

Article

Contribution of Interface Fracture Mechanism on Fracture Propagation Trajectory of Heterogeneous Asphalt Composites

Jianxin He ^{1,2}, Liang Liu ^{1,2,*}, Haihua Yang ^{1,2}, M. R. M. Aliha ^{3,*} and Hamid Reza Karimi ^{3,4}

¹ College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, China; xjnydx_hjx@sina.com (J.H.); yt_3759@126.com (H.Y.)

² Xinjiang Key Laboratory of Hydraulic Engineering Security and Water Disasters Prevention, Urumqi 830052, China

³ Welding and Joining Research Center, School of Industrial Engineering, Iran University of Science and Technology (IUST), Tehran 16846-13114, Iran; karimi_h@civileng.iust.ac.ir

⁴ School of Civil Engineering, Iran University of Science and Technology, Tehran 16846-13114, Iran

* Correspondence: Liuhualiang1978@sina.com (L.L.); mrm_aliha@iust.ac.ir (M.R.M.A.)

Abstract: Asphalt mixture is a type of textured composite material made of aggregates and mastic part. Overall strength and failure behavior in such materials depends on the texture or heterogeneity of the mixture. In particular, the crack growth mechanism from the tip of the pre-crack is significantly affected by the texture of the asphalt composite and environmental conditions. The crack can extend through the soft mastic, tight aggregates or interface of the mastic/aggregates. In this research, by performing some fracture tests on a typical asphalt mixture with different test specimens under mode I, mixed mode I/II and mixed mode I/III, the fracture resistance and trajectory of propagating crack is studied at two low and medium temperatures (i.e., -15 and $+15$ °C). The load bearing capacity and the fracture resistance of the tested asphalt samples increases by decreasing the temperature. It is also shown that a significant part of fracture plane passes through the soft mastic and boundary of aggregates (i.e., the interface of aggregates and mastic) and only about 10–15% of the fracture surface of the propagating crack passes via the tight aggregates by breaking them. This percentage decreases for mode II and III loading conditions and higher testing temperatures. Compared to brittle and isotropic materials, the fracture path of the asphalt mixture shows more deviation, and this deviation increases for those mixtures containing coarser aggregates in the ligament and tested under medium temperature conditions.

Keywords: asphalt concrete; fracture trajectory; fracture surface; mode I; mixed mode I/II and I/III; heterogeneity and temperature effect; aggregate/mastic interface



Citation: He, J.; Liu, L.; Yang, H.; Aliha, M.R.M.; Karimi, H.R. Contribution of Interface Fracture Mechanism on Fracture Propagation Trajectory of Heterogeneous Asphalt Composites. *Appl. Sci.* **2021**, *11*, 3013. <https://doi.org/10.3390/app11073013>

Academic Editor: Mirmilad Mirsayar

Received: 23 February 2021

Accepted: 14 March 2021

Published: 27 March 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Cracking phenomena and the fracturing of pavements are common modes of failure in overlay structures, especially in cold regions [1–5]. At low temperature conditions, the probability of crack propagation from pre-existing flaws increases due to traffic loading or thermal fatigue loads induced by daily or seasonal temperature changes. A real asphalt mixture used in pavements is a multi-phase material made of some ingredients including coarse and fine aggregates, binder (or bitumen), air voids and sometimes additives in the shape of fibers or powders. Hence, the overall mechanical properties of these randomly distributed composites significantly depend on the mix-design and type of the ingredients [6–8]. In particular, the type of asphalt mixture can noticeably affect the load bearing capacity, fatigue life and propagation of fracture trajectory in these composites. Due to the loading type or environmental effects, the fracturing of asphalt pavements may take place in different basic modes including mode I (crack opening), mode II (crack in-plane sliding), mode III (crack out-of-plane tearing) and any combinations of these modes called mixed mode (e.g., mixed mode I/II, I/III, II/III or I/II/III) [9]. Accordingly,

several researchers have investigated the fracture behavior of these composite materials using different testing methods under the mentioned loading modes [9,10]. The fracture mechanics approach and linear elastic fracture mechanics were used in the mid-1970s for studying the fracture behavior of asphalt composite materials [10]. Afterwards, some experimental testing methods and test samples including the edge cracked rectangular beam specimen subjected to four-point bend loading and the semi-circular bend (SCB) specimen were employed by Molennar et al. [11,12] for investigating the mode I fracture of the asphalt mixtures. Other test configurations such as the modified indirect tensile disc (MITD) specimen [13], disc-shape compact-tension specimen [14], single edge notch beam (SENB) subjected to three-point bend [9,15], wedge splitting disc (WSD) [16], edge notch disc bend (ENDB) [17–24], edge notch disc diametral compression (ENDC) [25–27], center cracked Brazilian disc subjected to diametral compression [28], semi-circular bend (SCB) specimen [29–34], and hollow disc (or ring shape) specimen containing center crack and loaded diametrically [35] are some of the test configurations employed in the literature for investigating the fracture resistance of asphalt mixtures. Any of these test samples are suitable for simulating and conducting specific modes of fracture. For example, the MITD and WSD are suitable for pure mode I testing. Other test configurations such as the SCB, three-point bend, hollow disc ring and Brazilian disc samples can be utilized for both mode I and mixed mode I/II fracture testing. On the other hand, the ENDB and ENDC test samples are capable of conducting pure mode I and mixed mode I/III fracture tests on asphalt mixtures.

As a randomly distributed heterogeneous composite mixture and due to the difference in the mechanical properties of the soft mastic part and tight aggregates, it is evident that the fracture behavior of asphalt mixtures depends on the location of initial crack inside the mixture. Indeed, if the pre-crack is located inside the aggregate or in the vicinity of bigger aggregates this can result in increasing the fracture resistance. Conversely, the cracking resistance of the asphalt mixture is reduced if the initial crack tip is placed inside the binder or soft mastic or fine aggregate mixture part. In addition to the influence of heterogeneity on the fracture strength of asphalt mixtures, the texture and composition of mixture can affect the path of propagating crack. Since the material is not homogenous, random distribution of aggregates inside the matrix of binder, soft mastic or fine aggregate matrix, may affect the trajectory of fracture during the crack propagation. Indeed, the crack can grow through the tight aggregates, soft mastic or interface of aggregate/mastic parts.

For more realistic analysis of the cracked asphalt mixtures, it is better to consider the asphalt composite material as a heterogeneous mixture, and hence some research papers have focused on the failure behavior of asphalt mixtures from this viewpoint. For example, Kim et al. [36] used discrete element method (DEM) and image processing technique (IPT) for 2-D modeling of a cracked heterogeneous asphalt mixture. Zhao et al. [37] investigated the growth and propagation of cracks using the semi-circular bend (SCB) samples by means of IPT and numerical modeling. They estimated the crack propagation path using the cohesive elements. Dai et al. [38] used 2-D finite element (FE) modeling and IPT to predict the fracture behavior of asphalt mixtures. Their goal was to predict the fracture path of the asphalt mixture under indirect tension. NG and Dai [39] numerically predicted the path of crack growth for the SENB and split tensile (ST) samples. Aliha et al. [40] used the aggregate generation and packing algorithm (AGPA) and 2-D FE models to estimate the trajectory of fracture in the SCB samples. They found that heterogeneous modeling of asphalt mixtures leads to a more realistic prediction for the path of crack propagation and the mode I and mode II stress intensity factors are sensitive to the crack tip location. Using the FE modeling and AGPA method [41–43] Aliha and coworkers also simulated the fracture behavior of asymmetric semi-circular bend (ASCB) sample by assuming the heterogeneity for the asphalt mixtures. Li and Guo [44] employed the AGPA and FE models to estimate the trajectory of crack growth in the SCB samples. They concluded that the distribution of aggregates, gradation, and angularity of the aggregates have considerable effects on the

path of fracture. Yin et al. [37,45] showed that the path of crack growth is sensitive to the aggregate distribution and cohesive strength of the aggregate/mastic interface.

However, in most of the previous works the effects of composite mixture and testing conditions have only investigated on the fracture toughness and load bearing capacity values. Indeed, very-limited studies are available for considering the influence of the mixture heterogeneity on the fracture trajectory and fracture surface of the asphalt composite mixtures at different testing and loading conditions. Therefore, in this research, using the results of experimental tests conducted on a typical asphalt mixture with different test geometries, the fracture trajectory is investigated for different loading modes and testing conditions. It is shown that the distribution of aggregates and testing temperature can significantly affect the path of mode I and the mixed mode fracture of the asphalt concrete.

2. Test Specimens

Some test samples including ENDB, SCB, BD, and SENB were selected for conducting the fracture experiment on the asphalt concrete and investigating the related fracture trajectory. Figure 1 shows the configurations of test samples. The ENDB specimen is a disc shape sample with radius R and height t that contains an edge crack along the disc diameter. By three-point bend loading of the disc and rotating the disc direction relative to the loading rollers, different combinations of mode I and mode III are introduced by the ENDB specimen. The SCB specimen is a semi-circular specimen with radius R and thickness t containing an edge crack of length a . The specimen is loaded by three-point bending and the state of mode I and II mixity can be altered by changing the crack inclination angle, crack location or loading roller distance relative to the crack as seen from Figure 1. The center crack Brazilian disc (BD) specimen is also a circular disc with radius and thickness R and t , respectively containing a center crack of length $2a$. Mode I and mixed mode I/II are obtained using this specimen by changing the crack inclination angle relative to the direction of diametral compression load applied to the disc specimen. The edge cracked beam specimen subjected to bend loading (i.e., SENB specimen) can be used for introducing pure mode I and some limited combinations of mode I and mode II (i.e., dominantly mode I case). The stress intensity factors (K_I , K_{II} and K_{III}) in the mentioned samples are functions of the specimen geometry and loading condition and can be written as:

$$K_i(\text{ENDB}) = \frac{3PS}{2Rt^2} \sqrt{\pi a} Y_i \left(\frac{a}{t}, \frac{S}{R}, \beta \right) \quad i = \text{I, III} \quad (1)$$

$$K_i(\text{SCB}) = \frac{P}{2Rt} \sqrt{\pi a} Y_i \left(\frac{a}{r}, \frac{S}{R}, \beta \right) \quad i = \text{I, II} \quad (2)$$

$$K_i(\text{BD}) = \frac{P}{Rt} \sqrt{\frac{a}{\pi}} Y_i \left(\frac{a}{R}, \beta \right) \quad i = \text{I, II} \quad (3)$$

$$K_i(\text{SENB}) = \frac{3PL}{tw^2} \sqrt{\pi a} Y_i \left(\frac{a}{w}, \frac{S}{L}, \frac{d}{S} \right) \quad i = \text{I, II} \quad (4)$$

where P is the applied load and Y_i are the geometry factors or normalized forms of the stress intensity factors that are functions of the specimen geometry and loading conditions [15,17,18,29,30,46,47]. The corresponding values of these geometry factors for any test specimen and mode mixity can be determined using the finite element analysis. For example, Table 1, illustrates the values of Y_I , Y_{II} and Y_{III} for pure and mixed mode loading conditions of the ENDB, SCB, BD, and SENB for some loading modes.

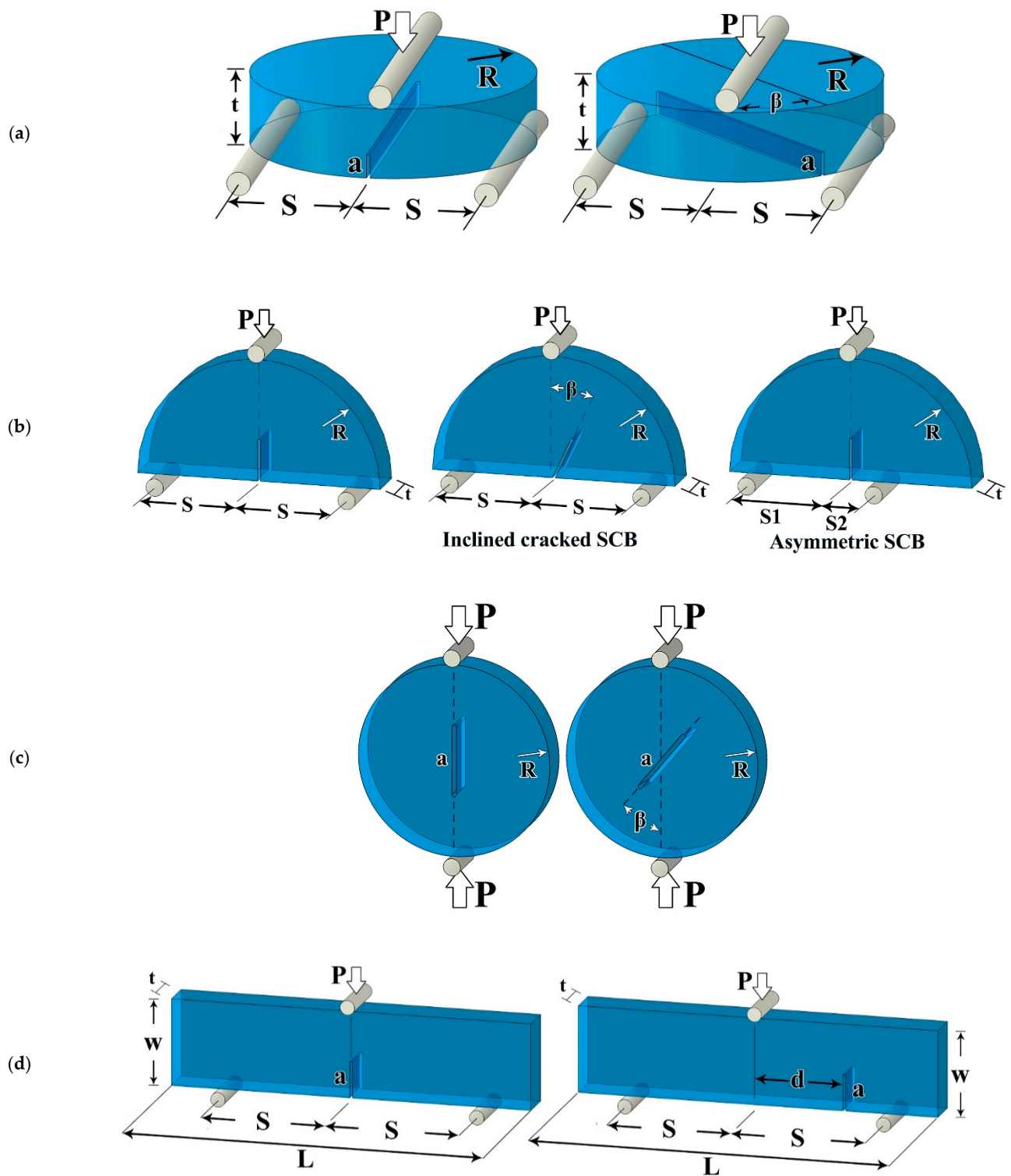


Figure 1. Description of test specimens employed for mode I, mixed mode I/II, and mixed mode I/III fracture; (a) edge notch disc bend (ENDB), (b) semi-circular bend (SCB), (c) Brazilian disc (BD) and (d) single edge notch beam (SENB).

Table 1. Corresponding values of geometry factors (Y_I , Y_{II} and Y_{III}) for the investigated test specimens under different mode mixities.

Specimen		Pure Mode I	Mixed Mode I/II	Pure Mode II	Pure Mode III	Mixed Mode I/III
SCB	Asymmetric SCB	Test condition	$S_1/R = 0.8$ $S_2/R = 0.8$	$S_1/R = 0.8$ $S_2/R = 0.083$	-	-
		Geometry factor	$Y_I = 4.0$	$Y_{II} = 21.37$	-	-
	Inclined cracked SCB	Test condition	-	$S/R = 0.65$ $\beta = 37^\circ$	-	-
		Geometry factor	-	$Y_{II} = 1.28$	-	-
ENDB	Test condition	$S_1/R = 0.9$ $S_2/R = 0.9$	-	-	$S/R = 0.95$ $\beta = 65^\circ$	$S/R = 0.95$ $\beta = 53^\circ$
	Geometry factor	$Y_I = 1.25$	-	-	$Y_{III} = 0.071$	$Y_I = 0.065$ $Y_{III} = 0.077$
BD	Test condition	$\beta = 0^\circ$	$\beta = 15^\circ$	$\beta = 28^\circ$	-	-
	Geometry factor	$Y_I = 1.1$	$Y_I = 1.1$ $Y_{II} = 0.8$	$Y_{II} = 1.8$	-	-
SENB	Test condition	$S_1/L = 0.7$ $S_2/L = 0.7$	$S/L = 0.7$ $d/S = 0.55$	-	-	-
	Geometry factor	$Y_I = 4.1$	$Y_I = 3.2$ $Y_{II} = 0.5$	-	-	-

3. Mix Design

The hot mix asphalt (HMA) of this research is composed of bitumen 60/70 with performance grade (64-22) and siliceous aggregates with the maximum nominal aggregate size (MNAS) of 12.5 mm. The physical properties of the used aggregates and also their gradations are illustrated in Tables 2 and 3, respectively.

Table 2. Physical properties of siliceous aggregates used for manufacturing the hot mix asphalt (HMA).

Test	Value	Test Method
Specific gravity	2.42 g/cm ³	ASTM C-127
L.A. Abrasion	23 (%)	AASHTO T-96
Absorption (coarse aggregate)	1.5 (%)	AASHTO T-85
Absorption (fine aggregate)	1 (%)	AASHTO T-84
Percent fracture (one face)	98 (%)	ASTM D5821
Percent fracture (two face)	91 (%)	ASTM D5821

Table 3. Aggregate gradation of the asphalt mixture.

Sieve Size	Passing Percent
19	100
12.5	95
9	80
4.75	59
2.36	43
1.18	30
0.5	18
0.3	13
0.15	8
0.075	6

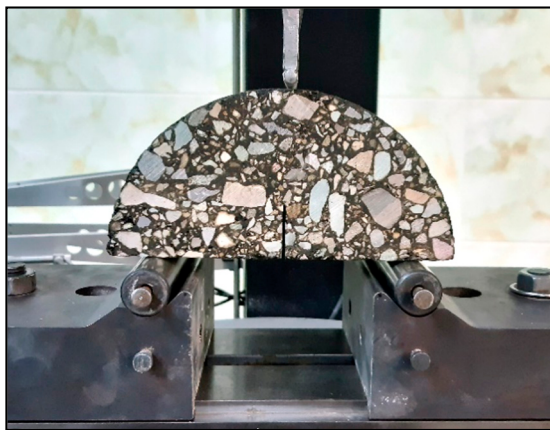
In order to determine the optimal percentage of bitumen, some asphalt samples with percentages of 4%, 5%, 6% and 7% bitumen were prepared. After mixing bitumen and aggregates, the samples were poured into a standard Marshall cylinder with diameter and height of 100 and 62.5 mm, respectively and compacted with a Marshall compactor (75 strokes per side of the sample). Based on some mechanical and physical parameters such as specific gravity of compacted asphalt, compressive strength, relative deformation of compacted asphalt mixture and volume of air void content, the optimal bitumen percentage for each asphalt mixture is determined. In this study, 18 cylindrical samples were manufactured and tested to obtain the control parameters of the mixtures. Table 4 shows the final physical and strength characteristics of the HMA material used for manufacturing the test specimens.

Table 4. Characteristics of manufactured HMA material.

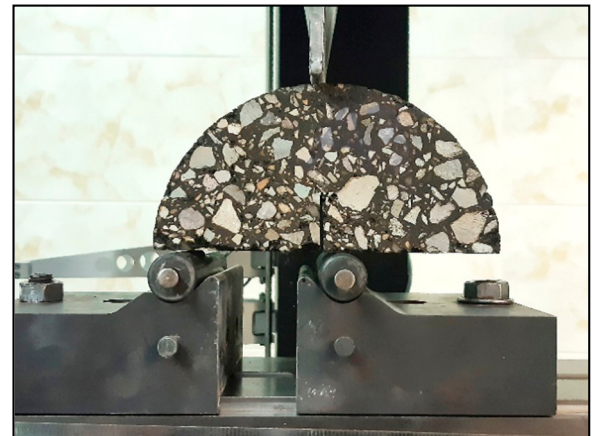
Optimal Bitumen (%)	Marshall Resistance (kN)	VMA * (%)	VFA ** (%)
5.8	12.2	14.6	67.8

* Voids in mineral aggregate (VMA): is the inter-granular space occupied by the asphalt and air void in a compacted mixture. ** VFA is the percentage of voids in the compacted aggregate mass filled with the asphalt mastic.

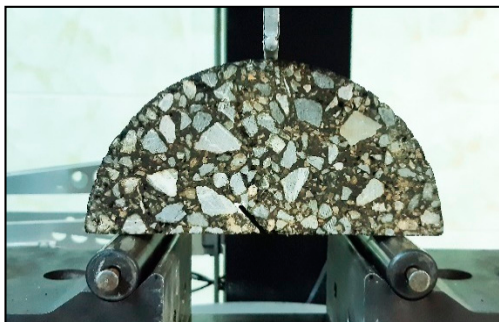
Using the obtained optimum bitumen percentage, the aggregate and binder were blended at 140 °C. Then for creating the disc shape samples including the ENDB, SCB and BD specimens the prepared mixture was compacted by a gyratory compactor machine (GCM) to produce cylindrical asphalt specimens with diameter of 150 mm and height of 120 mm. In addition, the beam samples were manufactured by casting the mixture inside a rectangular mold with dimensions of 400 × 50 × 50 mm³. Since, the air void content has noticeable influence on the mechanical and strength properties of the asphalt mixtures, the void percentage in all prepared asphalt samples was considered constant and equal to 4.7% for the sake of comparison of the experimental results. The manufactured cylindrical samples were then sliced by a specific designed fixture and by means of a high-speed rotary diamond saw blade to obtain circular discs of height approximately 35 and 50 mm. A very thin rotary diamond saw blade with thickness of 0.5 mm was used to introduce an initial artificial straight edge crack in the ENDB, SCB and SENB samples; but the center crack in the BD specimen was created using water jet cutting machine. The prepared test samples with different geometries were tested using a test machine at two test temperatures of −15 and 15 °C (room temperature). The loading rate in all experiments was constant and equal to 3 mm/min. Figure 2 shows the testing setup for some of the samples.



SCB



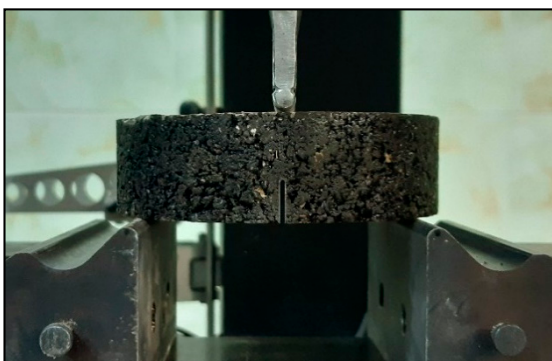
Asymmetric SCB



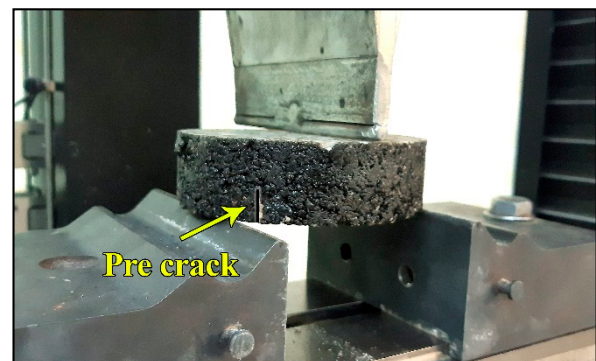
Inclined cracked SCB



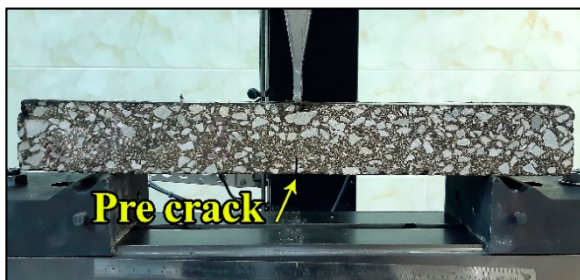
BD



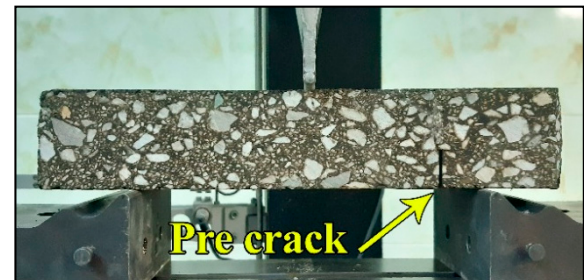
ENDB



ENDB



SENB



SENB

Figure 2. Experimental testing setup for conducting the fracture experiments under different loading modes and using different test configurations.

4. Results and Discussion

4.1. Fracture Resistance Values of Tested Samples

Figure 3 shows some of the load-displacement curves obtained for the tested ENDB, SCB, BD and SENB samples at low and medium temperature conditions. For the low temperature tests, it can be seen that the loading curves are linear and asphalt mixture exhibits as a brittle material. Therefore, the framework of linear elastic fracture mechanics (LEFM) is valid for this testing condition. However, some evidences of non-linearity in the load-displacement curves are seen for the medium temperature condition due to viscosity of bitumen material. However, the onset of fracture takes place for both temperature conditions at a critical level of loading applied to each sample. This situation is known by the peak load value in the load-displacement curve. Therefore, the critical value of stress intensity factor for each specimen can be determined by replacing the peak loads into Equations (1)–(4) and using the geometry factors given in Table 1. The results of critical stress intensity factors (K_{If} , K_{IIIf} and K_{IIIIf}) that are representative values for the resistance of tested asphalt mixtures at the onset of fracture initiation under different fracture modes and temperatures are presented in Table 5. The results illustrated in this Table, demonstrate the sensitivity of critical stress intensity factor value a same asphalt mixture to the geometry of test specimen (disc, semi disc and rectangular beam), loading mode (i.e., modes I, II, III or tensile, shear or tear type), loading type (compression, bending) and temperature (low and medium temperature). For example, for pure mode I loading and low temperature conditions in which the LEFM is valid, as shown in this research and explained in many previous works e.g., [1–10], where it can be seen that the K_{If} value of a same asphalt mixture depends on the test specimen utilized for testing. The value of mode I fracture toughness increases from 0.66 MPam^{0.5} (obtained from the BD specimen) to 0.82 MPam^{0.5} (obtained from the SCB specimen). According to recent works published by Aliha and co-workers [25,26,48], the mode I fracture toughness of asphalt mixtures depends on the geometry and loading conditions of the employed test specimen. Based on their finding (that is confirmed in this research as well), the mode I fracture toughness value obtained from the diametral compression test is lower than the value obtained by bending type specimen. They also proposed a theoretical model for considering the influence of geometry and loading condition on the mode I fracture toughness value of asphalt mixtures. Comparison of presented results in Table 5 also demonstrates that the fracture and cracking resistance of an asphalt mixture reduces generally under application of shear type loads (i.e., mode II and mode III) relative to opening mode failure. Furthermore, according to Table 5, the cracking resistance of the asphalt mixture decreases significantly by moving from the low temperature condition to the medium temperature condition. This could be due to reducing the stiffness of mastic or bitumen part at higher temperatures.

Table 5. Critical values of stress intensity factors obtained from different specimens under low and medium temperatures.

Specimen	Temperature	Pure Mode I	Mixed Mode I/II		Pure Mode II	Pure Mode III	Mixed Mode I/III	
		K_{If}	K_{IIIf}	K_{IIIIf}	K_{IIIf}	K_{IIIIf}	K_{IIIf}	K_{IIIIf}
SCB	Asymmetric SCB	Low	0.82	0.54	0.54	0.78	-	-
		Medium	0.38	0.21	0.21	0.34	-	-
	Inclined cracked SCB	Low	-	0.51	0.57	0.68	-	-
		Medium	-	0.20	0.23	0.29	-	-
ENDB	Low	0.78	-	-	-	0.45	0.41	0.48
	Medium	0.40	-	-	-	0.21	0.22	0.25

Table 5. Cont.

Specimen	Temperature	Pure Mode I	Mixed Mode I/II		Pure Mode II	Pure Mode III	Mixed Mode I/III	
		K_{If}	K_{If}	K_{IIIf}	K_{IIIf}	K_{IIIIf}	K_{If}	K_{IIIIf}
BD	Low	0.66	0.45	0.41	0.82	-	-	-
	Medium	0.32	0.25	0.22	0.45	-	-	-
SENB	Low	0.75	0.62	0.07	-	-	-	-
	Medium	0.36	0.29	0.03	-	-	-	-

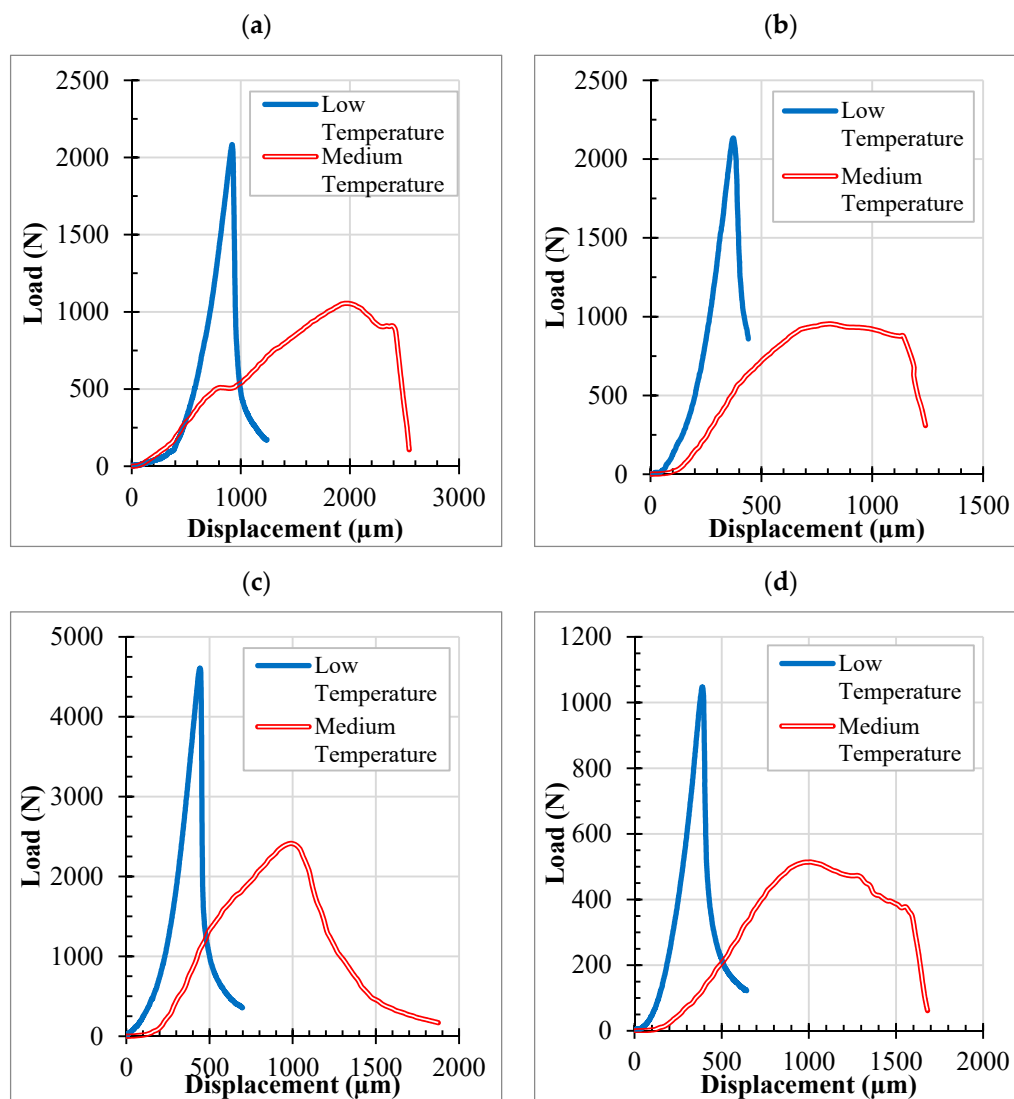


Figure 3. Typical load-displacement curves obtained by low and medium temperature tests; (a) ENDB, (b) SCB, (c) BD and (d) SENB.

4.2. Fracture Trajectory Results

4.2.1. Mode I Fracture

Figure 4 shows the fracture trajectories of the tested SCB, ENDB, BD and SENB specimens under mode I. For the pure mode I case, it is expected to see a self-similar and straight fracture path. The overall mode I fracture trajectory for the broken asphaltic samples is straight, but some deviations and local zig-zag type path is observed. The amount of deviation depends on some parameters such as the size of the aggregate,

the distribution of the coarse aggregate inside the asphalt mixture and also the testing temperature. Indeed, the propagating crack rounds the aggregates located in the ligament and in these regions an interface fracture between the boundary of the aggregates and the mastic part can control the mechanism of the asphalt fracture. However, if a coarse aggregate is located exactly in front of the crack tip or in the middle of the ligament and is oriented normal to the crack propagation path, the fracture can grow through such aggregates. This is probably because breaking the aggregate needs lesser energy than moving along the longer path of the aggregate's boundary (i.e., interface of aggregate and mastic) to round the aggregate. For those situations in which there is no aggregate in the route of fracture, the crack growth can occur with less energy and with the driving force through the mastic part. The path of fracture in such regions is straight with no significant kinking.

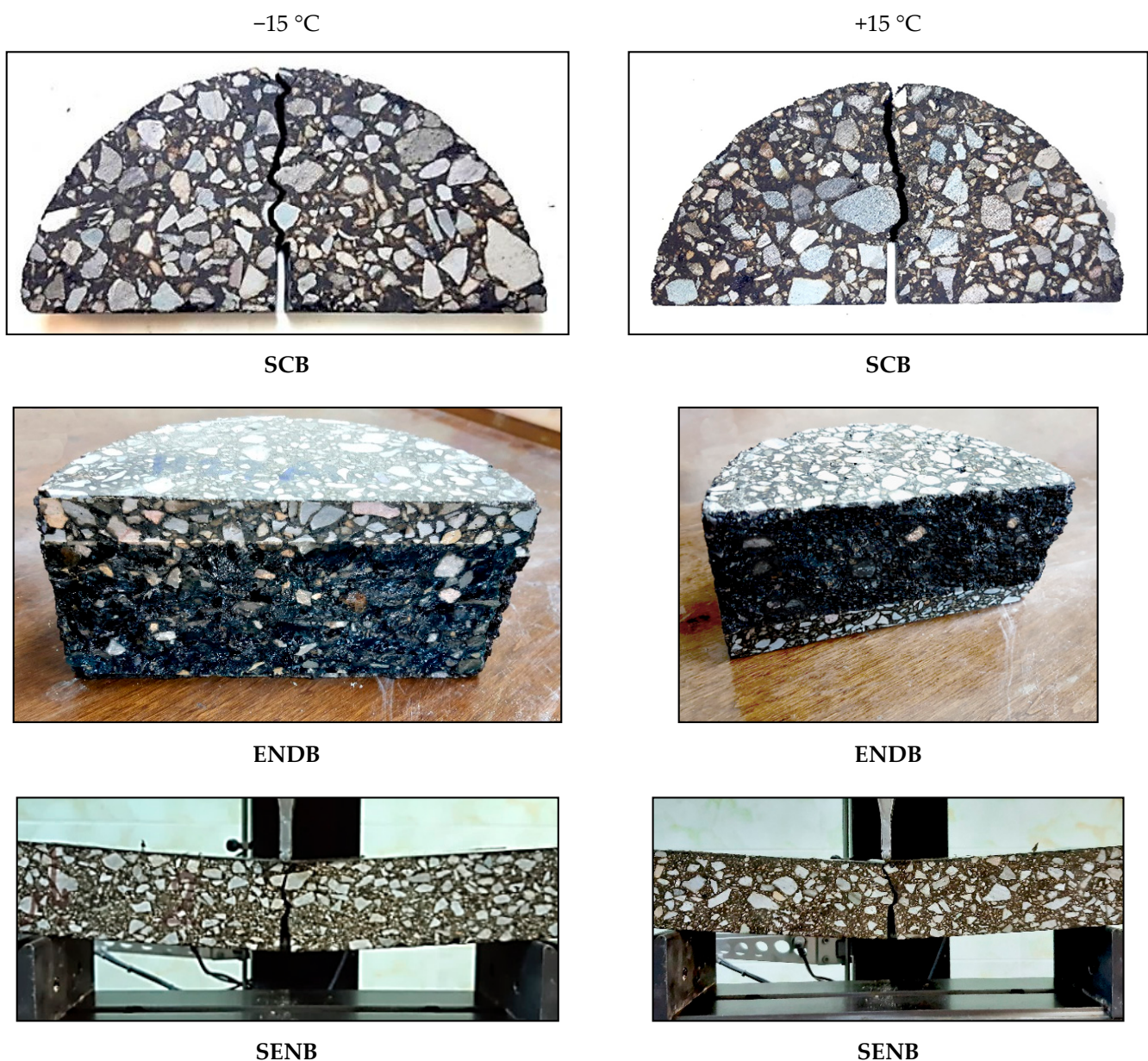


Figure 4. Mode I fracture trajectory observed for some of the tested configurations at low and medium temperatures.

Figure 5 shows different regions (i.e., through the aggregates, through the mastic and through the boundary of aggregates or interface of aggregates/mastic) for the growth of propagating crack inside the texture of an asphalt mixture under mode I loading.

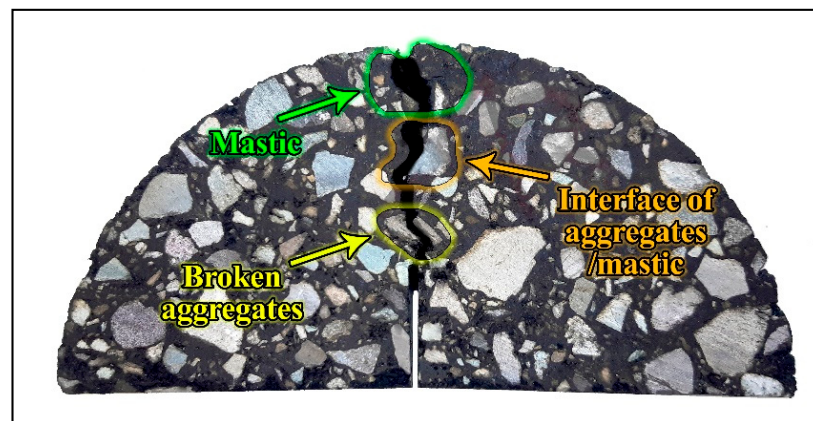


Figure 5. Path of the propagating crack through either the mastic, aggregate or aggregate/mastic interface.

The test temperature also plays a significant role in the trajectory of propagating crack in the asphalt mixtures. This is mainly due to the visco-elastic nature of bitumen used in the mixture of asphalt concrete materials. At low temperature conditions, the bitumen behaves as a brittle and linear elastic material. The higher stiffness of bitumen at low temperatures will result in a brittle-type fracture for the whole asphalt mixture with higher load bearing capacity as shown in Figure 3 and Table 5. In this temperature condition, the fracture propagation shows less deviation from the straight line. However, under higher temperatures (such as room or medium temperature conditions) the fracture trajectory grows only through the mastic part or passes along the boundary of aggregate/soft mastic part. Indeed, for even small size aggregates located in front of the propagating crack, fracture dose not grow through or inside the aggregate and due to lower stiffness of mastic, it tends to round the aggregate and grow from the interface of aggregate/mastic. Figure 6 shows typical test samples tested at low and intermediate temperatures.

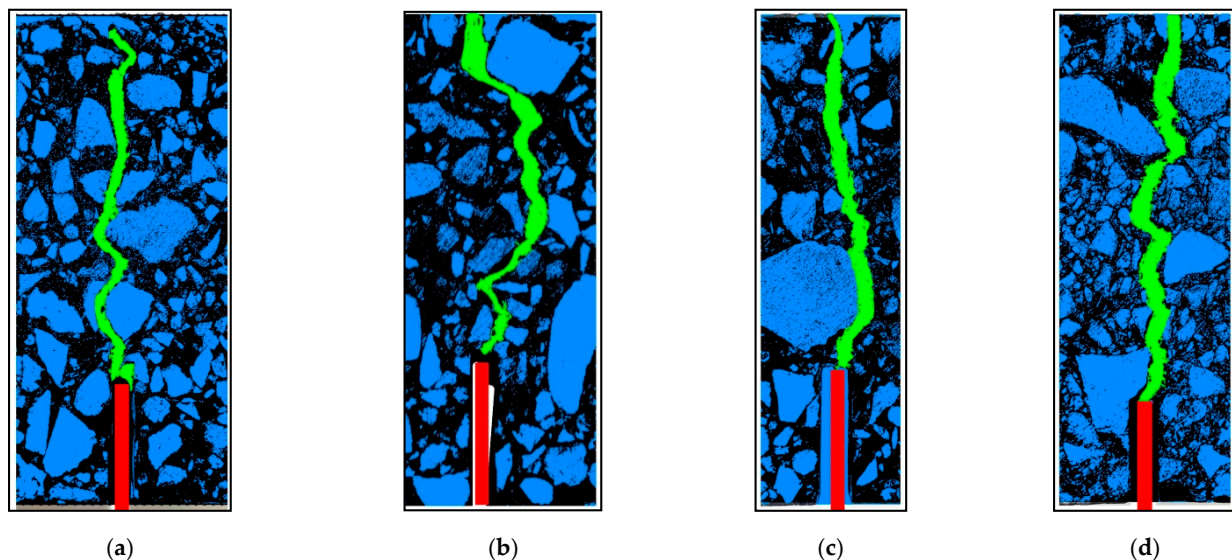


Figure 6. Effect of aggregate distribution and temperature on the fracture trajectory of tested asphalt mixtures, (a) $-15\text{ }^{\circ}\text{C}$, (b) $+15\text{ }^{\circ}\text{C}$, (c) large aggregate in front of the crack, (d) small aggregate in front of the crack.

As a conclusion, the heterogeneity and visco-elastic behavior of the asphalt mixtures can affect the cracking behavior of the asphalt mixtures. Increasing the amount of non-homogeneity and the size of aggregates and increasing the temperature results in greater deviation of fracture trajectory from the straight line. Figure 7 compares the mode I fracture

trajectory of the investigated asphalt samples with the cracking path of an isotropic and brittle model material (e.g., Perspex or Polymethylmethacrylate that is known as PMMA). This figure obviously shows the difference of the fracture trajectory in these two materials.

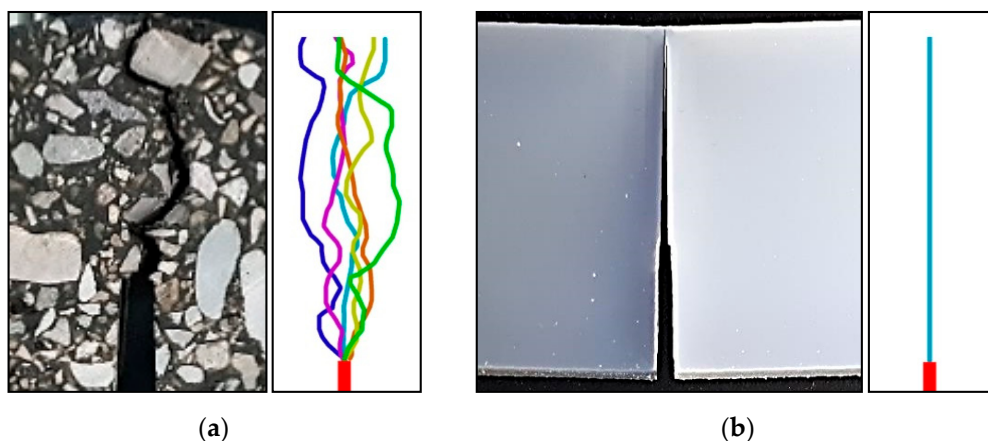


Figure 7. Comparison of mode I fracture path obtained from isotropic and heterogeneous mixture; (a) asphalt, (b) Polymethylmethacrylate (PMMA).

The fracture surface of the tested asphalt samples with different geometries are also presented in Figure 8a. According to this figure although the overall fracture surface is flat but there is a rough surface due to propagation of fracture mainly from the boundary of the aggregates. However, the fracture surface shows some evidences for breakage of the tight aggregates, demonstrating that the fracture can either grow through the coarse aggregates. Using image processing technique, the observed fracture surface was divided into three parts: (i) passed through the aggregates, (ii) passed through the mastic and (iii) passed through the interface of aggregate and mastic. For example, these three regions are shown in Figure 8b with white, green and black colors, respectively for mode I fracture surface of SCB, ENDB and SENB samples tested at low temperature conditions. Using the utilized image processing method, the contribution of different regions or cracking mechanisms can be studied better for the asphalt mixtures. For example, for the SENB specimen tested under low temperature, it was observed that approximately 15% of the fracture surface belongs to the broken aggregates. In addition, it was seen from the observations of the fracture surface that typically about 20% of the fracture surface grows along the interface of aggregate/mastic or boundary of coarse aggregates. However, a significant part of the fracture surface in the tested mode I samples (i.e., approximately 65%) passes via the inside of soft mastic part.

SENB:



Figure 8. *Cont.*

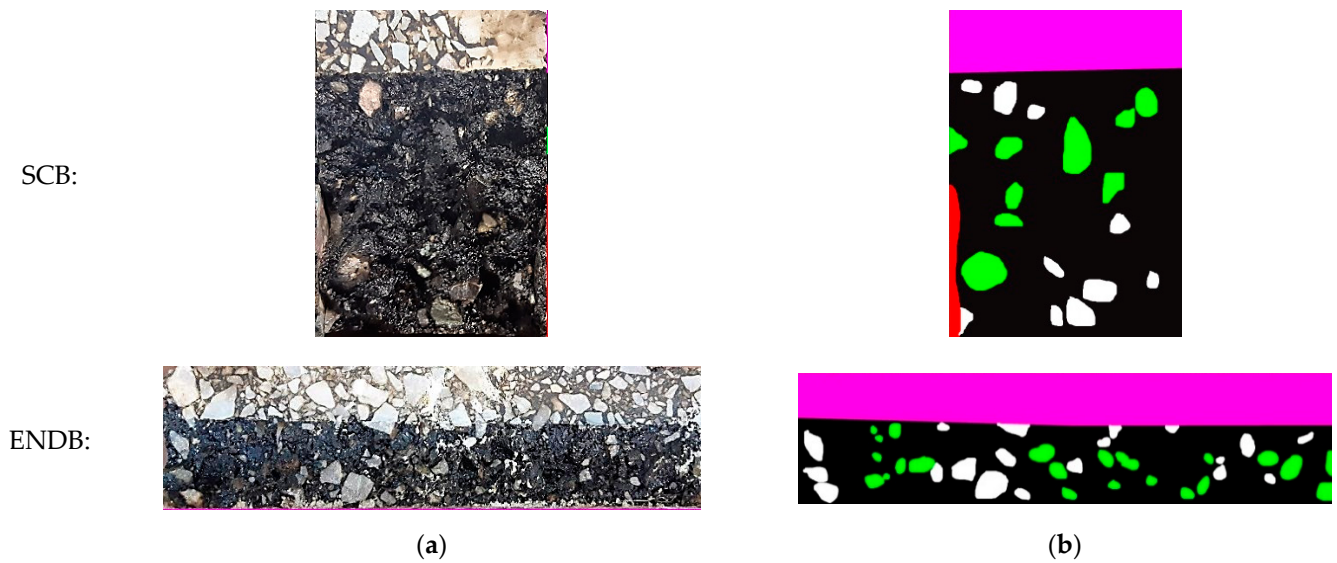


Figure 8. (a) Fracture surface of broken asphalt samples under mode I loading; (b) the fraction of different cracking mechanisms observed by the image processing for the tested mixtures.

4.2.2. Mixed Mode Fracture Trajectory

As expected, the trajectory of the asphalt fracture under mixed mode loading is not self-similar and a curved in-plane and out-of-plane fracture path is often seen for the tested mixed mode I/II and I/III, respectively. Figure 9 presents some of the observed fracture paths for the mixed mode I/II of the tested asphalt specimens. Again, according to this figure, the propagating curve crack may alter its route to round the coarse aggregates located in front of the crack. The fracture trajectory deviation depends on the mode mixity, distribution of aggregates and also the test temperature. Compared to the mode I case, mixed mode I/II fracture grows mostly through the interface and soft mastic parts and the propagating crack rarely breaks the aggregates.



Figure 9. *Cont.*

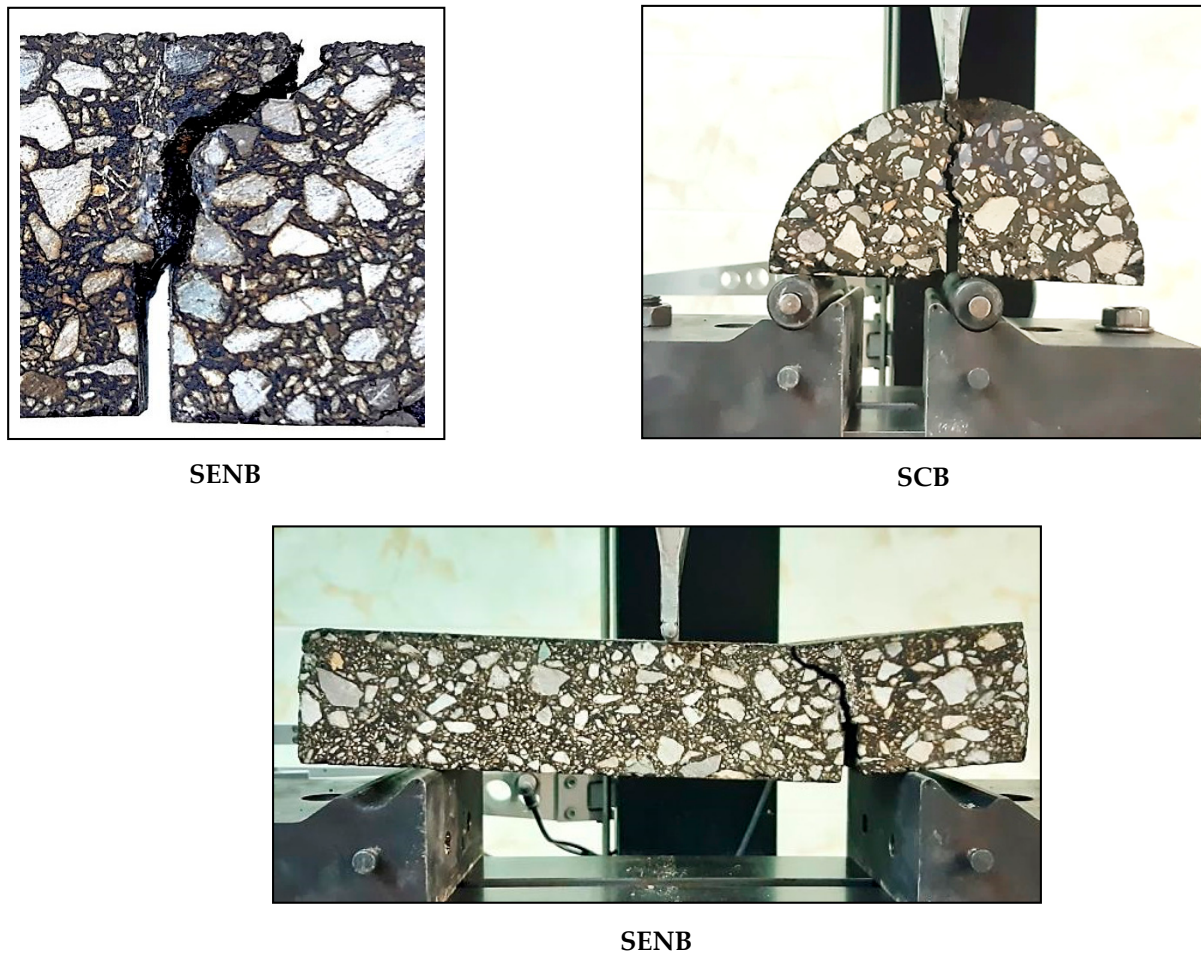


Figure 9. Fracture trajectories observed for mixed mode I/II in different asphaltic test samples.

Figure 10 compares the fracture trajectories of investigated asphalt samples with a brittle homogenous material (e.g., PMMA) for mixed mode I/II. Different manners are seen for the fracture trajectory of mixed mode as seen from this figure. The heterogeneity of the asphalt mixture can affect the fracture initiation direction and even concavity or convexity of the fracture path and indeed, depending on the distribution of aggregates, the interface fracture (or rounding the aggregates) is the preferred trajectory for propagation of crack under mixed mode I/II. The difference between the fracture paths of isotropic PMMA material and heterogeneous visco-elastic asphalt material becomes more at higher temperatures and mixtures containing greater amount of large size aggregates in the ligament of tested samples.

Similar to the mode I case, the fracture surface observed for the mixed mode I/II shows a rough surface passing mainly through the soft mastic and boundary of aggregates (or interface of aggregate/mastic). Observation of fracture surface under mixed mode loading indicates that more than 85% of the fracture path grows through the mastic or interface of aggregate/mastic. The roughness of fracture surface in the heterogeneous asphalt mixture is also greater than the surface of isotropic material with the same mode mixity.

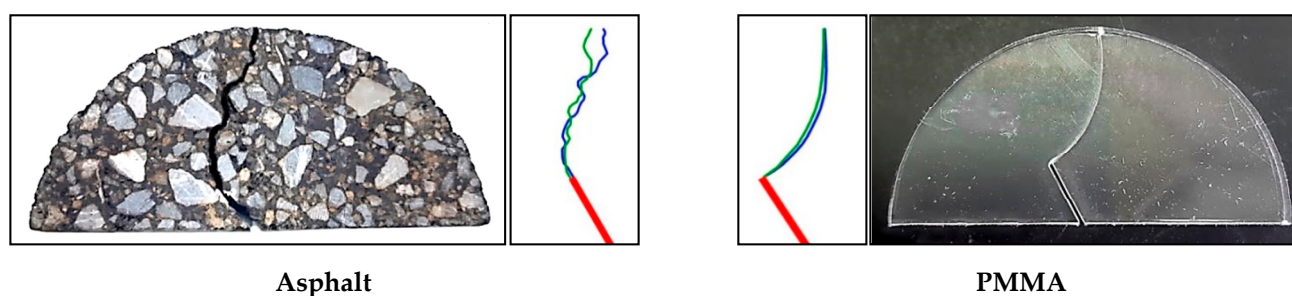


Figure 10. Comparison of fracture trajectory obtained for isotropic PMMA and heterogeneous asphalt mixture under mixed mode I/II.

The mode III and mixed mode I/III fracture grows in a twisted manner and out-of the plane of the initial crack. Figure 11 shows the mode III fracture trajectory observed for the ENDB specimen made of asphalt mixture for low and medium temperatures. Close observation of the mixed mode I/III and mode III fracture surface reveals that by contributing the mode III component on the fracture behavior of the heterogeneous asphalt mixture, the fracture grows mainly through the interface of aggregate/mastic or the mastic part. In other words, the coarse aggregates are rarely broken during the propagation of mode III fracture. This can be attributed to the lower resistance of the binder and soft mastic against the tear type deformation compared to its tensile resistance.

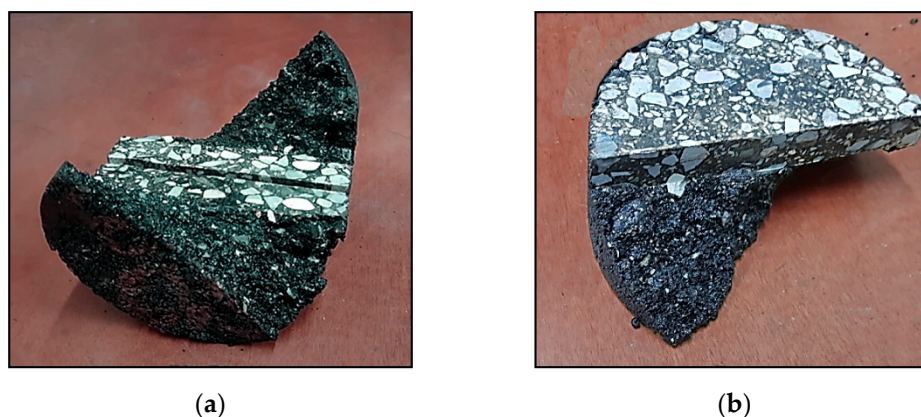


Figure 11. Fracture path and fracture surface of the asphalt mixture tested with the ENDB specimen under mode III (a) low temperature and (b) medium temperature.

In addition, the roughness of the fracture surface made of the asphalt samples is greater than the isotropic PMMA material tested under mode III as compared in Figure 12. The fracture tends to round the aggregates instead of breaking the aggregates and this behavior is more pronounced for the intermediate temperature condition.

As a conclusion, the influence of some affecting parameters such as heterogeneity, loading mode and temperature was investigated in this research for identifying the fracture mechanism of the propagating crack in the ligament of the asphalt concrete composites. Table 6 compares and summarizes the percentages and contribution of the passing fracture path through different locations (aggregates, mastic or interface of aggregate/mastic) for different test specimens, fracture modes and test temperatures. It can be seen that in general, the fraction of the aggregate breakage during the crack growth of the asphalt mixture becomes smaller for mode II and mode III loading and higher temperatures. Indeed, for such situations the fracture propagates mainly through the interface of aggregate/mastic and soft binder parts. Understanding the contribution of different cracking mechanisms (i.e., propagating the fracture surface through the tight aggregates, soft mastic or interface of tight and soft parts) can provide better knowledge for estimating the service life of asphalt pavement structures.



Figure 12. Comparison of fracture surface roughness after mode III failure obtained from (a) asphalt concrete and (b) Polymethylmethacrylate.

Table 6. Contribution of aggregate, mastic and interface of aggregate/mastic on the fracture path of tested asphalt concrete materials under different mode mixities and temperatures.

Specimen	Fracture Path Location	Mode-I		Mode-II or Mixed Mode I/II		Mode-III or Mixed Mode I/III	
		Low Temp	Medium Temp	Low Temp	Medium Temp	Low Temp	Medium Temp
SCB	mastic	60	80	75	90	-	-
	aggregates	30	12	5	0	-	-
	interface of aggregate/mastic	10	8	20	10	-	-
ENDB	mastic	70	85	-	-	90	95
	aggregates	15	10	-	-	5	0
	interface of aggregate/mastic	15	5	-	-	5	5
BD	mastic	70	90	85	90	-	-
	aggregates	20	5	10	2	-	-
	interface of aggregate/mastic	10	5	5	8	-	-
SENB	mastic	65	90	90	93	-	-
	aggregates	15	2	5	2	-	-
	interface of aggregate/mastic	20	8	5	5	-	-

5. Conclusions

- The fracture resistance, fracture trajectory and fracture surface of the asphalt samples were investigated under different mode mixities and testing conditions using different test samples and configurations.
- The fracture resistance values (i.e., critical stress intensity factors, K_{If} , K_{IIIf} and K_{IIIIf}) were dependent to the shape of test sample, applied loading type, loading mode, and temperature. Generally, the fracture resistance was decreased by increasing the test temperature and changing the loading mode from tensile type to shear type.
- The heterogeneity of the asphalt mixture and location of the coarse aggregates in the route of fracture propagation along the ligament can noticeably affect the trajectory of fracture. The fracture path shows more deviations relative to the path observed for a model brittle and isotropic material, when the coarser aggregates are located in front of the trajectory of propagating crack. Indeed, the crack tends to round the aggregates in most of the cases and propagate through the softer mastic part or the interface of aggregate/mastic.
- Increasing the temperature can result in more deviation in the fracture trajectory because of the reduction in the stiffness of mastic and bitumen relative to the aggregate and tendency of the crack to not grow through the aggregates by rounding them.

- Observation of fracture surface for all mode mixities revealed that a significant part of the fracture surface (i.e., greater than 80% of the fracture surface) propagates through the mastic and interface of aggregates/mastic. This percentage increases with increasing the test temperature or adding the contribution of mode II or mode III in the process of asphalt cracking.

Author Contributions: Conceptualization, L.L. and M.R.M.A.; methodology, M.R.M.A.; validation, H.R.K. and J.H.; formal analysis, J.H., L.L. and H.R.K.; investigation, L.L., H.Y. and H.R.K.; writing—original draft preparation, M.R.M.A.; writing—review and editing, M.R.M.A.; visualization, H.R.K. and H.Y.; supervision, M.R.M.A. and L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study did not involve tests on humans or animals.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wagoner, M.P.; Buttlar, W.G.; Paulino, G.H.; Blankenship, P. Investigation of the fracture resistance of hot-mix asphalt concrete using a disk-shaped compact tension test. *Transp. Res. Rec. J. Transp. Res. Board* **2005**, *1929*, 183–192. [\[CrossRef\]](#)
2. Li, X.; Braham, A.F.; Marasteanu, M.O.; Buttlar, W.G.; Williams, R.C. Effect of Factors Affecting Fracture Energy of Asphalt Concrete at Low Temperature. *Road Mater. Pavement Des.* **2008**, *9*, 397–416. [\[CrossRef\]](#)
3. Wagoner, M.P.; Buttlar, W.G.; Paulino, G.H. Disk-shaped compact tension test for asphalt concrete fracture. *Exp. Mech.* **2005**, *45*, 270–277. [\[CrossRef\]](#)
4. Wang, H.; Zhang, C.; Li, L.; You, Z.; Diab, A. Characterization of Low Temperature Crack Resistance of Crumb Rubber Modified Asphalt Mixtures Using Semi-Circular Bending Tests. *J. Test. Eval.* **2016**, *44*, 847–855. [\[CrossRef\]](#)
5. Aliha, M.; Behbahani, H.; Fazaali, H.; Rezaifar, M. Study of characteristic specification on mixed mode fracture toughness of asphalt mixtures. *Constr. Build. Mater.* **2014**, *54*, 623–635. [\[CrossRef\]](#)
6. Aliha, M.; Fazaali, H.; Aghajani, S.; Nejad, F.M. Effect of temperature and air void on mixed mode fracture toughness of modified asphalt mixtures. *Constr. Build. Mater.* **2015**, *95*, 545–555. [\[CrossRef\]](#)
7. Mirsayar, M.M.; Shi, X.; Zollinger, D.G. Evaluation of interfacial bond strength between Portland cement concrete and asphalt concrete layers using bi-material SCB test specimen. *Eng. Solid Mech.* **2017**, 293–306. [\[CrossRef\]](#)
8. Marasteanu, M.O.; Dai, S.; Labuz, J.F.; Li, X. Determining the Low-Temperature Fracture Toughness of Asphalt Mixtures. *Transp. Res. Rec. J. Transp. Res. Board* **2002**, *1789*, 191–199. [\[CrossRef\]](#)
9. Kim, H.; Wagoner, M.P.; Buttlar, W.G. Micromechanical fracture modeling of asphalt concrete using a single-edge notched beam test. *Mater. Struct.* **2008**, *42*, 677–689. [\[CrossRef\]](#)
10. Majidzadeh, K. *Application of Fracture Mechanics for Improve Design of Bituminous Concrete*; Rep, FHWA-RD-76-91, 1 & 2; Federal Highway Administration: Washington, DC, USA, 1976.
11. Molenaar, A.A.A. Fatigue and reflection cracking due to traffic loads. *J. Assoc. Asphalt Technol.* **1984**, *53*, 440–474.
12. Molenaar, A.A.; Scarpas, A.A.; Liu, X.; Erkens, G. Semi-circular bending test; simple but useful. *J. Assoc. Asphalt Technol.* **2002**, *71*, 794–815.
13. Roque, R.; Zhang, Z.; Sankar, B. Determination of crack growth rate parameters of asphalt mixtures using the Superpave IDT. *J. Assoc. Asphalt Technol.* **1999**, *68*, 404–433.
14. Stewart, C.M.; Oputa, C.W.; Garcia, E. Effect of specimen thickness on the fracture resistance of hot mix asphalt in the disk-shaped compact tension (DCT) configuration. *Constr. Build. Mater.* **2018**, *160*, 487–496. [\[CrossRef\]](#)
15. Link, R.P.; Wagoner, M.; Buttlar, W.; Paulino, G. Development of a Single-Edge Notched Beam Test for Asphalt Concrete Mixtures. *J. Test. Eval.* **2005**, *33*, 33. [\[CrossRef\]](#)
16. Jamaaoui, A.; Pop, O.; Ktari, R.; Millien, A.; Petit, C. Analyzing of Wedge Splitting Test on Asphalt Pavement Using Optical Measurements. *J. Test. Eval.* **2017**, *45*, 1959–1970. [\[CrossRef\]](#)
17. Motamedi, H.; Fazaali, H.; Aliha, M.; Amiri, H.R. Evaluation of temperature and loading rate effect on fracture toughness of fiber reinforced asphalt mixture using edge notched disc bend (ENDB) specimen. *Constr. Build. Mater.* **2020**, *234*, 117365. [\[CrossRef\]](#)
18. Pour, P.H.; Aliha, M.R.; Keymanesh, M.R. Evaluating mode I fracture resistance in asphalt mixtures using edge notched disc bend endb specimen with different geometrical and environmental conditions. *Eng. Fract. Mech.* **2018**, *190*, 245–258. [\[CrossRef\]](#)
19. Aliha, M.; Razmi, A.; Mousavi, A. Fracture study of CONCRETE composites with synthetic fibers ADDITIVE under modes I and III Using endb specimen. *Constr. Build. Mater.* **2018**, *190*, 612–622. [\[CrossRef\]](#)

20. Aliha, M.; Bahmani, A.; Akhondi, S. A novel TEST specimen for investigating the mixed MODE I+III fracture toughness of hot MIX asphalt composites—Experimental and theoretical study. *Int. J. Solids Struct.* **2016**, *90*, 167–177. [\[CrossRef\]](#)
21. Mansourian, A.; Hashemi, S.; Aliha, M.R. Evaluation of pure and mixed MODES (I/III) fracture toughness of Portland cement concrete mixtures containing RECLAIMED asphalt pavement. *Constr. Build. Mater.* **2018**, *178*, 10–18. [\[CrossRef\]](#)
22. Eghbali, M.; Fallah Tafti, M.; Aliha, M.; Motamedi, H. The effect of endb SPECIMEN geometry on mode I fracture toughness and Fracture energy of HMA and SMA mixtures at low temperatures. *Eng. Fract. Mech.* **2019**, *216*, 106496. [\[CrossRef\]](#)
23. Aliha, M.; Pour, P.J.H. Fracture resistance study for hot mix asphalt mixture under out of plane sliding mode. *Eng. Fract. Mech.* **2020**, *238*, 107230. [\[CrossRef\]](#)
24. Shahryari, N.; Keymanesh, M.; Aliha, M. Specimen type effect on measured low-temperature fracture toughness of asphalt concrete. *Fatigue Fract. Eng. Mater. Struct.* **2021**, *44*, 551–567. [\[CrossRef\]](#)
25. Aliha, M.; Sarbijan, M.; Bahmani, A. Fracture toughness determination of modified HMA mixtures with two novel disc shape configurations. *Constr. Build. Mater.* **2017**, *155*, 789–799. [\[CrossRef\]](#)
26. Bahmani, A.; Farahmand, F.; Ataei, F.; Aliha, M.R.M. Mixed mode I/III fracture parameters for edge-notched diametrically compressed disc specimen. *Mater. Des. Process. Commun.* **2019**, *1*. [\[CrossRef\]](#)
27. Bahmani, A.; Farahmand, F.; Janbaz, M.; Darbandi, A.; Ghesmati-Kucheki, H.; Aliha, M. On the comparison of two mixed-mode I + III fracture test specimens. *Eng. Fract. Mech.* **2021**, *241*, 107434. [\[CrossRef\]](#)
28. Mubarak, M.; Abd-Elhady, A.A.; Sallam, H.E.M. Mixed mode fracture toughness of recycled tire rubber-filled concrete for airfield rigid pavements. *Int. J. Pavement Res. Technol.* **2013**, *6*, 8–14.
29. Ameri, M.; Nowbakht, S.; Molayem, M.; Aliha, M.R.M. Investigation of fatigue and fracture properties of asphalt mixtures modified with carbon nanotubes. *Fatigue Fract. Eng. Mater. Struct.* **2016**, *39*, 896–906. [\[CrossRef\]](#)
30. Ameri, M.; Mansourian, A.; Pirmohammad, S.; Aliha, M.; Ayatollahi, M. Mixed mode fracture resistance of asphalt concrete mixtures. *Eng. Fract. Mech.* **2012**, *93*, 153–167. [\[CrossRef\]](#)
31. Pérez-Jiménez, F.; Botella, R.; Moon, K.-H.; Marasteanu, M. Effect of load application rate and temperature on the fracture energy of asphalt mixtures. Fénix and semi-circular bending tests. *Constr. Build. Mater.* **2013**, *48*, 1067–1071. [\[CrossRef\]](#)
32. Li, X.-J.; Marasteanu, M.O. Using Semi Circular Bending Test to Evaluate Low Temperature Fracture Resistance for Asphalt Concrete. *Exp. Mech.* **2010**, *50*, 867–876. [\[CrossRef\]](#)
33. Aliha, M.R.M.; Amirdehi, H.R.F. Fracture toughness prediction using Weibull statistical method for asphalt mixtures containing different air void contents. *Fatigue Fract. Eng. Mater. Struct.* **2017**, *40*, 55–68. [\[CrossRef\]](#)
34. Aliha, M.R.M.; Behbahani, H.; Fazaali, H.; Rezaifar, M.H. Experimental study on mode I fracture toughness of different asphalt mixtures. *Sci. Iran. Trans. A Civ. Eng.* **2015**, *22*, 120.
35. Zeinali, A.; Mahboub, K.C.; Blankenship, P.B. Development of the indirect ring tension fracture test for hot-mix asphalt. *Road Mater. Pavement Des.* **2014**, *15*, 146–171. [\[CrossRef\]](#)
36. Kim, H.; Buttlar, W.G. Discrete fracture modeling of asphalt concrete. *Int. J. Solids Struct.* **2009**, *46*, 2593–2604. [\[CrossRef\]](#)
37. Zhao, Y.; Jiang, L.; Zhou, L.; Jiang, J. Heterogeneous Fracture Simulation of Asphalt Mixture under Beam Bending Test with Cohesive Zone Modeling. *Transp. Res. Congr. 2017* **2019**. [\[CrossRef\]](#)
38. Dai, Q.; Sadd, M.H.; Parameswaran, V.; Shukla, A. Prediction of Damage Behaviors in Asphalt Materials Using a Micromechanical Finite-Element Model and Image Analysis. *J. Eng. Mech.* **2005**, *131*, 668–677. [\[CrossRef\]](#)
39. Ng, K.; Dai, Q. Investigation of Fracture Behavior of Heterogeneous Infrastructure Materials with Extended-Finite-Element Method and Image Analysis. *J. Mater. Civ. Eng.* **2011**, *23*, 1662–1671. [\[CrossRef\]](#)
40. Aliha, M.; Ziari, H.; Mojaradi, B.; Sarbijan, M.J. Heterogeneity effects on mixed-mode I/II stress intensity factors and fracture path of laboratory asphalt mixtures in the shape of SCB specimen. *Fatigue Fract. Eng. Mater. Struct.* **2019**, *43*, 586–604. [\[CrossRef\]](#)
41. Aliha, M.; Sarbijan, M. Effects of loading, geometry and material properties on fracture parameters of a pavement containing top-down and bottom-up cracks. *Eng. Fract. Mech.* **2016**, *166*, 182–197. [\[CrossRef\]](#)
42. Ziari, H.; Aliha, M.R.M.; Mojaradi, B.; Sarbijan, M.J. Investigating the effects of loading, mechanical properties and layers geometry on fatigue life of asphalt pavements. *Fatigue Fract. Eng. Mater. Struct.* **2019**, *42*, 1563–1577. [\[CrossRef\]](#)
43. Aliha, M.; Ziari, H.; Fard, E.S.; Sarbijan, M.J. Heterogeneity effect on fracture parameters of a multilayer asphalt pavement structure containing a top-down crack and subjected to moving traffic loading. *Fatigue Fract. Eng. Mater. Struct.* **2021**. [\[CrossRef\]](#)
44. Li, W.; Guo, L. Meso-fracture simulation of cracking process in concrete incorporating three-phase characteristics by peridynamic method. *Constr. Build. Mater.* **2018**, *161*, 665–675. [\[CrossRef\]](#)
45. Yin, A.; Yang, X.; Gao, H.; Zhu, H. Tensile fracture simulation of random heterogeneous asphalt mixture with cohesive crack model. *Eng. Fract. Mech.* **2012**, *92*, 40–55. [\[CrossRef\]](#)
46. Ayatollahi, M.; Aliha, M. Wide range data for crack tip parameters in two disc-type specimens under mixed mode loading. *Comput. Mater. Sci.* **2007**, *38*, 660–670. [\[CrossRef\]](#)
47. Fayed, A.S. Numerical evaluation of mode I/II SIF of quasi-brittle materials using cracked semi-circular bend specimen. *Eng. Solid Mech.* **2018**, *6*, 175–186. [\[CrossRef\]](#)
48. Fuan, S.; Ke, M.; Kanghe, L.; Kun, L.; Aliha, M. Influence of specimen geometry on mode I fracture toughness of asphalt concrete. *Constr. Build. Mater.* **2021**, *276*, 122181. [\[CrossRef\]](#)