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Research Article

Investigation on the Feasibility of Different Semicircular Bend Methods for Asphalt Concrete

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Cracking of asphalt pavement is mostly caused by the mixed fracture of asphalt concrete. Determining a simple, repeatable, and accurate method is necessary for evaluating the fracture resistance of asphalt concrete. To explore the mixed fracture performance of asphalt concrete and determine the feasibility of different semicircular bend methods, the mixed fracture performances of asphalt concrete at medium and low temperatures were measured. The mixed fracture modes were realized through changing the position of the support and notch or changing the notch angle. After that, the crack propagating characteristics, crack initiation angle, and fracture toughness were analyzed. Results show that temperature has a significant impact on the fracture path, and crack initiation angle at low temperature follows the generalized maximum tangential stress (GMTS) theory. The measured fracture toughness ratios are lower than the theoretical value of GMTS criterion, but the established empirical model has higher accuracy. In the semicircular bend method, changing the positions of the support and notch is stable and repeatable. Therefore, this method may be preferred to evaluate the mixed fracture performance of asphalt concrete in the future.

1. Introduction

As a major concern of asphalt pavement, cracks seriously affect the service life of the pavement. Accurately evaluating and improving the crack resistance of asphalt concrete is one of the important topics to reduce pavement cracking [1]. Based on the theory of fracture mechanics, the cracking of asphalt concrete is divided into pure tensile failure (mode I), pure shear failure (mode II), and mixed fracture [2].

In the 1980s, Chong and Kuruppu [3] used the semicircular bend test to explore the fracture toughness of rocks in mixed modes for the first time, which provided a new method for studying the mixed fracture properties of materials. The load-displacement curve of the semicircular bend test is stable. The semicircular bend method can be used not only to determine the fracture and fatigue properties of asphalt concrete [4–6] but also to evaluate the low-temperature fracture resistance of asphalt cores from the construction site [7]. The good applicability of this method makes it rapidly popularized in road engineering research. In order to measure the mixed fracture toughness of asphalt concrete, mixed fracture mode is often achieved by adjusting the position of the support and notch or the angle of the notch [8–10]. The fracture characteristics of the specimens through moving the positions of the notch and the support were in good agreement with the theoretical values [11–13].

However, Ameri and Primohammad [14] found that changing the notch angle could easily lead to premature failure at the location around acute angles, and the crack propagation path was inconsistent with the theoretical results while only changing the position of the support, and this phenomenon was more prominent in mode II. It can be seen that, although the semicircular bend test has a good application prospect in the analysis of the fracture performance of asphalt concrete, the feasibility of different methods is not consistent. Therefore, this work conducts experimental tests on different semicircular bend methods. The applicability and accuracy of different semicircular bend methods were compared, so as to clarify the applicability of various methods to asphalt materials. It will provide a reference for the comprehensive evaluation of asphalt concrete mixed fracture performance.

2. Materials and Methods

2.1. Materials. The asphalt with a penetration grade 70, which is called AH-70#, and basalt aggregate are used to prepare asphalt mixture, and their properties are listed in Tables 1 and 2. The filler is limestone powder. The gradation AC-13, which is recommended by China technical specifications JTG D50-2017, is adopted in this paper, and the gradation curve is shown in Figure 1. According to the Marshall test, the optimal asphalt content is 4.6%, the apparent density of the mixture is 2.43 g/cm^3, and the air void in asphalt mixture is 3.62%. The Marshall specimens with a diameter of 152.4 mm and a height of 95.3 mm were formed by the Marshall method, and then the Marshall specimens were cut to make four semicircular specimens with a thickness of about 45 mm for use according to the work of Guo et al. [15].

2.2. Semicircular Bend Test. In order to realize the mixed fracture of asphalt concrete, this paper designs different fracture modes by adjusting the position, notch angle, and support span. In the field of fracture mechanics, the mixed mode parameter M^e ($0 \le M^e \le 1$) is generally used to characterize different fracture modes: $M^e = 1$, it is the pure mode I fracture; $M^e = 0$, it is the pure mode II fracture, and M^e is obtained using the following formula.

$$M^e = \frac{2}{\pi}\arctan\left(\frac{K_I}{K_{II}}\right). \quad (1)$$

In equation (1), K_I is the stress intensity factor of mode I fracture, MPa·m$^{0.5}$, and K_{II} is the stress intensity factor of mode II fracture, MPa·m$^{0.5}$. K_I and K_{II} are calculated using the following equations:

$$\begin{cases} K_I = \dfrac{P}{2Rt}\sqrt{\pi a}\,Y_I, \\ \\ K_{II} = \dfrac{P}{2Rt}\sqrt{\pi a}\,Y_{II}. \end{cases} \quad (2)$$

In equation (2), P is the peak load; R is the radius of the specimen; t is the thickness of the specimen; a is the notch length; and Y_I and Y_{II} are geometric parameters, which are only related to the size and can be determined by the finite element method. Based on the existing research results [13], this paper uses the plane stress model to determine Y_I and Y_{II}. The thickness of the model is set to 1 mm, the radius of the semicircular model is 76 mm, the length of the notch is 20 mm, and the elastic modulus in FE analysis is 2000 Mpa. On the basis of studies [12, 14], the influence of Poisson's ratio is modest, so this paper uses Poisson's ratio of 0.35 for FEM analysis. The load is set to 1N. After FE analysis, the geometric parameters of different modes are determined and listed in Table 3. Considering the different test methods for mixed mode fracture, 10 typical conditions were selected in this paper.

Table 1: Properties of AH-70# asphalt.

Items	Values	Test methods
Penetration (25°C, 0.1 mm)	68	ASTM D5
Softening point (°C)	48.0	ASTM D36
Ductility (15°C, cm)	>100	ASTM D113
Flashing point (°C)	285	ASTM D92
Mass loss after TFOT, 163°C, 5 hours (%)	0.15	ASTM D6
Penetration ratio after TFOT (%)	78.8	ASTM D5
Ductility after TFOT (cm)	6.5	ASTM D113
Density (g/cm^3)	1.034	ASTM D70

After determining the position of the notch, a diamond cutting machine was used to make the notch with a width of 2 mm. Before test, the semicircular specimens were kept in a chamber at −10°C and 20°C for more than 24 hours to keep the temperature of specimens stable. Afterwards, the bend test was carried out in 5 minutes using an electrical universal testing machine without environmental box. According to the recommendation of the Chinese specification JTG E20-2011, a loading rate of 1 mm/min is often used in the low-temperature test, so the loading rate was 1 mm/min in this paper, and the diameter of the roller support was 25 mm. An industrial camera was used to capture the photos of specimen surface in real time to analyze the crack propagation characteristics. The test procedure is shown in Figure 2.

2.3. GMTS Criterion. To accurately predict the material fracture properties using the fracture test results, the maximum tensile stress (MTS) criterion was often employed to predict the mixed fracture parameters, but this theory does not consider the effect of the T stress at the notch tip, which may result in large errors sometimes [16]. Considering the T stress, the MTS criterion evolves into the generalized tangential tensile stress (GMTS) criterion, which is widely used in the analysis of mixed fracture properties [17]. T stress can be expressed as follows:

$$T = \frac{P}{2Rt}T^*, \quad (3)$$

where T^* is the normalized form of T stress and can be obtained with finite element analysis, and T^* for different fracture modes are listed in Table 2. The GMTS criterion indicates that the crack occurs within the region, which can be controlled by the critical radius r_c of the notch tip, and the propagating direction of the crack is perpendicular to the direction of maximum tangential stress. When the crack length exceeds the critical radius r_c, the crack begins to expand in further. According to existing results [18], the critical radius r_c changes with temperature. The values were 0.0084 m and 0.0056 m at −10°C and 20°C, respectively. The tangential stress at the notch tip can be calculated using equation (4).

Table 2: Properties of aggregates.

Sieve size (mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Apparent gravity (g/cm^3)	2.716	2.723	2.681	2.679	2.694	2.708	2.713	2.713	2.712	2.712
Moisture uptake ratio (%)	0.49	0.57	0.63	0.52	—	—	—	—	—	—

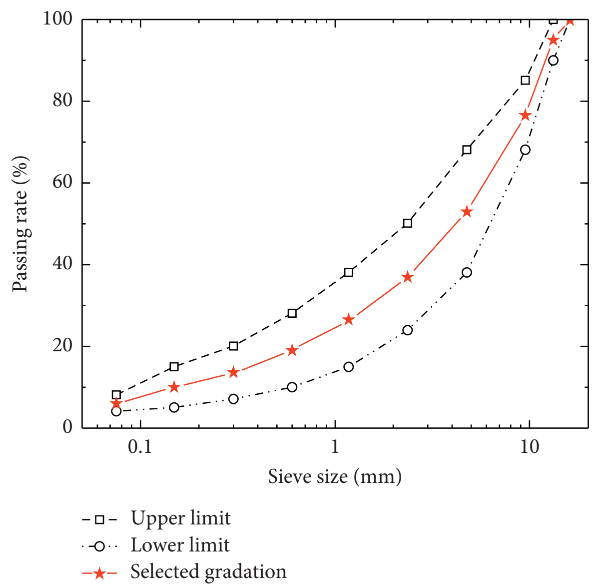


Figure 1: Experimental gradation.

$$\frac{1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_{\mathrm{I}}\cos^2\frac{\theta}{2}-\frac{3}{2}K_{\mathrm{II}}\sin\theta\right]+T\sin^2\theta+\mathrm{O}\left(r^{1/2}\right). \quad (4)$$

In equation (4), r is the notch tip extension radius; θ is the notch tip extension angle; and $\mathrm{O}(r^{1/2})$ is the high-order term, which can be ignored. According to the GMTS criterion, the crack initiation angle can be determined when $\partial\sigma_{\theta\theta}/\partial\theta|_{\theta=\theta_0}=0$, namely,

$$\left[K_{\mathrm{I}}\sin\theta_0+K_{\mathrm{II}}(3\cos\theta_0-1)\right]-\frac{16}{3}T\sqrt{2\pi r_c}\cos\theta_0\sin\frac{\theta_0}{2}=0. \quad (5)$$

Substituting (2) and (3) into equation (5), the crack initiation angle can be obtained by using the following equation:

$$\left[Y_{\mathrm{I}}\sin\theta_0+Y_{\mathrm{II}}(3\cos\theta_0-1)\right]-\frac{16}{3}T^*\sqrt{\frac{2r_c}{a}}\cos\theta_0\sin\frac{\theta_0}{2}=0. \quad (6)$$

The GMTS criterion shows that when the stress reaches a critical value, the crack starts to propagate in the direction of θ_0. According to (4), the critical stress can be expressed as follows:

$$\sigma_{\theta\theta_0}=\frac{1}{\sqrt{2\pi r_c}}\cos\frac{\theta_0}{2}\left[K_{\mathrm{I}}\cos^2\frac{\theta_0}{2}-\frac{3}{2}K_{\mathrm{II}}\sin\theta_0\right]+T\sin^2\theta_0. \quad (7)$$

For mode I fracture, K_{IC} can be expressed as

$$K_{\mathrm{IC}}=\sigma_{\theta\theta_0}\sqrt{2\pi r_c}. \quad (8)$$

While the critical stress intensity factor for the mode I is equal to the fracture toughness, i.e., $K_{\mathrm{I}}=K_{\mathrm{IC}}$, at the same time $K_{\mathrm{II}}=0$ and $\theta_0=0$. Therefore, the fracture toughness K_{IC} for mode I also can be expressed as follows:

$$K_{\mathrm{IC}}=\cos\frac{\theta_0}{2}\left[K_{\mathrm{I}}\cos^2\frac{\theta_0}{2}-\frac{3}{2}K_{\mathrm{II}}\sin\theta_0\right]+\sqrt{2\pi r_c}T\sin^2\theta_0. \quad (9)$$

Generally, the mode I fracture toughness of materials is often measured in the experiment. The ratios of stress intensity factor to fracture toughness ($K_{\mathrm{I}}/K_{\mathrm{IC}}$, $K_{\mathrm{II}}/K_{\mathrm{IC}}$) are often analyzed in order to utilize K_{IC} to evaluate the mixed fracture properties of materials. After the transformation of (9), we can get (10) and (11).

$$\frac{K_{\mathrm{I}}}{K_{\mathrm{IC}}}=\left[\cos\frac{\theta_0}{2}\left(\cos^2\frac{\theta_0}{2}-\frac{3}{2}\frac{Y_{\mathrm{II}}}{Y_{\mathrm{I}}}\sin\theta_0\right)+\sqrt{\frac{2r_c}{a}}\,\frac{T^*}{Y_{\mathrm{I}}}\sin^2\theta_0\right]^{-1}, \quad (10)$$

$$\frac{K_{\mathrm{II}}}{K_{\mathrm{IC}}}=\left[\cos\frac{\theta_0}{2}\left(\frac{Y_{\mathrm{I}}}{Y_{\mathrm{II}}}\cos^2\frac{\theta_0}{2}-\frac{3}{2}\sin\theta_0\right)+\sqrt{\frac{2r_c}{a}}\,\frac{T^*}{Y_{\mathrm{II}}}\sin^2\theta_0\right]^{-1} \quad (11)$$

Once the K_{IC} is determined through experiment, the stress intensity factors K_{I}, K_{II} and the crack initiation angle of any mixed mode will be determined by using the GMTS theory.

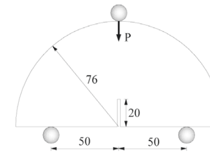
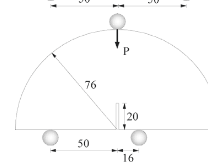
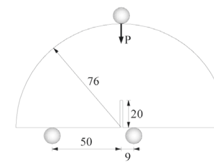
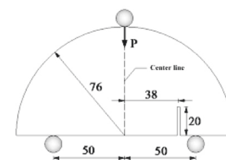
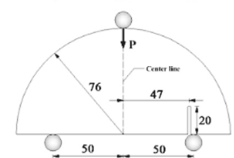
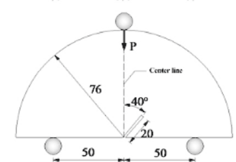
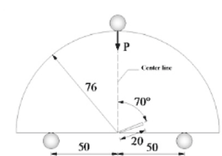
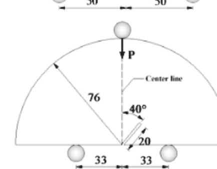
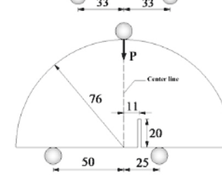
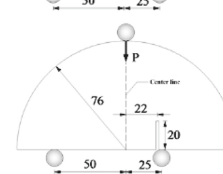
3. Results and Discussion

3.1. Crack Propagation Characteristics. An industrial camera was utilized to take real-time photos in the loading procedure and then analyze the crack propagation characteristics of different modes. Crack propagation characteristics were marked in yellow line, as shown in Table 4.

On the basis of the crack propagation characteristics of typical specimens listed in Table 4, it can be seen that the crack development at 20°C shows a dispersed distribution due to the influence of coarse aggregate under the same loading mode, and the influence of coarse aggregate is not obvious at −10°C. The cracks are concentrated and expanded along the direction of the main crack at low temperature. Herein, the coarse aggregate has a significant influence on the fracture path at medium temperature.

For the case of mixed mode $M^e=0.7$ (condition 6#), changing the notch angle can realize the mixed fracture of asphalt concrete, which is in line with the designed experimental expectation. For the cases of $M^e=0.5$, the crack initiation position of conditions 2#, 7#, and 8# occurred near the support, which deviates from the designed fracture expectation. It proves that only moving the support position or changing the notch angle could not ensure the crack initiation firstly occurs at the notch tip. Although the stress concentration caused by the roller support cannot be ignored, Ameri and Primohammad [14] showed that even if the diameter of the roller support was adjusted, the fracture of condition 2# still

Table 3: Parameters of mixed fracture modes.

No.	M^e	S_1 (mm)	S_2 (mm)	b (mm)	α (°)	Y_I	Y_{II}	T^*	Schematic
1#	1	50	50	—	—	3.66	0	−0.58	
2#	0.5	50	16	—	—	0.99	0.99	−1.72	
3#	0	50	9	—	—	0	1.79	−3.91	
4#	0.5	50	50	38	—	1.45	1.36	−1.47	
5#	0	50	50	47	—	0	2.24	−3.92	
6#	0.7	50	50	—	40	2.14	1.10	1.8	
7#	0.5	50	50	—	70	0.81	0.73	2.72	
8#	0.5	33	33	—	40	0.71	0.74	1.99	
9#	0.5	50	25	11	—	1.22	1.29	−1.9	
10#	0	50	25	22	—	0	2.46	−4.74	

S_1 represents the distance from the left support to the mid-span, S_2 represents the distance from the right support to the mid-span, b is the distance from the notch to the mid-span, and T^* represents the tangential stress in the area near the notch tip.

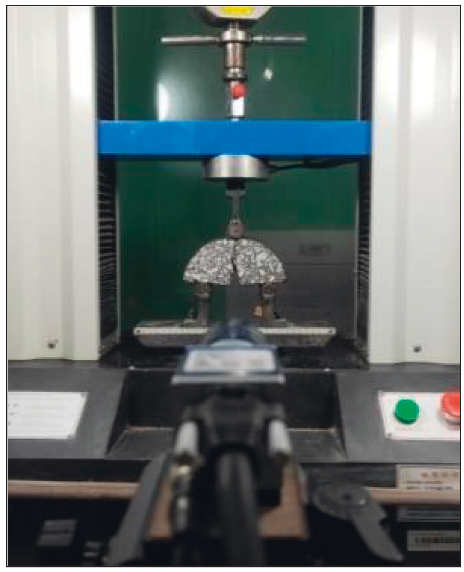


Figure 2: Process of semicircular bend test.

Table 4: Typical crack propagation characteristics of different modes.

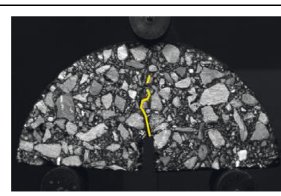
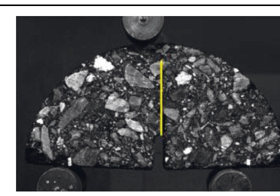
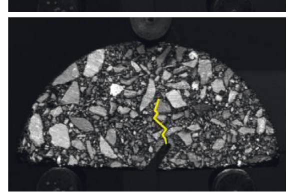
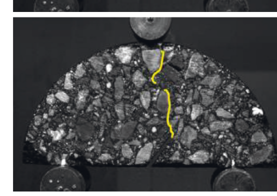
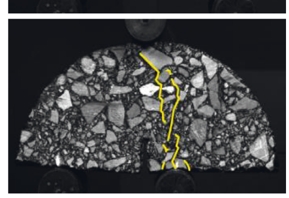
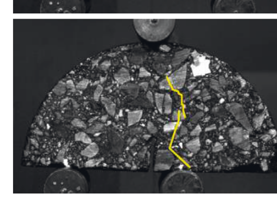
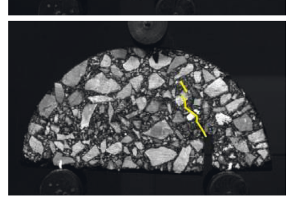
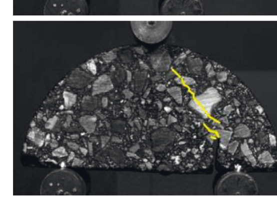
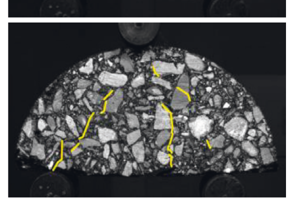
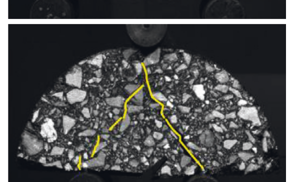
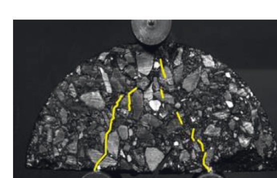
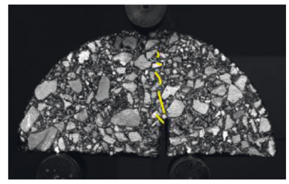
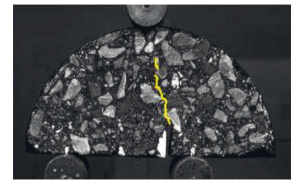
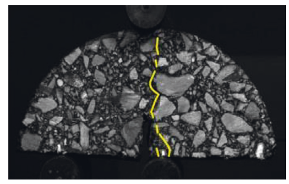
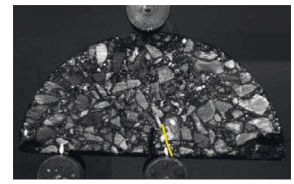
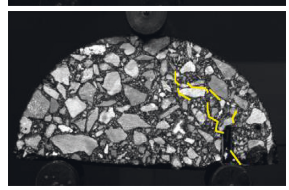
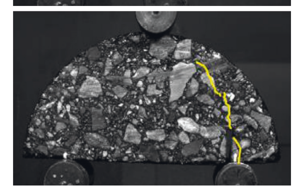
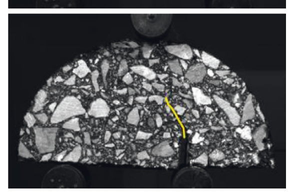
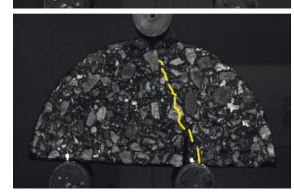
No.	M^e	20°C	−10°C
1#	1		
6#	0.7		
2#	0.5		
4#	0.5		
7#	0.5		Specimen fabrication failed
8#	0.5		

Table 4: Continued.

No.	M^e	20°C	−10°C
9#	0.5		
3#	0		
5#	0		
10#	0		

generated at the supporting position, and one possible way was to set steel gaskets on the support [19]. The methods that only change the notch position or synchronously adjust the positions of support and the notch (i.e., 4# and 9#) can effectively prevent the fracture in the vicinity of the support, which can achieve the designed experimental expectation. Therefore, these two methods have better feasibility for investigating the mixed fracture performance of asphalt concrete.

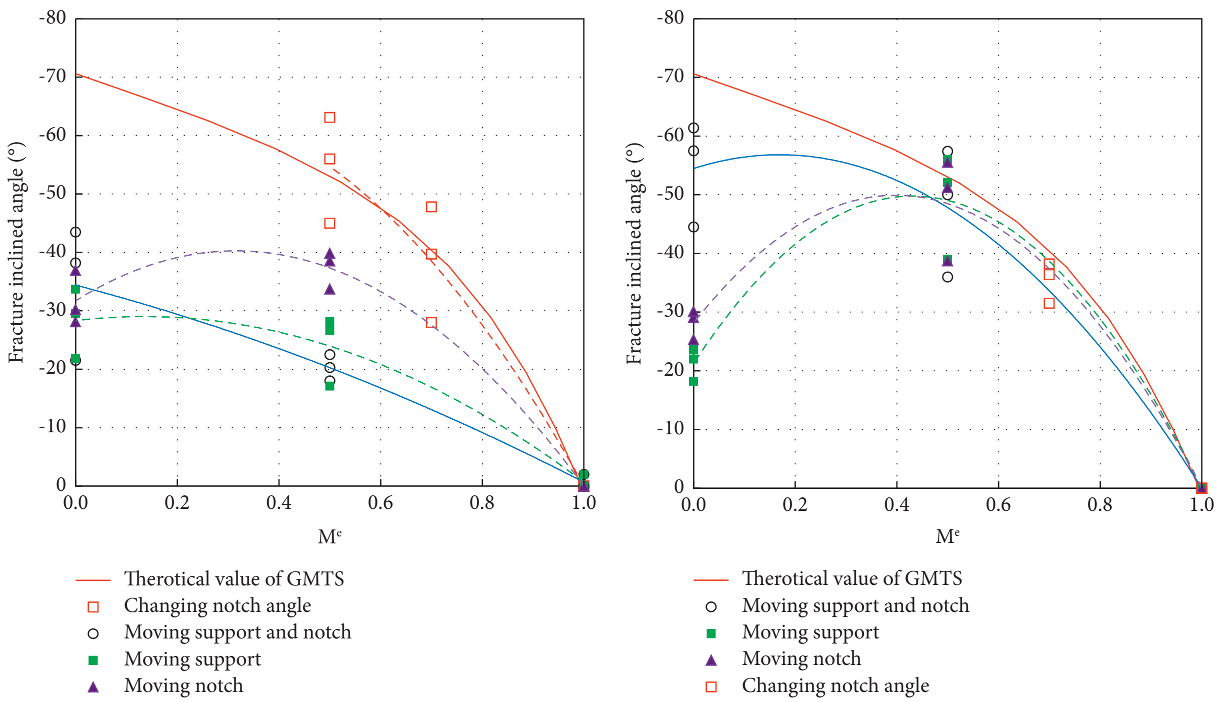
In addition, it can also be observed from condition 7# that it is difficult to ensure the processing quality of the specimen by changing the notch angle when the span is 100 mm. There is no guarantee that every specimen can be prepared successfully. If the span is shorten (such as condition 8#), the cracks also first generate near the support position during the loading process even though the notch angle and the quality of specimen can be guaranteed. Hence, when M^e is large and the proportion of tensile stress is high, changing the notch angle is feasible. It should be noted that the feasibility of changing the notch angle is inadequate when M^e is less than 0.5.

For the pure mode II fracture characteristics of 3#, 5#, and 10#, changing the support position and the notch angle induced the crack initiation near the support, and the crack initiation direction was almost along the mixed fracture path. It can be inferred that the stress concentration is significant, and the stress transmission path in the vicinity of the notch is blocked by notch when it is close to the support, which leads to the crack initiation at the support. So, there is a damage risk near the support for the pure shear fracture mode in the semicircular bend test.

3.2. Comparative Analysis of Crack Initiation Angle. In order to accurately predict the fracture path of asphalt concrete, the crack initiation angle was determined by using (6) based on the GMTS theory, and the difference between the theoretical angle and the measured one was analyzed. To eliminate the errors from the specimen processing, the results of the remaining 9 conditions in addition to 7# were selected for comparison, as shown in Figure 3. The negative angle in Figure 3 means counterclockwise rotation direction.

As shown in Figure 3(a), the measured fracture initiation angle through changing notch angle is almost consistent with the theoretical value of GMTS at medium temperature, but the discreteness of the angle is large, and the standard deviation is about 10°. The fracture initiation angles measured through the other means are all less than the theoretical value of GMTS. When M^e is lower than 0.5, the growth of fracture initiation angle becomes slow. Although the measured angles are lower than the theoretical ones, their changing trends are similar. It can be inferred that the GMTS criterion cannot accurately predict the fracture path of asphalt concrete at medium temperature.

It can be seen from Figure 3(b) that the tensile action occupies the main proportion when M^e is higher than 0.5, and the measured fracture initiation angles of these four bend means are almost consistent with the theoretical results of GMTS at −10°C. With the increase of shearing action, the fracture initiation angle gradually deviates from the theoretical value of GMTS when M^e is less than 0.5. In addition, the measured angles by changing the positions of support and notch are the closest to the theoretical value of GMTS.



(a) (b)

FIGURE 3: Comparison of fracture initiation angles at different temperatures: (a) 20°C and (b) −10°C.

For the pure shear mode, the deviations between the measured angles and the theoretical values are the largest by changing the support position or the notch position. Based on the angles at medium and low temperatures, it is proved that temperature has a significant effect on the fracture path of asphalt concrete. The GMTS criterion is suitable for describing the low-temperature fracture performance of asphalt concrete. At medium temperature, a large error would generate if one uses the GMTS criterion to predict the fracture path.

3.3. Comparative Analysis of Fracture Toughness Ratio. It can be seen from the above analysis that the notch is close to the support, which causes the area in the vicinity of support to crack first in the pure shearing fracture test. The larger the M^e is, the lower the differences between the measured and the theoretical values are. Fortunately, the critical fracture toughness K_{IC} of mode I is easy to measure, the fracture toughness K_{IIC} for pure shear mode II can be estimated using the mixed fracture criterion, which had been widely applied in the field of fracture mechanics. Therefore, this paper discusses the applicability of GMTS criterion based on K_I/K_{IC} and K_{II}/K_{IC}. Based on the results as shown in Table 2, the fracture initiation angle is determined and substituted in (10) and (11) to obtain the theoretical values of K_I/K_{IC} and K_{II}/K_{IC}, the ratios of stress intensity factor to fracture toughness. The experimental K_I/K_{IC} and K_{II}/K_{IC} can be calculated by using (2). These ratios are shown in Figure 4.

It can be seen from Figure 4 that the measured K_{II}/K_{IC} at medium and low temperatures is all lower than the theoretical values, and the measured K_{II}/K_{IC} is about 0.3 lower than the theoretical value. This may be caused by the

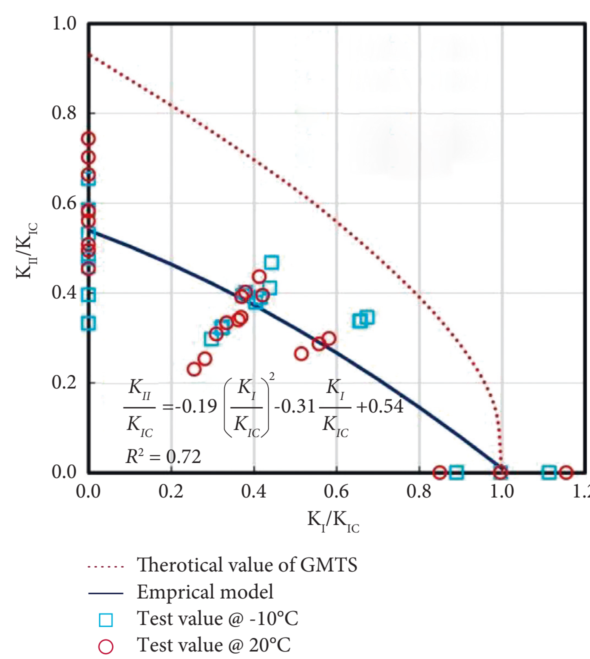


FIGURE 4: Comparison on the ratios of fracture toughness.

experimental control precision and the influence of coarse aggregate inside the asphalt concrete [20–23]. The critical shear fracture toughness K_{IIC} would be overestimated when it was estimated by using the GMTS criterion and the critical fracture toughness K_{IC} of mode I. The empirical model established in Figure 4 has a good correlation with the experimental values, and this empirical model effectively reduces the prediction error. In order to verify the validity of

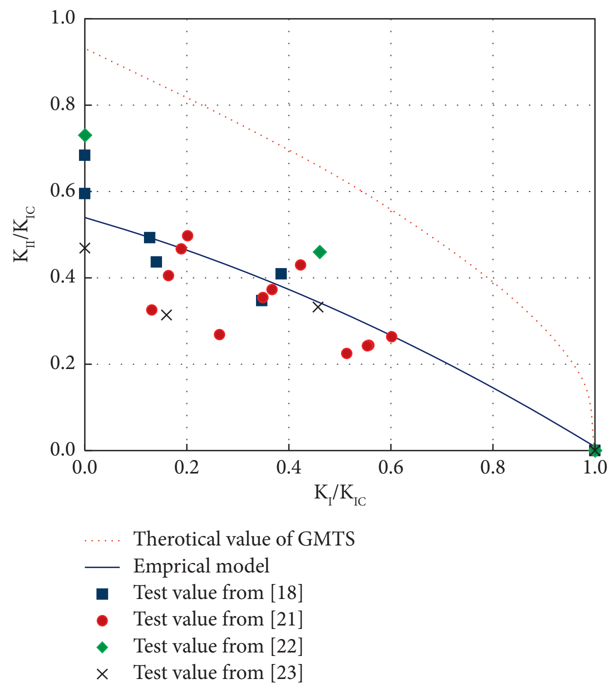


Figure 5: Verification on the empirical model.

Table 5: Feasibility analysis of different methods.

Test method	Advantages	Drawbacks	Priority
Moving support only	Notch remains in the mid-span, easy preparation	Cracks generate and propagate from the support, and the fracture initiation angle is discrete	4
Moving notch only	Easy preparation, cracks first generate and propagate from notch tip.	The vicinity of support is severely damaged in the pure shear mode	2
Changing notch angle only	Cracks propagate at the notch tip	The angle control requirements are high, and when the span is small, it will be destroyed first near the support, and it is difficult to measure in the pure shear mode	3
Moving support and notch synchronously	Notch is easy to be cut, cracks propagate along the notch tip, and good repeatability	High accuracy requirement for notch position	1

the empirical model in this paper, the experimental data from the existing literature were also taken in this part, and their results were collected and are shown in Figure 5.

It can be seen from Figure 5 that the predicted ratios using the empirical model are closer to the experimental data than that using the GMTS criterion, and the prediction deviation of the empirical model is smaller than that of GMTS. It can also be seen that the empirical model established in this paper has good universality for different mixtures.

3.4. Feasibility of Different Methods. It can be determined from the previous analysis that different test methods have significant influences on the low-temperature fracture performance of asphalt concrete. Taking into account the difficulty of preparing procedure and the discreteness of test results, the four methods selected in this paper are comprehensively evaluated, as shown in Table 5.

It can be seen from Table 5 that different methods have their own advantages and disadvantages. In addition to the method of moving support only, the other three methods can ensure that the crack propagates along the notch tip. Although the position of the notch remains unchanged, it is beneficial to the processing of the specimen, but it still cannot avoid the fracture in the vicinity of support, which is particularly serious in the pure shear fracture mode. Changing the notch angle can realize the crack propagation along the notch tip. For semicircular specimens, it is difficult to realize the pure shear mode by changing the notch angle due to the limitation of the size of the notch. However, changing the support position and the notch position has good repeatability for asphalt mixture and can ensure that the crack generates and propagates along the notch tip. It can also be determined that cracking near the support easily leads to the failure of the pure shear fracture test due to the limitation of processing, and it is difficult to control the pure shear fracture test.

4. Conclusions

(1) Temperature and fracture mode have significant influences on the crack propagation path of asphalt concrete. At medium temperature, the crack initiation and propagation path are affected by the coarse aggregate, while asphalt concrete mostly exhibits elastic fracture at low temperature, and the coarse aggregate has no influence on the fracture path. For the pure shear mode, asphalt concrete is prone to first fracture near the supports.

(2) In addition to the method of changing the notch angle, the crack initiation angle obtained from other methods is quite different from the theoretical value of GMTS at medium temperature. The crack initiation is closely related to the semicircular bend method at low temperature, and this difference is more prominent in mode II fracture. The measured ratios of fracture toughness are lower than the theoretical value of GMTS, but the empirical model can be used to exactly describe the relationship of fracture toughness ratios.

(3) For the selected bend methods in this work, changing the positions of the support and notch synchronously is stable and repeatable; this method is suggested to be popularized and applied on the mixed fracture behavior of materials in the future, but attention should be paid to controlling the positioning accuracy of the notch [21–23].

Data Availability

All the data obtained from several experiments are included in the paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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