# Effect of Characteristic Specifications on Fracture Toughness of Asphalt Concrete Materials

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**Abstract** In this research, the fracture toughness ($K_{Ic}$) of different compositions of asphalt mixtures is investigated experimentally and the effects of asphalt characteristic specifications including the aggregate size, aggregate type (i.e. limestone and siliceous), air void percentage and bitumen type on fracture toughness is studied. Several edge cracked specimens with the shape of semi-circular and subjected to symmetric three point bend loading were manufactured with different compositions and then tested at -15$^o$c. The experimental results showed the noticeable influence of characteristic specifications of asphalt mixtures on the value of fracture toughness. Generally, the value of fracture toughness decreases for those mixtures containing smaller size of aggregates made of siliceous with higher percentages of air voids and softer binder types.

**Keywords** Asphalt mixture, Low temperature, Fracture toughness, Characteristic specifications

## 1. Introduction

Annually huge amount of money is spent for the design, construction and maintenance of asphalt pavements. Many types of cracks (e.g. top-down cracks in the surface of asphalt pavements) initiated due to daily or seasonal cyclic thermal loads or mechanical traffic loading are known as one of the main causes for the overall failure and a common mode of deterioration in asphalt pavement of roads and highways. Consequently, asphalt cracking may increase noticeably the maintenance and rehabilitation cost of pavements and hence the investigation of crack growth behavior in the asphalt pavements and overlays is an important issue for design, construction and maintenance of roads and highways in many countries. Under subzero and very low temperatures, asphalt pavements often behave as a brittle material and, hence, the risk of sudden fracture from pre-existing cracks in the pavement increases.

Some experimental studies have been done in the past for investigating the crack growth behavior of asphalt pavements, using different test specimens. From the experimental view point, a suitable test specimen for asphalt mixtures should 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. The edge cracked rectangular beam subjected to three or four point bending [1, 2], the disc shape compact-tension specimen [3-5] and the semi circular bend (SCB) specimen subjected to three point bend loading [6-9] are some of the most frequently used configurations for fracture toughness testing of asphalt materials. For example, the fracture resistance of various asphalt mixtures has been investigated experimentally using SCB, the edge cracked rectangular beam specimen subjected to four-point loading, and the center crack plate under tension specimens by Molennar and coworkers [10,11]. Chen et al. [12] also employed the SCB specimen to study the effect of temperature on the fracture toughness of asphalt mixtures. Among the mentioned specimens, the SCB specimen can be considered as a suitable and favorite configuration for asphalt mixtures because it can be manufactured easily from standard field coring equipments or gyratory compactor machines and then it can also be tested easily by using ordinary testing apparatuses and fixtures. Moreover, in comparison with the rectangular beam specimens, the SCB samples need less asphalt mixtures for specimen preparation and consequently decrease the weight of test samples and cost of experiments. Hence, the SCB specimen has been used in the past for investigating the fracture behavior of asphalt mixtures [6-12]. Fig. 1 shows the SCB specimen schematically which is a semi-circular specimen of radius *R* and thickness *t*. When the SCB specimen is subjected to symmetric three-point bending with a loading span of 2S, the vertical edge crack of length *a* experiences pure mode I deformation (crack opening). The specimen can also be used for mixed mode I/II (tension – shear) experiments simply by inclining its direction relative to the applied load *P* direction or changing its location relative to the loading points.

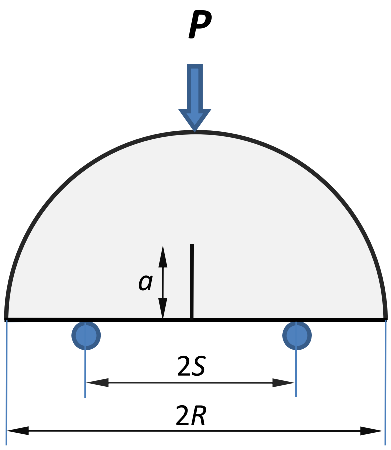



Figure 1. The edge cracked SCB specimen subjected to symmetric bend loading.

Since asphalt mixtures are complicated materials, their properties, performance, durability and mechanical strength depend strongly on the composition of the ingredients, manufacturing process, mix design, type of aggregates and binders, service and temperature conditions and etc. Therefore, in this research, fracture resistance of different compositions of asphalt mixture is investigated experimentally using SCB specimen and the effects of asphalt characteristic specifications including the aggregate size, air void percentage and bitumen type on fracture load and fracture toughness are studied.

## 2. Asphalt mixtures manufacturing

For preparation of asphalt mixtures, two aggregate types made of limestone and siliceous with three gradations (i.e. aggregate sizes of No. 4, 5 and 6 according to Iranian paving standard- code 234) were considered. The corresponding nominal maximum aggregate size (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 asphalt mixtures of this study have been presented in Table 1. Also, two binder penetration grade of 60/70 (the most commonly used type for paving the roads in Iran) and 85/100 (a suitable type for cold climates) were utilized for preparation of asphalt mixtures. 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.

Table 1. Asphalt mixture aggregate gradation

| Gradation number | NO.4 | NO.5 | NO.6 |
|---|---|---|---|
| | NMAS: 12.5mm | 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 test | Unit | Binder type | |
|---|---|---|---|---|
| | | | 60-70 | 85-100 |
| Specific Gravity (25 °C) | ASTM D70 | gr/cm3 | 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 | mm2/s | 810 | 512 |
| Kinematic Viscosity @ 135 °C | ASTM D2170 | mm2/s | 420 | 221 |
| Kinematic Viscosity @ 150 °C | ASTM D2170 | mm2/s | 232 | 120 |
| Penetration index (PI)a | – | – | –1.12 | -1.98 |

[a] PI = [1952 – 500 log ($Pen_{25}$) – 20SP] / [50 log ($Pen_{25}$) – SP – 120]

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 |
| Lime stone aggregates | 4.8 | 5.1 | 5.7 | 4.6 | - | - |
| Siliceous aggregates | 5.2 | - | - | - | - | - |

## 3. Specimen manufacturing and testing

After mixing the aggregates (i.e. limestone and siliceous of different sizes) with binders (i.e. 60/70 and 85/100 bitumen) at 155$^{o}$C, cylindrical specimens with diameter of 150 mm and height of 130 mm were manufactured using super pave gyratory compactor machine (SGC). The numbers of gyratory rotations (i.e.35, 70 and 90) were also varied that results in changing the void percentage in the prepared mixtures. The cylinder were then sliced using a rotary diamond saw machine to obtain circular discs of height approximately about 30 mm. Each disc was splited into two halves to produce two semi circles. A very narrow notch with length of 20 mm and width of 0.4 mm was then introduce at the middle of flat edge by a very thin rotary high speed diamond saw blade. Consequently, several edge cracked SCB specimens were manufactured and maintained in a freezer with temperature of -15°C for 6 hours to conduct the fracture tests. Fig. 2 shows some of the steps of specimen preparation for fracture toughness experiments.

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

After preparation of the test samples, they were tested using a compression test machine having capacity of 15kN. The tests were carried out at -15°C under displacement control conditions with a constant cross head speed of 3 mm/min. The SCB specimens were tested using a three-point bend fixture with the loading span of 2$S$ = 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 low temperature of -15°C. Others [13-15] have also mentioned that the asphalt mixtures behave as a linear elastic material at low subzero temperatures. Therefore, fracture toughness of the tested asphalt mixtures were determined from the maximum load recorded for each test. A total number of 45 specimens with different compositions were manufactured and for each mix design, three SCB specimens were tested successfully. Fig. 3 shows the test setup and a typical load-displacement curve obtained for one of the tested specimens.

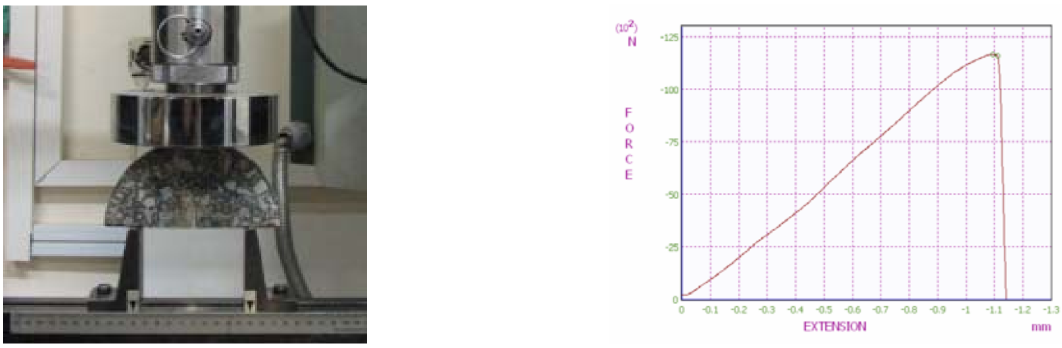



Figure 3. loading setup used for testing of SCB specimen made of asphalt mixture and a typical load-displacement curve obtained for -15°C.

## 4. Results and discussion

Mode-I fracture toughness ($K_{\mathrm{Ic}}$) was determined for each cracked SCB specimen from following equation [16]:

$$K_{\mathrm{Ic}} = \frac{Y_I P_{\mathrm{f}}}{2Rt}\sqrt{\pi a} \tag{1}$$

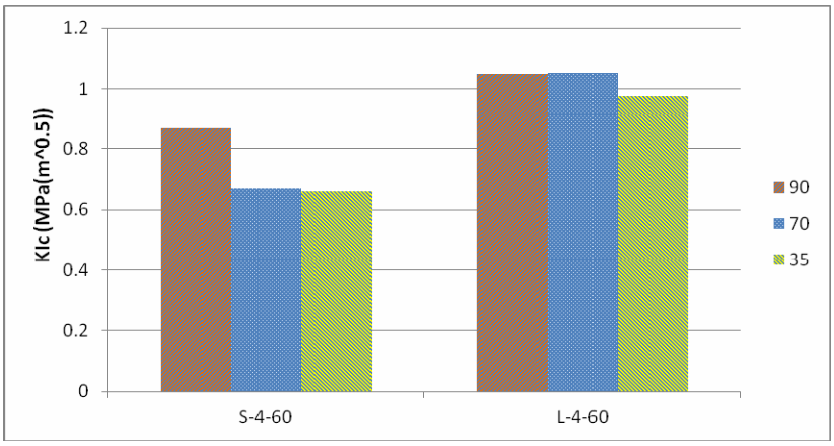
where $P_{\mathrm{f}}$ and $Y_{\mathrm{I}}$ are the critical peak (or fracture) load and the geometry factor for the SCB specimen, respectively. $Y_{\mathrm{I}}$ is function of the crack length to radius ratio ($a/R$) and the loading span to radius ratio ($S/R$). Some analytical and numerical solutions are available for obtaining $Y_{\mathrm{I}}$ [e.g. 16,17]. For example, for the tested mode I samples in this research (i.e. with $a/R$ = 0.27 and $S/R$ = 0.67), the corresponding geometry factor has been determined by Ayatollahi and Aliha [16] using finite element analysis as: $Y_{\mathrm{I}}$ = 3.73.

By recording the final fracture loads from the experiments, the corresponding values of $K_{\mathrm{Ic}}$ for the tested asphalt materials were calculated from Eq. (1) for different compositions of the asphalt mixture. Details of the experimental results including critical fracture load and corresponding value of fracture toughness for each 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). According to the obtained results the average Averages value of $K_{\mathrm{Ic}}$ for the tested mixtures varies between 0.6 MPa.m$^{0.5}$ and 1MPa.m$^{0.5}$.

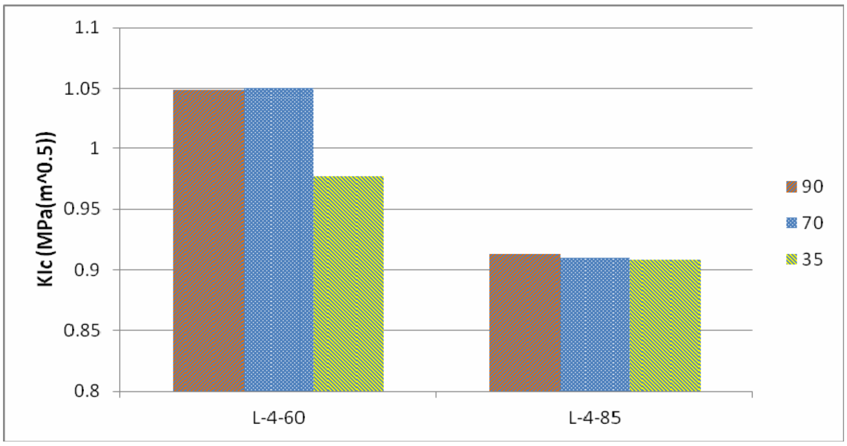
Fig. 4 compares the influence of asphalt characteristic specifications on the value of mode I fracture toughness. As seen from this figure, generally by increasing the void percentage (i.e. decreasing the number of gyratory rotations in the SGC machine) the value of $K_{\mathrm{Ic}}$ is reduced and this reduction is more pronounced for mixtures containing siliceous aggregates. As shown in Fig. 4a, it can be concluded that depending on the void percentage the value of fracture toughness for mixtures made of limestone is about 25 to 60% greater than the corresponding values of $K_{\mathrm{Ic}}$ for siliceous mixtures. A noticeable increase in the value of fracture toughness is also seen when the stiffer binder (i.e. bitumen 60/70) is used (see Fig. 4b). This is mainly because of the higher stiffness of the asphalt mixture which increases the crack growth resistance. Moreover, based on Fig. 4 (c) it is obvious that $K_{\mathrm{Ic}}$ increases when the size of aggregates becomes greater in the asphalt mixtutre. This can be attributed to the lesser amount of binder and greater amount of aggregates in the texture of asphalt mixture which can increase the general stiffness and strength and the required fracturing load of the material. Consequently, According to the results of this research, the risk of low temperature brittle fracture in the asphalt mixtures can be generally increased for siliceous aggregates, smaller aggregate sizes, higher percentages of voids and the higher penetration grades of the binders.

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

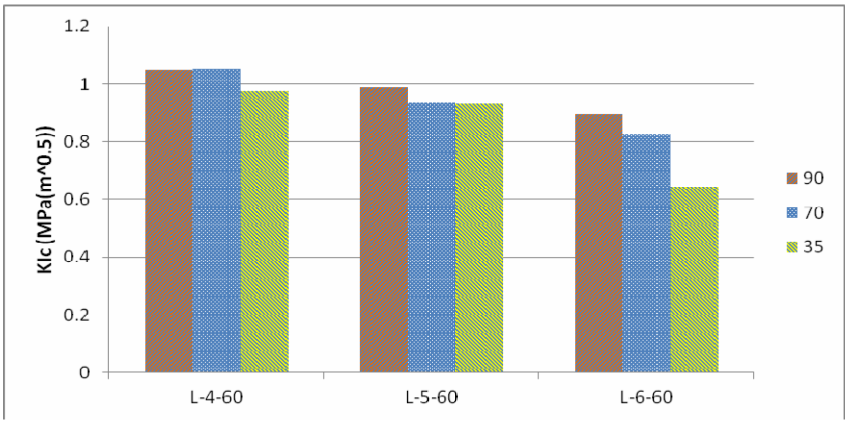
| specimen | Gyratory rotation numbers | Sample Number | Peak load (N) | Average of peak load (N) | Average of $K_{Ic}$ ($MPa.m^{0.5}$) |
|---|---|---|---|---|---|
| S-4-60 | 90 | 1 | 4174 | 4732 | 0.87 |
| | | 2 | 4381 | | |
| | | 3 | 5641 | | |
| | 70 | 1 | 3220 | 3651.33 | 0.67 |
| | | 2 | 3556 | | |
| | | 3 | 4178 | | |
| | 35 | 1 | 3501 | 3603.66 | 0.66 |
| | | 2 | 4100 | | |
| | | 3 | 3210 | | |
| L-4-60 | 90 | 1 | 5268 | 5713.33 | 1.05 |
| | | 2 | 5583 | | |
| | | 3 | 6289 | | |
| | 70 | 1 | 5343 | 5724.66 | 1.05 |
| | | 2 | 5326 | | |
| | | 3 | 6505 | | |
| | 35 | 1 | 5000 | 5323.33 | 0.98 |
| | | 2 | 4997 | | |
| | | 3 | 5973 | | |
| L-4-85 | 90 | 1 | 4770 | 4977 | 0.91 |
| | | 2 | 4579 | | |
| | | 3 | 5582 | | |
| | 70 | 1 | 4937 | 4956 | 0.91 |
| | | 2 | 4700 | | |
| | | 3 | 5231 | | |
| | 35 | 1 | 5160 | 4947 | 0.91 |
| | | 2 | 4732 | | |
| | | 3 | 4949 | | |
| L-5-60 | 90 | 1 | 4622 | 5384.33 | 0.99 |
| | | 2 | 5337 | | |
| | | 3 | 6194 | | |
| | 70 | 1 | 4673 | 5084 | 0.93 |
| | | 2 | 5495 | | |
| | | 3 | - | | |
| | 35 | 1 | 5165 | 5072 | 0.93 |
| | | 2 | 4930 | | |
| | | 3 | 5121 | | |
| L-6-60 | 90 | 1 | 4803 | 4894.33 | 0.90 |
| | | 2 | 5160 | | |
| | | 3 | 4720 | | |
| | 70 | 1 | 4193 | 4511.66 | 0.83 |
| | | 2 | 4731 | | |
| | | 3 | 4611 | | |
| | 35 | 1 | 3765 | 3506 | 0.64 |
| | | 2 | 3405 | | |
| | | 3 | 3348 | | |




(a)




(b)




(c)

Figure 4. Comparison of asphalt characteristic specifications on the fracture toughness ($K_{\mathrm{Ic}}$) of different asphalt mixtures.

## 5. Conclusions

- Fracture toughness of different asphalt mixtures was determined experimentally using several SCB specimens at 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.
- It was observed that the risk of low temperature fracturing in the asphalt mixtures increases for mixtures containing siliceous aggregates, smaller aggregate sizes, greater percentages of voids and higher penetration grades of the binders.

## References

[1] A. Braham, W. Buttlar, F. Ni, Laboratory Mixed-Mode Cracking of Asphalt Concrete Using the Single-Edge Notch Beam, Road Mater Pave Des, 11, ( 2010) 947-968.

[2] M. P. Wagoner, W. G. Buttlar, G. H. Paulino, Development of a Single-Edge Notched Beam Test for Asphalt Concrete Mixtures, Journal of Testing and Evaluation, 33, (2005), Paper ID JTE12579

[3] M. P. Wagoner, W. G. Buttlar, G. H. Paulino, P. Blankenship, Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-Shaped Compact Tension Test, Transp Res Rec,1929, ( 2005)183-192.

[4] H. Kim, M. P. Wagoner, W. G. Buttlar, Numerical fracture analysis on the specimen size dependency of asphalt concrete using a cohesive softening model, Constr Build Mater, 23, ( 2009) 2112-2120.

[5] B. Behnia, E. V. Dave, S. Ahmed, W. G. Buttlar, H. Reis, Effects of Recycled Asphalt Pavement Amounts on Low-Temperature Cracking Performance of Asphalt Mixtures Using Acoustic Emissions, Transp Res Rec, 2208, (2011) 64-71.

[6] M. Ameri, A. Mansourian, S. Pirmohammad, M.R.M Aliha, M.R. Ayatollahi, Mixed mode fracture resistance of asphalt concrete mixtures, Engng Fract Mech 93, (2012), 153-167.

[7] J. H. Liu, Fatigue Life Evaluation of Asphalt Rubber Mixtures Using Semi-Circular Bending Test, Adv Mater Res, 255,(2011) , 3444-3449.

[8] X. J. Li, M.O. Marasteanu, Using Semi Circular Bending Test to Evaluate Low Temperature Fracture Resistance for Asphalt Concrete, Exp Mech, 50,(2010) 867–876.

[9] L. N. Mohammad, M. Kim, M. Elseifi, Characterization of Asphalt Mixture’s Fracture Resistance Using the Semi-Circular Bending (SCB) Test, 7th RILEM International Conference on Cracking in Pavements, RILEM Bookseries 4, (2012) 1-10.

[10] A. A. A. Molenaar, A. Scarpas, X. Liu, G. Erkens, Semi-circular bending test; simple but useful. J Assoc Asphalt Tech, 71, (2002) 794–815.

[11] J. M. M. Molenaar, A.A.A. Molenaar, X. Liu, Resistance to crack-growth and fracture of asphalt mixture. In: 6th international RILEM symposium on performance testing and evaluation of bituminous materials; 2003. pp. 618–25.

[12] X. Chen, W. Li, H. Li, Evaluation of fracture properties of epoxy asphalt mixtures by SCB test. J Southeast Univ, 25, (2009) 527–530.

[13] M. Novak, B. Birgisson, R. Roque. Near-surface stress states in flexible pavements using measured radial tire contact stresses and ADINA. Comp Struct, 81, (2003), 859–870.

[14] X. J. Li, M. O. Marasteanu, The fracture process zone in asphalt mixture at low temperature. Engng Fract Mech 77, (2010) 1175–1190.

[15] M. Fakhri, M. Farokhi, P. T. Kheiry, Modeling of top-down cracking (TDC) propagation in sphalt concrete pavements using fracture mechanics theory. Adv Test Charact Bituminous Mater II, (2009) 681–692.

[16] M.R. Ayatollahi, M.R.M. Aliha, Wide range data for crack tip parameters in two disc-type specimens under mixed mode loading, Comp Mater Sci, 38, (2006) 660-670.

[17] I. Lim, I. W. Johnston, S.K. Choi, Stress intensity factors for semi-circular specimens under three-point bending, Engng Fract Mech, 3, (1993) 363–82.