Comparison of fracture test standards for a super pave dense-graded hot mix asphalt

Calvin Maurice Stewart a,∗, Jesús Gerardo Reyes a, Victor M. Garcia b

a Department of Mechanical Engineering, The University of Texas at El Paso, United States
b Department of Civil Engineering, The University of Texas at El Paso, United States

Abstract

The objective of this work is to compare the semi-circular bend (SCB) and disk-compact tension (DCT) fracture tests for asphalt-aggregate mixtures. Fracture tests are performed. Statistical analysis, digital image correlation, and 3D scans show that the SCB tests measure a low fracture resistance with a high coefficient of variation due to stress concentrations and plasticity developing at the anvil contact point. The DCT test is found to measure a high fracture resistance with a low coefficient of variation. The DCT tests is determined to provide a superior measurement of fracture resistance. Evidence concerning the physical problems with SCB is provided.

Keywords:
Fracture resistance
Hot mix asphalt
Test standards
Digital image correlation
Repeatability

1. Introduction

The accumulation of cracks in HMA layers is often due to damage induced by repeated traffic loading and climatic effects: defined as fatigue cracking [1]. The cracking of HMA layers is one of the predominate forms of distress observed in flexible pavements, that significantly reduce service life [2]. An HMA overlay must have a balance of both good rut and crack resistance properties, to perform well in the field [3–5]. Over the past decade, HMA’s designed in Texas have been modified to minimize the deformation of roads and moisture susceptibility of new mixtures using the Hamburg rutting test. This test applies vertical deformation to a specimen simulating constant traffic loading. Less attention has been paid to the cracking resistance of the new HMA surfaces. Stiffer binders and good stone-to-stone contact may improve rut resistance but it may also reduce the mix flexibility and cracking resistance [3].

The pavement industry is moving towards physics-based computational models as opposed to data-founded models for life prediction. Experimental fracture mechanics has become the de facto choice of many scientists and researchers in this area to obtain physical measures of fracture resistance. Much effort has been directed towards the development of testing and analysis methods to study the cracking mechanisms of asphalt pavement [4–9]. To date, several performance tests have been proposed to determine the cracking resistance of HMAs such as the flexural fatigue, dissipated creep strain energy, indirect tension, Texas overlay, single-edge notch bend, disk-shaped compact tension (DCT), and semi-circular bend (SCB) tests [10]. So far, the definitive or best fracture test method to determine the cracking resistance of asphaltic materials has yet to be determined.
Hot mix asphalts exhibit a viscoelastic plastic response, where cracks tend to grow through the asphalt binder and along the asphalt-aggregate interfaces. This tortuous cracking process creates a large plastic zone that exceeds the small-scale plasticity limitation of the linear elastic fracture mechanics (LEFM) approach. The fracture toughness $K_{IC}$ has continued to be used to analyze the fracture resistance of HMAs despite the deficits of LEFM [11–15]. The LEFM approach is assumed reasonable if the test temperature is $10^\circ C$ below the performance grade lower limit of the asphalt binder and the modulus changes less than 5% for the duration of the test. These conditions are rarely met. In practice HMAs are subjected to a wider temperature range. As an alternative, elastic-plastic fracture mechanics (EPFM) has been introduced to measure the fracture resistance of HMAs. In EPFM, fracture resistance is measured using the energy of fracture (i.e. the energy required to open a crack).

The EPFM-based DCT and SCB tests have been identified as two of the most popular approaches to fracture resistance measurement of HMAs [16]. The prevalence of SCB testing stems from its simplicity, repeatability, and consistency [9]. Recent studies by the Louisiana Transportation Research Center have shown that the SCB test is promising in evaluating the cracking resistance of HMAs [7]. They concluded that specimens with a pre-fabricated notch are more suitable at measuring the cracking properties of asphalt mixtures. The SCB test exhibits certain advantages as a cracking resistance predictor:

(a) different notch depths, notch orientations, and specimen positioning can be introduced; hence, mixed-mode fracture properties can be evaluated directly;
(b) the test setup and procedure are fairly simple and rapid;
(c) the SCB specimens can be prepared directly from cylindrical samples obtained from standard cores prepared in a superpave gyratory compactor or can be taken from field cores; and
(d) multiple specimens can be obtained from one field core, reducing the error caused by the heterogeneity among cores [17].

The main disadvantages of the SCB test is that it is susceptible to operator error where a small misalignment of the specimen will lead to mixed-mode fracture and fracture resistance measurements can exhibit low repeatability. The DCT test exhibits certain advantages as a cracking resistance predictor:

(a) according to the National Cooperative Highway Research Program, the DCT test often produces the lowest coefficient of variation (COV) of all HMA fracture tests with a COV in the 10–15% range [18];
(b) the DCT test provides a larger fracture area which is important because it reduces the impact that a single large aggregate or zone of weakness might have on the overall fracture resistance of the HMA [19];
(c) a specimen can be prepared directly from a cylindrical sample obtained from standard cores prepared in a superpave gyratory compactor or can be taken from field cores.

The main disadvantage of the DCT test is that it is more laborious to machine DCT specimen in comparison to other standard geometry.

Dense grade super-paves (SP-Ds) have aggregate size distributions that provide a high degree of compaction resulting in higher fatigue and fracture strength [20]. Chen and Huang conducted indirect tension tests on a SP-D mixture and observed that the average tensile strength is 1.08 MPa with variability of 0.1 MPa. Increasing the coarse aggregate angularity from zero to one hundred percent reduced the tensile strength of SP-D [21]. Wu and colleagues conducted SCB tests on thirteen SP-D mixtures at room temperature (25°C). The SP-Ds with lower tensile strength offer higher fracture resistance and vice versa (from 0.57 to 1.53 kJ m⁻²). Kim and colleagues conducted a DCT-based study on the effect of the constituents on the fracture energy of twenty-eight HMAs at 2°C below, 10°C above, and 22°C above the lower temperature grade. It was concluded that the binder, air void content, and dominant aggregate type have a large influence on the fracture energy values calculated at high temperature, but not at mid or low temperature [12]. A review of literature finds that few studies that compare and contrast the accuracy and repeatability of SCB and DCT test standards for HMAs have been performed.

In this study, the room temperature fracture resistance of a SP-D HMA is evaluated using two competing SCB test standards and a DCT test standard. The AASHTO TP105 standard for SCB is performed using ten specimens with the standard notch depth (24 ± 1.5 mm) to calculate the fracture energy, \( G_f \) and fracture toughness, \( K_{IC} \) [22]. The provisional AASHTO TPXXX standard for SCB is performed using five repetitions of three specimens with different notch depths (24, 30, 36 ± 1.5 mm) to calculate the critical energy release rate, \( J_c \) [23]. The ASTM D7313 standard for DCT is performed using four specimens with a standard notch depth (62.5 ± 2.5 mm) to calculate the fracture energy, \( G_f \) [24]. The fracture resistance parameters of SCB and DCT standards are compared. The digital image correlation (DIC) technique is employed to analyze the strain field near the crack tip. Fracture area analysis using a 3D scanner is performed to compare the fracture area resulting from SCB and DCT tests.

2. Materials and test methods

2.1. Material

A dense-grade superpave (SP-D) hot mix asphalt (HMA) is the subject material. The material was sourced in Abilene, TX and transported to the UTEP Center for Transportation Infrastructure Systems for specimen preparation. The properties of the SP-D are summarized in Table 1. The gradation of the SP-D mix is depicted in Fig. 1. The typical distribution of the aggregates, mastic, and binder in the SP-D mix is shown in Fig. 2.

2.2. Specimen preparation

The SCB and DCT specimens are trimmed from standard 150 mm diameter by 114 mm thick briquettes compacted with a superpave gyratory compactor in accordance with AASHTO T312 (ASTM D6925) [13,14]. After the briquette reaches room temperature, a disk shape specimen is trimmed from the middle of the briquette and the disk is quality checked for an air-void percentage (AV%) target of 7 ± 1.0%. A typical disk specimen is shown in Fig. 2a. Two SCB specimens as depicted in Fig. 2b can be extracted from a disk. One DCT specimen as depicted in Fig. 2c can be extracted from a disk. A schematic and dimensions of the SCB and DCT specimens is provided in Fig. 3a and b respectively.

2.3. Mechanical test equipment

The SCB and DCT tests were conducted using an INSTRON 5969 Table-Top Universal Test System. This electromechanical frame is capable of 0.001–600 mm/min displacement rates and equipped with a 50 kN load cell. The data captured from the
INSTRON machine during tests included time, load, and load-line displacement. Specimens were exposed to the laboratory room temperature of 27 °C during testing.

2.4. Semi-Circular Bend (SCB) test

The AASHSTO TP105 and provisional AASHSTO TPXXX test standards for SCB specimen are based on the calculation of the fracture energy, \( G_f \) and critical strain energy release rate, \( J_c \) respectively [22,23]. It is important to note that both quantities \( G_f \) and \( J_c \) are equal representations of the critical J-integral. The \( G_f \) represents the single specimen method proposed by Rice [25] while \( J_c \) represents the multiple specimen method proposed by Begley and Landes [26]. The different nomenclature is due to inconsistency in the test standards.

A schematic of the test setup for SCB testing is shown in Fig. 3a. For both SCB standards, the specimen is mounted into a three-point bending fixture and subjected to compressive displacement. The three-point bend fixture consists of a top loading anvil and two support anvils under the specimen with a diameter of 5 mm. No seating load is applied to the specimen; however, the anvil is placed into neutral contact with the specimen just before testing. Tests are performed with a constant displacement rate of 5 mm/min at a room temperature of 27 °C. The test is stopped once the specimen has completely fractured.

2.4.1. AASHTO TP105

The AASHTO TP105 SCB standard calculates the fracture energy, \( G_f \) using the single-specimen geometry-specific solution for the \( J_c \) of a three-point bending specimen originally proposed by Rice and adopted by RILEM TC 50-FMC [22,25,27]. The fracture energy, \( G_f \) is a fracture mechanics concept that represents the amount of energy required to create a unit surface area of a crack. The fracture energy is obtained using the work of fracture, \( W_f \) (total area under the load versus load-line displacement curve) depicted in Fig. 4a. The fracture energy, \( G_f \) is computed as follows

![Fig. 1. Gradation of aggregates in SP-D HMA.](image1)

![Fig. 2. SP-D HMA specimen (a) disk, (b) SCB, and (c) DCT.](image2)
\[ G_f = \frac{W_f}{A_{\text{lig}}} \quad A_{\text{lig}} = (r - a)b \]  

where \( G_f \) is the fracture energy (kJ m\(^{-2}\)), \( W_f \) is the work of fracture (J), \( A_{\text{lig}} \) is the ligament area (mm\(^2\)), \( r \) is the specimen’s radius (mm), \( a \) is the notch depth (mm), and \( b \) is the specimen thickness (mm). It should be noted that a unit conversion is needed to calculate \( G_f \) using the given units.

The AASHTO TP105 standard also provides a procedure for calculating the fracture toughness, \( K_{IC} \) (MPa m\(^{0.5}\)) \[22\]. The fracture toughness, \( K_{IC} \) is defined as the stress intensity factor corresponding to the initiation of the crack. Fracture toughness, \( K_{IC} \) is computed as follows

\[ K_{IC} = \sigma_0 \sqrt{\pi a} \]  

where \( Y_{I(0.8)} \) is the dimensionless geometric factor, \( \sigma_0 \) is the applied stress, and \( a \) is the notch depth. The applied stress is calculated as \( \sigma_0 = P_{\text{max}}/2\pi r \) where \( P_{\text{max}} \) is the peak load, and \( r \) and \( t \) are the specimen radius and thickness respectively. The dimensionless geometric factor, \( Y_{I(0.8)} \) is calculated using the following

\[ Y_{I(0.8)} = 4.782 + 1.219 \left( \frac{a}{r} \right) + 0.063 \exp \left[ 7.045 \left( \frac{a}{r} \right) \right] \]  

where \( a \) is the notch depth (mm) and \( r \) is the specimen’s radius (mm) \[28,29\].

2.4.2. AASHTO TPXXX

The provisional AASHTO TPXXX SCB standard calculates the critical strain energy release rate, \( J_c \), using the non-geometry specific solution to determine \( J_c \) \[26,32\]. This method requires multiple specimens to calculate \( J_c \) as proposed by Begley and Landes \[26\]. The critical strain energy release rate is obtained by determining the change in strain energy to failure, \( U \) with respect to notch depth, \( a \). The strain energy to failure, \( U \) is calculated as the strain energy up to the peak load as depicted in Fig. 4b. The critical strain energy release rate, \( J_c \) is computed as follows

\[ J_c = -\left( \frac{1}{b} \right) \frac{dU}{da} \]  

(a) SCB and (b) DCT specimen.

(a) (b) Displacement, \( u \)

Force, \( F \)

Force, \( F \)

Displacement, \( u \)

Fig. 3. Schematic and dimensions of (a) SCB and (b) DCT specimen.

Fig. 4. Strain energy measurement for SCB and DCT (a) \( G_f \) and SCB (b) \( J_c \).
where \( b \) is the thickness (mm), \( a \) is the notch depth (mm), \( U \) is the strain energy to failure (J), and \( dU/da \) is the change of strain energy with notch depth (kN). It should be noted that a unit conversion is needed to calculate \( J_c \) using the given units.

### 2.5. Disk-Shaped Compact Tension (DCT) test

The ASTM D7313 DCT standard calculates the fracture energy, \( G_f \) using a single-specimen geometry-specific solution [24]. A schematic and dimensions of a DCT specimen is shown in Fig. 3b. A seating load of 0.2 kN (45 lbf) is applied. Tests are performed with a constant crack mouth opening displacement of 0.017 mm/s at a room temperature of 27 °C. The test is stopped when the post-peak load drops by 22 lbf. The fracture energy, \( G_f \) for DCT is calculated similar to (Eq. (1)) for SCB as follows

\[
G_f = \frac{W_f}{B \cdot (W - a)}
\]

(5)

where \( W_f \) is the work of fracture (J) depicted in Fig. 4a, \( B \) is the thickness (mm), and \( (W - a) \) is the initial ligament length (mm).

### 2.6. 3D digital image correlation

Three-dimensional digital image correlation (3D DIC) is performed using a Correlated Solutions VIC-3D DIC system. Using the VIC-3D software, the surface displacements \((u, v, w)\) can be captured. These displacements are then processed to calculate the strain vector and principal strain. Before correlation, photos of a calibration square are taken to provide a physical reference of pixel distances. Next, specimens are primed with a randomly applied speckle pattern and inserted into the test frame. The speckles act as reference points. Tunable LED lights are focused on the specimen to increase the contrast of captured photographs and subsequently increase the accuracy of digital image correlation.

### 2.7. 3D surface scanning

The fractured specimen are 3D scanned to produce a 3D CAD replication of the fracture surface using a Makerbot Digitizer 3D Scanner. The scanner has a nominal dimensional accuracy of ±2 mm and detail resolution of 0.5 mm. This device uses two lasers and a rotating platform to generate a 3D dimensional replication of the surface of 3D objects. The Makerware software, exports a stereo lithography format file (.STL). The AutoDesk MeshMixer software is employed to analyze the physical features of the 3-D .STL files. The 3D scanner and software introduce error into the fracture area measurement; however, considering the size of the available fracture area (in all cases >2500 mm²) and resolution of the 3D scanner (0.5 mm) it is determined that this error will not have a significant impact on the fracture area recorded.

### 3. Results and discussion

#### 3.1. SCB - AASHTO TP105

The AASHTO TP105 SCB test method was performed on ten 24 mm specimens to measure the fracture energy, \( G_f \) and fracture toughness, \( K_{IC} \). The average load versus load-line displacement curve of the ten SCB specimens is depicted in Fig. 5. Error bars of one standard deviation were added to illustrate the repeatability of the tests. The error bars increase with strain after the peak load has been reached. This indicates decrease repeatability post the peak load.

The resulting fracture energy and toughness calculated using AASHTO TP105 are summarized in Table 2. The average peak load, work of fracture, fracture energy, and fracture toughness were calculated as 1400 N, 1.57 J, 0.595 kJ m⁻², and 0.287 MPa m⁰.₅ respectively. Fracture toughness, \( K_{IC} \) presented the lowest COV value at 12.7% while the COV of fracture energy, \( G_f \) is relatively high at 26.9%. Applying one standard deviation, the fracture energy, \( G_f \) should vary between 0.435–0.755 kJ m⁻². These results are comparable to those established by Wu and colleagues for thirteen superpave mixtures, with the room temperature SCB-calculated fracture energy, \( G_f \) ranging from 0.57 to 1.53 kJ m⁻² [9].

#### 3.2. SCB - AASHTO TPXXX

The provisional AASHTO TPXXX SCB test method was performed using three notch depths (24, 30, 36 ± 1.5 mm). The test for each notch depth was repeated five times to assess repeatability. The strain energy to failure, \( U \) was calculated for all specimen (see Fig. 4b) and plotted against the notch depth to compute the change of strain energy, \( dU/da \). The resulting plot is depicted in Fig. 6. A linear function used to determine the change of strain energy, produced a low coefficient of determination, \( R^2 \) of 0.186. This low value indicates significant scatter in the experiments. The supporting parameters to determine the critical strain energy release rate, \( J_c \) are summarized in Table 3. The \( J_c \) was calculated as 0.593 kJ m⁻². This value compares well to the room temperature SCB-calculated \( J_c \) of a control superpave obtained by Mull and colleagues at 0.540 kJ m⁻² [14].
3.3. DCT - ASTM D7313

The ASTM D7313 DCT test method was performed on four 62.5 mm notched specimens to measure the fracture energy, \( G_f \). The average load versus load-line displacement curve of the four SCB specimens is depicted in Fig. 7. Error bars of one standard deviation were added to illustrate the repeatability of the tests. The error bars decrease after the peak load has been reached suggesting good repeatability.

The resulting fracture energy, \( G_f \) calculated using ASTM D7313 are summarized in Table 4. The average peak load, work of fracture, and fracture energy are 632 N, 3.37 J, and 0.805 kJ m\(^2\) respectively. The fracture energy, \( G_f \) has a low COV of 13.3%.

Applying one standard deviation, the fracture energy, \( G_f \) should vary between 0.698 and 0.912 kJ m\(^2\).

3.4. Comparison of fracture resistance parameters

3.4.1. SCB (AASHTO TP105) versus SCB (AASHTO TPXXX)

A comparison of the fracture resistance parameters of the two SCB standards is provided in Fig. 8. The average fracture energy, \( G_f \) using AASHSTO TP105 and the critical strain energy release rate \( J_c \) using AASHSTO TPXXX are almost identical at 0.595 and 0.593 kJ m\(^2\) respectively; an absolute difference of only 0.34%. The TP105 calculated fracture toughness, \( K_{IC} \) yields the lowest COV at 13% while \( G_f \) is much higher at 26.9%. A COV cannot be assigned to the TPXXX calculated \( J_c \) due to the way that \( J_c \) is measured; however, the COV of the strain energy to failure, \( U \) for the 24, 30, and 36 mm notched specimens are 14.9%, 31.9%, and 38.6% respectively. This expanding COV indicates decreasing repeatability as the available fracture area

<table>
<thead>
<tr>
<th>Specimen name</th>
<th>AV%</th>
<th>Notch depth, ( a ) (mm)</th>
<th>Peak load, ( P_{max} ) (N)</th>
<th>Work of fracture, ( W_f ) (J)</th>
<th>Fracture energy, ( G_f ) (kJ m(^2))</th>
<th>Fracture toughness, ( K_{IC} ) (MPa m(^{0.5}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>11A</td>
<td>6.5</td>
<td>24</td>
<td>1259</td>
<td>1.32</td>
<td>0.499</td>
<td>0.257</td>
</tr>
<tr>
<td>11B</td>
<td>7.0</td>
<td>24</td>
<td>1572</td>
<td>1.90</td>
<td>0.717</td>
<td>0.320</td>
</tr>
<tr>
<td>12A</td>
<td>7.1</td>
<td>24.4</td>
<td>1184</td>
<td>1.05</td>
<td>0.398</td>
<td>0.244</td>
</tr>
<tr>
<td>12B</td>
<td>7.2</td>
<td>22.9</td>
<td>1308</td>
<td>1.36</td>
<td>0.502</td>
<td>0.257</td>
</tr>
<tr>
<td>13A</td>
<td>7.3</td>
<td>25.4</td>
<td>1394</td>
<td>1.28</td>
<td>0.497</td>
<td>0.297</td>
</tr>
<tr>
<td>13B</td>
<td>7.3</td>
<td>24.1</td>
<td>1488</td>
<td>1.62</td>
<td>0.614</td>
<td>0.304</td>
</tr>
<tr>
<td>14A</td>
<td>7.5</td>
<td>24.1</td>
<td>1516</td>
<td>1.56</td>
<td>0.591</td>
<td>0.310</td>
</tr>
<tr>
<td>14B</td>
<td>7.5</td>
<td>24.1</td>
<td>1716</td>
<td>2.38</td>
<td>0.898</td>
<td>0.351</td>
</tr>
<tr>
<td>15A</td>
<td>8.0</td>
<td>24.5</td>
<td>1157</td>
<td>1.18</td>
<td>0.451</td>
<td>0.240</td>
</tr>
<tr>
<td>15B</td>
<td>7.8</td>
<td>24</td>
<td>1408</td>
<td>2.09</td>
<td>0.786</td>
<td>0.287</td>
</tr>
<tr>
<td>Average</td>
<td>7.3</td>
<td>24</td>
<td>1400</td>
<td>1.57</td>
<td>0.595</td>
<td>0.287</td>
</tr>
<tr>
<td>St. dev.</td>
<td>0.4</td>
<td>1</td>
<td>178</td>
<td>0.43</td>
<td>0.160</td>
<td>0.037</td>
</tr>
<tr>
<td>COV %</td>
<td>5.8%</td>
<td>2.5%</td>
<td>12.7%</td>
<td>26.9%</td>
<td>26.9%</td>
<td>12.7%</td>
</tr>
</tbody>
</table>

Fig. 5. Average load-displacement curve for 24 ± 1.5 mm SCB specimens according to AASHTO TP105.
decreases. The average COV of strain energy to failure, 28.5%, is only slightly larger than the COV of $G_f$ at 26.9%. Overall, the standards present high accuracy (relative to each other) but low precision, high COV, measures of fracture resistance. A large population of specimens is required to arrive at a statistically significant measure of fracture resistance. While TP105 offers a method to calculate $K_{IC}$, and $K_{IC}$ exhibits a low COV, the use of $K_{IC}$ is not reasonable for most service temperatures (above 10°C of the performance grade lower limit) [22].

The established TP105 test method appears to be the more promising SCB standard when the following advantages are considered.

- The fracture toughness, $K_{IC}$ and energy, $G_f$ are calculated for each specimen and thus less tests are required to produce a statistically significant measure of fracture resistance.
- A single notch depth is required for the fracture toughness $K_{IC}$ and energy $G_f$ calculations.

3.4.2. SCB (AASHTO TP105) versus DCT (ASTM D7313)

A comparison of the fracture energy, $G_f$ calculated using SCB and DCT is provided in Fig. 8. The SCB approach produced an average $G_f$ of 0.595 kJ m$^{-2}$ with a COV of 27% while the DCT approach produced an average $G_f$ of 0.805 kJ m$^{-2}$ with a COV of 13.3%. Comparing the load versus displacement curves for each standard (Figs. 5 and 7) it is observed that the peak load experienced in SCB is more than double that of DCT while DCT experienced more than double the elongation of SCB.

![Fig. 6. Strain energy to failure vs notch depth plot according to provisional AASHTO TPXXX.](image)

<table>
<thead>
<tr>
<th>Notch</th>
<th>Specimen name</th>
<th>AV %</th>
<th>Notch depth, $a$ (mm)</th>
<th>Peak load, $P_{max}$ (N)</th>
<th>Strain energy to failure, $U$ (J)</th>
<th>Change of strain energy, $dU/da$ (kJ)</th>
<th>Critical strain energy release rate, $J_c$ (kJ m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 ± 1.5 mm</td>
<td>11A</td>
<td>6.5</td>
<td>24.00</td>
<td>1259</td>
<td>1.324</td>
<td>-0.0301</td>
<td>0.593</td>
</tr>
<tr>
<td></td>
<td>12A</td>
<td>7.1</td>
<td>24.40</td>
<td>1184</td>
<td>1.046</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13A</td>
<td>7.3</td>
<td>25.40</td>
<td>1394</td>
<td>1.283</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14A</td>
<td>7.5</td>
<td>24.10</td>
<td>1516</td>
<td>1.564</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15A</td>
<td>8.0</td>
<td>24.50</td>
<td>1157</td>
<td>1.183</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 ± 1.5 mm</td>
<td>18A</td>
<td>7.5</td>
<td>30.20</td>
<td>1624</td>
<td>1.731</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18B</td>
<td>7.6</td>
<td>31.00</td>
<td>1499</td>
<td>1.453</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20A</td>
<td>7.4</td>
<td>30.00</td>
<td>1571</td>
<td>1.493</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>22B</td>
<td>7.8</td>
<td>31.00</td>
<td>1029</td>
<td>0.966</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25A</td>
<td>7.5</td>
<td>31.00</td>
<td>1018</td>
<td>0.744</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36 ± 1.5 mm</td>
<td>25B</td>
<td>7.2</td>
<td>37.00</td>
<td>1475</td>
<td>1.254</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>26A</td>
<td>7.6</td>
<td>36.10</td>
<td>1047</td>
<td>0.864</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>26B</td>
<td>6.2</td>
<td>36.00</td>
<td>1315</td>
<td>1.362</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27A</td>
<td>7.2</td>
<td>36.50</td>
<td>771</td>
<td>0.600</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27B</td>
<td>7.4</td>
<td>36.00</td>
<td>731</td>
<td>0.589</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Examining the tabular value for the work of fracture, \( W_f \) (Tables 2 and 4), it is observed that the \( W_f \) of DCT is 114% larger and carries half the COV of SCB. Possible sources for the large COV of SCB are:

- stress concentrations and plasticity developing at the anvil contact points;
- misalignment of the specimen, resulting in an otherwise asymmetrical loading setup;
- aggregates (of varying shape and size) along the fracture area acting as obstacles or accelerants to fracture, increasing or decreasing the fracture resistance;

It is hypothesized that the former and later are the primary cause of variation and these variations decrease as the available fracture area increases. Hot mix asphalts are an inherently heterogenous and uncertain material. A rule of thumb for transportation materials is that the coefficient of variation of mechanical properties must be below 15%; however, some researchers have stated up to 25% is acceptable [30]. The ASTM D7313 DCT tests standard defines the COV limit for fracture energy at 15.7%. The two AASHTO standards do not provide any information concerning COV limits. In literature, COVs much larger than 15.7% are routinely reported [30,31]. Composition (particle size, particle properties, air void content, etc.), moisture, and test temperature can have a significant impact on the repeatability of measurements. For the given test conditions, the ASTM D7313 DCT test method is the most reliable approach to measure fracture resistance. The DCT approach exhibits a low COV such that a smaller test matrix can be used to obtain statistically significant fracture resistance measures.

3.5. Digital image correlation

Three-dimensional DIC was performed on a 24 mm SCB and 62.5 mm DCT specimen respectively. Contours of the opening strain are provided in Fig. 9. The opening strain contours where collected near 80% of the peak load before crack initiation was observed. In both specimen, strain concentrations are observed. Strain concentrations correlate to the presence of stress concentrations. These concentrations indicate the possible crack initiation sites as well as identify the state of tension or compression in the specimen.

<table>
<thead>
<tr>
<th>Specimen name</th>
<th>AV%</th>
<th>Peak load, ( P_{\text{max}} ) (N)</th>
<th>Work of fracture, ( W_f ) (J)</th>
<th>Fracture energy, ( G_f ) (kJ m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D</td>
<td>6.2</td>
<td>691.06</td>
<td>2.923</td>
<td>0.698</td>
</tr>
<tr>
<td>5D</td>
<td>6.5</td>
<td>653.46</td>
<td>3.984</td>
<td>0.951</td>
</tr>
<tr>
<td>7D</td>
<td>6.7</td>
<td>643.30</td>
<td>3.359</td>
<td>0.802</td>
</tr>
<tr>
<td>10D</td>
<td>6.1</td>
<td>541.08</td>
<td>3.213</td>
<td>0.767</td>
</tr>
<tr>
<td>Average</td>
<td>6.38</td>
<td>632.22</td>
<td>3.370</td>
<td>0.805</td>
</tr>
<tr>
<td>STD</td>
<td>0.28</td>
<td>64.14</td>
<td>0.448</td>
<td>0.107</td>
</tr>
<tr>
<td>COV %</td>
<td>4.3%</td>
<td>9.1%</td>
<td>13.3%</td>
<td>13.3%</td>
</tr>
</tbody>
</table>

Fig. 7. Average load-displacement curve for the DCT specimens according to ASTM D7313.
For the SCB specimen, strain concentrations are observed at both the notch tip as well as the loading anvil with the magnitude at the notch tip being only 29% larger than that at the loading anvil. This suggests that plasticity could develop at the anvil contact point during cracking. As the crack propagates, the compressive field at the anvil will interact with the tensile field at the crack tip and negatively impact the work of fracture, \( W_f \), in the cracking zone. Due to the size of the SCB specimen, the intensity of the strain concentration is highly dependent on the aggregates near the notch tip and anvil contact point. The strain concentration variation contributes to the high coefficient of variation observed in the calculated fracture energy, \( G_f \).

For the DCT specimen, strain concentrations are observed at the notch tip as well as the back edge of the specimen with the magnitude at the notch tip being 350% larger than that on the back edge of the specimen. The concentration at the notch tip will dominate the cracking response of the specimen. The concentration at the back edge of the specimen is not expected to negatively impact fracture energy calculations.

Overall, it is determined that the SCB specimens are susceptible to a large strain concentration at the anvil contact point.

### 3.6. Three-dimensional fracture area analysis

Three-dimensional scans of a 24 mm SCB and 62.5 mm DCT specimen were performed. Measurements of both the male and female fracture areas for each specimen were recorded. Only the 24 mm SCB specimen was scanned because it represents the best-case scenario with the largest fracture area of the three available SCB specimen notch depths.

A graphical depiction of the ideal versus actual fracture surface of male SCB and DCT specimen are provided in Fig. 10. The ideal fracture area is considered the area available for fracture if a planar crack is formed along the ligament. The ideal frac-
ture area is equal to the distance from the crack tip to the edge of the specimen multiplied by specimen thickness. For the 24 mm SCB and 62.5 mm DCT specimen, the ideal fracture area is equal to 2590.8 and 4191 mm$^2$ respectively such that the ideal fracture area of the DCT specimen is 61.8% larger than the SCB specimen.

The actual fracture area of the SCB and DCT specimen are depicted as 3D scans in Fig. 10b and d. In both specimen, crack initiation occurs at the notch tip and propagates towards the far edge of the specimen. During propagation, the crack grows through the binder around the heterogeneously disturbed aggregates leading to a rough fracture surface. A fast fracture region is absent in the SCB specimen while for the DCT specimen it is almost equivalent in ligament length to the propagation region. The presence of the fast fracture region is important in fracture testing. The fast fracture region indicates that the fracture energy, $G_f$ or critical strain energy release rate, $J_c$ has truly been exceeded in the specimen and the remaining area available for fracture offers little resistance to rupture. A lack of the fast fracture region means that plasticity (or general yielding) is the main driving forces behind crack propagation and the specimen continues to offer resistance to fracture up to cleavage.

Slight non-planar cracking is observed in the fast fracture region of the DCT specimen shown in Fig. 10d. Non-planar cracking is often reported in bituminous mixtures. While the ASTM D7313 for DCT does not mention the limits for non-planar cracking, the European Standard EN 12697-44 for SCB states that a test is valid as long as the crack ends in a zone 10% of the diameter from the center of the load line [33]. This forms a 13$^\circ$ right triangle along the ligament length. For the DCT geometry, this would allow a 19 mm crack offset before the test is declared invalid. The definition of the valid zone is necessary to mitigate high COVs. The number of invalid tests increases with nominal aggregate size. A cause of these variations are instances where the notch is cut into large hard aggregate particles. The notch embedded in a particle will alter the overall fracture resistance of the specimen. The DCT specimen depicted in Fig. 10d is valid.

Measurements of the actual fracture area for male and female pieces are provided in Fig. 11. Overall, the actual fracture area is much larger than the idea as indicated by the absolute differences in Fig. 11. The actual fracture area of male and
female pieces for both the SCB and DCT specimen are not equal. The difference in fracture area of male and female pieces could be due to different magnitudes of elastic recovery, plastic deformation, and aggregate spallation.

It is hypothesized that the number and size of individual aggregates can have a significant impact on the average fracture resistance and COV measured in fracture tests. This can be illustrated using a schematic of the SCB and DCT specimen with representative aggregates as shown in Fig. 12. For SCB specimens as shown in Fig. 12a, the ratio between the average aggregate size and fracture area is high such that the number of aggregates acting as obstacles to crack propagation is low. For DCT specimens as shown in Fig. 12b, the ratio between the average aggregate size and the fracture area is low such that the number of aggregates acting as obstacles to crack propagation is high. By lowering the ratio between average aggregate size and fracture area, the influence of individual aggregates is minimized. Essentially, a higher fracture area will improve the average fracture resistance and COV since the fracture resistance measured will come closer to that of a homogenous representative volume element (RVE). Currently, the fracture area available in the SCB specimen is inadequate. Nondestructive measurement of the average aggregate size of each SCB and DCT specimen followed by fracture testing could provide the preponderance of evidence necessary to prove this hypothesis. For asphaltic materials there are no established specimen size empirical equations for fracture testing similar to those for metallic materials as described in ASTM E399 [34]. An empirical study to determine these equations would increase the scientific rigor of the established testing methods.

4. Conclusions

During this study, the room temperature fracture resistance of a dense-grade superpave HMA material was evaluated using two SCB test standards and a DCT test standard. A comparative analysis of the statistics of fracture resistance parameters, 3D-DIC strain field at the crack tip, and fracture surface using a 3D scanner was performed to determine the most physically realistic and repeatable test standard. The following can be concluded.

Regarding SCB:

- The SCB fracture energy standard (AASHTO TP105) is found to be superior to the provisional critical strain energy release rate standard (AASHTO TPXXX-15) with the former requiring less specimen and providing a COV for repeatability analysis.
- Overall, the SCB tests produced a low average fracture energy with a high COV when compared to DCT.
- The SCB specimen geometry offers a small fracture area. The work of fracture COV increases as the available fracture area decreases. It is hypothesized that the average aggregate size relative to the available fracture area is not ideal in SCB specimen. The fracture area enlarged if the influence of individual aggregates is to minimized.
- The 3D-DIC strain contours of SCB show that the strain concentration at the crack tip is not dominant and the concentration at the anvil contact points can have a large influence on crack propagation.
- The fractography of SCB does not show a fast fracture region, indicating plasticity (or general yielding) is the dominant mechanism contributing to cleavage.

Regarding DCT:

- The DCT test produces a high average fracture energy with a low COV when compared to SCB.
- The DCT specimen geometry offers a large fracture area such that individual aggregates do not play a significant role in crack propagation.

![Fig. 12. Schematic of (a) SCB and (b) DCT specimen with representative aggregates.](image-url)
The 3D-DIC strain contours of DCT show that the strain concentration at the crack tip is dominant and concentrations at the load points and/or on the back edge do not interfere with crack propagation.

The fractography of DCT shows a fast fracture region, indicating that the fracture energy or critical strain energy release rate has been reached.

It is concluded that the DCT standard is superior to both SCB standards. Further work is needed fully validate this claim. A larger test matrix including more repeat tests would improve the statistical significance of the fracture resistance measurements. Additional HMA mixtures should be evaluate to determine the extent that average aggregate size influences variability. An analysis of the strain and displacement fields during crack initiation, propagation, and fracture should be performed using 3D-DIC to obtain a clearer picture concerning the onset of fast fracture and the influence of strain concentrations away from the crack tip. In addition, 3D-DIC can be applied to measure a full traction-opening displacement relationship for the ligament and measure the crack advancement towards a length scale parameter to characterize the fracture phenomenon, see e.g. [35]. In-situ volumetric scans using X-ray microtomography could also be conducted to characterize the evolution of the 3D crack during fracture, see e.g. [36].

Acknowledgments

We would like to thank Steven D. Ambroz, Carlos A. Catzin, Jose L. Coronel, Mohammad Shafinul Haque, and Victor M. Ornellas for their contributions to project. We also would like to thank the Center for Transportation Infrastructure Systems (CTIS), especially their Executive Director Dr. Imad Abdallah and Director Dr. Soheil Nazarian, as well as the Challenger-Columbia Materials Research Facility for the use of equipment and materials. This research was supported with funds from the Southern Plains Transportation Center.

References


