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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.

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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, $K_c \neq K_{Ic}$, 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.

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

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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_c and fracture energy, G_f parameters were evaluated. Fracture toughness, K_c 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_c 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_c; however, thicknesses from 40 to 50 mm exhibit no change in K_c. 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_c 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 uniaxial thermal stress and strain test (TRSST/UTSST), 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_c 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°) 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_c 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 E399-12e3 [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

$$a, B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{YS}}\right)^2 \tag{1}$$

where K_{Ic} is the approximate plane-strain fracture toughness, σ_{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_c, reported everywhere with respect to thickness [6].

In this study, the effect of specimen thickness on the K_c 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_c 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