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Experimental study on mode I fracture toughness of different asphalt mixtures

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Abstract. Low temperature cracking is one of the main distresses observed in pavements made of hot mix asphalt mixtures. As a material property, the fracture toughness of asphalt pavements is a fundamental parameter for estimating the load bearing capacity and resistance of cracked pavements against crack growth. In this paper, the fracture toughness (K_{Ic}) of different and various compositions of asphalt mixtures is obtained experimentally, and the effects of asphalt characteristic specifications and its composition are investigated on the value of K_{Ic}. Several asphalt mixtures were prepared with three aggregate sizes, two aggregate types (limestone and siliceous), different air void percentages ranging from 3.5 to 8%, and two binders (60/70 and 85/100). Other similar work has only studied the influence of limited characteristic parameters on the low temperature fracture resistance of asphalt mixtures. Several Semi-Circular Bend (SCB) specimens subjected to three point bend loading were manufactured with different compositions and were then tested at −15°C. The experimental results showed the noticeable influence of characteristic specifications of asphalt mixtures on the value of K_{Ic}. Generally, the value of K_{Ic} decreases for those mixtures containing a smaller size of aggregates made of siliceous, with higher percentages of air voids and softer binder types.

1. Introduction

Annually, huge amounts of money are spent on the design, construction and maintenance of asphalt pavements. Depending on the climate and traffic service conditions of roads and highways, several distresses and deterioration modes can decrease the safe and reliable operational performance of pavements. Many types of crack (e.g. reflective cracks, alligator cracks and top-down cracks on the surface of asphalt pavements) are initiated due to improper construction and implementation of the paving process. Daily or seasonal cyclic thermal loads, mechanical traffic loading, or a combination of both, under service conditions, are known to be the main causes of deterioration and overall failure of asphalt pavements. Consequently, asphalt cracking may increase, noticeably, the maintenance and rehabilitation costs of pavements. Hence, in many countries, the investigation of crack growth behavior in asphalt pavements and overlays is an important issue for the design, construction and maintenance of roads and highways. On the other hand, asphalt cracking is commonly observed in cold regions and under low temperatures. This is mainly because under low and subzero temperatures, asphalt pavements often behave

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as a brittle material, and, hence, the risk of sudden fracture from pre-existing cracks in the pavement may increase significantly.

There have been many experimental and laboratory research studies to investigate the effects of influencing factors on the fracture behavior of asphalt mixtures. As a fundamental parameter, the fracture toughness of asphalt materials defines the resistance of pavements and overlays against crack growth. Majidzadeh [1], Molenaar [2] and Morrison and Rodriguez [3] were among the first researchers who tried to obtain, experimentally, the value of fracture toughness for asphaltic materials using edge cracked rectangular bend beam specimens. During the past decades, other researchers have also investigated the fracture behavior and fracture toughness of asphalt mixtures from different aspects. Since asphalt mixtures are particulate composite materials containing aggregates (with different sizes, shapes and types), binders, some kinds of additive or modifier, and air voids, their fracture and crack growth behavior could be affected by the characteristic specifications and compositions of the mixture. Mobasher et al. [4] used an R-curve approach to compare the fracture resistance of asphalt mixtures made of various percentages of neat bitumen and asphalt rubber. They demonstrated that samples containing asphalt rubber show higher fracture toughness, and increasing bitumen percentage will lead to an increase in fracture resistance in both types of bituminous mixture. Behnia et al. [5] investigated, experimentally, the fracture resistance of some asphalt mixtures using the acoustic emission method. Ayatollahi and Pirmohammad [6] studied the effect of temperature on mode I and mode II fracture toughness of typical hot mix asphalt. Li and Marasteanu [7] indicated that the geometry of the test sample may have a noticeable effect on the fracture test results. For instance, they reported that the effect of void content on the fracture strength of asphalt mixtures tested with a semicircular bend specimen is more pronounced than the fracture strength of the same material tested by a disk-shaped compact tension specimen.

As a material property, the value of fracture toughness for any cracked material can be only obtained experimentally using suitable testing methods. A general equation for obtaining the fracture toughness (K_{Ic}) of a cracked material is given as follows:

$$K_{\mathrm{Ic}} = Y\sigma\sqrt{\pi a}, \tag{1}$$

where σ is the critical applied stress at the onset of fracture, which is obtained from a fracture experiment, a is the crack length, and Y is the geometry factor, which is function of the specimen geometry and its loading condition. From the experimental viewpoint, a suitable test specimen for asphalt mixtures should

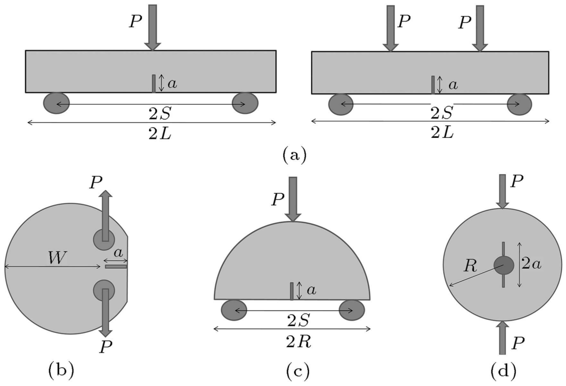


Figure 1. Geometry and loading configuration of frequently used samples for asphalt fracture toughness experiments: (a) Rectangular three or four point bend beam; (b) disc shape compact tension specimen; (c) semi-circular bend specimen; and (d) modified indirect tension test specimen.

have simple geometry and loading setup. Accordingly, a few test specimens have been used in the past by researchers to obtain the value of fracture toughness for asphalt materials. An edge cracked rectangular beam subjected to three or four point bending [8-10], a modified indirect tension test specimen [11], a disc shaped compact tension specimen [12,13,5] and a Semi Circular Bend (SCB) specimen subjected to three-point bend loading [14-17,7] are some of the most frequently used configurations for fracture toughness testing of asphalt and bituminous materials. Figure 1 shows schematically the geometry and loading conditions of the mentioned specimens.

For example, a review of literature shows that the fracture behavior of various asphalt mixtures has been investigated experimentally using the SCB, the edge cracked rectangular beam specimen subjected to four-point loading and the center crack plate under tension specimens by Molennar et al. [14,18]. Marasteanu et al. [19] also determined the fracture toughness of an asphalt concrete using an edge cracked three-point bend beam. Tekalur et al. [20] employed an edge cracked rectangular beam specimen subjected to three point bending to study the mechanical and fracture behavior of hot mix asphalt under two different loading rates. Nguyen et al. [21] examined the crack growth resistance of asphalt mixtures using a symmetric four-point bend specimen. The compact tension specimens with circular or rectangular configurations have been also used by Wagoner [8,12], Edwards and Hesp [22], and Marasteanu et al. [19] to obtain the value of fracture energy or fracture toughness in asphalt concretes, experimentally. Roque and Zang [11] used a modified indirect tension test method using a circular disc containing a small center hole and subjected to diametral compression to obtain the fracture toughness and also fatigue crack growth parameters of asphalt mixtures. In comparison with the conventional, center cracked, circular disc specimen (often called the Brazilian disc), introducing two same line cracks from the edges of the center hole in this specimen is much easier for asphalt materials. Chen et al. [23] also employed the SCB specimen to study the effect of temperature on the fracture toughness of asphalt mixtures. Some other researchers [24] tested the shear (i.e. mode II) fracture toughness or mixed mode tensile-shear fracture behavior (mixed mode I/II) of asphalt concretes using different test configurations, including disc type samples, such as the SCB specimen [9,16,25]. For example, Ameri et al. [16] recently studied the mixed mode I/II fracture toughness of a typical asphalt mixture by means of a modified SCB specimen, and obtained experimentally the critical values of mode I and mode II stress intensity factors for different combinations of modes I and II in the tested SCB specimen.

Among the mentioned specimens, the SCB specimen can be considered a suitable and favorite configuration for testing asphalt mixtures, because it can be manufactured easily from standard field coring equipment or gyratory compactor machines, and can also be tested easily using ordinary testing apparatus and fixtures. Moreover, in comparison with rectangular beam specimens, the SCB samples need less asphalt mixtures for specimen preparation, which, consequently, decreases the weight of the test samples and the cost of experiments. While introducing a center crack in the full circular shape specimens is not convenient, and the risk of specimen failure from pin locations due to tensile loading in the disc shape compact tension specimen is high, the existence of edge crack (which can be introduced easily) and also application of compression load in the SCB specimen are two other advantages of SCB specimen. Hence, the SCB specimen has been used frequently in the past for investigating the fracture behavior of asphalt mixtures or other concrete-like materials [6,7,14-17,26]. Recently, AASHTO proposed the use of the SCB specimen as a standard method for measuring the mode I fracture toughness of asphalt mixtures, in addition to the previously suggested disc shaped compact tension specimen. According to Figure 1(c), the SCB specimen is a semi-circular specimen of radius R and thickness t, which is subjected to symmetric three-point bending with a loading span of $2S$. Thus, when it is loaded by vertical force, P, the vertical edge crack of length, a, would experience pure mode I deformation (crack opening), due to the symmetry of geometry and loading relative to the crack plane. The SCB specimen can also be used for mixed mode I/II (tension-shear) experiments simply by inclining the crack direction relative to the applied load P direction [25,27,28] or changing its location relative to the loading points [16,29,30].

As mentioned earlier, hot mix asphalt mixtures are complicated materials and, thus, their properties, performance, durability and mechanical strength depend strongly on the composition of the ingredients, the manufacturing process, the mix design, the type of aggregates and binders, the service loads and temperature conditions, etc. Therefore, in this research, fracture toughness and the crack growth resistance of different compositions of asphalt mixtures are investigated experimentally using the SCB specimen. Also, the effects of asphalt characteristic specifications, including the aggregate size, air void percentage and bitumen type, on fracture load and fracture toughness are studied at a subzero temperature. Other similar research work has only investigated very limited mixtures and comprehensive fracture toughness studies in this research could be useful.

It is shown that the asphalt characteristic specifications have noticeable influences on the low temperature crack growth behavior of hot mix asphalt mixtures.

2. Specimen manufacturing from hot mix asphalt mixtures

For preparation of asphalt mixtures, two aggregate types made of limestone (obtained from the Asbcheran mine, Damavand, Tehran, Iran) and siliceous (obtained from a mine in Shahriar-Tehran, Iran) with three gradations (i.e. aggregate sizes of Nos. 4, 5 and 6, according to the Iranian paving standard-code 234) were considered. The corresponding Nominal Maximum Aggregate Sizes (NMAS) for these three aggregate size numbers are 12.5 mm, 9 mm and 4.75 mm, respectively. The aggregate gradations and their percentages used for the asphalt mixtures of this study have been presented in Table 1. Also, two

Table 1. Asphalt mixture aggregate gradation.

Gradation number	No. 4	No. 5	No. 6
	NMAS: 12.5 mm	NMAS: 9 mm	NMAS: 4.75 mm
Sieve size	Passing percent		
19	100	100	100
12.5	95	100	100
9	80	85	100
4.75	59	70	90
2.36	43	49.5	82.5
1.18	30	33	60
0.5	18	22	45
0.3	13	15	23.5
0.15	8	10	11.5
0.075	6	6	10

Table 2. Specifications of binders.

Test	Standard	Unit	Binder type	
			60/70	**85/100**
Specific gravity (25°C)	ASTM D70	gr/cm^3	1.03	1.01
Flash point (Cleveland)	ASTM D92	°C	308	294
Penetration (25°C)	ASTM D5	°C	62	94
Ductility (25°C)	ASTM D113	cm	100	105
Softening point	ASTM D36	°C	49	42
Kinematic viscosity @ 120°C	ASTM D2170	mm^2/s	810	512
Kinematic viscosity @ 135°C	ASTM D2170	mm^2/s	420	221
Kinematic viscosity @ 150°C	ASTM D2170	mm^2/s	232	120
Penetration Index (PI)	—	—	-1.12	-1.98

Table 3. Optimum percentages of binders for asphalt mixture samples.

Binder type	Penetration grade 60/70			Penetration grade 85/100		
NMAS (mm)	12.5	9	4.75	12.5	9	4.75
Limestone aggregates	4.8	5.1	5.7	4.6	-	-
Siliceous aggregate	5.2	-	-	-	-	-

binder penetration grades of 60/70 (PG 64-22) (the most commonly used type for paving roads in Iran) and 85/100 (PG 52-28) (a suitable type for cold climates) were utilized for preparation of the asphalt mixtures. The specifications of each binder have been presented in Table 2. Using the Marshall Mix design method, the optimum percentages of binders were determined as presented in Table 3. After mixing the aggregates (i.e. limestone and siliceous of different sizes) with binders (i.e. 60/70 and 85/100 bitumen) at 155°C, cylindrical specimens with a diameter of 150 mm and a height of 130 mm were manufactured using a Superpave Gyratory Compactor machine (SGC).

In order to study the effects of air voids in the experiments, three numbers of Gyratory Rotation (GR) (i.e. 35, 70 and 90 rotations) were also considered for compacting the mixtures. The cylinders were then sliced using a rotary diamond saw machine to obtain circular discs of an approximate height of 30 mm. The air void percentage of each semi-circle was measured and it was found that the maximum difference between the air void content of manufactured mixtures is less than 0.1%. Thus, the distribution of the air void in the manufactured test samples was reasonably the same or similar.

The cylinders were cooled with water during the cutting process. Each disc was split into two halves to produce two semi circles. A very narrow notch with a length of 20 mm and a width of 0.4 mm was then introduced at the middle of the flat edge by a very thin rotary high speed diamond saw blade.

Figure 2. Some of the steps for preparing the SCB test specimens.

Consequently, several SCB specimens containing vertical edge cracks were manufactured with different compositions and specifications. Before conducting the fracture toughness experiments, the SCB specimens were maintained in a freezer with an inside temperature of −15°C for 6 hours. Figure 2 shows some of the steps of specimen preparation for the manufactured SCB specimens made of hot mix asphalt mixtures and with different compositions.

3. Fracture toughness experiments

After preparation of test samples, they were tested using a compression test machine having a capacity of 15 kN. The tests were carried out at −15°C under displacement control conditions with a constant cross head speed of 0.05 mm/s. The fracture behavior of asphalt mixtures under low temperature (i.e. subzero) conditions has been generally investigated by a linear and elastic fracture mechanics approach. Due to the lower limit performance temperatures of the used binders (i.e. −22°C for 60/70 bitumen, and −28°C for 85/100 bitumen), the framework of Linear Elastic Fracture Mechanics (LEFM) would be well suited for the chosen test temperatures in this research.

The SCB specimens were tested using a three-point bend fixture with a loading span of $2S = 100$ mm (i.e. $S/R = 0.67$). For conducting the tests, the SCB specimens were placed carefully inside the fixtures and then were loaded until the final fracture. The complete load-displacement data were recorded during the tests using a computerized data logger. The load-displacement curves for all the samples were nearly linear, showing the brittle failure behavior of the tested asphalt mixtures at a low temperature of $-15°$C. Others have also mentioned that asphalt mixtures behave as a linear elastic material at low subzero temperatures in the typical range of 0 to $-25°$C [9,31,32-34]. For example, Li and Marasteanu [31] and Kim et al. [9] tested some cracked asphalt mixtures at subzero temperatures and observed that the load-displacement diagrams are nearly linear. Therefore, the fracture toughness of tested asphalt mixtures can be determined using the concepts of LEFM by means of the maximum load recorded for each test. For each mix design, three SCB specimens were tested successfully and the duration of each test was, typically, about 60 s.

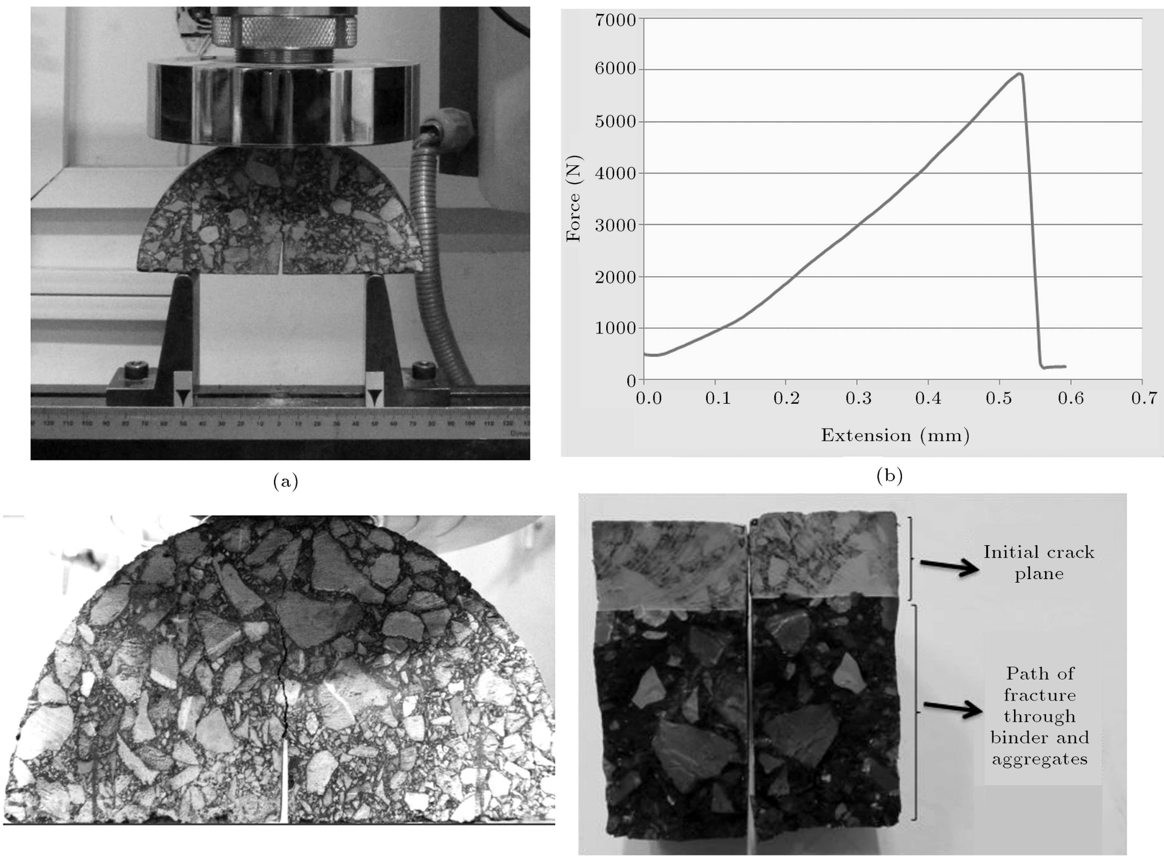
Consequently, a total number of 45 SCB specimens with different compositions and mixture specifications were fractured. Figure 3 shows the test setup and a typical load-displacement curve obtained for one of the tested specimens and one of the fractured specimens. It was observed that at a critical level of applied load, the fracture suddenly started from the tip of the crack and grew rapidly along the line of the initial notch (i.e. along a straight path, even through the hard aggregates, with no significant curving) until the top loading point. This observation shows that the path of crack growth in mode I fractured SCB specimens is self-similar and stable. Hence, the SCB specimen is a suitable configuration for mode I fracture testing of hot mix asphalt mixtures at low temperatures.

4. Results and discussion

Mode I fracture toughness (K_{Ic}) was determined for each cracked SCB specimen from the following equation [32]:

$$K_{\mathrm{Ic}} = \frac{P_f}{2Rt}\sqrt{\pi a}\,Y_I(a/R, S/R), \tag{2}$$

where P_f and Y_I are the critical peak (or fracture) load and the geometry factor for the SCB specimen, respectively. Y_I is a function of the crack length



(c)

Figure 3. (a) Loading setup used for testing the SCB specimen made of asphalt mixture. (b) A typical load-displacement curve obtained for the SCB test sample. (c) A typical fracture path observed for the SCB specimens.

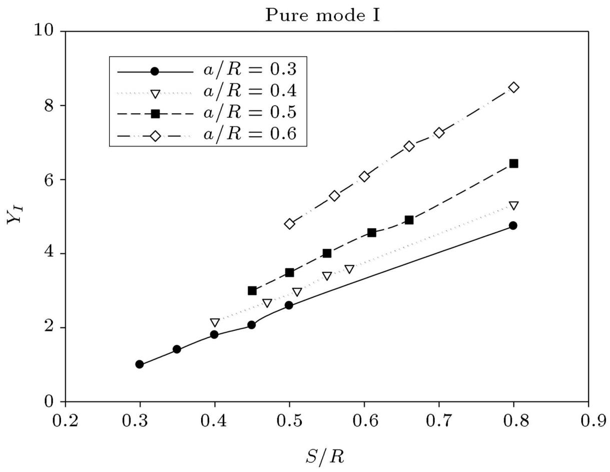


Figure 4. Variations of pure mode I geometry factor (Y_I) with a/R and S/R in the SCB specimen [35].

to radius ratio (a/R) and the loading span to radius ratio (S/R). Some analytical and numerical solutions are available for obtaining Y_I [35,36]. For example, using the finite element method, Ayatollahi and Aliha [35] analyzed the SCB specimen and computed numerically the mode I and mode II geometry factors of the SCB specimen under various loading and geometry conditions. Figure 4 shows the variations of Y_I corresponding to pure mode I conditions for different values of a/R and S/R extracted from Ayatollahi and Aliha [35]. Accordingly, for the tested mode I samples in this research (i.e. with $a/R = 0.27$ and $S/R = 0.67$), the corresponding value of Y_I is obtained equal to 3.73 from Figure 4. Although the real cracked SCB specimens have three dimensional (3D) shapes, numerical 3D fracture analysis of this specimen has demonstrated that the difference between the 2D and 3D resulted in this specimen is not significant [37,38]. Hence, the use of 2D fracture parameters for calculating the critical stress intensity factor is applicable with good accuracy.

By recording the final fracture loads from the experiments, the corresponding values of K_{Ic} for the tested asphalt materials were calculated from Eq. (2) for different compositions of the asphalt mixture. Details of the experimental results, including critical fracture load and corresponding value of fracture toughness for each tested specimen, have been presented in Table 4. The first column in this Table defines the mix type, and, for easy understating, the specimens are designated as $x - y - z$ in which x indicates the type of aggregate (i.e. L for limestone and S for siliceous), y indicates the aggregate size number (i.e. 4, 5 and 6), and z shows the binder type (i.e. 60 for 60/70 and 85 for 85/100). The calculated range of K_{Ic} was between 0.6 MPa.m$^{0.5}$ and 1 MPa.m$^{0.5}$. These figures are in the range reported for typical asphalt mixtures tested

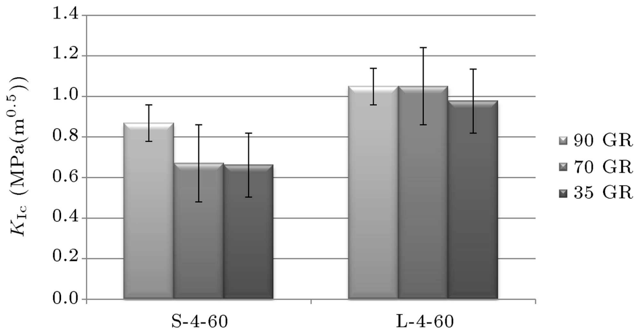


Figure 5. Effect of aggregate type on the fracture toughness (K_{Ic}) of tested asphalt mixtures.

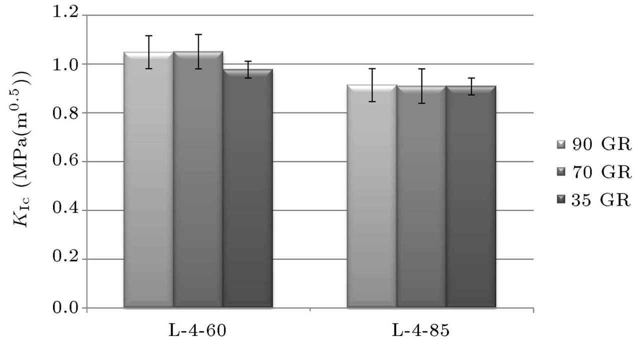


Figure 6. Effect of binder penetration grade on the fracture toughness (K_{Ic}) of tested asphalt mixtures.

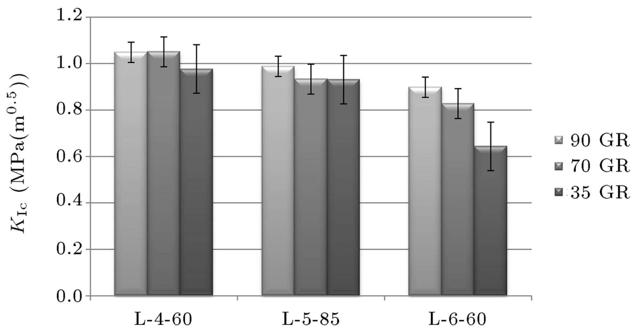


Figure 7. Effect of aggregates size on the fracture toughness (K_{Ic}) of tested asphalt mixtures.

at low temperatures with different test specimens and methods [6,16,25,39]. Figures 5-7 compare the influence of asphalt characteristic specifications on the value of mode I fracture toughness. The values of K_{Ic} obtained from the fracture test carried out on asphalt mixtures containing limestone and siliceous aggregates at various compaction levels have been presented in Figure 5. Consequently, the higher fracture resistance of hot mix asphalt made of limestone aggregates can be attributed to the higher strength and stiffness of this type of material, better compatibility in absorption and adhesion with bitumen, and also, more appropriate compaction. In Figure 6, the K_{Ic} of asphalt samples made of soft (85/100) and semi-hard (60/70) binders are illustrated at various compaction levels. For the

Table 4. Details of the fracture loads and fracture toughness data obtained for the tested asphalt mixtures.

Specimen	Gyratory rotation numbers	Average of void (%)	Sample number	Peak load (N)	Average of peak load (N)	Average of K_{Ic} (MPa.m$^{0.5}$)
S-4-60	90	4.2	1	4174	4732	0.87
			2	4381		
			3	5641		
	70	5.5	1	3220	3651.33	0.67
			2	3556		
			3	4178		
	35	6.3	1	3501	3603.66	0.66
			2	4100		
			3	3210		
L-4-60	90	3.6	1	5268	5713.33	1.05
			2	5583		
			3	6289		
	70	4	1	5343	5724.66	1.05
			2	5326		
			3	6505		
	35	5.6	1	5000	5323.33	0.98
			2	4997		
			3	5973		
L-4-85	90	3.4	1	4770	4977	0.91
			2	4579		
			3	5582		
	70	4.2	1	4937	4956	0.91
			2	4700		
			3	5231		
	35	5.4	1	5160	4947	0.91
			2	4732		
			3	4949		
L-5-60	90	3.8	1	4622	5384.33	0.99
			2	5337		
			3	6194		
	70	4.2	1	4756	5084	0.93
			2	5290		
			3	5226		
	35	6.2	1	5165	5072	0.93
			2	4930		
			3	5121		
L-6-60	90	4	1	4803	4894.33	0.90
			2	5160		
			3	4720		
	70	5.3	1	4193	4511.66	0.83
			2	4731		
			3	4611		
	35	8	1	3765	3506	0.64
			2	3405		
			3	3348		

sake of comparison, the grading and aggregate types were kept identical in both asphaltic mixtures (i.e. limestone aggregates with size No. 4). According to this figure, mixtures constructed using 60/70 bitumen demonstrate higher fracture toughness in comparison with samples made with 85/100 bitumen. This may be related to the higher stiffness of the mix prepared with a 60/70 binder and, therefore, with higher resistance against crack initiation. According to Eq. (2), the onset of initial fracture at the tip of the crack in the SCB specimen is proportional to the maximum peak load, and the stiffer and harder binder (i.e. 60/70) provides higher resistance against the initial stage of cracking. However, apart from the fracture initiation stage, the softer binders may show greater fracture energy during the crack growth stage and breakage of the asphalt mixtures. This trend can be vividly seen in lower compaction levels as well. This is true, despite the fact that samples with 85/100 bitumen show lower viscosity at the compaction time period and, therefore, have a lower void content. On the other hand, they are less susceptible to compaction rate. However, it seems that, at least, in this case, the stiffness of the asphalt mixture is more important than its void content on the value of fracture toughness.

Figure 7 shows the effect of aggregate size on the fracture toughness of asphalt mixtures. For the sake of comparison and in order to study the effect of aggregate size, other characteristic specifications, such as bitumen and aggregate type, were kept constant. Indeed, asphalt mixtures composed of 60/70 bitumen and limestone aggregates, but with three types of grading (Nos. 4, 5 and 6) were chosen for investigating the influence of aggregate size on K_{Ic}. Experimentally, obtained results show that by reducing aggregate size in bituminous mixtures, the fracture toughness is decreased. Lower interlocking between aggregates, the lower stiffness of the mix caused by higher bitumen content and the existence of vulnerable locations to start and propagate cracks are some of the main reasons for this observation. It should be noted that mixtures with smaller aggregates tend to show higher sensitivity against compaction energy. In fact, inferior compaction and increasing void content have a considerable effect on reducing the fracture strength of asphaltic mixtures with small aggregates. Moreover, as seen from Figure 7, the sensitivity of fracture toughness to compaction energy becomes more when the size of the aggregates becomes smaller in the asphalt mixtures. The averages of the whole fracture results obtained in this research have been presented in Figure 8. A comparison of presented data in this figure shows that the fracture toughness of different asphalt mixtures, with different characteristics, varies in the range of 0.65 and 1.05 MPa. m$^{0.5}$. This range is in agreement with the reported fracture toughness values for the low temperature crack growth resistance of similar asphalt concretes [4,6,7,10,16,32,39]. The obtained figures are between the reported values for K_{Ic} of plain concrete (about 0.5 MPa.m$^{0.5}$) and polymer concrete (about 1.8 MPa.m$^{0.5}$) [26,40-42].

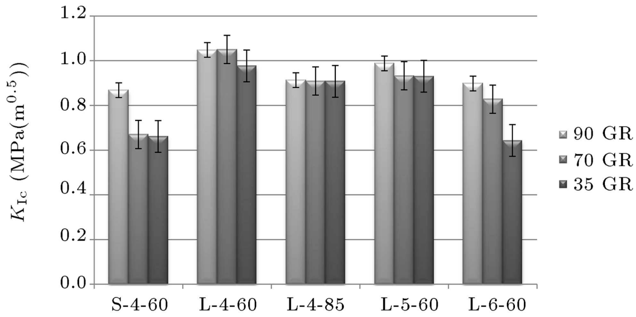


Figure 8. Effect of characteristic specification on the fracture toughness (K_{Ic}) of tested asphalt mixtures.

Consequently, according to the results of this research, the risk of low temperature brittle fracture in asphalt mixtures can be generally increased for mixtures containing siliceous aggregates, smaller aggregate size, higher percentages of voids, and higher penetration grades of binders. It is finally noted that optimizing the composition of tested asphalt mixtures to obtain the highest resistance against low temperature cracking is currently being investigated by the authors.

5. Conclusions

- Fracture toughness of different asphalt mixtures was determined experimentally using several cracked SCB specimens under low temperature conditions.
- The influence of asphalt characteristic specifications, such as void percentage, aggregate type, aggregate size and binder type, were studied on the value of mode I fracture toughness.
- For asphaltic mixtures made of smaller aggregates and harder binders, the compaction energy of mixtures can significantly affect the crack growth resistance of asphalt materials.
- Asphalt mixtures with larger aggregate size and containing limestone aggregates show higher resistance against brittle fracture.

Nomenclature

a :	Crack length of SCB specimen (mm);
a/R :	Crack length to radius ratio;

K_I : Mode I stress intensity factor (MPa$\sqrt{m}$);

K_{IC} : Mode I critical stress intensity factor (MPa$\sqrt{m}$);

NMAS : Nominal Maximum Aggregate Size (mm);

P_f : Critical peak (or fracture) load for the SCB specimen (N);

R : Radius of SCB specimen (mm);

SCB : Semi Circular Bending specimen;

S/R : Loading span to radius ratio;

t : SCB specimen thickness (mm);

Y : Geometry factor for the SCB specimen;

Y_I : Mode I geometry factor for the SCB specimen;

σ : Critical applied stress (MPa).

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