Effect of specimen thickness on the fracture resistance of hot mix asphalt in the disk-shaped compact tension (DCT) configuration

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HIGHLIGHTS

- The plane-strain condition does not exist in 50 mm thick DCT specimen.
- Linear elastic fracture mechanics theory can be used to optimize layer thicknesses.
- Fracture surfaces do not distinguish between the plane-stress and strain conditions.

ABSTRACT

In this study, the effect of specimen thickness on the fracture resistance of a dense-graded hot mix asphalt (HMA) is investigated. The fracture toughness, \( K_c \), and fracture energy, \( G_f \), in triplicate DCT specimens with width-to-thickness ratios ranging from 1.46 to 4.4 is measured at 27°C. The coefficient of variation (COV) of \( K_c \) and \( G_f \) is calculated to determine reliability as a function of thickness. Photos of cracked specimens and 3D surface scans are employed to study how the crack path and fracture surface changed with thickness. The ASTM specifications and linear-elastic fracture mechanics theory are applied to show that \( K_c \) does not reach a plane-strain condition, \( K_c - K_{IC} \), for the given ratios. The average \( K_c \) increases with thickness while the COV is inconsistent with thickness. The average \( G_f \) is independent of thickness but the COV decreases with thickness; thus, \( G_f \) is thickness-dependent. The crack path and fracture surface cannot be used to identify the plane-stress or plane-strain condition due to large aggregates dominating the fracture process. A method for estimating the specimen thickness required for the plane-strain condition and a method to estimate the thickness at which fracture toughness is maximized is demonstrated.

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1. Introduction

Cracking is the most common mode of degradation contributing to failure in flexible pavements. The rapid initiation of cracks shortens the service life of pavement and increases maintenance costs. Hot mix asphalts (HMAs) offer low construction and maintenance costs when compared to concrete yet the problem of cracking persists. There is a need to elucidate the cracking behavior of HMAs to enable proactive maintenance management of transportation infrastructure. HMA layers are subjected to out-of-phase thermo-mechano-chemical fatigue due to the varying types of roads, traffic patterns, and climate across the world. Due to the complex nature of HMA’s (an irregular distribution of aggregates in a bitumen matrix) fracture tests exhibit low repeatability. A systematic investigation into the factors that contribute to this problem is needed. Previous work has shown that specimen geometry plays a key role in repeatability [1]. The current paper investigates specimen thickness as a factor of interest.

Hot mix asphalts are heterogeneous composites consisting of brittle aggregates held within a viscoelastic-plastic bitumen matrix. The aggregates include crushed stone (large), sand (fine), and mineral (filler) at varied sizes and spatial distributions. Fracture is driven by the friction between interlocked aggregates coated with binder that are responsible for the material dilation and nucleation of micro-cracks. The micro-cracks propagate into major cracks due to overload, repeated mechanical loading, thermal cycling, and synergistic effects. At low temperature, the probability of crack initiation is increased due to the quasi-brittle response of the binder and thermal-expansion mismatch with the aggregate as opposed to
the ductile response observed at elevated temperature [2,3]. Composition and aggregate gradation play an integral role in the repeatability of fracture tests where large aggregates lead to a high coefficient of variation (COV) in experiments [4].

Several researchers have investigated the fracture resistance of asphalt mixtures [1–18]. The semi-circular bending (SCB) test is a common fracture test for HMAs due to the simplicity of specimen preparation and testing [5]. Saha and Biligiri conducted a review of the state-of-the-art concerning SCB testing of asphalt mixtures [6]. Current standards recommend a specimen thickness of 50 mm [7,8]. Both the fracture toughness, $K_{Ic}$, and fracture energy, $G_f$, parameters were evaluated. Fracture toughness, $K_{I}$, was found to be independent of thickness between 25 and 75 mm at temperatures below 15 °C; however, as temperature increases the magnitude of $K_{I}$ decreases and the COV increases. Fracture energy, $G_f$, was determined to be dependent on asphalt grade and temperature; however, the effect of thickness was not discussed. In theory, $G_f$ of homogeneous linear-elastic materials is insensitive to size; however, since HMAs are heterogeneous viscoelastic-plastic materials this may not hold true. In a follow-on study, Saha and Biligiri [9] evaluated the homothetic fracture resistance behavior of dense grade HMA materials (i.e. the dependence on asphalt content, air voids, temperature, and thickness) using the SCB test. Tests were performed at temperatures of 5–25 °C with thicknesses from 30 to 50 mm. Increasing the thickness from 30 to 40 mm increased the $K_{Ic}$; however, thicknesses from 40 to 50 mm exhibit no change in $K_{I}$. A major advantage of the SCB configuration is the ability to measure the mixed-mode fracture resistance of HMAs [10,11]. Aliha and colleagues performed a series of experiments on the mode I, II, III and mixed cracking of HMAs in the SCB configuration [11–15]. It was determined that SCB is an extremely versatile configuration for examining the mixed-mode cracking observed in transportation materials under multiaxial states of stress.

Specimen geometry plays a key role in the average $K_{Ic}$ and COV. The Texas A&M Transportation Institute evaluated the performance of several fracture test configurations including the disk-shaped compact tension (DCT), semi-circular bending (SCB), indirect tension (IDT), thermal stress-restrained specimen test or uni-axial thermal stress and strain test (TRSSST/UTSSST), Texas overlay (Texas OT), bend beam fatigue (BBFT), simplified viscoelastic continuum damage (S-VCD), and the repeated direct tension (DT) test [16]. The tests were compared with regards to test complexity, correlation to field performance, test variability, test sensitive to mix design parameters, and cost. The DCT, SCB, and Texas OT were found to have the lowest cost and exhibit good correlation to field performance; however, DCT was observed to produce the lowest COV. To further examine these conclusions, Stewart et al. [1] performed a comparative analysis of the SCB and DCT mode I fracture energy test standards on a dense-graded Superpave HMA. The SCB and DCT tests were conducted according to AASHTO TP105-13 and ASTM D7313-13 at the thickness of 50 mm (recommended in ASTM D7313) and a temperature of 27 °C [7,8]. The SCB tests produced a low $G_f$ with a high COV when compared to DCT. The DCT geometry offers more fracture area for cracking propagation making it a more repeatable test.

Wagoner et al. [17] performed DCT fracture energy tests on four asphalt mixtures ranging from typical Illinois to polymer-modified interlayer mixtures. For a single mixture at −10 °C, the thickness was profiled from 25 to 75 mm. Fracture energy, $G_f$, was found to increase with thickness while the COV also increased from 13 to 19%. Kim et al. [18] found that increasing the diameter of a specimen from 100 to 450 mm led to an increase in $G_f$ while the COV remained relatively constant near 15%.

According to linear-elastic fracture mechanics (LEFM) theory, the fracture toughness of a homogeneous material is thickness dependent up to the plane-strain condition where the value becomes a constant material property [19–21]. The size or thickness dependence is associated with the transition from plane-stress to plane strain as illustrated in Fig. 1. The fracture toughness, $K_{Ic}$, is called the “apparent” fracture toughness when it is thickness-dependent and is called the “plane-strain” fracture toughness, $K_{Ic}$ when it becomes an intrinsic material property that is not thickness-dependent. In plane-stress, the direction of maximum shear stress is in the anti-plane direction ($±45^\circ$) leading to the formation of a slant crack or shear lips. Under plane-stress, microstructural defects play a significant role in fracture toughness resulting in a high COV. As thickness increases, the specimen transitions from plane-stress to a plane-strain condition. In plane-strain, the direction of the maximum shear stress is in-plane leading to a flat fracture surface. The field of defects in the material homogenize such that the fracture toughness resolves to a horizontal asymptote with a low COV. By reviewing LEFM theory, it can be concluded that

- the plane-strain fracture toughness, $K_{Ic}$, is a conservative measure of fracture resistance.
- for design it would be advantageous to determine the thickness where the apparent fracture toughness, $K_{Ic}$, is maximized and the COV is reasonable [19–21].

Since HMAs are heterogeneous composites, and the theory described above may not hold true, there is a need to investigate the thickness-dependence of the fracture resistance of HMAs.

It is important to check the ASTM requirements for the plane-strain condition. ASTM developed two standards to support the measurement of the $K_{Ic}$ in metallic and homogeneous materials: ASTM E399-12(e1) [22] and ASTM E1820-16 [23], respectively. A key requirement of these two standards is that the width-to-thickness ratio, $W/B$, shall remain between 2 and 4. The standard ratio is $W/B = 2$. Another requirement is that the following inequality be enforced

$$a/B \geq 2.5 \left( \frac{K_{Ic}}{\sigma_{YS}} \right)^2$$

where $K_{Ic}$ is the approximate plane-strain fracture toughness, $\sigma_{YS}$ is the yield strength, $a$ is the crack length, and $B$ is the thickness. The fracture toughness cannot be considered plane-strain, $K_{Ic}$, when this condition is violated, and it must be defined as the apparent fracture toughness, $K_{Ic}$, reported everywhere with respect to thickness [6].

In this study, the effect of specimen thickness on the $K_{Ic}$ and $G_f$ of a dense-graded HMA is investigated using DCT specimens at a temperature of 27 °C. The DCT configuration was selected due to the availability of an ASTM test standard [7] and the low COV expected in this configuration [1,16]. The tests are performed at width-to-thickness ratios ranging from 1.46 to 4.4. Statistical analysis is performed to investigate how $K_{Ic}$ and $G_f$ evolve as a function of thickness. Photos of cracked specimens and 3D surface scans are employed to determine how the crack path and fracture surface change with thickness.

### 2. Material and test methods

#### 2.1. Hot mix asphalt

The material in this study is a dense-graded HMA (designated as Type-C by Texas Department of Transportation) used in West Texas. The properties of the mix are summarized in Table 1. The
gradation is listed in Table 2. The relevant aggregates and binder were sampled and transported to the Center for Transportation Infrastructure Systems at The University of Texas at El Paso (UTEP) where specimens were prepared and tested.

2.2. Specimen preparation

The HMA mixture is heated to 132 ± 3 °C to liquefy the binder and improve mold-ability. Standard 150 mm diameter by 114 mm thick briquettes are compacted with a superpave gyratory compactor according to AASHTO T312-15 and ASTM D6925-15 [24,25]. After the briquette reaches room temperature, a disk shape specimen is excised from the middle using a masonry saw to the desired thickness. The disk is quality checked for an air-void percentage (AV%) target of 7 ± 1.0%. Disks with the proper AV% are machined into DCT specimen according to ASTMS D7313-13[7]. One DCT specimen can be extracted from each disk with the dimensions illustrated in Fig. 2. Specimen were prepared with thicknesses of 25, 40, 50, and 75 mm. The width-to-thickness range is $W/B = 4.6$.

2.3. Mechanical test equipment

The mechanical tests were conducted using an INSTRON 5969 Table-Top Universal Test System. The test frame is equipped with an Instron 3119-609 Environmental Chamber capable of regulating temperature from $-100$ to $+350$ °C. Load and displacement limits were set for the load cell, crosshead displacement, and extensometers to avoid equipment damage. The specimens were set to an isothermal temperature of 27 °C for the duration of each test. The data captured during each test includes time, load, and line displacement.

2.4. Test method

2.4.1. DCT fracture toughness (Modified from ASTM E1820-16)

Fracture toughness tests are performed according to ASTM E1820-16 the “Standard Test Method for Measurement of Fracture Toughness” [23]. The standard provides a procedure for calculating the fracture toughness, $K_c$ (MPa-m$^{0.5}$) of DCT specimens. The fracture toughness $K_c$ is defined as the stress intensity factor, $K_i$ corresponding to the initiation of a crack in a homogenous, linear-elastic body. Fracture toughness, $K_c$, is typically measured at the peak load, $P_c$ depicted in Fig. 3 [1]. For the DCT geometry, the stress intensity factor, $K_i$ is computed as follows

$$K_i = \frac{P_i}{(B_B W)^{1/2}} f(a_i/W)$$

(2)

where $i$ is the data point, $P_i$ is the load at the $i$th data point (N), $W$ is the width (mm), $f$ is the dimensionless geometry factor, $a_i$ is the crack length at the $i$th data point (mm), $B_B$ is the net thickness (mm), and $B = B_B$ if no side grooves are present.

The dimensionless geometry factor, $f$ for the DCT geometry is calculated as

$$f(a_i/W) = \frac{\{(2 - a_i/W)[(0.76 + 4.8(a_i/W) - 11.58(a_i/W)^2 + 11.43(a_i/W)^3 - 4.08(a_i/W)^4)]\}}{\left(1 + a_i/W\right)^{3/2}}$$

(3)

The plane-strain fracture toughness, $K_c$ is obtained by profiling the apparent fracture toughness, $K_a$ as a function of thickness and

### Table 1

Summary of HMA properties.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Type-C</th>
</tr>
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<tbody>
<tr>
<td>NMAS (mm)</td>
<td>19</td>
</tr>
<tr>
<td>Asphalt performance grade</td>
<td>PG 70-22</td>
</tr>
<tr>
<td>Binder substitution</td>
<td>PG 64-22</td>
</tr>
<tr>
<td>Optimal asphalt content (%)</td>
<td>4.6</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.001</td>
</tr>
<tr>
<td>Binder percent (%)</td>
<td>4.6</td>
</tr>
<tr>
<td>VMA (%) at optimum AC</td>
<td>15.2</td>
</tr>
</tbody>
</table>

### Table 2

Gradation chart of Type-C mix.

<table>
<thead>
<tr>
<th>Sieve size</th>
<th>Type-C (Percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot;</td>
<td>100.0</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>99.3</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>92.4</td>
</tr>
<tr>
<td>No. 4</td>
<td>52.7</td>
</tr>
<tr>
<td>No. 8</td>
<td>36.9</td>
</tr>
<tr>
<td>No. 30</td>
<td>18.6</td>
</tr>
<tr>
<td>No. 50</td>
<td>14.0</td>
</tr>
<tr>
<td>No. 200</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Fig. 1. Fracture toughness and fracture surface versus thickness in homogeneous linear-elastic materials.

Fig. 2. Specimen Thickness, $B$.
finding the horizontal asymptote where $K_c = K_{mc}$ is insensitive to thickness.

Before testing, the specimens were fatigue pre-cracked until the notch grew by $D_a > 0.2$ beyond the initial notch length. The maximum stress intensity factor, $K_{max}$ during pre-cracking did not exceed 60% of the estimated plane-strain fracture toughness $K_{Ic}$.

2.4.2. DCT fracture energy (According to ASTM D7313-13)

Fracture energy tests are performed according to ASTM D7313-13 the “Standard for determining the fracture energy of asphalt-aggregate mixtures” [7]. The standard calculates the fracture energy, $G_f$ using a single-specimen solution. Tests are performed with a constant crack mouth opening displacement, CMOD of 0.017 mm/s. The standard does not call for pre-cracking so it was not preformed. The fracture energy, $G_f$ is calculated as follows

$$G_f = \frac{U_f}{B \cdot (W - a)}$$

where $U_f$ is the work of fracture (J), $B$ is the thickness (mm), and $(W - a)$ is the initial ligament length (mm). The work of fracture, $U_f$ is calculated as the area under the load-CMOD curve depicted in Fig. 3 using the quadrangle rule as follows

$$U_f = \sum_{i=1}^{n} (u_{i+1} - u_i) \cdot (P_i) + 0.5 \cdot (u_{i+1} - u_i) \cdot (P_{i+1} - P_i)$$

where $n$ is the number of data points, $u$ is the CMOD, and $P$ is the load.

2.5 D Surface scanning

The fractured specimens 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. The 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.

3. Results and discussion

3.1. ASTM requirements

Preliminary experiments were performed to check the ASTM plane-strain condition [Eq. (1)]. The AASHTO TP 105, ASTM E399, and ASTM E1820 standards recommend at least triplicate tests for each material condition [8,22,23]. Three indirect tensile tests (IDT) were performed recording an average yield strength, $\sigma_{YS}$ of 849 kPa. Three DCT tests were performed at a specimen thickness of 50 mm measuring an average fracture toughness of 0.265 MPa√m. Taking these properties and evaluating [Eq. (1)], it is estimated that a specimen thickness of 244 mm or greater is required to achieve the plane-strain condition. To maintain a width-to-thickness ratio within the recommended range of $2 \leq W/B \leq 4$; the specimen width must be between 488 mm ≤ $W \leq 976$ mm. A specimen with the above dimensions is not practical to test and exceeds the typical thickness of laid HMA. In summary, for dense-graded HMA at 27 °C, the fracture toughness measured using the standard DCT dimensions is the “apparent” fracture toughness, $K_c$ and must be reported with specimen thickness.

3.2. Fracture toughness

Fracture toughness tests were performed on triplicate specimens prepared at four thicknesses. The test results are presented in Table 3 with the load-displacement curves shown in Fig. 4. On average, the peak load increases with thickness. At a given thickness, the peak load varies. The peak load variation is linked to the different initial notch length measured for each specimen after pre-cracking. The critical crack length was optically measured (at the instant of fracture) using a three-dimensional digital image
correlation (3D-DIC) system. The 3D-DIC system consists of a set of cameras that capture images of the surface of the specimen. These images are synchronized with load cell data and the image corresponds to the peak load is used to measure the critical crack length. The critical crack length is plotted with respect to peak load in Fig. 5. Peak load versus critical crack length exhibits a linear relationship with a negative-slope. As the critical crack length increases the peak load decreases. The trend follows LEFM theory where when the fracture area decreases the force needed for fracture decreases. The dimensions, peak load, and critical crack length are applied to calculate the fracture toughness, $K_c$. Fracture toughness is plotted against thickness in Fig. 6a. When compared to the LEFM theory in Fig. 1, the HMA is under plane-stress at the given thicknesses. Theory states there exists a maximum fracture toughness in the transition from plane-stress to plane-strain. A quadratic function is fitted to the fracture toughness versus thickness data as follows

$$K_c(B) = C_0 + C_1 B^2 + C_2 B + C_3.$$ 

Taking the derivative of the function and setting it equal to zero, the maximum fracture toughness is approximately 0.295 MPa at a thickness of 88 mm. It is important to note that the thickness where fracture toughness is maximized is specific to the cracking mode (mode I), composition (dense-grade HMA used in West Texas), temperature, and geometry (DCT). The COV of $K_c$ is plotted versus thickness in Fig. 6b. The COV is of acceptable magnitude for HMAs (below 15% acceptable, below 5% excellent) but is inconsistent at the given thicknesses with an unexplained drop at 40 mm.

**Table 3**

Fracture toughness of dense-graded HMA.

<table>
<thead>
<tr>
<th>Specimen name*</th>
<th>Thickness, $B$</th>
<th>Air voids, AV</th>
<th>Critical crack length, $a_c$</th>
<th>Peak load, $P_c$</th>
<th>Apparent fracture toughness, $K_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(%)</td>
<td>(mm)</td>
<td>(N)</td>
<td>(MPa $\sqrt{m}$)</td>
</tr>
<tr>
<td>K25-1</td>
<td>26.5</td>
<td>6.9</td>
<td>37.1</td>
<td>236.5</td>
<td>0.171 ± 0.035 17.5</td>
</tr>
<tr>
<td>K25-2</td>
<td>27.0</td>
<td>6.3</td>
<td>43.0</td>
<td>223.6</td>
<td>0.184 ± 0.026 14.0</td>
</tr>
<tr>
<td>K25-3</td>
<td>25.1</td>
<td>6.4</td>
<td>54.5</td>
<td>190.4</td>
<td>0.236 ± 0.035 17.5</td>
</tr>
<tr>
<td>K40-1</td>
<td>41.4</td>
<td>7.1</td>
<td>39.2</td>
<td>463.7</td>
<td>0.228 ± 0.025 11.1</td>
</tr>
<tr>
<td>K40-2</td>
<td>39.9</td>
<td>7.1</td>
<td>44.0</td>
<td>377.7</td>
<td>0.227 ± 0.023 10.1</td>
</tr>
<tr>
<td>K40-3</td>
<td>41.2</td>
<td>7.1</td>
<td>54.9</td>
<td>332.5</td>
<td>0.252 ± 0.030 15.1</td>
</tr>
<tr>
<td>K50-1</td>
<td>50.4</td>
<td>6.8</td>
<td>38.5</td>
<td>678.3</td>
<td>0.277 ± 0.027 18.1</td>
</tr>
<tr>
<td>K50-2</td>
<td>57.8</td>
<td>6.3</td>
<td>40.3</td>
<td>645.5</td>
<td>0.232 ± 0.021 14.1</td>
</tr>
<tr>
<td>K50-3</td>
<td>48.9</td>
<td>7.5</td>
<td>47.8</td>
<td>548.4</td>
<td>0.288 ± 0.031 16.1</td>
</tr>
<tr>
<td>K75-1</td>
<td>73.2</td>
<td>7.3</td>
<td>47.8</td>
<td>695.8</td>
<td>0.248 ± 0.019 12.1</td>
</tr>
<tr>
<td>K75-2</td>
<td>73.4</td>
<td>6.6</td>
<td>59.2</td>
<td>625.3</td>
<td>0.307 ± 0.026 17.1</td>
</tr>
<tr>
<td>K75-3</td>
<td>73.6</td>
<td>6.8</td>
<td>71.1</td>
<td>393.7</td>
<td>0.311 ± 0.015 11.1</td>
</tr>
</tbody>
</table>

*KXX-Y: K – fracture toughness test, XX – specimen thickness in mm, Y – test number at XX.

**Fig. 4.** Load-displacement of fracture toughness tests at thicknesses (a) 25 to (d) 75 mm.
A high COV is expected in plane-stress since microstructural features become dominant at small thicknesses, particularly in heterogeneous materials.

In summary, for dense-graded HMA at 27°C, $K_c$ depends on specimen thickness between 25 and 75 mm. It is estimated that the specimen is under plane-stress at $B \leq 88$ mm and plane-strain at $B \geq 244$ mm. These findings are dependent on composition, temperature, and specimen. Different HMA compositions and gradations will have different mechanical properties. The deformation and fracture mechanisms of HMAs change with temperature. Specimen that offer large fracture areas will produce lower COVs. The mode I DCT configuration does not reflect the actual multiaxial state of stress induced in the surface of flexible pavement layers during traffic loads; however, it is a useful configuration to consistently evaluate the basic fracture resistance of these materials. If a fracture toughness test can be configured to perfectly replicate the cracking mode, composition, temperature, and geometry of flexible pavement layers in-service, a design engineer can apply the LEFM theory demonstrated here to maximize the fracture resistance of flexible pavement layers by deriving the optimal thickness. The COV must be involved in the design process such that the decision is based not only on performance but reliability.

### 3.3. Fracture energy

Fracture energy tests were performed on triplicate specimens at four different thicknesses. The test results are presented in Table 4 with the load-displacement curves shown in Fig. 7. The fracture energy load-displacement curves have a tight grouping when compared to the fracture toughness tests in Fig. 4. At a given thickness, the peak load remains relatively constant. This trend relates to the absence of pre-cracking. On average, the peak load and work of fracture increase with thickness. The initial dimensions and work of fracture are applied to calculate the fracture energy, $G_f$. Fracture energy and the COV is plotted against thickness in Fig. 8a and b.

**Table 4**

Fracture Energy of Dense-Graded HMA.

<table>
<thead>
<tr>
<th>Specimen Name*</th>
<th>Thickness, B (mm)</th>
<th>Air voids, AV (%)</th>
<th>Ligament length, $W - a$ (mm)</th>
<th>Work of fracture, $U_f$ (J)</th>
<th>Fracture energy, $G_f$ (J m$^{-2}$)</th>
<th>Avg. COV (%)</th>
<th>Std. Dev. COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G25-1</td>
<td>26.9</td>
<td>6.8</td>
<td>83.9</td>
<td>1.265</td>
<td>560.7</td>
<td>714.7</td>
<td>±167.1</td>
</tr>
<tr>
<td>G25-2</td>
<td>27.1</td>
<td>6.1</td>
<td>77.8</td>
<td>1.457</td>
<td>691.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G25-3</td>
<td>25.2</td>
<td>6.3</td>
<td>81.6</td>
<td>1.835</td>
<td>892.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G40-1</td>
<td>41.5</td>
<td>7.5</td>
<td>81.3</td>
<td>2.634</td>
<td>780.6</td>
<td>718.2</td>
<td>±70.32</td>
</tr>
<tr>
<td>G40-2</td>
<td>41.8</td>
<td>7.0</td>
<td>79.8</td>
<td>2.141</td>
<td>642.0</td>
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<tr>
<td>G40-3</td>
<td>42.3</td>
<td>7.3</td>
<td>82.5</td>
<td>2.555</td>
<td>732.0</td>
<td></td>
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<tr>
<td>G50-1</td>
<td>53.1</td>
<td>6.4</td>
<td>82.3</td>
<td>2.915</td>
<td>667.2</td>
<td>645.6</td>
<td>±19.98</td>
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<tr>
<td>G50-2</td>
<td>53.0</td>
<td>6.9</td>
<td>79.4</td>
<td>2.700</td>
<td>641.8</td>
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<tr>
<td>G50-3</td>
<td>54.7</td>
<td>6.8</td>
<td>82.4</td>
<td>2.830</td>
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<tr>
<td>G75-1</td>
<td>74.7</td>
<td>7.5</td>
<td>81.5</td>
<td>4.153</td>
<td>682.1</td>
<td>700.8</td>
<td>±23.44</td>
</tr>
<tr>
<td>G75-2</td>
<td>75.0</td>
<td>7.5</td>
<td>80.5</td>
<td>4.186</td>
<td>693.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G75-3</td>
<td>76.0</td>
<td>7.9</td>
<td>82.3</td>
<td>4.548</td>
<td>727.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*GXX-Y: G – fracture energy test, XX – specimen thickness in mm, Y – test number at XX.
respectively. On average, fracture energy remains approximately 700 J/m² at thicknesses between 25 and 75 mm; however, this statistic is misleading when the COV is considered. The COV of $G_f$ is thickness-dependent and decreases as the thickness increases from 23.4% at 25 mm to 3.3% at 75 mm. Statistically, the likelihood of achieving a consistent fracture energy in replicate tests decreases as thickness decreases. Thus, fracture energy is thickness dependent. The standard 50 mm thickness (recommended by ASTM D7313-13) is sufficient to obtain consistent fracture energy measurements at a COV of 3.1%.

In summary, for dense-graded HMA at 27°C, the COV of $G_f$ is thickness-dependent and decreases as the thickness increases from 23.4% at 25 mm to 3.3% at 75 mm. Statistically, the likelihood of achieving a consistent fracture energy in replicate tests decreases as thickness decreases. Thus, fracture energy is thickness dependent. The standard 50 mm thickness (recommended by ASTM D7313-13) is sufficient to obtain consistent fracture energy measurements at a COV of 3.1%.

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3.4 Crack path

Photographs of the crack path for each $K_c$ and $G_f$ specimen are presented in Figs. 9 and 10, respectively. In both tests and at all
thicknesses, the primary crack propagates through the bitumen bypassing most large aggregates. From specimen-to-specimen, the crack is torturous and travels uniquely through the heterogeneous structure following a path of least resistance. The crack path is perturbed by obstacles (such as large well-bonded aggregates) and weak zones (voids, weakly-bonded interfaces, etc.). In limited cases, the crack bisects moderately sized aggregates. These failed aggregates are primarily found at long cracks near the points where the specimen separated in half. In summary, for dense-graded HMA at 27 °C, there is no trend between crack path and thickness.

3. 5D surface scanning

In homogeneous linear-elastic materials, the fracture surface should evolve with thickness as illustrated in Fig. 1. Under plane-stress, a slant crack should be observed. In the transition from plane-stress to plane-strain a mixed-mode fracture surface, including both shear lips and a flat surface, should be observed. In plane-strain, the fracture surface should be flat with minimal shear lips.

3D surface scans taken of $G_f$ specimens at different thicknesses are shown in Fig. 11. The trends for homogeneous linear-elastic materials do not hold for dense-graded HMA. It was previously determined that dense-graded HMA is in plane stress when $B \leq 88$ mm and plane-strain when $B \geq 244$ mm. Examining the 3D scans, the fracture surfaces at all thicknesses are non-planar and reside between 0 and 45°. The crack bypasses aggregates leading to a tortuous and cratered fracture surface. It is possible that the crack may become more planar as the specimen approaches plane-strain, $B > 244$ mm; however, the gradation chart for the dense-graded mix used (Table 2) suggests the fracture surface can remain out-of-plane by up to 19 mm (the largest aggregates size). In summary, for dense-graded HMA at 27 °C, 3D scans of the fracture surface cannot reasonable predict the plane-stress or plane-strain condition.

4. Conclusions

The goal of this effort was to evaluate the effect of thickness on the fracture resistance of HMA mixtures in the DCT configuration. For dense-grade HMA tested at 27 °C, it is determined that

- checking the requirements of ASTM E399-12 and E1820-16, [Eq. (1)], the specimens are in plane-stress when $B \leq 88$ mm and plane-strain when $B \geq 244$ mm.
- the fracture toughness is maximized at $B = 88$ mm.
dimensions can be applied to any HMA mixture towards improving the design and performance of flexible pavement layers. In future work, fracture resistance tests will be performed under service-like conditions including the cracking mode, strain rate, temperature, and geometry. Thermo-mechano-chemical fatigue tests will be designed to simulate (in an accelerated manner) the degradation of HMAs.

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References


