

Research on fracture performance of epoxy asphalt concrete based on double-K fracture criterion

M Zhang, Z D Qian¹ and Y C Xue

Intelligent Transport System Research Center, Southeast University, Nanjing, Jiangsu, China

Email: qianzd@seu.edu.cn

Abstract. After cracks appear on steel bridge deck epoxy asphalt concrete pavement, cracks propagate fast under vehicle load. This paper studied the fracture performance of epoxy asphalt concrete, utilized single edge notched beam (SEB) three-point bending test, measured the load (P) exerted on epoxy asphalt SEB; utilized digital camera to record the fracture process of epoxy asphalt SEB, extracted the images according to the required sampling frequency and utilized Image-Pro Plus to measure the crack mouth opening displacement (CMOD) of epoxy asphalt SEB on the extracted images; calculated the double-K fracture parameters according to the P-CMOD curve. Results indicate that K_{IC}^{ini} of epoxy asphalt concrete is $1.11 \text{ MPa}\sqrt{m}$ and K_{IC}^{un} of epoxy asphalt concrete is $2.31 \text{ MPa}\sqrt{m}$ at -15°C ; K_{IC}^{ini} of epoxy asphalt concrete is $1.02 \text{ MPa}\sqrt{m}$ and K_{IC}^{un} of epoxy asphalt concrete is $1.83 \text{ MPa}\sqrt{m}$ at -5°C ; K_{IC}^{ini} of epoxy asphalt concrete is $0.77 \text{ MPa}\sqrt{m}$ and K_{IC}^{un} of epoxy asphalt concrete is $1.82 \text{ MPa}\sqrt{m}$ at 5°C . The double-K fracture parameters of epoxy asphalt concrete increase slightly when the temperature decreases at the scope of -15°C to 5°C . The relation of K_{IC}^{ini} , K_{IC} and K_{IC}^{un} is $K_{IC}^{ini} < K_{IC} < K_{IC}^{un}$.

1. Introduction

Epoxy asphalt concrete is a kind of steel bridge deck pavement materials in China. Fatigue crack is the typical damage of steel bridge deck epoxy asphalt pavement. When steel bridge deck epoxy asphalt pavement have cracks, there is stress concentration at each crack tip of epoxy asphalt pavement under repeated load. It will lead to a rapid crack propagation until steel bridge deck pavement system damages.

Previous studies on fracture behavior of epoxy asphalt concrete were mainly about the usual fracture criterion, such as stress intensity factor criterion, CTOD criterion and J-integral criterion by laboratory test and numerical simulation [1-5]. In recent years, researchers began to focus on the



double-K fracture criterion. And the double-K fracture criterion had been successfully used to estimate the fracture behavior of cement concrete [6, 7].

Epoxy asphalt concrete belongs to thermosetting asphalt concrete. The fracture of epoxy asphalt concrete belongs to brittle fracture below 5°C. The fracture of epoxy asphalt concrete belongs to elastoplastic fracture above 5°C [8]. In this paper, double-K fracture parameters of epoxy asphalt concrete has been tested by laboratory experiment and double-K fracture criterion of epoxy asphalt concrete has been put forward.

2. The double-K fracture criterion of concrete and test method

The crack propagation process of concrete can be divided into 3 stages: initial fracture, stable propagation and unstable propagation [9]. According to double-K fracture criterion, when stress intensity factor (K_I) is smaller than initial critical stress intensity factor (K_{IC}^{ini}), crack cannot propagate; when stress intensity factor (K_I) equals initial critical stress intensity factor (K_{IC}^{ini}), crack begins to propagate; when stress intensity factor (K_I) is bigger than initial fracture critical stress intensity factor (K_{IC}^{ini}) and smaller than unstable fracture critical stress intensity factor (K_{IC}^{un}), crack propagation is stable; when stress intensity factor (K_I) equals unstable fracture critical stress intensity factor (K_{IC}^{un}), unstable propagation of crack begins; when stress intensity factor (K_I) is bigger than unstable fracture critical stress intensity factor (K_{IC}^{un}), the crack is at unstable propagation stage.

Traditional double-K fracture parameters test method of single edge notched beam [10] is adopted in this paper and the detail steps is shown as below.

(1) Plot the force-crack mouth opening displacement curve (P-CMOD curve). Choose a P_i and the corresponding $CMOD_i$ of the linear growth stage of P-CMOD curve. Measure the crack depth (a_0). Calculate the elastic modulus (E) by equation (1) [11]. The parameter “a” represents the crack depth, “S” represents the span of 3-point bending test, “B” represents the width of beam and “W” represents the height of beam.

$$E = \frac{6aSV_1(\alpha)}{C_iBW^2} = \frac{24a}{C_iBW} V_1(\alpha) \quad (1a)$$

$$C_i = CMOD_i / P_i \quad (1b)$$

$$\alpha = a/W \quad (1c)$$

$$V_1(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2} \quad (1d)$$

(2) Put the force value of the initial fracture moment (P_{ini}) and initial crack-depth ratio (a_0) into equation (2) and calculate K_{IC}^{ini} .

$$K_I = \frac{3PS}{2BW^2} \sqrt{W} f(\alpha) \quad (2a)$$

$$f(\alpha) = \frac{\alpha^{1/2}}{(1-\alpha)^{3/2}(1+3\alpha)} \left\{ p_\infty(\alpha) + \frac{4}{\beta} [p_4(\alpha) - p_\infty(\alpha)] \right\} \quad (2b)$$

$$p_4(\alpha) = 1.9 + 0.41\alpha + 0.51\alpha^2 - 0.17\alpha^3 \quad (2c)$$

$$p_{\infty}(\alpha) = 1.99 + 0.83\alpha - 0.31\alpha^2 + 0.14\alpha^3 \quad (2d)$$

$$\alpha = a/W \quad (2e)$$

$$\beta = S/W \quad (2f)$$

(3) Put the maximum force value ($P_{\max}$), corresponding crack mouth opening displacement (CMOD_c) and the calculated modulus (E) into equation (1). Then calculate the critical effective crack depth (a_c).

(4) Put the maximum force value ($P_{\max}$) and critical effective crack depth (a_c) into equation (2) and calculate K_{IC}^{un} .

3. Laboratory test

The mechanical characteristics of 3-point bending test is similar to the mechanical characteristics of steel bridge deck pavement cracks [12]. The 3-point bending test of single edge notched beam is used in this paper so that to test the double-K fracture parameters of epoxy asphalt concrete. The schematic of 3-point bending test device and the specimen size is shown in Figure 1.

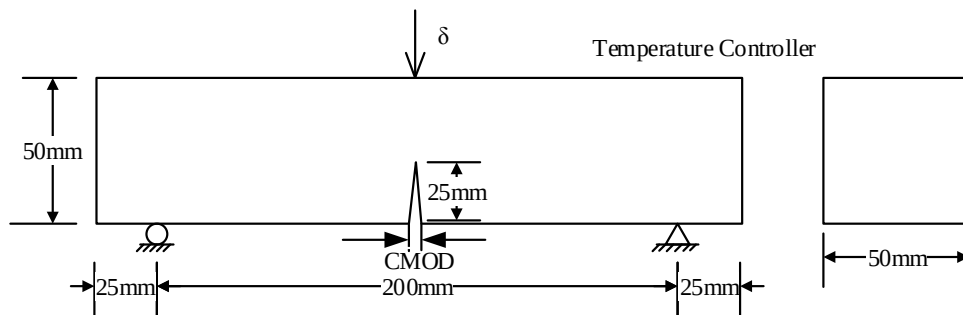


Figure 1. Schematic of 3-point bending test device.

Servo-hydraulic testing machine is used in this paper to load on single edge notched beam. The rate of deflection is 1mm/min. The test device will record the force (P) and the displacement of load location (δ). Clip gauge was usually used to measure the crack mouth opening displacement (CMOD) of single edge notched beam [13]. However, this method to measure the crack mouth opening displacement (CMOD) of single edge notched beam cannot obtain the crack mouth opening displacement (CMOD) at initial fracture moment. Digital camera is used to record the fracture process of single edge notched beam in this paper so that to obtain the crack mouth opening displacement (CMOD) at initial fracture moment and unstable propagation moment. The extracted pictures from video is shown in Figure 2. Image-Pro Plus is used to measure the crack mouth opening displacement (CMOD). Moreover, according to the recorded P and CMOD, the P-CMOD curve can be plotted.



Figure 2. Crack propagation process.

The gradation scope and synthetic gradation curve of epoxy asphalt mixture is shown in Figure 3. Asphalt-aggregate ratio is 6.5%. Single edge notched beams are fabricated according the specimen size which is shown in Figure 1. In order to reinforce the contrast between crack and specimen, white paint was painted on crack edges, as is shown in Figure 4.

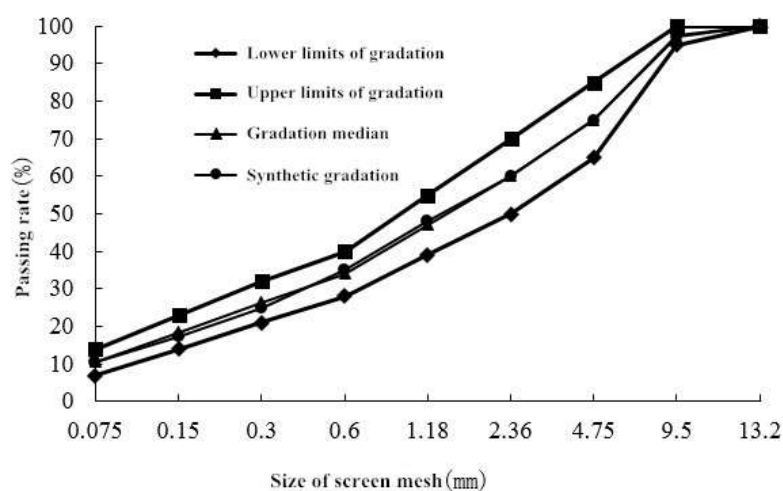


Figure 3. Gradation scope and synthetic gradation curve of epoxy asphalt mixture.



Figure 4. 3-point bending specimen.

Double-K fracture criterion is used to describe the fracture behavior of brittle cement concrete. Epoxy asphalt concrete fracture is brittle fracture below 5°C while epoxy asphalt concrete fracture is elastoplastic fracture above 5°C [8]. Double-K fracture parameters of epoxy asphalt concrete is tested at 5°C, -5°C and -15°C, respectively.

4. Results and discussion

The P-CMOD curves of epoxy asphalt concrete single edge notched beams under the 3 specified temperatures are shown in Figure 5.

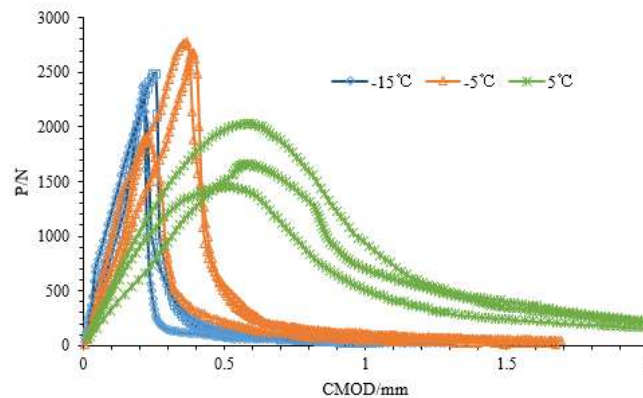


Figure 5. P—CMOD curves under different temperatures.

According to Figure 5, epoxy asphalt concrete fracture is brittle fracture at the temperature of 5°C, -5°C and -15°C.

According to the recorded video of fracture process, the initial fracture moment is found out and then the load value at initial fracture moment is extracted. The parameters of equation (1) and equation (2) to calculate double-K fracture parameters is shown in Table 1. The span length of 3-point bend test is 20cm and the width of the single edge notched beam is about 5cm. The modulus of epoxy asphalt concrete single edge notched beam are calculated by equation (1).

Double-K fracture parameters of epoxy asphalt concrete at the temperature of 5°C, -5°C and -15°C are calculated by equation (2). Then the critical stress intensity factor of epoxy asphalt concrete at the temperature of 5°C, -5°C and -15°C are calculated according to ASTM-E399 [14].

Table 1. Calculating parameters.

T(°C)	No.	a_0 (cm)	W(cm)	α_0	P_{ini} (N)	E(MPa)	P_{max} (N)	CMOD _c (mm)
-15	-15-1	2.6	5.13	0.507	2151.2	3057.6	2392.1	0.215
	-15-2	2.72	5.38	0.506	2348.4	3225.8	2508.6	0.256
	-15-3	2.63	4.98	0.528	2054.6	3211.0	2151.7	0.213
-5	-5-1	2.22	4.98	0.446	2691.8	1893.1	2782.7	0.365
	-5-2	2.37	5.35	0.443	2578.1	1742.9	2687.0	0.389
	-5-3	2.44	4.93	0.495	1828.6	2308.7	1908.5	0.223
5	5-1	2.70	5.31	0.508	1607.1	869.8	1670.2	0.568
	5-2	2.50	5.28	0.473	1398.1	943.6	1456.6	0.532
	5-3	2.58	5.35	0.482	1969.8	1153.5	2040.8	0.583

According to Table 2, the double-k fracture parameters and critical stress intensity factor of epoxy asphalt concrete increase slightly when the temperature decreases at the scope of -15°C to 5°C. However, the modulus of epoxy asphalt concrete increase much faster than double-k fracture parameters and critical stress intensity factor of epoxy asphalt concrete when the temperature decreases at the scope of -15°C to 5°C, so the lower the temperature is, the more easily the epoxy

asphalt concrete crack will propagate.

Table 2. Double-K fracture parameters of epoxy asphalt concrete.

T(°C)	No.	α_0 (cm)	$\bar{\alpha}_0$	K_{IC}^{ini}	$\bar{K}_{IC}^{ini}$	K_{IC}^{un}	$\bar{K}_{IC}^{un}$	K_{IC}	$\bar{K}_{IC}$
-15	-15-1	0.507	0.	1.07		1.91		2.04	
	-15-2	0.506	5	1.14	1.11	2.72	2.31	1.96	2.02
	-15-3	0.528	1	1.11		2.30		2.05	
-5	-5-1	0.446	0.	1.13		1.93		2.05	
	-5-2	0.443	4	1.04	1.02	1.84	1.83	1.76	1.82
	-5-3	0.495	6	0.89		1.73		1.65	
5	5-1	0.508	0.	0.79		1.49		1.35	
	5-2	0.473	4	0.62	0.77	1.75	1.82	1.07	1.31
	5-3	0.482	9	0.89		2.22		1.50	

^a T: Temperature.

^b No.: Specimen number.

^c The units of K_{IC}^{ini} , $\bar{K}_{IC}^{ini}$, K_{IC}^{un} , $\bar{K}_{IC}^{un}$, K_{IC} and $\bar{K}_{IC}$ are $\text{MPa}\sqrt{\text{m}}$.

Comparing the double-k fracture parameters and critical stress intensity factor of epoxy asphalt concrete at the same temperature, the relation of K_{IC}^{ini} , K_{IC} and K_{IC}^{un} is $K_{IC}^{ini} < K_{IC} < K_{IC}^{un}$. And K_{IC}^{un} is similar to K_{IC} , so double-K fracture parameters can reflect the fracture behavior of epoxy asphalt concrete more accurately than critical stress intensity factor.

5. Conclusions

The results of this paper indicate that K_{IC}^{ini} of epoxy asphalt concrete is $1.11 \text{ MPa}\sqrt{\text{m}}$ and K_{IC}^{un} of epoxy asphalt concrete is $2.31 \text{ MPa}\sqrt{\text{m}}$ at -15°C ; K_{IC}^{ini} of epoxy asphalt concrete is $1.02 \text{ MPa}\sqrt{\text{m}}$ and K_{IC}^{un} of epoxy asphalt concrete is $1.83 \text{ MPa}\sqrt{\text{m}}$ at -5°C ; K_{IC}^{ini} of epoxy asphalt concrete is $0.77 \text{ MPa}\sqrt{\text{m}}$ and K_{IC}^{un} of epoxy asphalt concrete is $1.82 \text{ MPa}\sqrt{\text{m}}$ at 5°C . The double-K fracture parameters of epoxy asphalt concrete increase slightly when the temperature decreases at the scope of -15°C to 5°C . The relation of K_{IC}^{ini} , K_{IC} and K_{IC}^{un} is $K_{IC}^{ini} < K_{IC} < K_{IC}^{un}$.

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References

- [1] Qian Z D, Li Z and Chen C H 2008 Fracture Criterion for Mode I Crack of Epoxy Asphalt Concrete Paving Course of Steel Bridge Pavement *China Journal of Highway and Transport* **21**(5) 33-38
- [2] Wang J Y, Qian Z D and Wang L B 2014 Three-dimensional Visualization Discrete Element Modeling of the Crack Development of Epoxy Asphalt Concrete *Journal of Hunan University (Natural Sciences)* **41**(6) 112-119
- [3] Chen T J, Huang W and Wang S J 2008 Numerical Analysis of Fatigue Crack Propagation in Asphalt Pavement on Steel Deck *Journal of Traffic and Transportation Engineering* **8**(4)

52-57

- [4] Chen C H 2008 Fracture Criteria and Fatigue Life Estimation of Steel Bridge Deck Pavement Based on Composite Beam Southeast University
- [5] Qian Z D and Hu J 2012 Fracture Properties Of Epoxy Asphalt Mixture Based on Extended Finite Element Method *Journal of Central South University* **19**(11) 3335-3341
- [6] Xu S L and Zhao G F 1992 Double-K Criterion of Concrete Structure Crack Propagation *China Civil Engineering Journal* **25**(2) 32-38
- [7] Xu S L and Reinhardt H W 1999 Determination Of Double-K Criterion for Crack Propagation in Quasi-Brittle Fracture, Part II: Analytical Evaluating And Practical Measuring Methods for Three-Point Bending Notched Beams *International Journal of Fracture* **98**(98) 151-177
- [8] Wang J Y 2013 Research on Fracture Behavior of Epoxy Asphalt Concrete Used for Steel Bridge Wearing Course under Meso-scale Southeast University
- [9] Xu S L 2002 The Calculation Approaches of Double-K Fracture Parameters of Concrete and a Possible Coding Standard Test Method for Determining Them *J of China Tree Gorges Univ. (Natural Science)* **24**(1) 1-8
- [10] Xu S L and Reinhardt H W 1999 Determination Of Double-K Criterion for Crack Propagation in Quasi-Brittle Fracture, Part I: Experimental Investigation Of Crack Propagation *International Journal of Fracture* **98**(2) 111-149
- [11] Jenq Y S and Shah S P 1985 Two Parameter Fracture Model for Concrete *Journal of Engineering Mechanics* **111**(10) 1227-1241
- [12] Li Z 2007 Research on Fracture Parameters and Fracture Energy of Epoxy Asphalt Concrete Southeast University
- [13] Wu Z M and Zhao G F 1995 CTOD_C Criterion of Concrete Crack Propagation *Journal of Dalian University of Technology* **35**(5) 699-702
- [14] ASTM E1290-99 2002 Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement