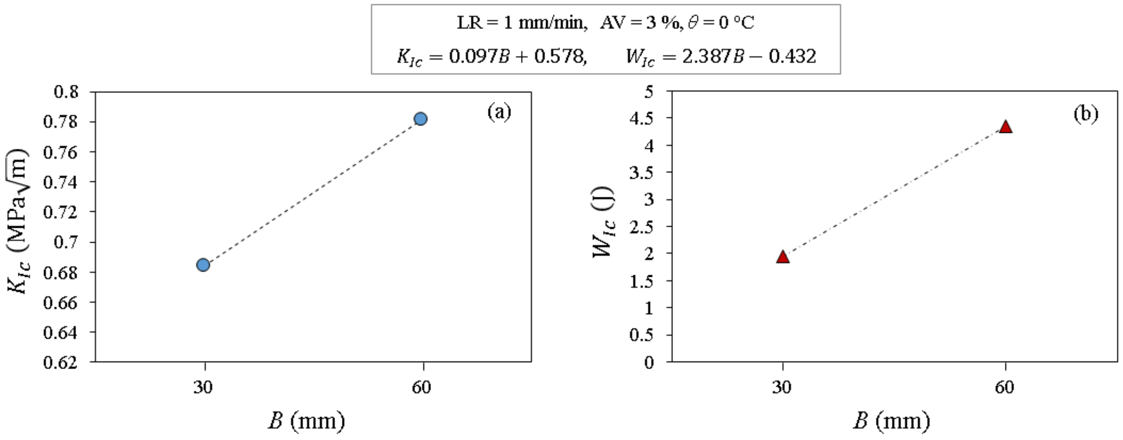

Fig. 6. The relationship between mode I fracture parameters (K_{Ic} and W_{Ic}) with the thickness of SCB specimen.

The influence of testing temperature on the fracture parameters of the investigated hot mix asphalt mixture is shown and compared in Fig. 7. As seen from these results, the corresponding values of K_{Ic} and W_{Ic} become more by decreasing the test temperature from zero to -20ºC. The bitumen used in the mixture of asphaltic mixtures is naturally a visco-elastic material and its mechanical behavior depends significantly on the temperature variation. The elastic modulus and stiffness of bitumen and consequently the whole asphaltic mixture increases by reducing the test temperature. This can be considered as the main reason to explain why the fracture toughness and work of fracture parameters (that are representative indexes for the resistance of asphaltic mixtures against cracking phenomenon) are enhanced by decreasing the test temperature. The curve of load-displacement data for the tested asphaltic mixtures showed a dominantly linear behavior and brittle type failure at such low temperature conditions. Therefore, the critical value of stress intensity factor obtained from the tested specimens at the onset of peak load can be considered as a representative index of fracture toughness. A linear regression relationship is therefore presented as Eqs. (3- 4) for estimating the values of K_{Ic} and W_{Ic} for other temperature ranges between 0 and -20ºC.

$$K_{\mathrm{Ic}} = -0.077\theta + 0.838 \qquad -20^{o}\mathrm{C} < \theta < 0 \tag{3}$$

$$W_{\mathrm{Ic}} = -0.255\theta + 2.465 \qquad -20^{o}\mathrm{C} < \theta < 0 \tag{4}$$

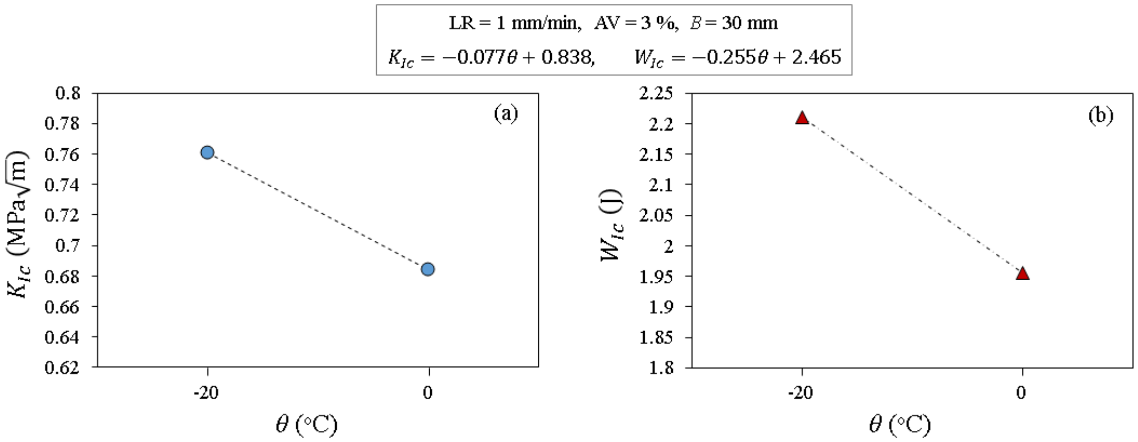

Fig. 7. Relationship between mode I fracture parameters (K_{Ic} and W_{Ic}) with the test temperature (θ) of HMA mixtures

In order to show the influence of air void content on the cracking resistance of asphaltic mixtures at low-temperature conditions, Fig. 8 presents the trends of K_{Ic} and W_{Ic} variations with air void percentage when this parameter varies from 3% to 7%. Both parameters are increased by decreasing the air void content. This finding seems rational and logical since the air void acts as a stress concentration factor inside the mixture of asphaltic concrete and increasing the number of such voids or air bubbles in the mixture can increase the risk of cracking and the fracture resistance of the hot mix asphaltic material. Indeed, by increasing the number of air bubbles the probability of initiation and coalescence of micro cracks from the boundary of air voids increases. Therefore, the overall load bearing capacity of the whole HMA mixture containing a greater number of voids can be reduced. In field situations, since the asphalt pavements and overlays are compacted more and more gradually by the passage of vehicles; it is expected that the rate of degradation in the asphalt will become slower due to lower void content. However, on the other hand the aging of bitumen and mastic parts has a negative effect on the performance and integrity and service life of the asphaltic mixtures such that in general the fracture resistance of aged and compacted overlays becomes lesser during the service life.

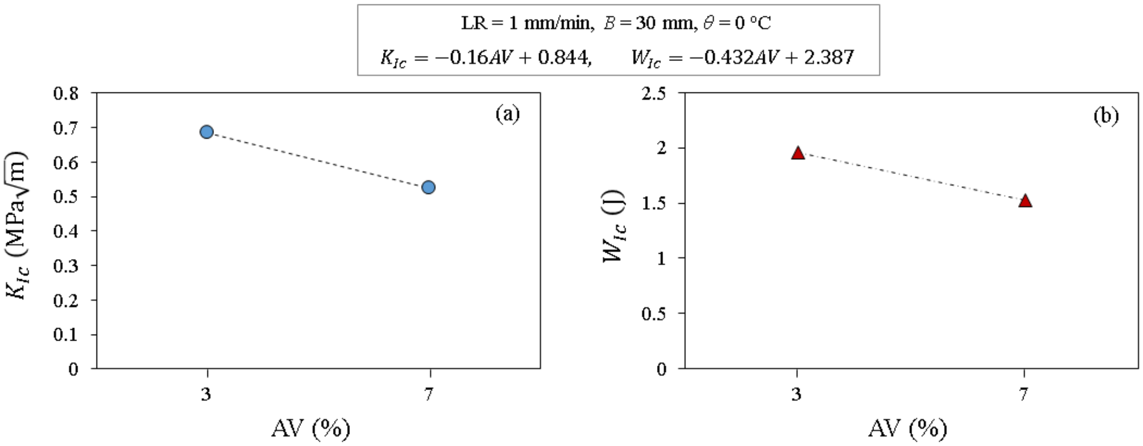

Fig. 8. Relationship between (a) K_{Ic} with the air void (AV) percentage of HMA and (b) W_{Ic} with the AV percentage in the tested HMA mixtures at low-temperature condition.

Fig. 9 also presents the variations and trends of mode I fracture parameters (K_{Ic} and W_{Ic}) with the loading rate. As the loading rate increases from 1 to 8 mm/min, both fracture parameters are increased slightly (up to 15%). Such improvement in the load carrying capacity of cracked asphalt mixtures with increasing the loading rate can be attributed to the stiffness of bitumen and visco-elastic nature of bitumen material. Increasing the loading rate in the laboratory experiments can be related to the speed of traffic loads and vehicles passing from the cracked overlays. Based on the experimental results of this research, by faster moving of the vehicles from the overlay the probability and risk of fracture propagation in the top-down cracks is reduced.

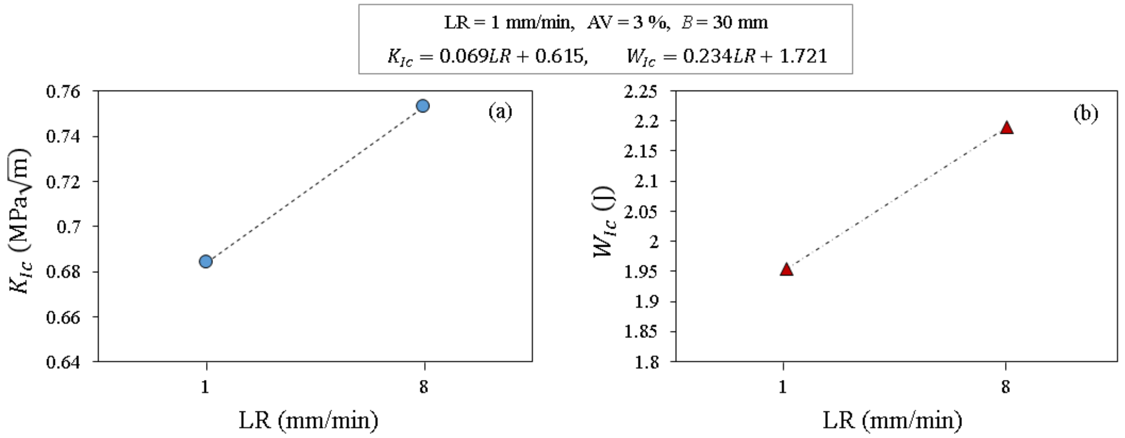

Fig. 9. The effect of loading rate on mode I fracture behavior of tested HMA concrete: (a) K_{Ic} versus LR and (b) W_{Ic} versus LR.

Fig. 10 shows the path of fracture observed for the tested SCB samples at different testing conditions. The fracture trajectory of growing crack at low-temperature conditions reveals that the fracture path follows dominantly a straight line for different samples and conditions. But some small deviations are seen in the path of growing crack through the ligament to round the coarse aggregates located along the ligament zone. It is finally mentioned that the experimental study of this research showed that all input variables (i.e. SCB thickness, void content, loading rate and test temperature) can affect the fracture behavior but among the investigated variables thickness of SCB specimen and test temperature had the minimum and maximum influences on the fracture toughness value, respectively.

Fig. 10. Propagation path of mode I fracture in the tested asphaltic samples under different testing conditions

6. Conclusions

- Fracture characteristics of hot mix asphaltic mixtures were investigated under low temperature conditions using edge notched symmetric SCB specimens.

- The effect of specimen thickness, loading rate, ambient temperature and air void percentage on mode I fracture toughness (K_{Ic}) and mode I work of fracture (W_{Ic}) was studied.
- Both fracture parameters were increased by increasing the thickness of SCB and increasing the loading rate. Also these two cracking resistance indexes were increased by decreasing the test temperature and void percentage.
- The fracture behavior of tested asphaltic mixtures under the considered test conditions and for the selected variables was dominantly linear and some linear regression empirical relations were proposed for describing the trends of variations of K_{Ic} and W_{Ic} with the input variables.
- Among the investigated input variables, it was observed that the test temperature, the loading rate, air void content and the thickness of SCB have the most important effects on the fracture toughness of HMA mixture, respectively.

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