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Determining Fracture Energy in Asphalt Mixture: A Review

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Abstract. One of the most common pavement distresses is related to surface cracking. Therefore, identifying and characterizing fracture properties of asphalt mixtures are significant towards a better pavement design. This study reviews four experimental methods used to determine the fracture energy in asphalt mixture. These methods include circular bending test (SCB), disc shape compact tension test, single-edge notched beam, and indirect tensile test. Each experimental method has its characteristics and advantages. These experimental methods are reviewed on the basis of their features, efficiency, and parameters measured. The coefficient of variation (COV) for the fracture tests reflects the result reliability of the test methods. Results with low COV value reflect low variance in the fracture test, whereas high COV indicates high variance. The review indicates that the SCB test is commonly used for determining the fracture energy in asphalt mixtures due to its simplicity and data reliability.

1. Introduction

Cracking issue in asphalt pavement is a major distress that can reduce its service life. Cracking initiation in asphalt mixture is mainly due to traffic loading (fatigue) and temperature impact particularly in cold weather, thereby leading to severe oxidation and moisture damage. To further investigate the cracking problem in asphalt mixture, researchers have performed numerous experimental tests on fracture mechanic particularly for crack resistance [1-3]. One of the most significant parameters in fracture mechanics for the evaluation of crack potential relies on fracture energy [4]. With the advancement of fracture mechanics, several laboratory tests on fracture energy of asphalt mixture have been developed, and then recognized as a standard procedure. However, no advanced experiments or single-fracture parameter is able to characterize asphalt mixture mechanism [5]. Providing standard testing procedures for the cracking assessment related to the mechanical parameters of a fracture obtained in the laboratory is challenging; this approach can reflect the in-service pavement quality [6]. The design of the test methods specifically dedicated to cracking properties has only begun in recent years when the existing asphalt mixtures have proven more susceptible to cracking than those mixtures optimized for better rutting resistance. Currently, several methods are commonly used to measure the cracking potential in asphalt mixture specified on the fracture energy (Gf). i.e., semi-circular bending test (SCB), disc-shape compact tension test (DCT), single-edge notched beam, and indirect tensile test (IDT). Therefore, this review could assist researchers and practitioners in the selection and improvement of the current applied methods for crack assessment.

2. Fracture energy

Fracture energy is an important material property. It is a measurement of material potential resistance against breakage. Fracture energy reflects the energy required to form a new fracture surface [7]. Moreover, it is measured by the ratio of work of fracture to the crack ligament area (thickness and ligament length of the specimen), where the work of fracture represents the area under the load– displacement curve (Figure. 1).

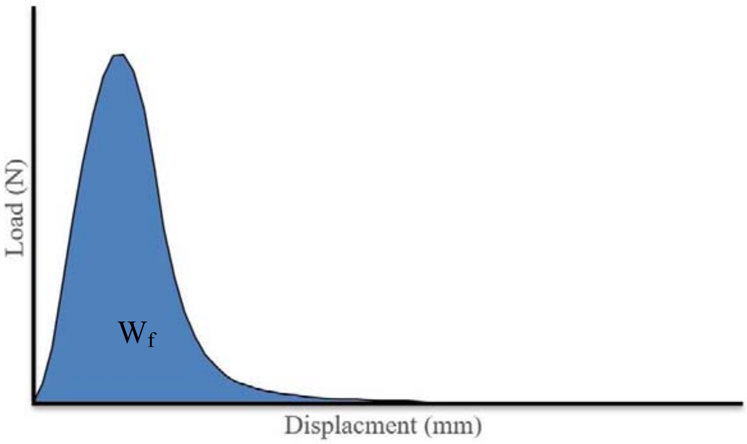


Figure 1. Load-Displacement Curve of Fracture Test

According to RILEM TC 50-FMC [8], the fracture energy G_f is calculated using Equations 1 - 3.

$$G_f = \frac{W_f}{A_{Lig}} \tag{1}$$

Where;

G_f = fracture energy (J/m^2), and
W_f = work of fracture (J),

$$W_f = \int_0^u P du \tag{2}$$

Where;

P = applied load (N),
u = load line displacement (m), and
A_{Lig} = ligament area (m_2)

$$A_{Lig} = (r - a) \times t \tag{3}$$

Where;

r = specimen radius (m),

a = notch length (m), and
t = specimen thickness (m).

3. Semi-Circular Bending Test

The SCB test, as shown in Figure 2, consists of a half-disk of compacted asphalt mixture with an initial notch (a) that is located at the center of the semicircular specimen. The figure also shows the stress distribution within the specimen under the applied loads. The fracture area of the SCB specimen is considered to have small fracture surface and short cracking path compared with IDT and DCT tests. This test method can either be performed using laboratory or cored field specimens. The specimen needs to be cut into two equal sections to produce two semicircular specimens. The top of the specimen is loaded vertically, and it is supported symmetrically by two rollers. Through the test, the crack notch starts to initiate in the tension zone and leads to a fracture of the specimen. Linear variable differential transformer (LVDT) and metal button on the test specimen can be used to measure the load point displacement. Furthermore, a clip-on gage (sensor gage) can be fixed at the bottom of the specimen to measure the crack mouth opening displacement (CMOD). The advantages of this test are as follows: the tests can be carried out on any loading devices typical in a compressive load strength of 10 kN. Initially, the SCB specimen geometry was used to evaluate the fractures of pre cracking rock materials with a sharp crack tip [9]. Subsequently, the SCB test was used by many researchers to investigate the fracture parameters of asphalt mixtures [10]. Its performance parameters, such as the fracture energy, peak load, and flexibility index are directly related to the fracture resistance of asphalt mixtures. These parameters were implemented by the Louisiana Department of Transportation, and then used by many highway departments [11].

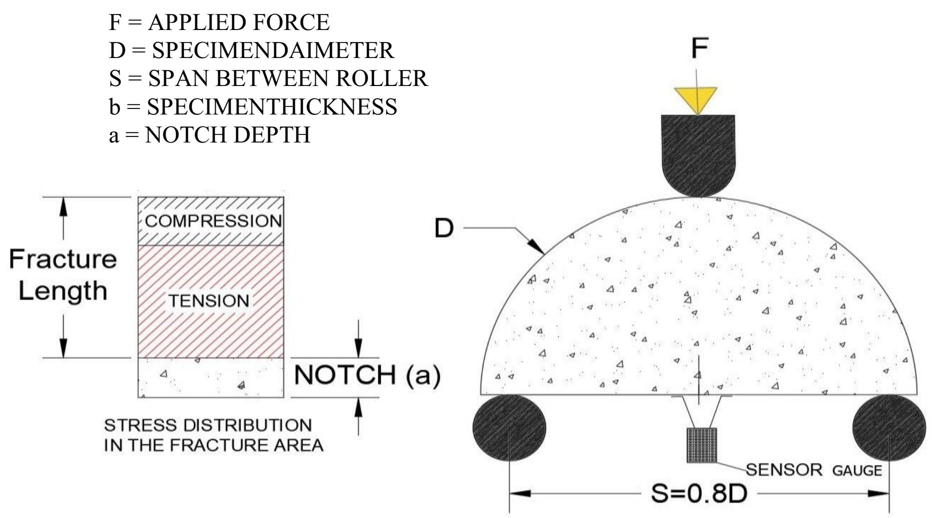


Figure 2. Semi-circular Bending Specimen

In a study performed by Li and Marasteanu [12], the SCB test was used to evaluate the fracture characteristics of different types of asphalt mixtures. The fracture energy according to the RILEM TC 50-FMC standard was used for evaluating the asphalt mixtures. The study evaluated the impact of different parameters including air voids, binder modification, binder type, test temperature, loading rates, and aggregate gradation. The study concluded that the SCB represents a repeatable fracture test for asphalt materials at low temperature. However, due to the fluctuation in the SCB fracture energy results, the coefficient of variation (COV) was higher than other alternative test methods. This finding is clearly shown in the result obtained by many researchers [13–18]. Despite the high COV, the test method is considered the most suitable for asphalt mixture specimens due to the simplicity of the testing machine and sampling [19]. The test method has been standardized and available as ASTM D8044-16 2016, [20].

4. Disk-shaped Compact Tension

The DCT is specified in ASTM D7313-13 [21]. The test method has been designed to determine the fracture energy of asphalt mixtures. Figure 3 shows the specimen geometry and the stress distribution of the DCT test. The fracture area of DCT is considered large and has longer crack path than that of the SCB test. The specimens of DCT can be fabricated from the laboratory-produced cylindrical specimen as well as specimens of standard cylindrical field cores. The test device applies tension force through the drilled holes, and the crack along the center of the specimen is propagated due to the tension force. The main geometric feature in DCT is the long crack path of the DCT specimen, which provides adequate time to analyze the crack propagation of asphalt mixtures in low-temperature testing condition [22]. The DCT test is favored over the SCB test, which has a short crack path, due to this feature. The disadvantage of DCT is the failure within the loading hole, thereby leading to the change in the initial notch length. Thus, the center of the specimen is increased. Wagoner [23] changed the position of the loading holes and proposed a new geometry by increasing the distance between the initial crack and holes. This approach prevents the failure of the loading holes under the applied loads. Past and recent works [22], [24–27] on the DCT specimen geometry have provided accurate and reliable load–CMOD curves and fracture energy values for asphalt mixtures at different test temperatures due to large fracture area compared with SCB test. This finding is supported by many researchers [23], [28–31] on the basis of the COV calculated on the fracture energy results.

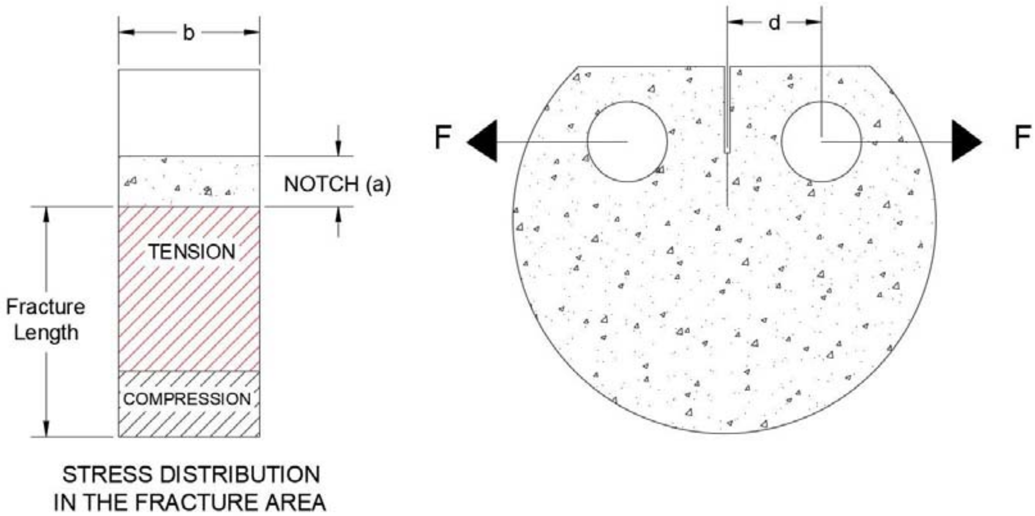


Figure 3. Disk-shaped Compact Tension Specimen

5.Single-edge Notched Beam

The SENB test is performed in accordance with ASTM E399 specification [32]. It can be carried out by applying three-point bending load on a beam specimen under various notch levels and temperatures. Figure 4 shows the setup of the three-point bending test and the stress distribution of the fracture region. The bearing span (S) is approximately 20 cm. Orginally, Majidizade et al. [33] effectively performed the SENB test in evaluating the fracture properties of asphalt mixtures.

Subsequently, a similar test was conducted by Little and Mahboub [34] in evaluating the impact of notch length and shape on the fracture energy of the binder samples. Mahboub [35] utilized SENB test in measuring the J-integral fracture energy of asphalt mixture. The test conducted by Mahboub [35] involved some modifications from ASTM E399 specification to suite the characteristics of asphalt mixture. In this study, electronic crack opening sensor was used to measure the crack length of the sample as the test was performed. Then, the SENB was applied on the asphalt mixture by different research works, such as Hoare [36], Petersen [37], and Chailleux, [38], to obtain the fracture properties. The SENB system was used to characterize fracture properties on various types of asphalt mixtures (modified and unmodified) under low temperature. The test method was widely used for determining the fracture energy of different types of asphalt mixture, loading rate, temperature, and sample dimension [39–41]. Furthermore, the results obtained by Petersen [37], Kim, [42], and Ding [39] showed that the COV of SENB fracture energy results is less than the SCB test results. The length of the crack path is significant for testing inhomogeneous ductile materials, such as the asphalt mixture [39].

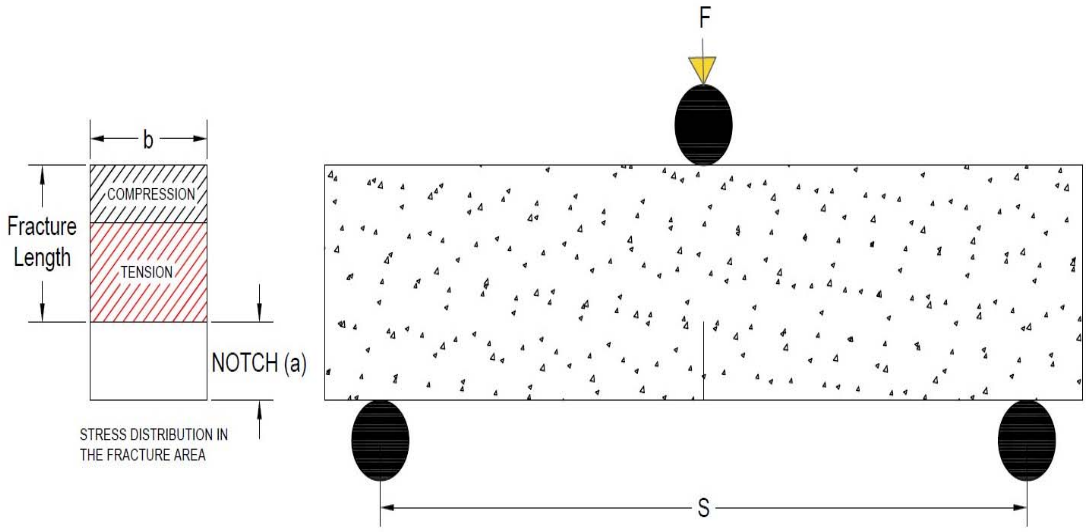


Figure 4. Single-Edge Notched Beam Specimen

6. Indirect Tensile Strength

The IDT is by far the most standard procedure generally used by most highway departments to determine the tensile strength of asphalt mixtures [43]. Figure 5 shows the loading frame and specimen geometry of the IDT, where the load is vertically applied at a constant rate. The figure illustrates that the tensile stress is directly proportional to the loading axis and eventually causes the specimen to break or crack in the vertical cross section. In addition, the white zone in the fracture area of the IDT exhibits large deformation during the test [44]. This deformation can cause high fluctuation in the IDT results and significantly affect the amount of energy needed to create the fracture. The fracture energy is the result of energy consumed in the plastic deformation and the energy consumed for creating a new fracture area, which can be determined using the vertical force and deformation [45], [46]. On the basis of the conceptual elasticity theory, the asphalt mixture specimen is considered homogeneous, isotropic and linear elastic. This theory applies a set of equal and diagonal loads (F) to develop a constant internal stress along the loaded diameter of the asphalt mixture specimen. The indirect tension test configuration has been designed with several good features on the basis of this theory. First, the use of compressive loading apparatus for determining the tensile strength of materials is more convenient than the direct tensile loading test. Then, the deformation of the specimen can be easily measured in one to three directions by using either one or two LVDTs in each direction. The apparatus can also be used with any existing loading frame, such as Marshall, unconfined, hydraulic system, and triaxle, which is available in most HMA testing laboratories. The simplicity and widespread availability of the IDT test equipment persuaded the researchers to develop other HMA tests with similar configurations, such as resilient modulus, IDT creep compliance, and IDT-repeated load fatigue test. The result has also shown that the triaxle shear strength of HMA can be correlated to its strength by applying the time–temperature superposition principles, and the results can be used to estimate the mixture cohesion [47,48]. Other researchers also indicate that the results from IDT strength test, IDT resilient modulus test, and IDT creep compliance tests can be used to estimate the dissipated creep strain energy of HMA and as an indicator for the top-down cracking potential of asphalt pavements.

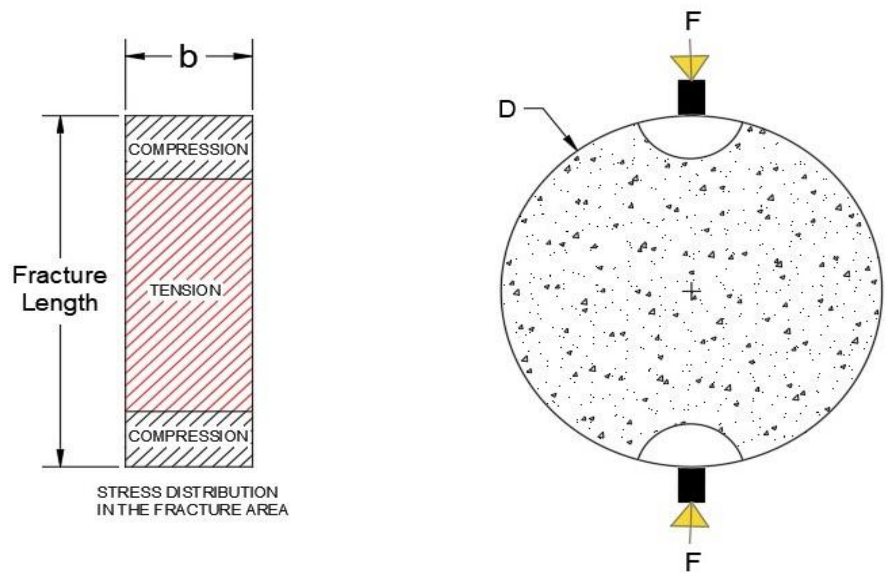
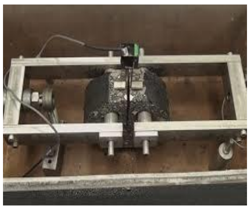


Figure 5. Indirect Tensile Loading Specimen

7. Comparison of Test Methods

The experimental fracture test, SCB, DCT, SENB, and IDT, several advantages, and disadvantages of each test method are reviewed. Each method has its preferred features and dimension that lead to different fracture energy results. The benefit of using SCB test method is its simplicity in conducting the test for samples prepared in the laboratory or extracted from the site. However, the disadvantage of this test is the stress complexity due to the curvature shape of the specimen. The SENB can conduct a mixed-mode fracture test (tensile and shear modes), the outcome of which is reflected in a simple stress distribution. The disadvantage of this test is its inability to conduct field core samples. The advantage of using DCT test is that it has a large sample, which provides long crack ligament that allows full characterization of crack propagation. However, this test requires complicated sample preparation along with the equipment setup particularly in highway laboratories. IDT has high fracture area and availability of test equipment in the highway laboratories. However, the disadvantage of IDT is its high deformation under the loading plate during the test, thereby leading to high variation in the test results. Table 1 illustrates the significant advantages and disadvantages related to each test method, depending on the discussed literature review.

Table 1. Methods of determining fracture parameters

Specimen Geometry	Advantages	Disadvantages	References
Semicircular Bending 	-Used by many researchers -Reliable test result -Ability to investigate mixed-mode fracture -Easy to fabricate from field cores -Standard ASTM test method for HMA	-Complicated stress distribution -Short crack length -Constraint for crack propagation to the top -Low-fracture surface area	[13], [36], [41-43]
Single-edge Notched Beam 	-Ability to investigate mixed-mode fracture -Simple specimen geometry -High fracture surface area	-Unsuitable for field cores -Constraint for crack propagation to the top	[34], [36], [44,45]
Disk-shaped Compact Tension 	-Suitable for field cores -High fracture surface area -Standard ASTM test method for HMA	-Failure around the loading holes -Complicated stress distribution -Requiring specific laboratory equipment's -Crack path deviation	[22], [44], [52]
Indirect Tensile Strength 	-Suitable for field cores -Standard ASTM test method for HMA -High-fracture surface area	-Crack path deviation -Complicated stress distribution -High deformation under the loading plate	[15], [44], [53], [54]

The variations of fracture energy are due to different specimen dimensions that affect the total energy consumed by the specimen weight and plastic deformation as a result of shape design in addition to the stress distribution throughout the specimen. Moreover, Figure 6 shows the COV of each test methods conducted by different researchers. The plot indicates that the least coefficient of variation in the data (fracture energy) analyzed is found for DCT method that shows better consistency in the results obtained compared with other test methods.

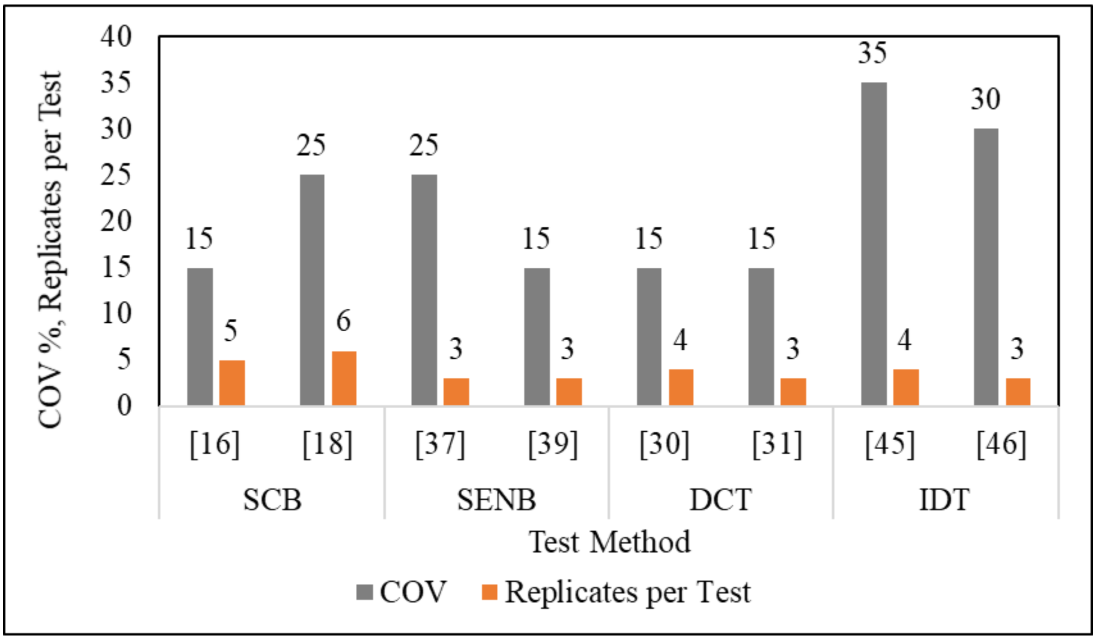


Figure 6. COV with replicates per test of fracture energy results obtained from different test methods

8. Conclusion

This review has concluded that the ITD test produces higher fracture energy than DCT, SENB, and SCB. The ITD test specimen preparation is the simplest among other methods given that the preparation does not require any cutting or gluing process. On the contrary, the DCT test has the lowest COV value for the fracture energy result followed by SENB, SCB, and ITD accordingly. The SCB fracture test is the most practical method due to the sensitivity of performance indicators under various test parameters in addition to the simplicity of the specimen preparation. In summary, fracture energy can be characterized by one of these test methods with different parameters and test limitations.

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