Civil Engineering Infrastructures Journal 2021, 54(1): 43-58
DOI: 10.22059/ceij.2020.287507.1610

RESEARCH PAPER

Providing a Prediction Model for Stress Intensity Factor of Fiber-Reinforced Asphalt Mixtures under Pure Mode III Loading Using the Edge Notched Disc Beam (ENDB)

Motamedi, H.[1], Amiri, H.R.[2]*, Fazaeli, H.[3] and Mohammad Aliha, M.R.[4]

[1] Ph.D. Student, Department of Civil Engineering, Yazd Branch, Islamic Azad University, Yazd, Iran.
[2] Assistant Professor, Department of Civil Engineering, Yazd Branch, Islamic Azad University, Yazd, Iran.
[3] Assistant Professor, Islamic Azad University, Tehran North Branch, Tehran, Iran.
[4] Assistant Professor, Welding and Joining Research Center, School of Industrial Engineering, Iran University of Science and Technology (IUST), Tehran, Iran.

Received: 30 Aug. 2019; Revised: 04 Sep. 2020; Accepted: 08 Sep. 2020

ABSTRACT: The use of Edge Notched Disc Beam (ENDB) sample has been proposed as a suitable geometry in performing fracture tests in different loading modes. The most important features of the ENDB samples include easy making, quick and easy sampling, simple testing, and the ability to examine a wide range of pure and combined loading modes. Using a wide range of fracture tests, a statistical model is proposed to predict the stress intensity factors of asphalt mixtures in terms of the pure torsion mode (mode III) loading in this study. To this end, the experiments were carried out at different temperature conditions (-5, -15 and -25 °C), different loading conditions (0.5, 1 and 5 mm/min), and on control and modified asphalt mixtures with different percentages of polyolefin-aramid fibers. The results showed that, with increasing the fiber content and loading rate, the fracture strength increased with average 25%, while an increase in fracture toughness due to lower temperature had an effect of less than 5%. Using the Response Surface Method (RSM), the prediction model of stress intensity coefficients of asphalt mixtures was presented in the pure torsion mode. The results of the proposed models had a good correlation with the results of the conducted fracture tests.

Keywords: Edge Notched Disc Beam Specimen, Fiber Reinforced Asphalt Mixture, Fracture Toughness, Mode III Loading, Response Surface Method.

1. Introduction

Without a doubt, asphalt mixtures experience diverse response due to different temperature and loading conditions. In this regard, intermediate temperature and low loading rate result in deterioration of asphalt concrete stems from pavement rutting, bleeding or slippage cracking. On the other hand, temperature reduction can dramatically increase binder elastic and brittle behavior can damage asphalt pavements. Traffic loadings can literally increase thermal effects which intensify

* Corresponding author E-mail: amiri@iauyazd.ac.ir

top-down cracks through whole pavement.

It is believed that the use of binder modifiers and rejuvenators can address the problem of high temperature pavement distresses due to some binder rheological and chemical characteristics improvements (Polacco et al., 2015; Jasso et al., 2015; Chen et al., 2019; Singh et al., 2017; Xu et al., 2016; Vural Kök et al., 2011; Gao et al., 2018; Fazaeli et al., 2012; Vural Kök et al., 2014; Siddig et al., 2018; Taherkhani and Afroozi, 2017; Taherkhani and Arshadi, 2018).

Researches also showed the greater pavement performance and durability when glass, polyester, carbon, cellulose and aramid fibers are used under both low and high temperature condition (Lee et al., 2005; Chowdhury et al., 2006; Mahrez and Karim, 2007; Shaopeng et al., 2007; Putman and Amirkhanian, 2004). For instance, it is showed that aramid fiber additives enhance Warm Mix Asphalt mixtures (WMA) (Fazaeli et al., 2012).

Low temperature cracking behavior of asphalt mixtures are rather complex. In this regard, numerous studies are applied to theoretically examine diverse fracture behavior of asphalt mixtures in terms of criteria like Stress Intensity Factor (SIF) or fracture energy (Ameri et al., 2011; Molenaar et al., 2002; Braham et al., 2010; XJ and MO, 2010; Behbahani et al., 2013; Wagoner et al., 2005a,b; Kim et al., 2009; XJ and Marasteanu, 2010; Tekalur et al., 2009; Ameri et al., 2012; Aliha et al., 2015c,d; Eghbali et al., 2019). Research conducted by Ameri et al (2011) demonstrated that based on varied pavement traffic loadings, different compositions of crack mode deformation (i.e. mode I, II and III) might be grown. Herein, the mode III contribute to crack mechanism. Additional researches investigated the impacts of pure pressure on pavement fracture mainly stems from the mode II crack or combination of the modes I and II. For instance, investigation of both modes I and II showed that the mode I was not the principal mode in asphalt pavement cracking (Aliha et al., 2015c,d).

Investigation of the mode III on the other hand has been rarely discussed in the literature. Avci et al. (2005) simultaneously examined modes I and III of polymeric concrete samples. But their investigation method lacked the production of dominant mode III while loading. Further conducted researches had the same issue of investigating dominant mode (Edward and Hesp, 2006; Wagoner et al., 2005b; Berto et al., 2013; Ayatollahi and saboori, 2015; Liu et al. (2004). However, recently a new method of asphalt concrete fracture toughness has been introduced which has eased the investigation of pure mode III. It also has served as Hot Mix Asphalt (HMA) mixture crack growth investigation (Aliha et al., 2015a,b, 2016).

As mentioned, few researches have examined the mode III of pavement cracking. Meanwhile, it seems that few studies have examined its loading rate, and temperature changes. The present research not only aimes to address these variables effects, but also to develop a regression method to correlate intensity factor of asphalt mixtures with discussed variables.

2. Materials

The asphalt mixture encompasses three main parts namely stone materials, bitumen, and air. The possible changes in the ratios of each of these three parts can affect the function of the asphalt mixtures. In this research, conditions of the test performing, including temperature and loading speed are examined. Therefore, the results of the experiments and the predicted model can be also applied to the steady-state conditions of the mixing design, including the gradation, material size, bitumen percentage, etc. The specifications of the materials used in the manufacture of samples are stated in the next sections.

2.1. Aggregate

Asphalt concrete mainly composed of aggregates. Both physical and chemical aggregate properties can dramatically influence on asphalt mixture design and performance. Limestone aggregate with nominal size of 19 mm was applied in the present study for asphalt mixture specimen preparation. Tables 1 and 2 depicts aggregate type and aggregate gradation specifications, respectively.

2.2. Bitumen

Despite the low percentage use of binder in asphalt mixtures, it might drastically impact asphalt mixtures due to its viscoelastic behavior. In this research, the PG 64-22 binder type was employed which is the most common type across Iranian road pavements. Table 3 shows the applied binder properties.

2.3. Polyolefin - Aramid Fiber

In this study, the Polyolefin-Aramid fiber was used to reinforce asphalt concrete pavement specimen and improve high temperature endurance. The fiber decomposes to two main parts namely; polyolefin (by 75% weight) and aramid Kevlar (by 25% weight) that can remarkably improve asphalt concrete tension strength. The specimens were prepared by adding varied dosage of Polyolefin-Aramid fiber (i.e. 0%, 0.025%, 0.05% and 0.1% of asphalt mixture weight). Mixture specimen preparation was mainly adopted form previous research of Fazaeli et al. (2016). Initially, aramid Kevlar fibers were randomly mixed with aggregates at 170 ˚C. Then, the Polyolefin part was dissolved in bitumen at 135 ˚C for about 3 minutes and then was added to the aggregates-fiber mixture. Figure 1 and Table 4, illustrates the specifications of the fiber used in this research.

(a) **(b)**

Fig. 1. Picture of: a) polyolefin – aramid fibers and; b) fiber reinforced asphalt mixture

Table 1. Physical specifications of fine and coarse aggregates used for manufacturing asphalt mixtures of this research

Specification	Unit	Limestone aggregate
Specific gravity (Coarse aggregate)	g/cm^3	2.638
Specific gravity (Fine aggregate)	g/cm^3	2.619
Loss angles abrasion	%	22
Solubility of sodium sulfate	%	0.7
Water absorption (Coarse aggregate)	%	0.7
Water absorption (Fine aggregate)	%	1.3
Percent fracture (One face)	%	100
Percent fracture (Two face)	%	100

Table 2. Gradation of lime stone aggregate

Sieve number (mm)	19	12.5	4.75	2.36	0.3	0.075
Upper limit	100	100	74	58	21	10
Selected percent	100	95	59	43	13	6
Lower limit	100	90	44	28	5	2

Table 3. Physical specification of binder used for manufacturing asphalt mixtures of this research

Specification	Unit	Standard method	Result	Standard limit
Specific gravity	g/cm^3	ASTM D70	1.013	-
Penetration at 25 °C	0.1mm	ASTM D5	63	60-70
Softening point of bitumen	°C	ASTM D36	56	49-58
Elasticity at 25 °C	cm	ASTM D113	> 100	> 100
The flash point of bitumen	°C	ASTM D92	304	> 232
Solubility in trichloroethylene	%	ASTM D2042	99	> 99
Kinematics viscosity in 135 °C	mm^2/s	ASTM D2170	344	-
Bitumen performance grade (PG)	-	-	22-64	-

Table 4. Physical properties of polyolefin – aramid fibers

Specification	Polyolefin	Aramid
Shape	Twisted strings and single-stranded	Single-stranded
Specific gravity (g/cm^3)	0.91	1.44
Tensile strength (psi)	70000	400000
Length (mm)	19	19
Color	Black	Yellow
Resistance Acid/Base	Ineffective	Ineffective
Melting Point (°C)	100	427

Using Marshall Mixture design procedure, different mixtures including varied fiber dosage percentage (i.e. 0%, 0.025%, 0.05% and 0.1%) and bitumen percentage (i.e. 3.0%, 3.5%, 4.0%, 4.5%, 5.0%, 5.5% and 6.0%) of the total mixture weight were examined and the optimum binder content was extracted amongst them. Table 5 depicts the resulted optimum mixture specifications. It is worth mentioning that all subsequent investigations are based up on the mixture with this optimum binder content.

3. Numerical Analysis and Finite Element Modeling

The ENDB specimen shown in Figure 2a can be described with "R", "t" and "a" parameters which stands for specimen radius, thickness and crack depth, respectively. The crack dispersed along both center and diameter of the disk. The 3-points bending beam (supported at distance of "S") test can be adopted for prepared laboratory disk specimen to investigate different crack modes whether it is pure modes of I and III or is compound I/III mode. This can be achieved by changing the θ parameter which is the crack direction. The θ = 0 results in the pure I mode and increased θ can be correspond to the compound I/III mode. Eq. (1) was used for stress intensity factors calculation of the mode III in the ENDB sample (Aliha et al., 2015b, 2016).

$$K_{III(ENDB)} = \frac{\left(6PS\sqrt{\pi a}Y_{III(ENDB)}\right)}{\mathrm{Rt}^2} \quad , Y_{III(ENDB)}\ \theta\left(\frac{a}{t}, \frac{S}{R}, \theta\right) \qquad (1)$$

where $K_{III(ENDB)}$: is the stress intensity factor of mode III cracking and P: is the reference load. Y: is defined as geometric parameter and can be calculated after Finite-Element analysis. All other parameters are as mentioned before.

Table 5. Specification of asphalt mixture samples manufactured by Marshall mix design method

Specification	Unit	Result
Asphalt content	%	4.2
Stability	Kgf	1260
Specific gravity	g/cm^3	2.36
Air void	%	4.5
Void in mineral aggregate (VMA)	%	14
Void filled by asphalt (VFA)	%	65

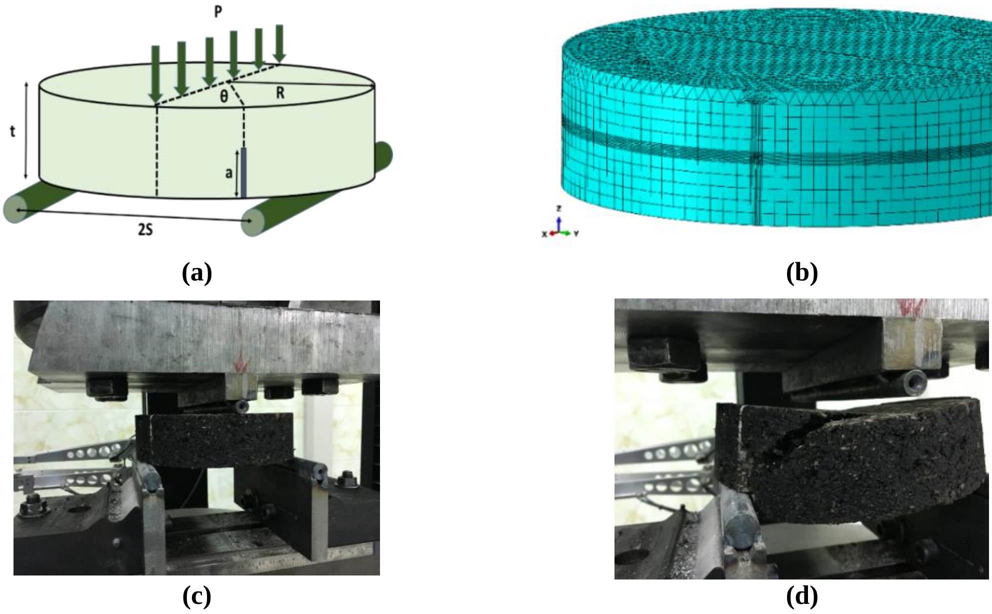


Fig. 2. a) Geometry specification and loading setup in the ENDB samples; Finite Element model in the ABAQUS code; Specification of loading setup; c) Before loading and; d) after loading

Figure 2b illustrates the 3D Finite Element model of ENDB specimen which was simulated 65000 times in ABAQUS software. ENDB asphalt concrete used for simulation had 4 GPa of module of elasticity (E) and Poisson ratio (ν) of 0.35. Reference applied load defined to be P = 150 N. Geometric model and test specifications i.e. “R”, “t”, “a”, “S” remained fixed throughout the simulations at the values of 75, 40, 20 and 67.5 mm, respectively. The crack direction (θ) varied in the domain of 0-67.5˚. Table 6 tabulates estimated Y_{III} after 6000 simulation runs of the ENDB specimen.

Accordingly, in order to simulate this loading mode for fracture testing, the angle between the loading line with the cracking line was 64 degrees and the support distance at this position was considered 67.5 mm. This is shown in Figures 2c and 2d.

4. Specimen Preparation and Testing Method

In the present study, asphalt specimens were gyratory compacted with different values of fiber additives. The resulted 15 and 14 cm height gyratory samples were then sliced into three discs with the same thickness of 4 cm. Then a 0.3 mm gap with the depth of 20 mm was created on the surface of each sliced discs. Figure 3 demonstrates the prepared disks accordingly.

The fracture test was carried out using the GALDABINI tension/compression loading machine. In this regard, the ENDB specimens were initially kept for 12 hours inside a chamber at three different temperatures including; -5, -15 and -25 °C. Then the test conducted under the pure mode III with varied loading rate of 0.5, 1 and 5 mm/min. Considering 3 replicate sample for each mixture with varied fiber additive content, cured under different temperatures and tested under varied loading rate, 108 ENDB specimens were laboratory prepared and tested. Examining the load-displacement curves of the ENDB tests, samples were found to behave as a brittle and linear materials regardless of the cured temperature and loading rates. Figure 4 demonstrates the ENDB test under the mode III of cracking. This figure further shows a typical load-displacement curve.

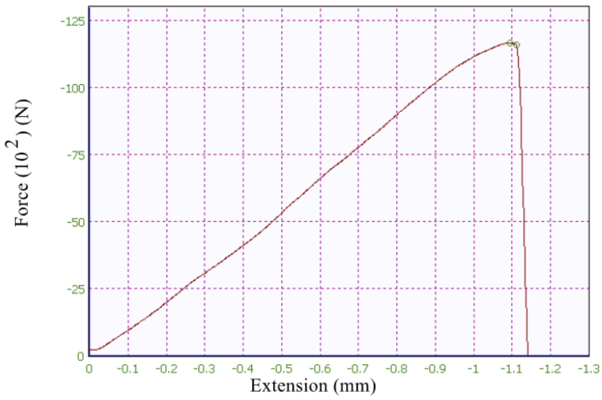
Table 6. Calculated geometric parameter (Y) in mode III (YIII) by ABAQUS

Parameters	Thickness (t) (mm)	Length of crack (a) (mm)	Support (S) (mm)	θ (°)	Y
Mode III (Y_{III})	40	20	67.5	64	0.0631

Fig. 3. Preparing and cutting process of ENDB specimen

(a)

(b)



(c)

Fig. 4. An overview of performing the fracture test in pure mode III: a) loading setup; b) fracture section and; c) load-displacement curves

Based on the mentioned procedures, the stress intensity factor of each laboratory tested ENDB sample was estimated using Eq. (1). Figure 5 illustrates the research methodology applied in the present study.

5. Results and Discussions

5.1. Experimental Results

According to the previous section, the values of stress intensity factors for mode III cracking were extracted. The impacts of different ENDB asphalt mixture variables on resultant fracture toughness are examined in this section and shown in Table 7.

5.1.1. Loading Rate Influence on Fracture Toughness of Asphalt Mixture

Figure 6 shows the values of the stress intensity factors for different asphalt mixtures under mode III loading. In this figure, changes in the mode III stress intensity factor have been shown as a measure of the strength of asphalt mixtures under varied loading rate at various temperatures. According to Figure 6a, at -5 °C and under mode III loading conditions, the stress intensity factor of the asphalt mixtures, increases for a fixed loading rate by increasing the percentage of fiber. This phenomenon might be seen for the whole specified loading rates. This implies that the modified fiber-reinforced asphalt mixtures can demonstrate a more efficient performance on the fracture toughness of asphalt mixtures at low temperatures. Adding aramid fibers with high tensile strength and 3-D distribution in the asphalt mixtures has led to the reinforcement of the asphalt mixtures against the applied forces at all directions.

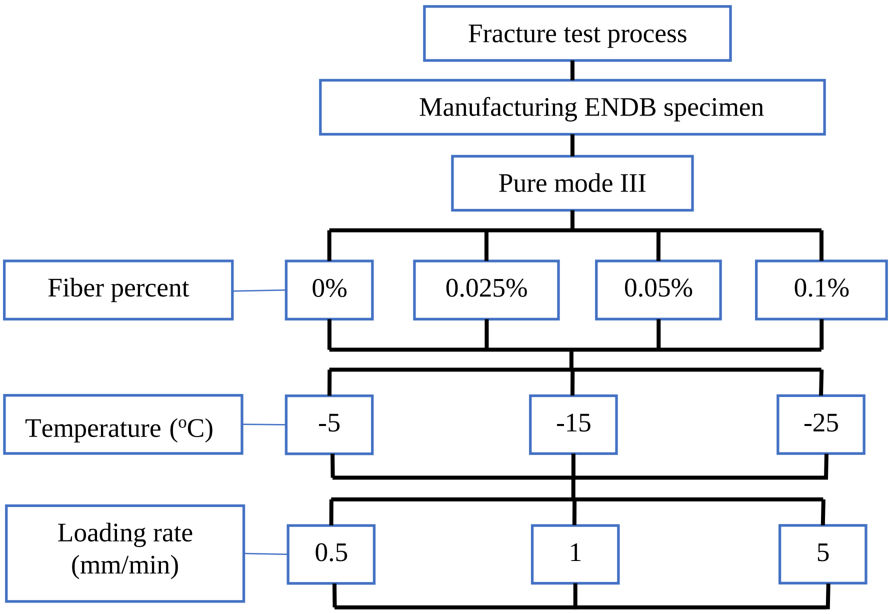


Fig. 5. Flowchart of experimental program

Table 7. Mode III stress intensity factors of the modified and unmodified asphalt mixtures at different loading rates and test temperatures

Stress intensity factor results				
Fiber (%)	**Loading rate (mm/min)**	**Test temperature (°C)**		
		-5	**-15**	**-25**
	0.5	0.31	0.32	0.32
0	1	0.34	0.35	0.35
	5	0.41	0.42	0.43
	0.5	0.35	0.37	0.38
0.025	1	0.37	0.38	0.39
	5	0.42	0.44	0.45
	0.5	0.37	0.39	0.4
0.05	1	0.4	0.42	0.43
	5	0.44	0.46	0.47
	0.5	0.38	0.4	0.4
0.1	1	0.44	0.45	0.47
	5	0.48	0.49	0.5

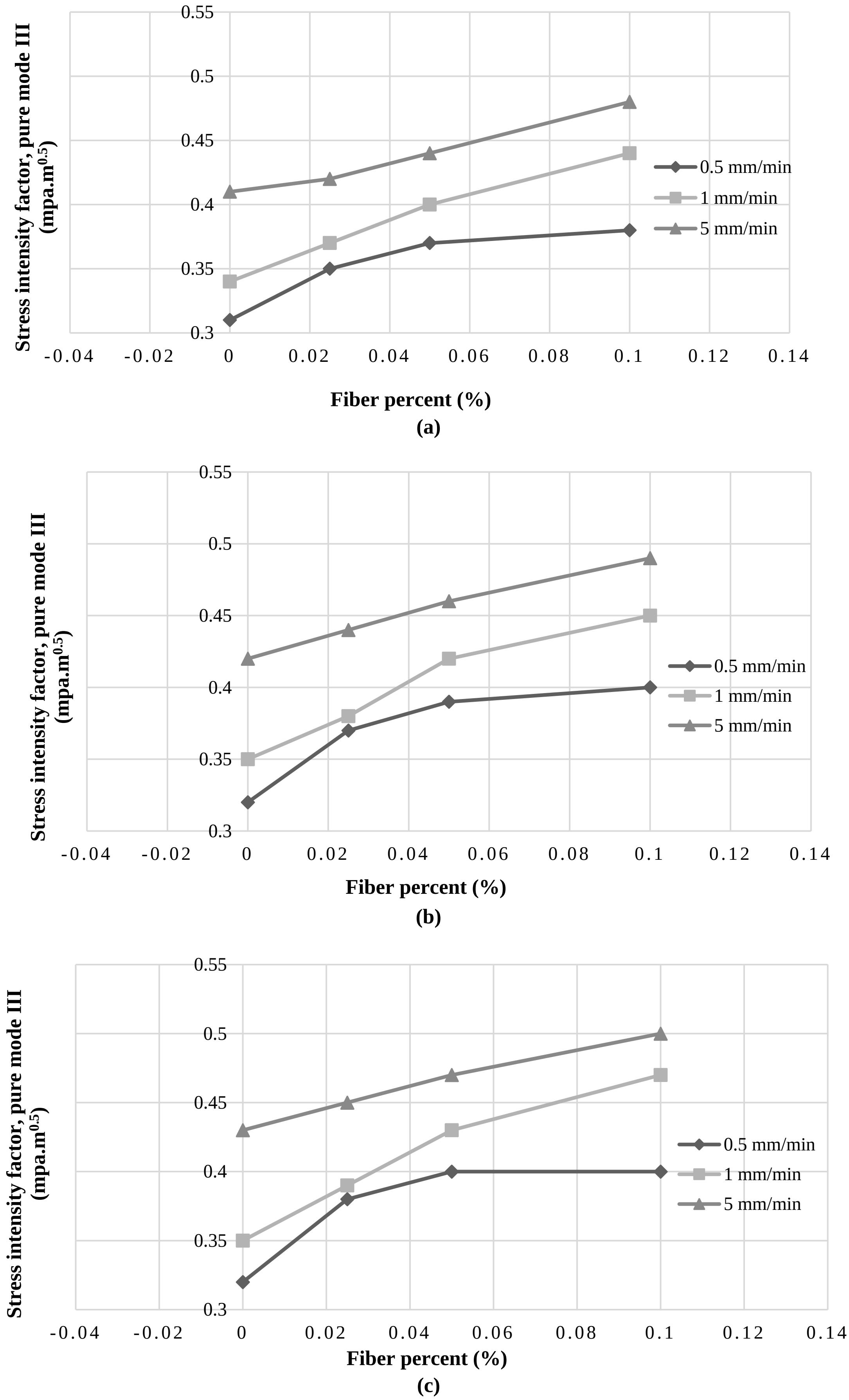


Fig. 6. Effect of the loading rate on mode III fracture toughness of asphalt mixture in different test temperatures: a) -5 °C; b) -15 °C and; c) -25 °C

Hence, after applying the load and the occurrence of micro-cracks at the initial time of loading and the involvement of the fiber bearing the applied tensions, the crack expansion will require further force, which will be associated with the increased stress intensity factor value.

Meanwhile, polyolefin fibers founded to raise the elastic behavior of the bitumen that will result in an increased final fracture load meaning the increased peak load in the load-displacement diagram. However, this may lead to area under curve reduction which result in increased brittle behavior of the samples and of course lowered fracture energy value.

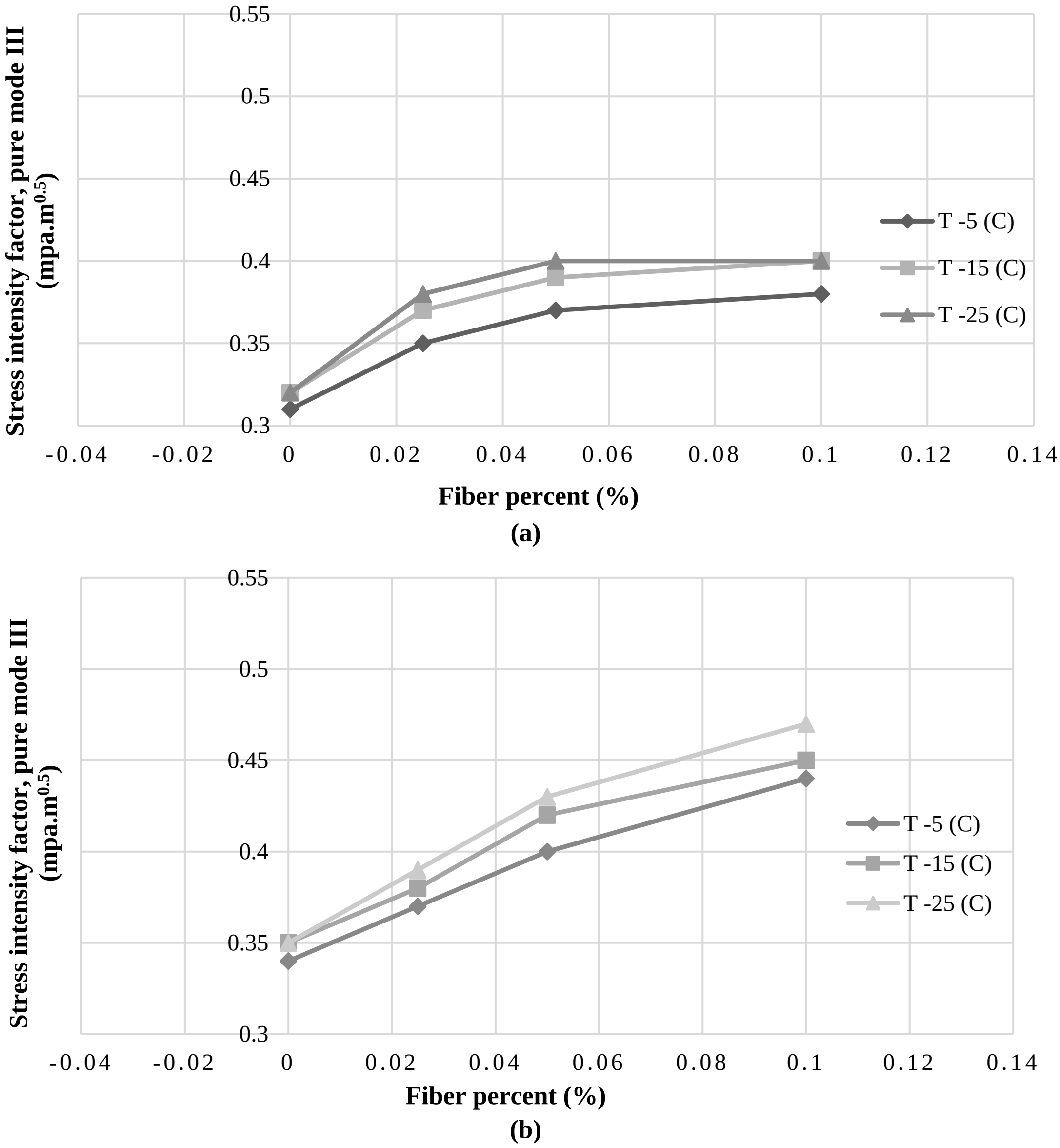
Looking at Figure 6a, one can realize that increasing loading rate can remarkably increase the fracture toughness values for all asphalt samples. This further indicates that the elastic behavior of the asphalt mixture becomes more pronounced at higher rates of applying load. Nevertheless, at every 3 loading rates, the modified asphalt samples with more fiber showed higher strength levels. By comparing Figure 6a with Figures 6b and 6c, it can be seen the same changes in the fracture toughness of the asphalt mixtures by changes made in the fiber percentages and the loading rates. However, with the test temperature dropping from -5 to -25°C, the increased stress intensity factors of the asphalt mixtures are seen in all control and modified samples with different percentages of fibers. According to the viscoelastic behavior of bitumen, the elastic behavior of bitumen increases at lower temperatures, which will be associated with an increase in the hardness of bitumen, and subsequently, in the hardness of the asphaltic mixture. The increased hardness of the asphaltic mixture at low temperatures results in an increase in the critical fracture load, and subsequently increases the fracture toughness of the mixture.

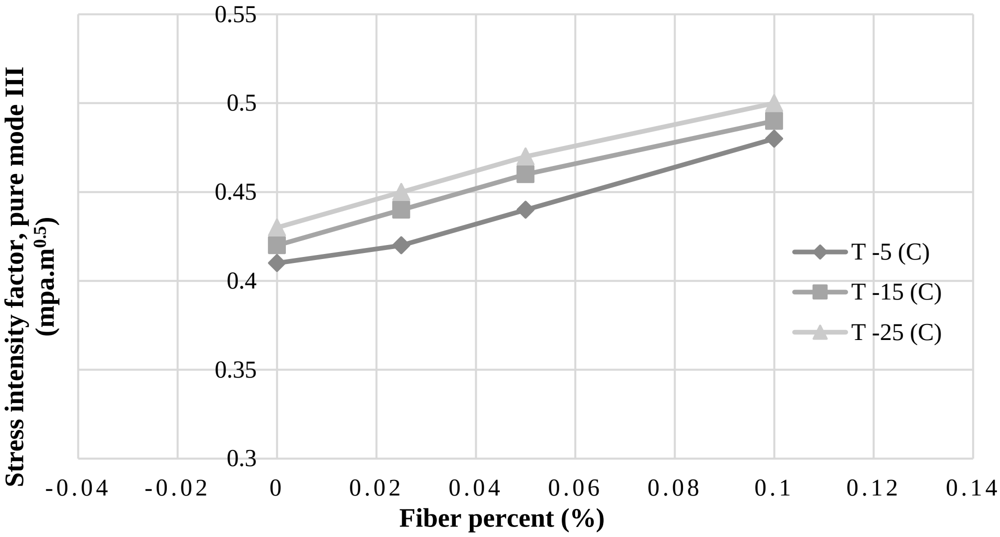
Compared to similar research findings by other researchers, the values of stress intensity factor in mode III conditions are lower than those of the mode I (Aliha et al., 2015a,b, 2016). Thus, under the same experiment conditions in terms of temperature and loading rate, the fracture toughness of the asphalt mixtures under III mode loading are 30% to 50% lower than the values calculated in the mode I (Aliha et al., 2016). Although the use of fibers has significantly increased the fracture toughness in the asphalt mixtures under mode III loading, however, even the use of fibers alone cannot compensate the weakness of the asphalt samples in the mode III loading compared to the modes I or II. This indicates the importance and criticality of the mode III loading in the occurrence of the cracking. This is while in most laboratory and numerical studies conducted in the area of investigating the fracture strength of the asphalt mixtures, the pure strain or pure shear fracture modes or a combination of these two have been examined (Molenaar et al., 2002; Braham et al., 2010; Behbahani et al., 2013; Wagoner et al., 2005a,b; Kim et al., 2009; Aliha et al., 2015c,d; Eghbali et al., 2019). However, Ameri et al. (2011) showed that the growth of a crack in the asphalt pavement is quite possible in the conditions of pure mode III loading or a combination of mode III with other modes and depends on the conditions and the placement of the vehicle wheel than to the crack.

5.1.2. Effect of Test Temperature on Fracture Toughness of Asphalt mixture

Figure 7 shows the effect of test temperature on the fracture toughness of asphalt mixtures at identical loading rates under modes I and III conditions. According to Figure 7a, the fracture toughness of the asphalt mixtures in the mode III and at a loading rate of 0.5 mm/mm, slightly increases as the test temperature decreases. This indicates the low impact of temperature decrease on the stress intensity factor in the mode III. By comparing Figures 7a and 7c, one can realize that the values of stress intensity factors increase at higher loading rates. This increase accounts for 32% and 26% at -5 °C for unmodified and modified asphalt mixture with 0.1% fiber. In fact, one can say that the impact of the loading rate on the values of stress intensity factors and the samples resistance to the fracture is greater than the effect of drop in the temperature.

The increase in the stress intensity factor of the samples is tangible with increasing the fiber percentages at all temperatures and loading rates. This variation range is respectively measured at a minimum value of 16% and in the maximum value of 34% depending on the test temperature and loading rate with increasing the fiber percentage from 0 to 0.1%. Therefore, it can be said that the effect of the fiber on the improvement of the crack resistance and the fracture of the asphalt mixture will be significant under the conditions of mode III loading. Given the sample geometry and length considered for the crack expansion, due to the wide extent of the fracture area in the mode III, and on the other hand, as the 3D distribution of fibers in the asphalt mixtures in all directions provides the possibility of the crossing of the crack growth path and the stress level created by the fibers in the asphalt mixture, then, the role of the fiber in controlling the growth of the crack will be more effective. Figure 8 shows the process of fracture and the cross-section area of the fracture site in two I and III modes of loading.





(c)

Fig. 7. Effect of test temperature on fracture toughness of asphalt mixture, loading rate of: a) 0.5 mm/min; b) 1 mm/min and; c) 5 mm/min

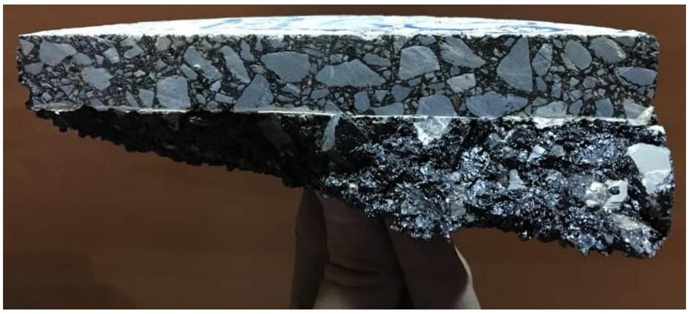


Fig. 8. The fracture propagation trajectory of tested asphalt mixture for the mode III fracture

5.2. Statistical Results: Analysis of Fracture Results Using RSM Method

In order to investigate the influence of affecting parameters (such as loading rate, temperature and fiber percentage) on the critical values of the mode III stress intensity factors, the Response Surface Method (RSM) was utilized. This method can be used as a useful statistical predictive technique for determining effect of the mentioned factors on the value of K_{III}. In RSM, each response (dependent variable) affected by some of independent variables. In addition, this method evaluates the effects of individual factors (for example, input parameters) and the interaction of parameters in each response.

The Central Composite Design (CCD) is the most common method of design in RSM technique. In this research the design expert 6.0.7 software was utilized for extracting a relation between the response (i.e. the stress intensity factors) and input parameters (i.e. temperature, loading rate and fiber). A second order regression model is often used in RSM methods as follows:

$$Y = C_{k0} + \sum_{i=1}^{4} C_{ki}\, x_i + \sum_{i=1}^{4} C_{kii}\, x_i^2 + \sum_{i<j=2}^{4} C_{kij}\, x_i x_j \tag{2}$$

where Y: is the dependent variable and C_{k0}, C_{ki}, C_{kii} and C_{kij}: are constant, linear, second order and regression factor, respectively, and x_i and x_j: are independent variably using the least square method.

In the corresponding regression equation, the coefficients of equation were determined using minimum squared method and the response was predicted. Analyzing models that represent the relationship between responses and test variables was carried out using RSM prediction models. In the obtained regression models, P-value (from 0 to 1) was used to determine the statistical significance of each of the parameters. The final regression models of variance analysis were performed with regard to the significance level of 0.05. In other words, variables with a P-value greater than 0.05 were not considered in the model.

Tables 8 and 9 present the variance analysis of prediction models of the mode III stress intensity factors, respectively. It is seen from these two tables that the P-value for the affecting parameters in the utilized model are less than 0.05. In the predictive model of pure mode III case the parameter A, B, C, BC, B^2 and C^2 have small P-value less than 0.05 and thus have significant effect on the KIII value.

The coefficient R^2 and R^2_{adj} were determined using Eqs. (3) and (4).

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} \quad (3)$$

$$R^2_{adj} = 1 - \frac{SS_{residual}/DF_{residual}}{SS_{total}/(DF_{model} + DF_{residual})} \quad (4)$$

where $SS_{residual}$: is the sum of residual, *DF*: is the degree of freedom, SS_{total}: is the sum of $SS_{residual}$ and SS_{model} .The greater value of R^2 and R^2_{adj} shows the better fitness of prediction model of experimental results as shown in Figure 9.

The following models were obtained for predicting the mode III fracture toughness of tested ENDB asphalt mixtures under different conditions and input parameters such as temperature, loading rate and fiber percentage. Figure 9 also shows the variation of mode III fracture toughness value under the influence of each input variable.

Table 8. Variance analysis of prediction model of the mode III loading

Source	Sum of squares	df	Mean Square	F Value	P-value prob. > F	Significant or insignificant
Model	0.08	6	0.013	151.05	< 0.0001	Significant
A-temperature	3.58E-03	1	3.58E-03	40.77	< 0.0001	Significant
B-load rate	0.037	1	0.037	426.19	< 0.0001	Significant
C-fiber	0.03	1	0.03	343.74	< 0.0001	Significant
BC	4.31E-04	1	4.31E-04	4.9	0.0348	Significant
B^2	3.21E-03	1	3.21E-03	36.55	< 0.0001	Significant
C^2	1.72E-03	1	1.72E-03	19.59	0.0001	Significant
Residual	2.55E-03	29	8.79E-05			

Table 9. Statistical parameters of the prediction model for Mode I and Mode III

Parameters	Std. Dev.	Mean	C.V. (%)	R-squared	Adj. R^2	Pred. R^2
KIII	9.38E-03	0.46	2.04	0.969	0.9626	0.9509

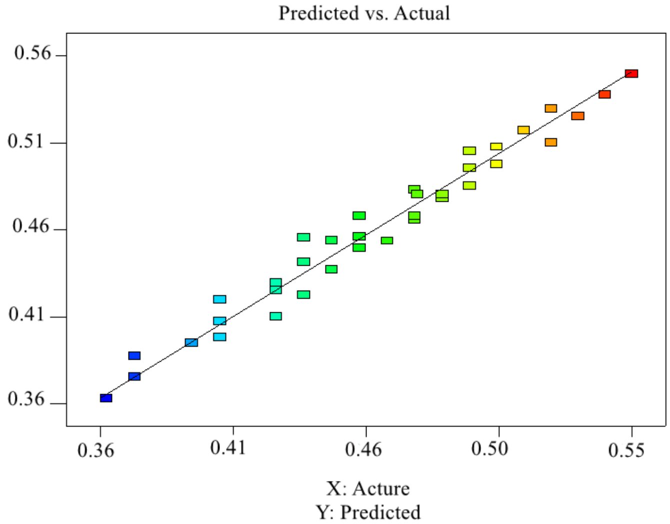
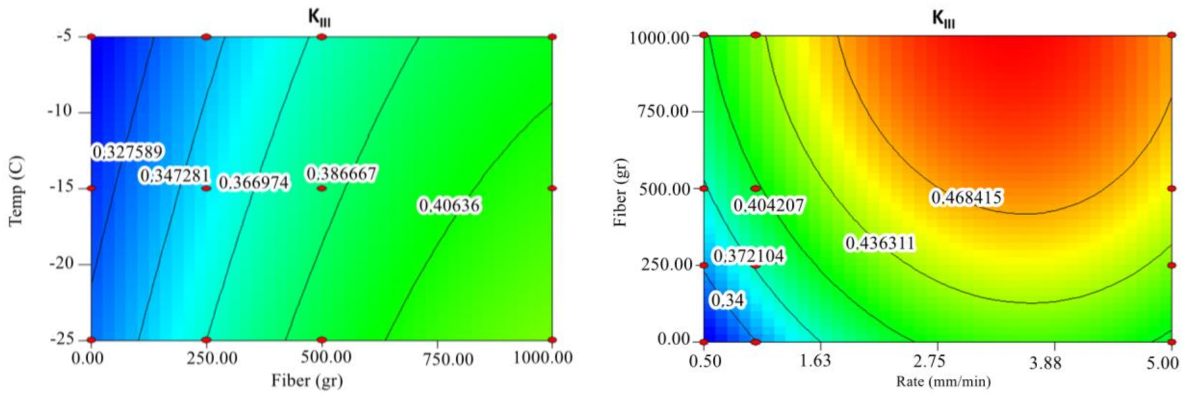


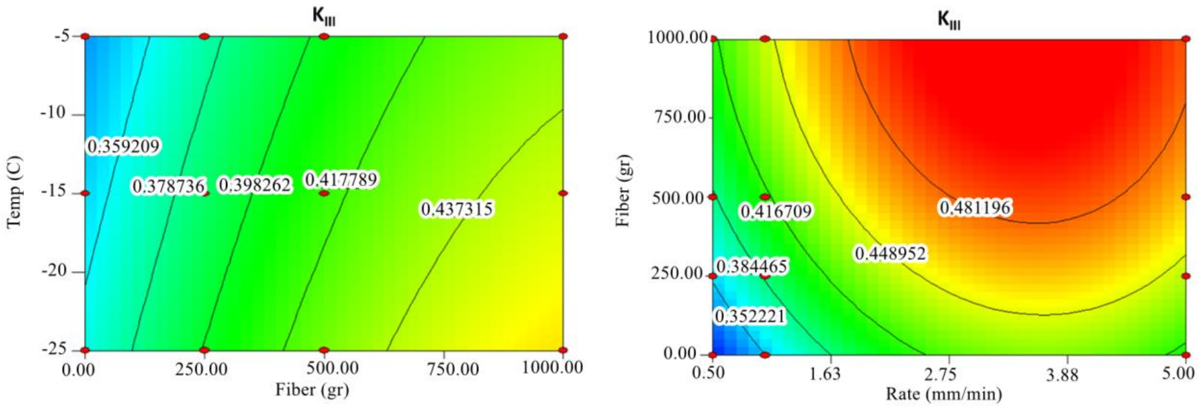
Fig. 9. Comparison of scatter plot fitted the experimental data and predicted model for mode III

Figure 10 shows changes in the coefficient of stress intensity predicted by the model presented in Figure 5 as a function of temperature and loading rate changes. The trend is consistent with the diagrams shown in Figures 6 and 7 Accordingly, the stress intensity coefficient of the samples increased with increasing fiber percentage and loading rate under the same test conditions. The rate of fracture toughness increased due to lower test temperature compared to other variables (increased loading rate and fiber content). This process has been followed both in the prediction model and in the results of the experiment.

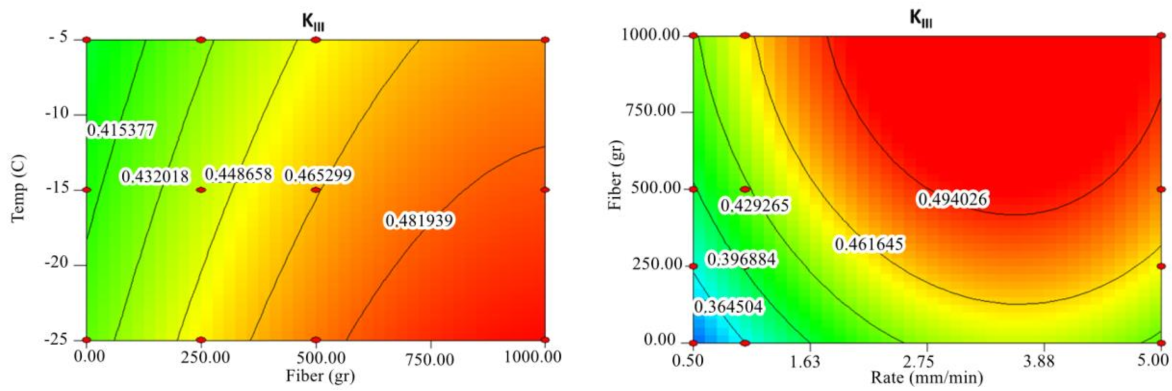
$$K_{III}^{0.86} = +0.31948 - 1.22202E - 003 * Temp + 0.080505 * Rete + 1.57318E - 004 * Fiber - 4.64752E - 006 * Rate * Fiber - 0.010984 * Rate^2 - 6.24267E - 008 * Fiber^2$$



(a1) Loading rate: 0.5 mm/min **(b1)** Temperature: -5 °C



(a2) Loading rate: 1 mm/min **(b2)** Temperature: -15 °C



(a3) Loading rate: 5 mm/min **(b3)** Temperature: -25 °C

Fig. 10. The variations of prediction model obtained for the tested mode III ENDB specimens for: a) Different loading rates and; b) different temperatures

6. Conclusions

Using a suitable geometry to perform the fracture test, the changes in the fracture toughness of asphalt mixtures were examined under the pure mode III of loading in this study. The impacts of parameters such as loading temperature, loading speed, and the fiber as a widely used additive in the asphalt mixture fracture strength were also evaluated. To this end, the ENDB was used to perform the fracture test, which provides the potential to conduct the experiment under the pure mode III. The study findings are as follows:

- The use of fiber-reinforced asphalt is recommended as a suitable method to increase the fracture strength of the asphalt mixtures. Increasing the fiber percentage can significantly increase the fracture toughness of the asphalt mixture.
- The temperature and loading rate can be considered as important and influential parameters in the mode III fracture toughness of the asphalts mixtures. Considering the viscoelastic behavior of the asphalt mixtures, the asphalt mixture behavior tends towards elastic behavior with decreasing temperature and increasing the rate of loading, which results in the increased fracture toughness and the strength of the mixture against the onset of crack expansion. However, the loading rate was found to be a more effective parameter in the results of the stress intensity factors in the pure III mode.
- The low values of the fracture toughness of the asphalt mixture in the mode III indicate the criticality of this mode of loading and the faster expansion of cracks in these situations. Obviously, paying attention to this finding in future researches is required.
- The proposed statistical model in this study can be a good predictor of the results of the fracture tests of asphalt mixtures using the ENDB sample in the III mode conditions
- The present model is proposed with respect to the materials used in this study. It is obvious that model calibration and its development to be generalizable to other asphalt mixtures can be considered in future studies.

7. Reference

Aliha, M.R.M., Bahmani, A. and Akhondi, S. (2015a). "Determination of mode III fracture toughness for different materials using a new designed test configuration", *Materials and Design*, 86, 863-871.

Aliha, M.R.M., Bahmani, A. and Akhondi, S. (2015b). "Numerical analysis of a new mixed mode I/III fracture test specimen", *Engineering Fracture Mechanics*, 134, 95-110.

Aliha, M.R.M., Behbahani, H., Fazaeli, H. and Rezaifar, M. (2015c). "Experimental study on mode I fracture toughness of different asphalt mixtures", *Scientia Iranica, Transactions A: Civil Engineering*, 22(1), 120-130.

Aliha, M.R.M., Fazaeli, H., Aghajani, S. and Moghadas Nejad, F. (2015d). "Effect of temperature and air void on mixed mode fracture toughness of modified asphalt mixtures", *Construction and Building Materials*, 95, 545-555.

Aliha, M.R.M., Bahmani, A. and Akhondi, S. (2016). "A novel test specimen for investigating the mixed mode I+ III fracture toughness of hot mix asphalt composites; Experimental and theoretical study", *International Journal of Solids and Structures*, 90, 167-177.

Ameri, M., Mansourian, A., Heidary Khavas, M., Aliha, M.R.M. and Ayatollahi, M. (2011). "Cracked asphalt pavement under traffic loading; A 3D Finite Element analysis", *Engineering Fracture Mechanics*, 78(8), 1817-1826.

Ameri, M., Mansourian, A. Pirmohammad, S., Aliha, M.R.M. and M.R. Ayatollahi, (2012). "Mixed mode fracture resistance of asphalt concrete mixtures", *Engineering Fracture Mechanics*, 93, 153-167.

Avci, A., Akdemir, A. and Arikan, H. (2005). "Mixed-mode fracture behavior of glass fiber reinforced polymer concrete", *Cement and Concrete Research*, 35(2), 243-247.

Ayatollahi, M. and Saboori, B. (2015). "A new fixture for fracture tests under mixed mode I/III loading", *European Journal of Mechanics - A/Solids*, 51, 67-76.

Behbahani, H., Aliha, M.R.M., Fazaeli, H. and Aghajani, S. (2013). "Experimental fracture toughness study for some modified asphalt mixtures", *Advanced Materials Research*, 723, 337-344.

Berto,F., Cendon, D., Lazzarin, A. and Elices, M. (2013). "Fracture behavior of notched round bars made of PMMA subjected to torsion at – 60 °C", *Engineering Fracture Mechanics*, 102, 271-287.

Braham, A., Buttlar, W. and Ni, F. (2010). "Laboratory mixed-mode cracking of asphalt concrete using the single-edge notch beam", *Road Materials and Pavement Design*, 11(4), 947-968.

Chen, Z., Pei, J., Wang, T. and Amirkhanian, S. (2019). "High temperature rheological characteristics of activated crumb rubber modified asphalts", *Construction and Building Materials*, 194, 122-131.

Chowdhury, A., Button, J.W. and Bhasin, A. (2006). "Fibers from recycled tire as reinforcement in hot mix asphalt", Report No. SWUTC/06/167453-1, Texas Transportation Institute, Texas A&M University System.

Edwards, M. and Hesp, S. (2006). "Compact tension testing of asphalt binders at low temperatures". *Transportation Research Record Journal*, 1962(1), 36-43.

Eghbali, M.R., Fallah Tafti, M., Aliha, M.R.M. and Motamedi, H. (2019). "The effect of ENDB specimen geometry on mode I fracture toughness and fracture energy of HMA and SMA mixtures at low temperatures", *Engineering Fracture Mechanics*, 216(4), 106496.

Fazaeli, H., Behbahani, H., Amini, A.A., Rahmani, J. and Yadollahi, G. (2012). "High and low temperature properties of FT paraffin modified bitumen", *Advances in Materials Science and Engineering*, 2012(Jan. 1), 1-7.

Fazaeli, H., Samin, Y., Pirnoun, A. and Dabiri, A. S. (2016). "Laboratory and field evaluation of the warm fiber reinforced high performance asphalt mixtures (case study Karaj; Chaloos road)", *Construction and Building Materials*, 122, 273-283.

Gao, J., Yan, K., He, W., Yang, Sh. and You, L. (2018). "High temperature performance of asphalt modified with Sasobit and Deurex", *Construction and Building Materials*, 164, 783-791.

Jasso, M., Hampl, R., Vacin, O., Bakos, D., Stastna, J. and Zanzotto, L. (2015). "Rheology of conventional asphalt modified with SBS, Elvaloy and polyphosphoric acid", *Fuel Processing Technology*, 140, 172-179.

Kim, H., Wagoner, M. and Buttlar, W. (2009). "Micromechanical fracture modeling of asphalt concrete using a single-edge notched beam test", *Materials and Structures*, 42(5), 677-689.

Lee, S.J., Rust, J.P., Hamouda, H., Kim, Y.R. and Borden, R.H. (2005). "Fatigue cracking resistance of fiber-reinforced asphalt concrete", *Textile Research Journal*, 75(2), 123-128.

Liu, S., Chao, Y.J. and Zhu, X. (2004). "Tensile-shear transition in mixed mode I/III fracture", *International Journal of Solids and Structures*, 41(22-23), 6147-6172.

Mahrez, A. and Karim, M.R. (2007). "Rutting characteristics of bituminous mixes reinforced with glass fiber", *Journal of the Eastern Asia Society for Transportation Studies*, 7, 2168-2172.

Molenaar, A., Scarpas, A., Liu, X. and Erkens, G. (2002). "Semi-circular bending test, simple but useful", *Association of Asphalt Paving Technologists*, 71, 794-815.

Polacco, G., Filippo, S. and Stastna, M.G. (2015). "A review of the fundamentals of polymer-modified asphalts: asphalt/polymer interactions and principles of compatibility", *Advances in Colloid and Interface Science*, 224, 72-112.

Putman, B.J. and Amirkhanian, S.N. (2004). "Utilization of waste fibers in stone matrix asphalt mixtures", *Resources, Conservation and Recycling*, 42(3), 265-274.

Shaopeng, W., Qunshan, Y., Ning, L. and Hongbo, Y. (2007). "Effects of fibers on the dynamic properties of asphalt mixtures", *Journal of Wuhan University of Technology-Materials Science Edition*, 22(4), 733-736.

Siddig, E., Feng, Ch. and Yi Ming, L. (2018). "Effects of ethylene vinyl acetate and nanoclay additions on high-temperature performance of asphalt binders", *Construction and Building Materials*, 169, 276-282.

Singh, D., Sawant, D. and Xiao, F. (2017). "High and intermediate temperature performance evaluation of crumb rubber modified binders with RAP", *Transportation Geotechnics*, 10, 13-21.

Taherkhani, H. and Afroozi, S. (2017). "Investigating the performance characteristics of asphaltic concrete containing nano-silica", *Civil Engineering Infrastructures Journal*, 50(1), 75-93.

Taherkhani, H. and Arshadi, M.R. (2018). "Investigating the creep properties of PET-modified asphalt concrete", *Civil Engineering Infrastructures Journal*, 51(2), 277-292.

Tekalur, S., Shukla, A., Sadd, M. and Lee, W. (2009). "Mechanical characterization of a bituminous mix under quasi-static and high strain rate loading", *Construction and Building Materials*, 23(5), 1795-1802.

Vural Kök, B., Yılmaz, M. and Akpolat, M. (2014). "Evaluation of the conventional and rheological properties of SBS+Sasobit modified binder", *Construction and Building Materials*, 63, 174-179.

Vural Kök, B., Yilmaz, M. and Guler, M. (2011). "Evaluation of high temperature performance of SBS+Gilsonite modified binder", *Fuel*, 90(10), 3093-3099.

Wagoner, M., Buttlar, W. and Paulino, GH. (2005a). "Development of a single-edge notched beam test for asphalt concrete mixtures", *Journal of Testing and Evaluation*, 33(6), 452-460.

Wagoner, M., Buttlar, W., Paulino, G. and

Blankenship, P. (2005b). "Investigation of the fracture resistance of hot-mix asphalt concrete using a Disk-Shaped Compact Tension test", *Transportation Research Record,* 1929(1), 183-192.

XJ, L. and Marasteanu, M. (2010). "Using semicircular bending test to evaluate low temperature fracture resistance for asphalt concrete", *Experimental Mechanics*, 50(7), 867-876.

XJ, L. and MO, M. (2010). "The fracture process zone in asphalt mixture at low temperature", *Engineering Fracture Mechanics*, 77(7), 1185-1190.

Xu, O., Xiao, F., Han, S., Amirkhanian S. and Wang, Z. (2016). "High temperature rheological properties of crumb rubber modified asphalt binders with various modifiers", *Construction and Building Materials*, 112, 49-58.