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Development of overlay tester for fracture test of asphalt mixture

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Abstract: To determine the fracture characteristics of asphalt mixture, a novel fracture test with modified loading modes, loading fixtures and the control system of the conventional overlay tester is implemented by the asphalt material performance tester (AMPT). In order to evaluate the validity of the proposed fracture test, four different loading rates, including 1, 2, 3 and 4 mm/min, are examined in the AMPT. The results indicate that the fracture behavior is similar to creep at a low loading rate and does not show significant marginal tail extension at a high loading rate. It clearly shows the phase of crack initiation, crack propagation and fracture at a loading rate of 3 mm/min. Besides, eight fracture parameters, such as fracture energy, tensile strength and tensile modulus, are applied to evaluate the fracture characteristics of asphalt mixture. Development of the overlay tester for the fracture test of asphalt mixture can be considered as a new fracture test of asphalt mixture.

Key words: asphalt mixture; fracture test; overlay tester; asphalt material performance tester (AMPT); fracture parameter

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The crack is probably the most challenging to predict and control among the several types of distresses that cause damage and the eventual failure of asphalt mixtures in highways. Cracks, including fatigue crack (both top-down and bottom-up), thermal (transverse) crack and reflective crack, are related to fracture; thus, the fracture resistance of asphalt mixtures significantly influences the service life of asphalt pavements. One of the most powerful tools for studying fracture processes and damage evolutions of engineering materials is fracture mechanics, which studies the response and failure of structures as a consequence of crack initiation and propagation. Since Majidzadeh et al. [1] introduced the fracture mechanics concept to the pavement field, the fracture mechanics approach has been widely used in characterizing and predicting pavement cracking analysis.

Currently two main approaches, computational simulation and fracture test, are widely regarded as useful tools to evaluate the fracture characteristics of asphalt mixture. The former is usually implemented by the finite element method, the discrete element method and the cohesive zone model, which has received increasing attention regarding crack development in asphalt mixture[2-4]. While the latter usually includes a semi-circular bending test (SC(B)), a single-edge notched beam test (SE(B)) and a disk-shaped compact tension test (DC(T))[5-8]. Most numerical simulations are based on the fracture tests to get the computational parameters for numerical simulation; therefore, the fracture test is regarded as the primary research for the fracture characteristics of asphalt mixtures. However, standardized fracture tests and fracture properties for asphalt mixtures have not yet been developed to the extent that reliable measurements of fracture properties can be routinely determined. In this paper, the overlay test is proposed as a new fracture test for asphalt mixtures by the AMPT. Since there is no overlay tester in China, as a substitute for the overlay tester, the AMPT, an economical and reliable test method, is utilized in this new fracture test.

1 Comparison of Fracture Test for Asphalt Mixture

The SC(B) has been most common for the fracture test for asphalt mixtures. The test is based on a semi-circular specimen with a single edge notch subjected to a three-point loading, as shown in Fig. 1(a). It has been widely used to characterize the fatigue resistance properties and fracture resistance of asphalt mixtures[6]. The specimens can be easily obtained from the in-place field and be fabricated from just one superpave gyratory compactor (SGC) specimen. But the crack propagation with the SC(B) geometry creates an arching effect with high compressive stress as the crack approaches the top edge. The high compressive stresses can arrest the crack, which further reduces the effective ligament, creating potentially invalid testing results. In the current SC(B) fracture procedure, a loading rate of 0.000 5 mm/s is used to test 150 mm diameter SC(B) specimens, and the temperature can be changed for different research aims.

The SE(B) is advantageous due to its relatively simple testing configuration of specimens[7], as shown in Fig. 1 (b). Compared with the other two fracture tests, the main advantage of the SE(B) is that the size of the liga-

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ment is large enough to encompass the fracture process zone. Nevertheless, the fabrication of specimens is not easily obtained in the laboratory, and it is impractical to extract beam specimens from the field. Nowadays, dimensions, loading rates and temperatures of the single-edge notched beam can also be varied for different testing aims.

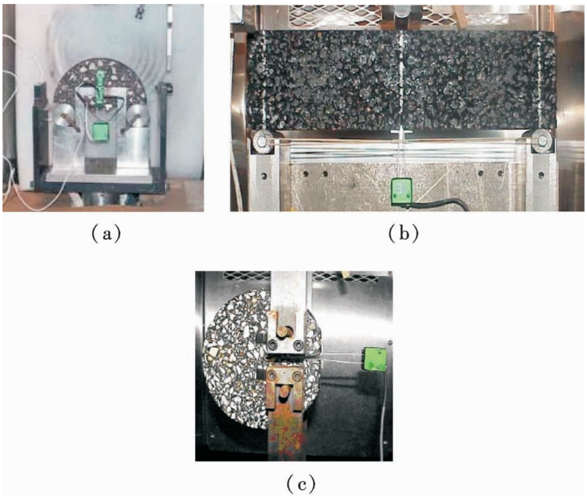


Fig. 1 Primary fracture tests for asphalt mixture. (a) SC(B) test; (b) SE(B) test; (c) DC(T) test

Another fracture test is the DC(T), which comes from the ASTM E399 standard test method describing the DC(T) specimen for obtaining the plane-strain fracture toughness of the metallic specimen. The updated DC(T) for the asphalt mixture has been conducted by Buttlar et al.[8]; a new DC(T) sample is shown in Fig. 1(c). DC(T) is easily obtained from the field and the laboratory; yet crack deviation and complex fabrication are obstacles for extensive utilization of DC(T). The DC(T) test is now specified as ASTM D7313-07a (2007), and a loading rate of 0.017 mm/s and the temperature of no less than 10 ℃ are advised.

All of these fracture tests need a compressive (or pull) load which is vertically applied on specimens in such manners so as to produce a constant crack mouth opening displacement (CMOD) rate, rather than be controlled by constant vertical displacement, and the CMOD is measured using an Epsilon clip gauge as shown in Fig. 1. All of the aforementioned fracture tests have their own advantages and disadvantages. However, the initial crack is needed to obtain crack propagation progress for these fracture tests, and it is usual that the results of the fracture test are influenced by the initial crack. Thus a new fracture test by the development of the overlay tester without the initial crack is advised in this paper.

2 Overlay Test

The overlay tester was designed by Lytton et al.[9] in the late 1970s. Zhou et al.[10] used the overlay tester and considered it as a reliable and practical test to evaluate crack resistance of hot mixture asphalt (HMA) overlays. However, one limitation of the previous work is that a long beam specimen is required. These are relatively difficult to fabricate in the laboratory and more difficult to obtain from the field. To solve these problems, an upgraded overlay tester is developed with the goal of being able to use 150 mm diameter specimens which can be easily fabricated in the laboratory or obtained from field cores.

The process of specimen preparation is shown in Fig. 2. First, a specimen is molded with a 150 mm diameter and a 62 mm height using the SGC. Then, the specimen is cut to a 38 mm height using a double blade saw. Finally, the opposite sides are trimmed off and a 76 mm wide specimen is obtained. The final specimen has dimensions of 150 mm in length by 76 mm in width and 38 mm in height.

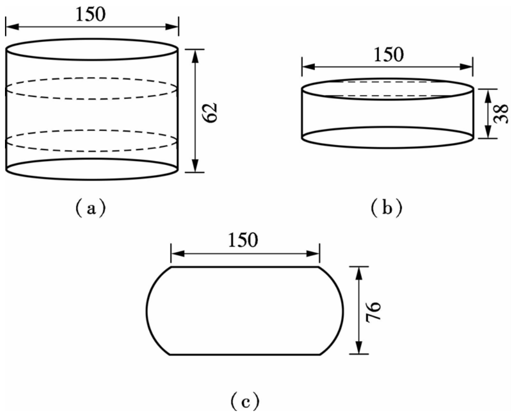


Fig. 2 Trimming specimen from molded sample. (a) Molded sample; (b) Trimming specimen's ends; (c) Overlay test specimen (unit: mm)

Unlike other fatigue tests which are controlled by a certain strain or stress, the upgraded overlay tester is conducted in a displacement-control mode, and the overlay test data includes time, displacement and load corresponding to a certain loading cycle as follows: The temperature is 0 to 25 ℃; the opening displacement is 0.5 to 2 mm; the typical opening displacement is 0.635 mm; the loading rate is one cycle per 10 s. A repeated load is applied in a cyclic triangular waveform with a constant maximum displacement shown in Fig. 3.

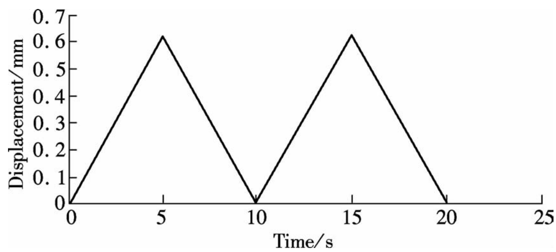


Fig. 3 Typical displacements used in the overlay test

The final results can be reasonably defined as the number of cycles for cracks to initiate and propagate through a specimen, as the peak load reduces to 7% of that in the first cycle. However, this approach has in the past been associated with high variability in the test results. Hence it is necessary to seek other alternative methods of both analyzing and interpreting the data measured from the overlay test. As a new test method, the development of the overlay tester for fracture tests under a monotonic load is proposed in this paper.

3 Test Development

3.1 Description of apparatus

The experimental setup is shown in Fig. 4, and it is certain that new molds are needed in the AMPT for this test. The load direction of the conventional overlay tester is horizontal, while the load direction of the AMPT overlay tester is vertical, as shown in Fig. 5. Cyclic direct tension loads are applied on the conventional overlay tester and the AMPT, whereas the modified overlay tester is run under the monotonic load for the fracture test just like other fracture tests.

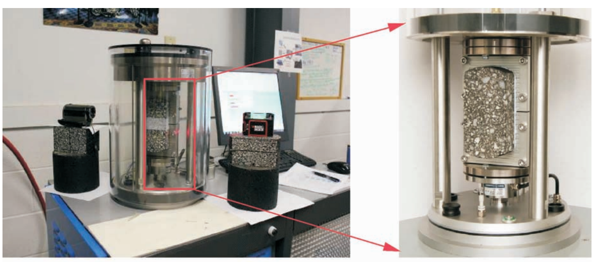
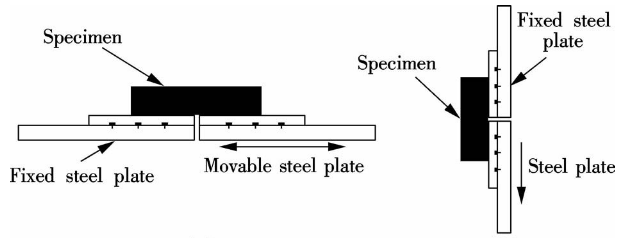

(a) (b)

Fig. 4 Experimental setup. (a) Overview of the whole testing setup in AMPT; (b) Closer view of specimen ready to be tested



(a) (b)

Fig. 5 Concept of the overlay tester. (a) Schematic of the typical overlay tester; (b) Schematic of the overlay tester in the AMPT

3.2 Loading rate

The temperature and the loading rate are critical factors for the fracture test, so these two factors must be evaluated for the new fracture test. In order that the crack can be propagated in a certain direction, the temperature of other asphalt mixture fracture tests is usually less than 0 ℃. However, stable crack propagation in the overlay test can be observed even at 25 ℃. So the temperature no more than 25 ℃ for the overlay test is acceptable. In this paper, 10 ℃ is used in the development of the overlay tester for the asphalt mixture fracture test. Another important parameter is the loading rate, and four trial loading rates 1, 2, 3 and 4 mm/min are selected. An experimental design is carried out to determine the loading rate of the overlay test, and a typical asphalt mixture (stone matrix asphalt, SMA) is used, which consists of a 9.5 mm maximum aggregate size with PG76-12 asphalt. Graduation is presented in Tab. 1 and the target air void is 5% approximately.

Tab. 1 Graduation of SMA %

Material design	Percent	Sieve/mm								
		12.5	9.5	4.75	2.36	1.18	0.60	0.30	0.15	0.075
Stone 1#	78	100	99.9	42.8	7.9	2.7	1.8	1.3	1.0	0.7
Stone 2#	16	100	100	99.9	85.5	63.6	48.1	33.6	21.2	13.5
Flyash	6	100	100	100	100	100	100	100	100	100
Blend	100	100	99.9	55.4	25.8	18.3	15.1	12.4	10.2	8.7

The results of load-displacement curves are shown in Fig. 6. Three phases, crack initiation, crack propagation and fracture, are observed during the test. At low loading rates, the asphalt mixtures behave as creep, e. g. Figs. 6(a) and (b), and this means that the viscosity effect of the asphalt mixtures plays an important role, while the fracture behavior of asphalt mixtures at high loading rates is more difficult to control, especially at the post-peak period when rapid crack growth occurs, e. g. Fig. 6(d). Thus, load-displacement response should be the most reasonable at a loading rate of 3 mm/min with marginal tail extension. In addition, other conclusions can be summed up as follows:

1) The peak load increases with the increasing loading rate from 2.741 to 3.129 kN.

2) Despite different loading rates, the initial slopes of the load-displacement curves remain at about 0.93.

4 Evaluation for Development of Overlay Tester

4.1 Fracture parameters

A monotonic load for the overlay test can be performed as a practical method to obtain fracture parameters of asphalt mixtures. Fracture energy is regarded as the parameter to evaluate the resistance crack, but only one parameter may not be reasonable to distinguish different kinds of asphalt mixture, so eight parameters are proposed to obtain more details of the fracture test in this paper.

Fig. 7 provides an illustration of the output data of a typical monotonic overlay test, and there are three distinct phases in the fracture process of asphalt mixture: phase of the crack initiation (part A in the load-displacement

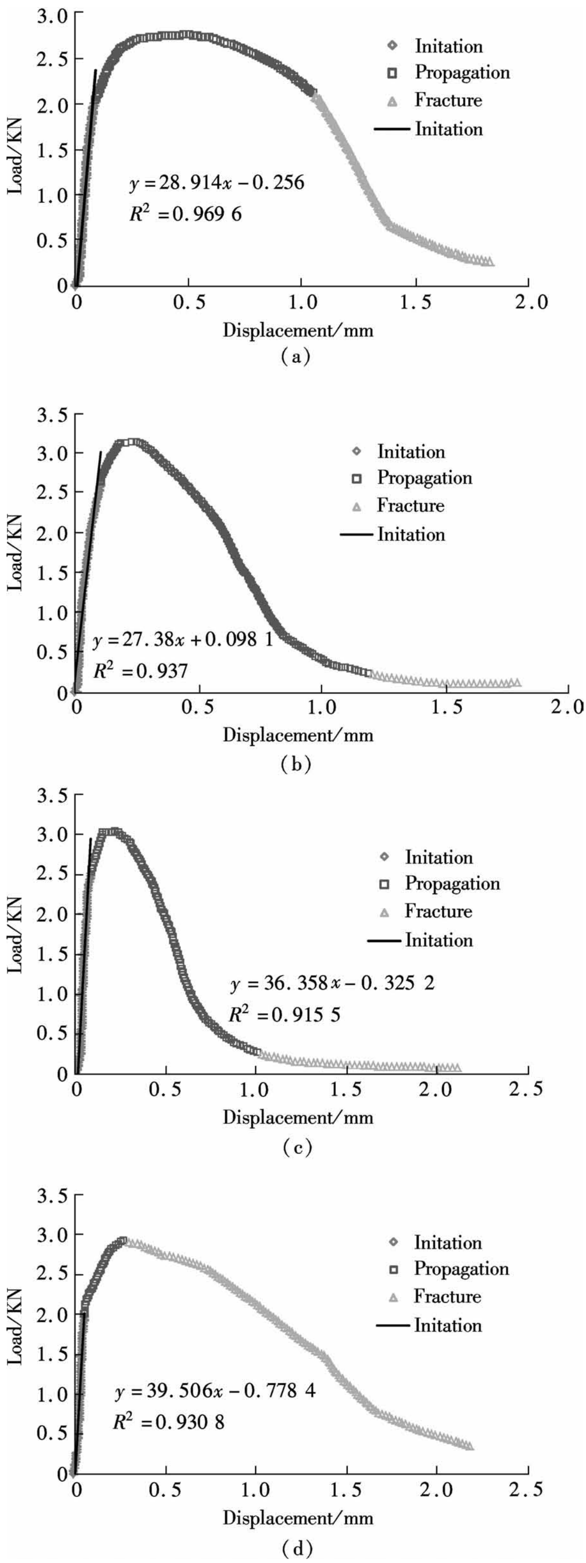


Fig. 6 Load-displacement of trial loading rates. (a) 1 mm/min; (b) 2 mm/min; (c) 3 mm/min; (d) 4 mm/min

curve), crack propagation (part B in the load-displacement curve) and fracture phase (part C in the load-displacement curve). The fracture parameters measured from the test are the total fracture energy G_f, the initiation tensile strength σ_t, the initiation tensile strain ε_t at initiation point load P_{a_1}, the tensile modulus E_t and the displacement ratio δ_{dis}. Specific fracture energy for the three phases of the overlay tester fracture test includes the fracture energy of crack initiation $G_{f,A}$, the fracture energy of crack propagation $G_{f,B}$ and the fracture energy of fracture $G_{f,C}$. The fracture parameters are calculated as

$$G_f = G_{f,A} + G_{f,B} + G_{f,C} = \frac{1}{tb}\int_0^{a_3} f(a)\,da \tag{1}$$

$$G_{f,A} = \frac{1}{tb}\int_0^{a_1} f(a)\,da \tag{2}$$

$$G_{f,B} = \frac{1}{tb}\int_{a_1}^{a_2} f(a)\,da \tag{3}$$

$$G_{f,C} = \frac{1}{tb}\int_{a_2}^{a_3} f(a)\,da \tag{4}$$

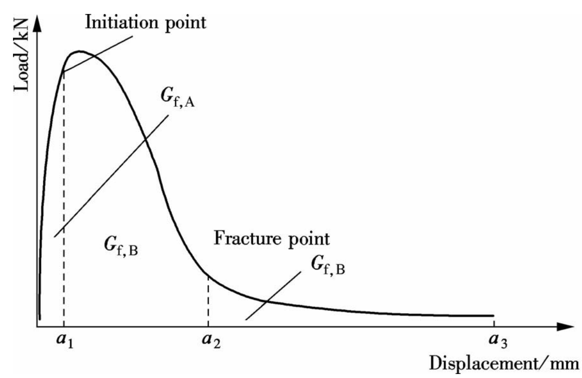


Fig. 7 Typical load-displacement behavior of asphalt mixture

Then, the initiation tensile strength σ_t measured is defined as

$$\sigma_t = \frac{P_{a_1}}{tb} \tag{5}$$

The initiation tensile strain ε_t at the initiation point (ductility potential) is calculated as

$$\varepsilon_t = \frac{D_{P_{a_1}}}{d} \tag{6}$$

Finally, the tensile modulus and the displacement ratio can be expressed as

$$E_t = \frac{\sigma_t}{\varepsilon_t} \tag{7}$$

$$\delta_{dis} = \frac{a_1}{a_3} \tag{8}$$

where t is the sample thickness; b is the sample width; d is the opening displacement of the base plate, $d = 2$ mm; $D_{P_{a_1}}$ is the displacement measured at the initiation point.

4.2 Test results

Three groups of fracture tests for SMA are accomplished, and the binder content (BC) of group 1 and group 3 is 6.5%, while the binder content of group 2 is 6.0%, and the air void of all groups is 5%. A fractured sample with a vertical fracture surface is shown in Fig. 8, and all the fracture parameters are obtained, as indicated in Tab. 2.

(a) (b)

Fig. 8 Fracture surface of overlay test sample

The results clearly indicate that the fracture energy can capture the change of the binder content between group 1 and group 2, because the binder content of group 1 is larger than that of group 2, and $G_{f,C}$ of group 1 is much greater than that of group 2. It well explains the influence of the binder content on post-peak behavior, which is related to the ductility of the asphalt mixture. Meanwhile, the results of eight fracture parameters of group 1 and group 3 are very close, so the variation of the new fracture test should be acceptable in spite of the fact that the fracture propagation zone is smaller than that other fracture tests, and the temperature which is not too low may be another reason for this result. In brief, the evaluation of the fracture test by the method of multi-parameters can indicate the differences of asphalt mixtures better.

Tab. 2 Fracture parameters of SMA by overlay test

Group	P_{a_1}/kN	ε_t	σ_t/kPa	E_t/MPa	a_1/mm	δ_{dis}	Fracture energy/(J · m^{-2})			
							$G_{f,A}$	$G_{f,B}$	$G_{f,C}$	G_f
1	3.265	0.139	1 117.02	8.05	0.278	0.11	182.86	662.15	64.72	909.73
2	3.018	0.117	1 022.07	8.71	0.235	0.13	132.92	640.95	9.03	782.89
3	3.295	0.156	1 160.14	7.45	0.311	0.12	217.39	653.14	80.18	950.72

5 Conclusion

The overlay tester is run at a loading rate of one cycle per 10 s with a fixed maximum opening displacement, and this paper presents the development of the overlay tester under the monotonic load by the AMPT. Since clear cracking can be seen during the overlay test at a temperature of 25 ℃ and the range of temperature controlled in the AMPT is 4 to 60 ℃, the test is carried out at a temperature of 10 ℃. With satisfactory preliminary work completed, a testing program is carried out to investigate the influence of the loading rate on the fracture test. To acquire a reasonable fracture behavior, 3 mm/min is considered as the loading rate of this test. Finally, three groups of SMA are used to examine the validity of the new fracture test, and eight parameters can show the differences in asphalt mixtures better.

It is impossible to fully discuss the AMPT overlay test in a single article, and other influencing factors for the test, such as temperature, dimension effects and depth of notch, should be briefly discussed. Besides, the evaluation of the multi-parameters method should be examined by not only SMA but also by other asphalt mixtures.

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基于改进型 overlay tester 沥青混合料的断裂试验

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摘要：为获得沥青混合料的断裂特性，改进了传统 overlay tester 试验的加载方式、试验模具和控制系统等，提出了在沥青混合料性能试验机（AMPT）上进行沥青混合料断裂试验的方法. 为验证该新型断裂试验方法的有效性，拟定了 1，2，3 和 4 mm/min 4 个断裂加载速率进行验证. 试验结果表明：在低速率加载条件下，沥青混合料呈现蠕变特征；在高速率加载条件下，沥青混合料断裂扩展特性不显著；在中间速率 3 mm/min 加载条件下，试验能够有效区分断裂的裂缝萌生、裂缝扩展和完全断裂的 3 个断裂过程. 此外，提出了断裂能、拉伸强度和拉伸模量等 8 个断裂参数评价沥青混合料的断裂特性. 改进后的 overlay tester 试验，为研究沥青混合料断裂特性提供了一个新的方法.

关键词：沥青混合料；断裂试验；overlay tester；沥青混合料性能试验机；断裂参数

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