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A Novel SCB Test for Determining Fracture Quantities of Bituminous Composites

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Abstract: Numerous non-Hookean fracture methods have been introduced to evaluate fracture parameters in quasi-brittle materials. In concrete structures, the effective crack model is widely used, and it requires determining the effective crack length and fracture toughness. Similarly, bituminous mixtures, which display ductile behavior at room temperature and brittle characteristics in colder conditions, demand non-Hookean fracture mechanics for accurate modeling due to defects like cracks and voids. This study focuses on assessing the fracture behavior of pure bituminous mixtures through experimental analysis. Ten semi-circular bending (SCB) specimens with varying initial crack lengths were prepared and subjected to three-point bending tests to capture load-displacement responses. The effective crack model, combined with the compliance technique, was utilized to calculate the fracture toughness of these samples. Findings aim to enhance understanding of fracture mechanisms in bituminous mixtures, contributing to the development of more durable pavements, especially under varying environmental conditions that influence material brittleness or ductility.

Keywords: Bituminous composites, Effective crack model, Fracture mechanics, Semi-circular bending test.

Introduction

Linear Elastic Fracture Mechanics (LEFM) were initially applied to concrete elements containing cracks by Kaplan (1961). However, the results of extensive tests, subsequently, illustrated that LEFM was not valid for cement-based materials such as mortar and concrete (Kesler et al., 1972). This inapplicability of LEFM was due to the existence of an inelastic zone with large-scale and full cracks in front of the crack tip in cementitious composites. This so-called fracture process zone (FPZ) was ignored by LEFM. Therefore, several investigators have recommended non-Hookean fracture mechanics approaches to characterize FPZ.

Initially, some computational approaches, referred to as cohesive crack models, were proposed, and these ways model the FPZ with a closing pressure that diminishes near the crack tip (Hillerborg et al., 1976; Bazant and Oh, 1983). Subsequently, the equivalent elastic fracture models, such as the two-parameter fracture model by Jenq and Shah (1985), the effective crack model (ECM) by Nallathambi and Karihaloo (1986), the size effect model by Bazant and Kazemi (1990), the double-K model by Xu and Reinhardt (1999), and the boundary effect method by Hu and Duan (2008) were developed, and they simulate the FPZ with an effective crack length.

Fracture experiments on semi-circular bending (SCB) samples have widely been performed to determine the fracture energy of asphalt mixtures, such as the fracture energy based on the work of fracture (G_F) and the critical strain energy release rate (J_c). Nevertheless, the asphalt concretes cannot be modelled utilizing only the concept of fracture energy. Thus, the work of fracture method was based on the fictitious crack model, requiring three parameters to characterize concrete fracture: G_F, tensile strength, and the relationship between crack closing pressure and crack opening displacement.

The utilization of SCB samples is quite wide in fracture mechanics experiments of asphalt and rock materials. Such samples also provide great advantages for determining the fracture mechanics-based performance of existing structures. Although a complex and expensive frame system is recommended by AASHTO (2015) for SCB-based asphalt concretes, the deformation of the loading head (or stroke) is commonly taken into account in the literature in determining the load-deformation relationship of SCB samples. However, such a measurement causes erroneous measurements, especially due to local deformations at the loading head and supports where the loads act on the asphalt material. In this study, it is aimed to develop a cheaper alternative test way that eliminates the aforesaid local deformations.

The Effective Crack Model (ECM) in Concrete Fracture

Several investigators have developed nonlinear fracture mechanics approaches to characterize FPZ. These models can be classified as the cohesive crack models and the equivalent elastic fracture models, such as the effective crack model (ECM) proposed by Nallathambi and Karihaloo (1986). The main aim of any approach is to determine the critical crack extension (size of FPZ) at the peak load $\Delta a = a_e - a_0$, in which a_e and a_0 are the effective crack length at the peak load and the initial crack length, respectively. When the stress intensity factor K_I, which describes the stress singularity at the crack tip under mode I loading, reaches the critical stress intensity factor (fracture toughness) K_{Ic}, the crack progress is unstable according to LEFM. The expression of LEFM can be presented for the general case in mode I in the following form:

$$K_{Ic} = \sigma_{Nc}\sqrt{\pi a_0}\,Y(g,p) \tag{1}$$

where σ_{Nc} is the nominal failure stress computed for the uncracked structure and $Y(g,p)$ is a dimensionless function of structure of geometry and load type. According to LEFM, it is assumed that the initial crack length a_0 in Eq. (1) does not change until it reaches the peak load. At this stage, the crack has a critical length and starts to progress in an unstable way. In reality, the crack propagates in a stable manner already at lower load until the peak load is reached since the size of FPZ can be larger than the sample size in quasi-brittle materials such as mortars, concretes, rocks, and bituminous materials. For this reason, according to Equation 1, the effective crack length a_e must be considered in the evaluation of K_{Ic} for quasi-brittle materials. However, a_e depends on structural size because it decreases as the member size increases, and it also depends on the geometry of the structure. Therefore, a unique fracture quantity is not adequate to simulate crack propagation in quasi-brittle materials.

The effective crack length a_e in ECM for the concrete fracture is computed from the secant stiffness of the real concrete structure at the peak load. The main idea behind the ECM approach can be explained with Figure 1, where are indicated the load-deflection plots of a beam with a central edge notch up to peak load. According to ECM, the fracture of a quasi-brittle material is described by two parameters, namely the critical stress intensity factor (the fracture toughness) K^e_{Ic} and the effective crack length a_e.

The stiffness of the real structure in the linear regime is proportional to the elasticity modulus (E). It can be determined from any pair of load and deflection values (P_i, δ_i) in this regime, as presented in Figure 1. Note that according to ECM, P_i can be selected to correspond approximately to $P_c/2$ in the load-displacement curve recorded in the bending sample of width b, depth d, and span s, as shown in Figure 1a. Consequently, the effective crack length is computed from two values taken from the load–displacement curve: the initial compliance C_i and the secant compliance C_s measured at the peak load, as indicated in Figure 1b.

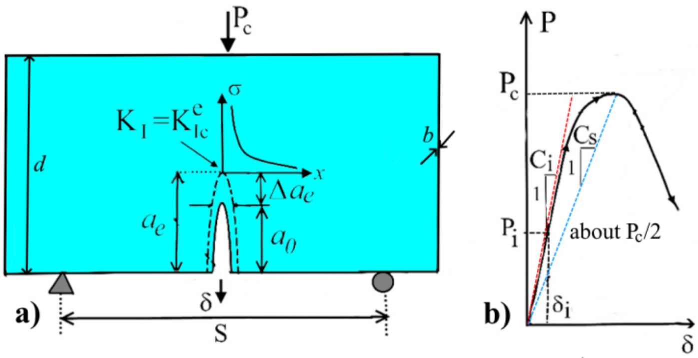

Figure 1. Modeling based on ECM of cracked structures a) notched beam b) typical load-δ curve

Nevertheless, the parameters included in any fracture model could be converted to the other concrete fracture models. To illustrate, it is possible to transform the fracture toughness parameter of ECM to the fracture energy parameter G_f, of the size effect model by using the well-known LEFM expression, which is presented below.

$$G_f = \left(K_{Ic}^e\right)^2 / E \tag{2}$$

The Modelling of SCB Samples According to ECM

Using compliance methods based on the two-parameter model and ECM, Ince et al. (2024) recently simulated eight series of asphalt SCB tests, the fracture characteristics of which are detailed in Figure 2a. Ince et al. (2024) derived two LEFM-based compliance functions for $0.03 \leq \alpha = a/r \leq 0.9$, considering cases of t/r = 0, 0.05, and 0.1 to simulate bituminous SCB specimens with s/r = 0.8 (where r is the sample radii), applying compliance techniques used in concrete fracture. In the aforesaid study, to reduce calculation errors, the geometry shown in Figure 2b was meshed using 100 finite elements along the crack line, while 8 quarter-point elements were employed around the crack tip. Subsequently, the important LEFM relationships, namely the stress intensity factor, crack mouth opening displacement, load line displacement, and crack opening displacement profile, were derived. However, when deriving the function of the load line displacement, the vertical displacement values at the crack mouth of the sample shown as δ_u in Figure 2b were used.

It was emphasized in this study that such a measurement causes erroneous measurements, especially due to local deformations at the loading head and support where the loads act on the asphalt material. Therefore, it was aimed to develop an alternative test method in the presented work that would eliminate unpredictable local deformations at three loading points. For this, in accordance with the measurement of the developed frame system, the displacement values at the upper limit level of the support of the sample, which are shown as δ_s in Figure 2b, were also determined using the finite element method. Consequently, when deriving the function of the load line displacement in this study, the relative displacement values ($\delta_r = \delta_u - \delta_s$) were used. The following expression was chosen for the relative displacement function:

$$\delta_r = \frac{P\alpha}{2bE} D_1\left(\alpha = \frac{a}{r}\right) \tag{3}$$

Here $D_1(\alpha)$ is the normalized function of the δ_r. The function of D_1 was determined by conducting a normalization of δ_r values with the individual ($P/2bE$) values. The following expression was produced using the least squares method for the normalized values based on the finite element method.

$$D_1(\alpha) = \frac{1}{0.2751\alpha - 0.7521\alpha^2 + 0.8489\alpha^3 - 0.6448\alpha^4 + 0.3872\alpha^5 - 0.1152\alpha^6} \tag{4}$$

The value 1/0.2751 in Equation 4 is therefore a constant valid for the unnotched SCB sample. Note that Ince (2025) also derived the aforesaid LEFM expressions for s/r= 0.50 and 0.65. The following procedures can be used in ECM-based analysis of SCB samples (Ince et al., 2024). At first, the modulus of elasticity can be derived for the SCB sample from Figure 1b as follows:

$$E = \frac{\alpha_0}{2bC_i} D_1(\alpha_0), \qquad C_i = \frac{\delta_i}{P_i} \tag{5}$$

According to Figure 2a, the effective crack length (or normalized effective crack length, α_e) is calculated by the trial-and-error method as follows:

$$\alpha_e = \alpha_0 \frac{C_s D_1(\alpha_0)}{C_i D_1(\alpha_e)} \tag{6}$$

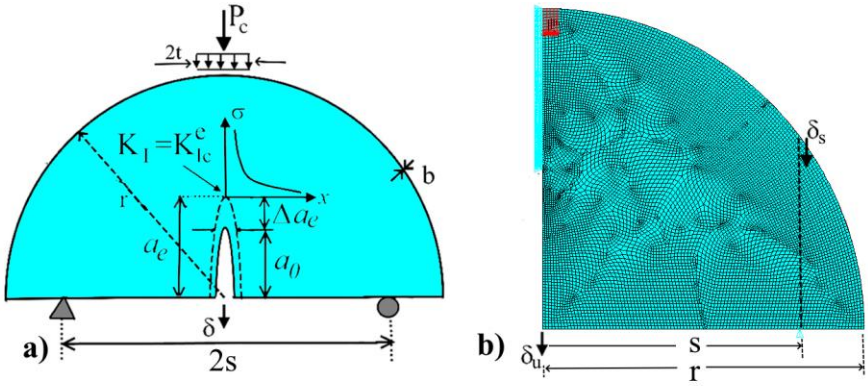

Figure 2. a) Fracture characteristics of the SCB sample b) finite element mesh generation of the sample

Consequently, the effective fracture toughness of the material can be determined for the sample in Figure 2a as follows:

$$K_{Ic}^{e} = \frac{P_c}{2br}\sqrt{\pi a_e}\,\frac{5.18 - 13.878\alpha + 27.145\alpha^2 - 26.887\alpha^3 + 10.321\alpha^4}{(1-\alpha)^{1.5}} \quad (7)$$

Experimental Program

Bitumen of grade B70/100 and density 1.033 was used in this investigation; it was procured from the TÜPRAS Batman refinery located in Turkey. Turkey's most common binder is the 70/100 grade, partly because of the country's climate. The aggregate gradation shown in Figure 3 was adhered to during the sample preparation procedure. It was found that the pure mixture's intended bitumen concentration was 4.67 %. The bitumen content was maintained constant for both pure and modified mixtures to guarantee that the binder content did not affect the mechanical qualities of the mixtures. The resulting material was compacted into cylindrical Marshall samples with a void ratio of 4 %, a height of approximately 60 mm, and diameters of 100 mm and 150 mm. A rotary compactor with an inclination angle of 1.25 ± 0.02◦ and a static pressure of 0.600 ± 0.018 MPa was used for this process. Then, SCB samples were created, notches were cut, and samples measuring 150 mm were split in half.

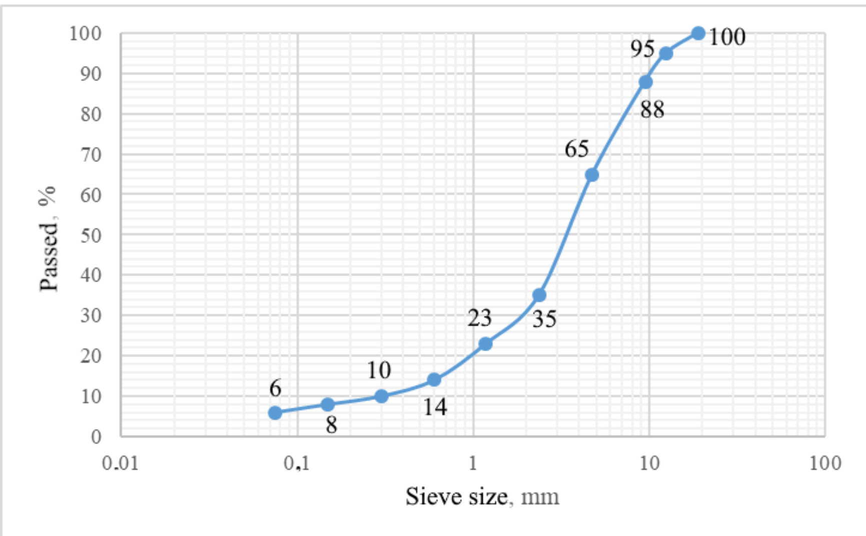

Figure 3. Aggregate gradation cure of the bituminous mixture used in this study

The methodology for preparing SCB test samples is illustrated in Figure 4, which illustrates the notch formation observed in the samples utilized in this research. Long cylindrical asphalt samples, measuring 60 mm in height and 150 mm in diameter, were compacted using a gyratory compactor. To achieve a uniform air void distribution, the top and bottom surfaces of the samples were trimmed by 5 mm from each end, resulting in final dimensions of 50 mm in height and 150 mm in diameter. Subsequently, the samples were bisected, and notches were incised at the center to create SCB test samples. Regardless of the sample thickness and mix design, notch lengths of about 10, 15, 20, and 30 mm were selected for 150 mm samples. The notch thickness is approximately 2 mm.

Figure 4. The preparation of a typical SCB sample

The displacement frame used for beams in the effective crack model, which is a popular method in the fracture mechanics of concrete, was adapted to the SCB sample as detailed in Figure 5. Thanks to the LVDT mounted on the end of the rod sliding on the rigid rectangular frame, the under-notch displacement was determined based on the frame support on the support. SCB tests were carried out at room temperature.

Nonlinear fracture toughness values of bituminous hot mix samples were computed according to the compliance method. Samples were loaded at 0.5 mm/min speed. The load-displacement curves of SCB samples tested are demonstrated in Figure 6. The crack patterns of samples are revealed in Figure 7.

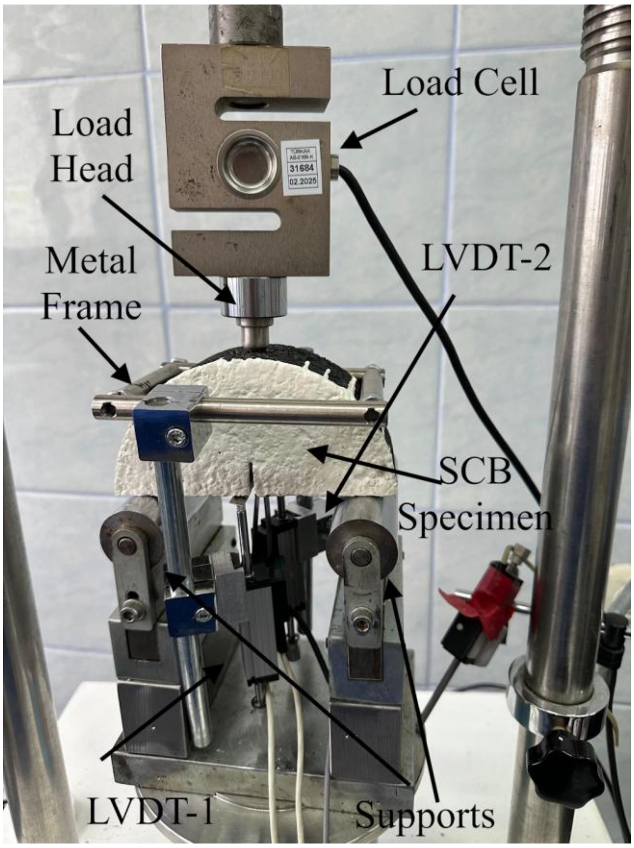

Figure 5. Test setup of SCB samples

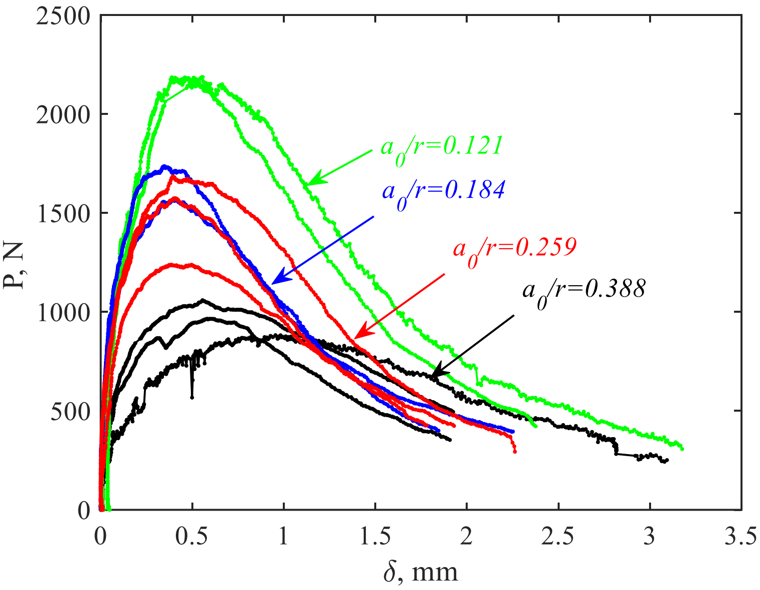

Figure 6. Load-displacement curves of SCB samples tested

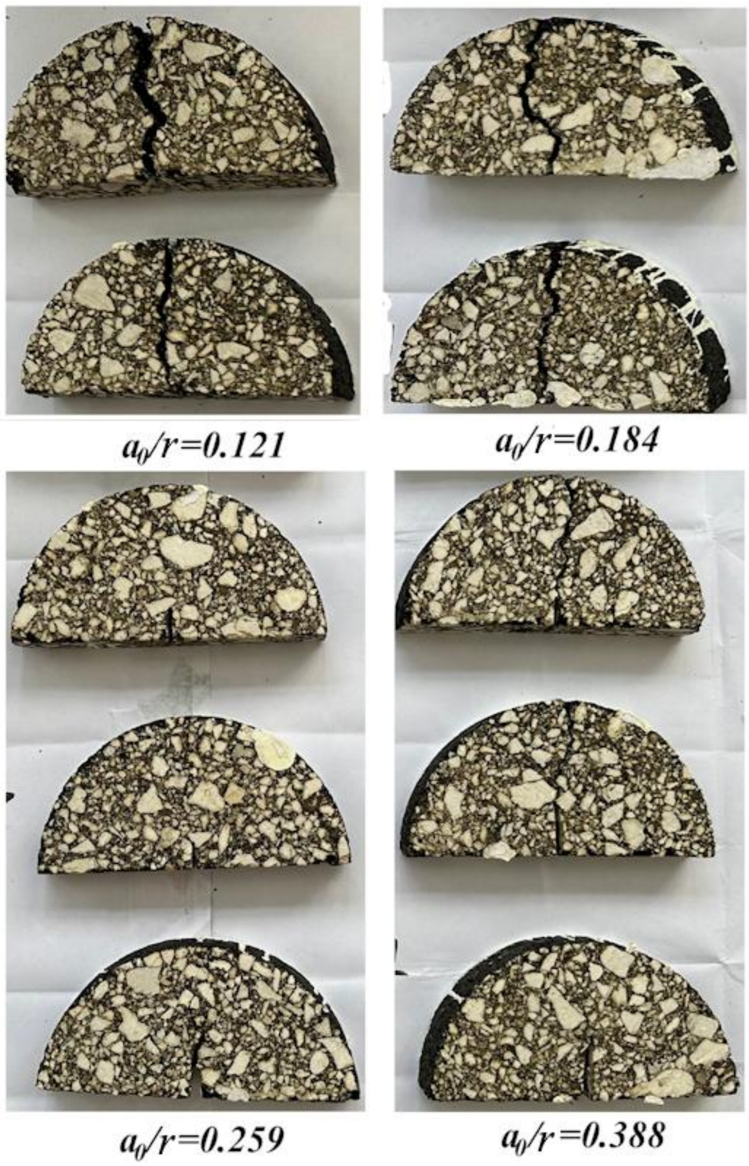

Figure 7. Fractured notched SCB samples

Analysis of Test Results

The sample width (b), sample radii (r) (or structural size), and the peak load values (P_c) of the notched SCB samples were reported in Table 1 according to the notch depths (a_0). By using Equations 3 to 7, the values of K^e_{Ic} were determined from the P-δ curve of each sample as shown in Figure 6. The initial compliance values (C_i), the secant compliance values (C_s), the relative initial notch lengths (α_0), the relative effective notch lengths (α_0), the fracture toughness parameters based on ECM (K^e_{Ic}), and the fracture energy (G_f) based on Eq. (2) are summarized for each sample in Table 2.

Table 1. Test results of SCB samples tested in this study

Sample	b mm	r mm	a_0 mm	P_c N
SCB1	54.85	73.1	8.58	2152
SCB2	55.06	73.51	9.17	2186
SCB3	54.69	73.58	12.9	1569
SCB4	52.96	73.47	14.19	1736
SCB5	54.8	73.12	18.01	1574
SCB6	53.74	74.07	19.22	1685
SCB7	54.81	74.46	20.24	1239
SCB8	53.61	72.70	28.03	882
SCB9	55.04	72.95	28.35	965
SCB10	55.14	73.74	28.66	1059

Table 2. Fracture parameters of SCB samples tested according to ECM

Sample	C_i mm/N	C_s mm/N	E MPa	$\alpha_0=a_0/r$	$\alpha_e=a_e/r$	K^e_{Ic} MPa√m	G_f N/m	G_F N/m
SCB1	0.000087	0.000250	530	0.117	0.430	0.480	435	1100
SCB2	0.000075	0.000253	627	0.125	0.475	0.554	490	1316
SCB3	0.000042	0.000254	1295	0.175	0.622	0.676	353	834
SCB4	0.000045	0.000200	1331	0.193	0.577	0.649	316	839
SCB5	0.000055	0.000260	1252	0.246	0.620	0.674	363	874
SCB6	0.000070	0.000234	1048	0.259	0.563	0.586	328	995
SCB7	0.000090	0.000311	825	0.272	0.576	0.443	238	855
SCB8	0.000334	0.001082	341	0.386	0.638	0.417	511	1020
SCB9	0.000142	0.000602	788	0.389	0.683	0.544	375	735
SCB10	0.000113	0.000525	989	0.389	0.696	0.634	406	975

When statistical validation was performed for the fracture toughness parameter based on ECM, the mean, standard deviation, and coefficient of variation (CV) values were calculated as 0.566 MPa√m, 0.095 MPa√m, and 16.8%, respectively. Since the CV value was less than 20%, it may be concluded that the approach used in this study gave reasonable results.

In addition to G_f based on the size effect model, the fracture energy based on the work of fracture (G_F) and the critical strain energy release rate (J_c) were evaluated in this study. For G_F, the work of fracture, W, is initially computed from the area under the P-δ, and the tail part of the curve of P-δ, W_{tail}, is subsequently conducted according to AASHTO (2015). Consequently, the fracture energy can be determined as follows:

$$G_F = \frac{W + W_{tail}}{b\left(r - a_0\right)} \tag{8}$$

G_F values for each sample tested in this study are summarized in the last column of Table 2. According to the multiple specimen method proposed for J_c, at first, P-δ plots are recorded for at least three different initiation notch lengths for statistical validity. Subsequently, the potential energy values, U, are determined by computing the area up to peak load under the P-δ plots, and they are normalized with specimen widths b. Finally, when the U values are plotted versus notch lengths a_0, the slope of the linear regression can be assumed as J_c. In Figure 8, the application of this computation is presented for SCB samples used in this study. According to this, as shown in Figure 8, the value of J_c was determined as 635 N/m for the determination coefficient R^2=0.66, which actually gives the percentage of explanation of the event.

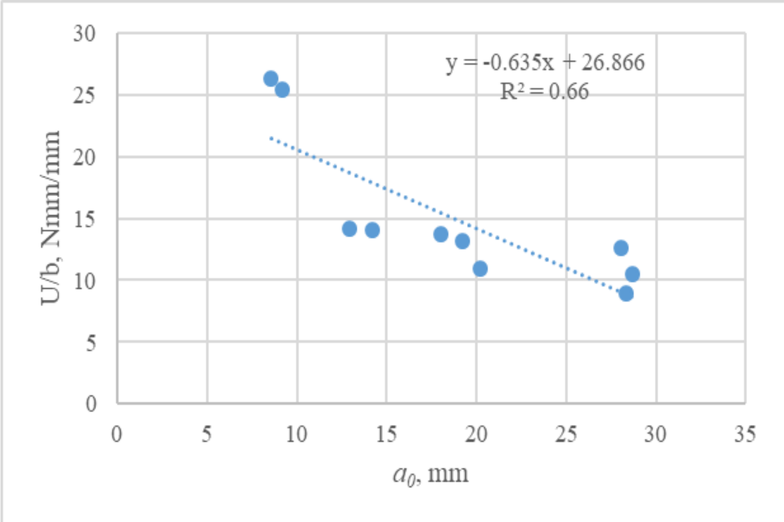

Figure 8. J_c analysis of the bituminous mixture used in this study

Conclusion

In this study, the effective crack model, which is widely used in concrete fracture analysis, was used to investigate the fracture behavior of asphalt concrete. The key findings are summarized below:

Until now, in hot bituminous mixtures, the fracture toughness parameter calculated based on LEFM is determined according to the effective crack model, which is a popular method in the fracture mechanics of quasi-brittle materials. Since the CV value was less than 20% for fracture toughness values computed, it may be concluded that the test setup used in this study gave reasonable results.The applications performed in this study revealed that the critical strain energy release rate value was between the fracture energy based on the work of fracture based on the fictitious crack model and the fracture energy based on the size effect model (G_F>J_c>G_f). According to Bazant (2002), the ratio of G_F/G_f is equal to 2.5 for quasi-brittle materials. Similarly, it can be seen that this ratio can be computed approximately as 2.5 for the last two columns of Table 2.

Recommendations

With the experimental setup developed here, SCB samples were used with pure bituminous hot mixtures at room temperature to determine nonlinear fracture parameters by only considering the load-displacement relationships. However, it should be emphasized that further studies can come up with more reliable results by investigating various types and sizes of aggregates to verify the above findings.

Scientific Ethics Declaration

*The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

*The authors declare that they have no conflicts of interest

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