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Evaluation of fracture properties of epoxy asphalt mixtures by SCB test

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Abstract: The fracture properties of epoxy asphalt mixtures (EAM) are evaluated based on J-integral and ultimate strength. Totally 60 semi-circular bending (SCB) specimens cored from superpave gyratory compactor (SGC) with three groups of notch depths are tested at the temperature of −10 and 20 ℃. The experimental results reveal good repeatability in EAM characterization. The tensile strength ratio of SCB to the indirect tensile test (IDT) is at a range of 1.4 to 1.7, and the ultimate strength of EAM is exponentially dependent on the notch depths. At the test temperatures, the critical J-integral value of EAM is much higher than that of hot mix asphalt (HMA) with thermo-plastic asphalt binder. The response mode of EAM changes from ductile mode to brittle mode and the fracture energy increases 30% when temperature decreases from 20 to −10 ℃, while its critical J-integral value decreases only 15%. It is concluded that EAM has better fracture resistance than thermo-plastic HMA; more fracture energy is needed to initiate cracks in EAM at low temperature, and the cracks propagate more rapidly than at room temperature.

Key words: epoxy asphalt mixture; tensile strength; critical J-integral; semi-circular bending test

Fracture resistance is one of the important requirements for asphalt pavement[1]. To study the fracture properties of asphalt materials, one of the most powerful tools is to incorporate fracture mechanics tools in HMA characterization. There are two approaches to fracture analysis. One is the stress intensity approach, and the other is the J-integral approach. The J-integral is better in characterizing the fracture properties of HMA[2-6]. The specimen used in fracture tests can be categorized into two groups: 1) Notched beam with slab compaction; 2) Cylindrical specimen prepared with gyratory compactor, such as the indirect tensile test (IDT), the semi-circular bending (SCB) test, and the disc-shaped compact tension test (DCT). The SCB test was originally used to characterize the fracture resistance of rocks[7]. In recent years, the SCB test has drawn more and more attention in road engineering due to its advantages[8]. It has been successfully used to characterize the tensile strength[8-9], fatigue resistance properties and fracture resistance[9-10] of HMA. A numerical solution is available with this configuration.

Fracture resistance is more critical for pavement on steel orthotropic bridge decks compared with asphalt pavement with subgrade[11-12]. Only a few materials can meet these requirements, one of which is the epoxy asphalt mixture. EAM is a thermo-setting polymer concrete with a slow curing, epoxy asphalt binder. The epoxy asphalt binder is a two-phase chemical system in which the continuous phase is an acid cured epoxy and the discontinuous phase is a mixture of specialized asphalts, which makes the mixture's performance different from that of traditional HMA. EAM has recently been used extensively in China as surfacing materials for orthotropic steel bridge decks after its successful application in the 2nd Nanjing Yangtze Bridge[13]. Great efforts have currently been made to investigate the fracture resistance of asphalt materials and the fracture performance of asphalt pavements on steel bridge decks, but few on EAM. Therefore, it has become a top priority to conduct a comprehensive research to evaluate the fracture resistance of EAM with well-documented test methods.

This paper presents part of a comprehensive research effort to evaluate the fracture properties of EAM for orthotropic steel decks. The scope of this study includes conducting SCB tests at 20 ℃ and −10 ℃ with a total of 60 semi-circular specimens. Previous efforts on the comparison of IDT and SCB tests were based on thermo-plastic HMA[9, 14]. In this paper, 20 IDT tests on EAM are conducted to be compared with 20 SCB tests.

1 Fracture Parameters

1.1 Tensile strength

The SCB tensile strength can be computed by[8]

$$\sigma_{\mathrm{h}} = 4.8\frac{P_{\max}}{Dt} \tag{1}$$

where σ_{h} is the tensile stress at the central bottom area of the specimens, MPa; P is the peak load, N; D is the diameter of the specimen, mm; t is the thickness, mm. It should be noted that Eq. (1) is valid only with a supporting span equal to $0.8D$. The SCB tensile strength is compared with standard ASTM IDT test results in order to verify whether the prefactor of 4.8 in Eq. (1) is suitable for EAM.

1.2 Critical J-integral

The definition of the critical J-integral is given as

$$J_{\mathrm{c}} = -\frac{1}{b}\frac{\mathrm{d}U}{\mathrm{d}a} \tag{2}$$

The utilization of the semi-circular specimen to determine the critical value of the J-integral we intend to use only two

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notch depths. On this basis, Eq. (2) can be rewritten as[2]

$$J_c = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2}\right)\frac{1}{a_2 - a_1} \tag{3}$$

where U_1 and U_2 are the strain energy values, calculated using the data from the beginning of the notched SCB test loading until the load reaches the maximum value; b_1 and b_2 are the thicknesses of the specimens with notch depths of a_1 and a_2, respectively.

As seen from Eq. (3), to determine the critical value of the J-integral we intend to use only two notch depths. In the current studies, however, three target notch depths are used to increase the accuracy of the value of J_c for EAM.

2 Laboratory Experiments

2.1 Materials

2.1.1 Aggregates

Both the coarse and the fine aggregates are basaltic, with a Los Angeles abrasion value of 12.1%, a polishing stone value of 51, a crushed stone value of 9.6%, an absorption of 0.2%, a compression strength of 138 MPa, and a bulk specific gravity of 2.995. The mineral filler is calcareous with a passing rate over 95% and a specific gravity of 2.75.

2.1.2 Epoxy asphalt binder

The epoxy asphalt binder is made from part A (epoxy resin) and part B (blend of asphalt and curing agent) with a proportion of 100 : 585. The properties and requirements of both parts are listed in Tabs. 1 and 2. The blend of part A and part B should be cured at 121 ℃ for 4 h to conduct tensile tests. The tensile test results of the cured epoxy asphalt binder are presented in Tab. 3.

Tab. 1 Properties and specifications of part A

Properties	Test results	Specification	
		Requirements	Test methods
Viscosity@23 ℃/(Pa · s)	14	10 to 15	ASTM D 445
Equivalent epoxide	188	185 to 192	ASTM D 1652
Gardner color	2	≤4	ASTM D 1544
Moisture content/%	0.02	≤0.05	ASTM D 1744
Flash point(COC)/℃	230	≥200	ASTM D 92
Specific gravity @23 ℃	1.17	1.16 to 1.17	ASTM D 1475
Appearance	Transparent amber	Transparent amber	Visual

Tab. 2 Properties and specifications of part B

Properties	Test results	Specification	
		Requirements	Test methods
Viscosity@100 ℃/(Pa · s)	0.21	≥0.14	Brookfield
Specific gravity @ 23 ℃	1.00	0.98 to 1.02	ASTM D 1475
Gardner color	0.01	Black	Visual
Acid value/(mg · g^{-1} KOH)	55	40 to 60	ASTM D 664
Flash point(COC)/℃	235	≥200	ASTM D 92

Tab. 3 Tensile test results of cured epoxy asphalt binder

Properties	Test results	Specification	
		Requirements	Test methods
Tensile strength @23 ℃/MPa	2.8	≥1.5	ASTM D 638
Elongation at break @23 ℃/%	250	≥200	ASTM D 638

2.2 Mixture design

The Marshall method is employed for EAM proportioning. The blended gradations of the aggregates and specifications are listed in Tab. 4. The optimum binder content is 6.5%, and the Marshall stability of the cured EAM at 60 ℃ is 58.5 kN.

Tab. 4 Aggregate gradation and specification %

Items	Sieve/mm					
	13.2	9.5	4.75	2.36	0.6	0.075
Specification	100	95 to 100	65 to 85	50 to 70	28 to 40	7 to 14
Blend gradation	100	97.5	74.5	59.6	33.6	10.4

2.3 SCB specimen geometry and preparation

As the previous research reveals that the fracture toughness of SCB specimens is independent on the specimen size[3], a specimen of 100 mm in diameter and 30 mm in thickness is selected. The SCB test configuration and specimens preparation are shown in Fig. 1. Standard IDT specimens are also drilled from SGC cylindrical specimens.

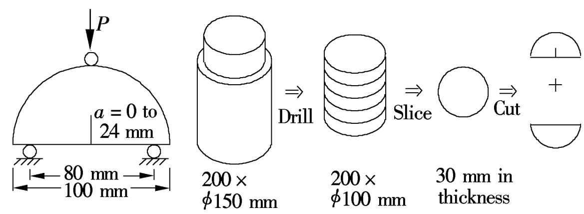

Fig. 1 SCB test configuration and specimen preparation

The mixture is compacted with SGC to obtain a target air void of 2.5%. The compaction temperature is 121 ℃ and the number of gyrations used is 100. The mixture is aged in 121 ℃ for 35 min before being compacted, and then cured at 121 ℃ for 4 h.

2.4 Testing procedure

As the cracks in deck pavement are intimately related to high tensile stresses that develop at normal and low temperatures[12], test temperatures of −10 ℃ and 20 ℃ are selected. The temperature of −10 ℃ is controlled by an environmental chamber. For the temperature of 20 ℃, an air conditioner is used. The specimens are tested in a universal testing system with a PowerTest package. A small seating load is first applied to the specimen to assure the contact between the loading roller and the specimen. A constant stroke of 50 mm/min is used for tensile strength tests. For the notched specimens, a loading rate of 1 mm/min is adopted. The loads and displacements are measured and recorded by the Power-Test package.

3 Results Discussion

3.1 Tensile strength

The average tensile strengths of the SCB test and the IDT test are listed in Tab. 5. The tensile strength of EAM with the SCB test is about 1.4 to 1.7 times that of the standard IDT test. The tensile strength from the SCB and standard IDT tests are different due to their stress states from pure flexural bending to biaxial stress state. The SCB test can be used to characterize the tensile strength of EAM with good repeatability. In comparison to the standard IDT results, a smaller prefactor value of 2.8 to 3.4 in Eq. (1) should be chosen to calculate the SCB tensile strength of EAM.

Tab. 5 Comparison of SCB and IDT test results

Temperature/℃	Tensile strength/MPa		Covariance/%		Ratio(SCB/IDT)		
	SCB	IDT	SCB	IDT	EAM	Huang[14]	van de Ven[2]
−10	34.19	24.58	5.3	14.5	1.4		
20	11.04	6.43	1.4	7.6	1.7	3.2 to 4.1	4.4

3.2 Load deflection behavior of notched specimen

The typical load-deflection behaviors of notched specimens under different temperatures are shown in Fig. 2. A brittle response is observed immediately before the maximum load is reached, and all the specimens are broken when the deflection reaches 0.24 to 0.27 mm. The failure mode changes into the ductile mode at 20 ℃ as shown in Fig. 2(b). Moreover, the fracture deflection is negatively dependent on the notch depth; these specimens give reproducible results, and always fracture in a similar path (see Fig. 3).

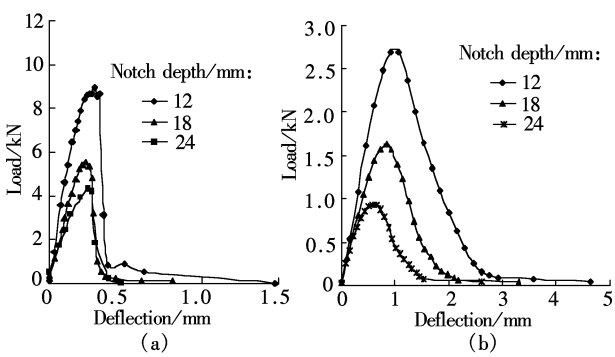

Fig. 2 Load-deflection behaviors of EAM in SCB test. (a) −10 ℃; (b) 20 ℃

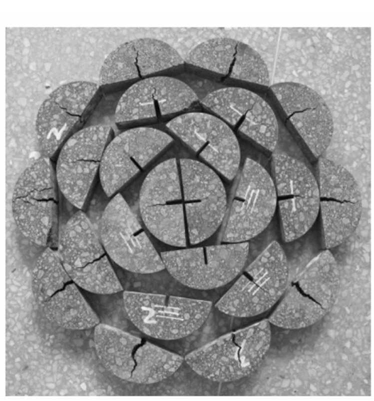

Fig. 3 Some tested specimens

Fig. 4 presents the results of the ultimate bearing capacity along unit thickness as a function of the ratio of the notch depth to the thickness. The comparison is meaningful as the specimens are of the same size. It can be seen from Fig. 4 that the ultimate bearing capacity decreases with the notch depth and the bearing capacity at −10 ℃ is 200% higher than that of 20 ℃.

3.3 Fracture resistance

In order to obtain the critical value of J-integral, the area under the loading portion of the load deflection curves, up to the maximum load, is measured from the curves as presented in Fig. 2. These values are then plotted as a function

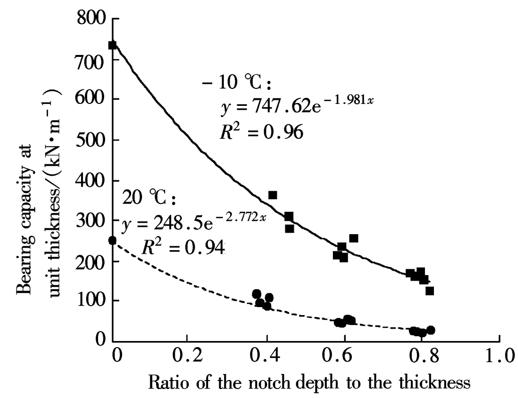

Fig. 4 The ultimate bearing capacity curve

of the notch depth as shown in Fig. 5. It can be seen that the repeatability of the test is reasonable. And the relationship between the total strain energy to failure and the notch depth is linear.

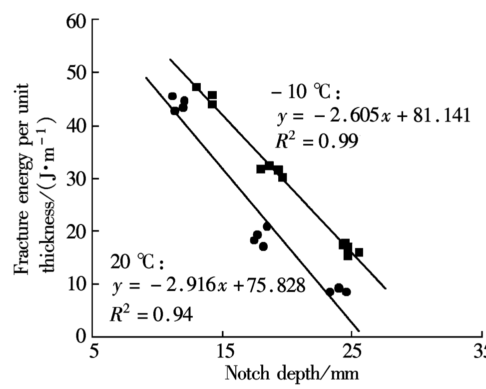

Fig. 5 The fracture energy per unit thickness for EAM as a function of notch depth

The critical fracture resistances, J_c, are presented in Tab. 6 in comparison with other HMA. A much higher J_c value of EAM reveals a better fracture resistance of EAM than HMA with thermo-plastic asphalt binders. It should be noted that, although the fracture energy per unit thickness at −10 ℃ is 30% higher than that at 20 ℃, the J_c of EAM at 20 ℃ is about 15% higher than that at −10 ℃, and the ultimate bearing capacity is even much higher. It can be explained by fracture mechanics[15–16]; i. e., initiation of cracks in EAM at low temperature requires more energy, while the cracks propagate more rapidly at low temperature due to the brittle response mode.

Tab. 6 The fracture toughness of EAM kJ/m²

Temperature/℃	EAC	AC-5 + 5% SEBS[2]	AC-20[2]
−10	2.60	0.42	
20	2.92		1.03

4 Conclusions

1) The SCB test can be used to characterize the tensile strength of EAM with good repeatability. The ratio of the

SCB to the IDT tests with EAM is 1.4 to 1.7.

2) Epoxy asphalt mixture has better resistance to fracture than HMA with thermo-plastic binders. A 15% decrease in J_c is observed when the temperature drops from 20 to −10 ℃.

3) The changes in load-deflection behavior and critical fracture resistance with temperature indicate a change in the mixture behavior from brittle to ductile behavior, revealing the capability of J-integral to characterize the fracture properties of EAM.

4) To initiate a crack in EAM at low temperature requires more energy input, while the propagation of cracks at low temperature is more rapid than at room temperature due to its response mode.

In general, the SCB test specimen is useful for measuring the fracture toughness of EAM. Further work is desirable to develop a constitutive material model and incorporate the model into the design for the pavement on steel bridge decks.

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基于 SCB 试验的环氧沥青混合料断裂特性评估

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摘要: 运用 J-积分与终极抗拉强度评估了环氧沥青混合料在 −10 ℃和 20 ℃的断裂特性, 共测试了 60 个不同切口深度的半圆弯曲试件. 结果表明, 环氧沥青混合料的半圆弯曲试验(SCB)结果复现性好; 由非切口试件的半圆弯曲试验与标准间接拉伸试验(IDT)所测得的环氧沥青混合料的抗拉强度, 其比值在 1.4 ~ 1.7 之间, 且 SCB 抗拉强度与切缝深度指数相关; 在 20 ℃与 −10 ℃试验条件下, 环氧沥青混合料具有比热塑性 HMA 高得多的临界 J-积分值; 当温度由 20 ℃降至 −10 ℃时, 环氧沥青混合料的响应模式由延性变为脆性, 断裂能增加 30%, 而临界 J-积分值下降 15%. 与热塑性 HMA 相比, 环氧沥青混合料的常温与低温抗裂性更好; 环氧沥青混合料低温起裂需要更高的能量, 但其裂纹扩展速度比常温时更快.

关键词: 环氧沥青混合料; 抗拉强度; 临界 J-积分; 半圆弯曲试验

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