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Development of a Flattened Indirect Tension Test for Asphalt Concrete

ABSTRACT: The indirect tension test (IDT) is frequently used in civil engineering because of its benefits over direct tension testing. In the mid-1990s, an IDT protocol was developed for evaluating tensile strength and creep properties of asphalt concrete mixtures, as specified by the American Association of State Highway Transportation Officials (AASHTO) in AASHTO T322. However, with the increased use of finer aggregate gradations and polymer modified asphalt binders in asphalt concrete mixtures, the validity of IDT strength results can be questioned in instances where significant crushing occurs under the narrow loading heads. Therefore, a new specimen configuration is proposed for indirect tension testing of asphalt concrete. In place of the standard loading heads, the specimen was trimmed to produce flat planes with parallel faces, creating a "flattened IDT." A viscoelastic finite element analysis of the flattened configuration was performed to evaluate the optimal trimming width. In addition, the numerically determined geometry was verified by means of laboratory testing of three asphalt concrete mixtures in two flattened configurations. This integrated modeling and testing study showed that when using fine aggregate gradations and compliant asphalt binders, crushing is significantly reduced while maintaining tensile stresses near the center of the specimen. Furthermore, creep compliances were evaluated using the flattened IDT and compared with those obtained following AASHTO T322. Some variation was observed between the creep properties evaluated from the different geometries, particularly for higher compliance values. As a preliminary assessment, the flattened IDT seems to be a suitable geometry for the evaluation of indirect tensile strength of asphalt concrete. Further testing and analysis should be performed on the flattened IDT arrangement for evaluation of the creep compliance. This study provides an initial step towards a possible revision of the current AASHTO standard for IDT testing of asphalt concrete mixtures.

KEYWORDS: indirect tensile test, creep test, tensile strength test, viscoelasticity, finite element modeling, asphalt concrete, pavement

Introduction

In the recently developed American Association of State Highway Transportation Officials (AASHTO) Mechanistic Empirical Pavement Design Guide, creep compliance and tensile strength are important input parameters for the prediction of low temperature cracking in flexible pavements. In addition, a number of other pavement cracking prediction models have been developed where tensile strength is a relevant parameter for fracture and/or damage models. Thus, it is important to accurately measure the tensile strength of asphalt concrete in the laboratory.

The indirect tension test (IDT) is a very practical configuration for the testing of asphalt concrete samples, as standard laboratory and field samples are typically cylindrical in shape. When samples are taken from the field, a core barrel is often utilized, producing cylindrical specimens. In addition, the laboratory equipment used to produce asphalt concrete samples can use a cylindrical shaped mold during compaction, as seen in Figs. 1 and 2 [1].

The IDT is frequently used in the evaluation of asphalt concrete materials due to its convenience for capturing both viscoelastic properties and tensile strength. During the Strategic Highway Research Program (SHRP) in the mid-1990s, a test protocol was developed for evaluating creep and strength properties of asphalt concrete mixtures [2,3] in indirect tension. The test was dubbed with the acronym IDT during the SHRP program and was subsequently specified by the AASHTO in AASHTO T322. Both properties are measured on the same sample, with the non-destructive creep test run before the destructive strength test.

With the increased use of finer aggregate gradations and polymer modified asphalt binders in asphalt concrete mixtures, however, the validity of the IDT strength test may be questionable. This is especially the case when crushing failures occur under the narrow loading strips prior to or in exclusion of the desired tensile failure, which is assumed to occur along a vertical plane spanning between the loading strips. Instead of the traditional 150 mm diameter, 50 mm thick cylindrical specimen, previous studies introduced a new specimen configuration for strength and creep testing of asphalt concrete [4,5]. In place of the loading heads at the top and bottom, the specimen was trimmed to produce flat planes with parallel faces, creating a flattened IDT. The amount of flatness is defined by an interior angle, α, where a higher α value indicates a wider flat face. Through the testing of three asphalt concrete mixtures, it was shown that the flattened IDT significantly reduced crushing in the vicinity of loaded areas while still providing reasonable strength and creep data. However, only a single α value was considered in the aforementioned study.

Objectives

Two flattened IDT configurations are investigated with three asphalt concrete mixtures to optimize the flattened IDT configuration for the accurate determination of tensile and creep properties and for the mitigation of crushing under the loading heads during strength testing. Towards this end, an integrated testing and modeling approach was utilized.

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FIG. 1—*Field sample extraction (left) and laboratory mold (right, from Ref 1); both fabrication methods produce 150 mm diameter samples of asphalt concrete.*

Background

The IDT setup developed for asphalt concrete (Fig. 3) uses a 19 mm wide loading strip on the top and bottom of the testing specimen. The loading ram compresses the sample at 12.5 mm/min as per AASHTO T322. In the standard testing configurations, asphalt mixtures can experience a crushing failure under the narrow loading heads, particularly with small aggregate structures and softer asphalt cement binders. Figure 4 illustrates one such example from the current study. The incorrect use of a tensile strength value obtained from a test where a crushing failure has occurred can have detrimental consequences on pavement design.

Wagoner et al. [6] briefly discussed this crushing problem for an asphalt concrete interlayer mixture manufactured with a highly modified polymer asphalt binder and fine aggregate gradation, which was specially designed to reduce reflective cracking in asphalt concrete overlay systems. One solution to this problem is to increase the contact area between the loading heads and the sample.

In the area of rock mechanics, the idea of a flattened Brazilian disk specimen has been studied [7–9]. This testing configuration increases the surface area between the loading heads and sample, thus reducing the extent of shear-type damage under loading heads and increasing the probability of specimens failing primarily due to tension along the axis of loading. However, flatter ends reduce the tensile stress in the middle of the specimen. Thus, it is important to identify an optimum test geometry that minimizes crushing and failures near the loading heads and at the same time provides sufficient tension in the middle of the specimen for a global tensile failure. Finite element (FE) simulations were employed in this study in an effort to optimize specimen geometry. With the geometry determined, tensile strength and creep analyses were performed for flattened IDT geometries, and results were compared with results obtained using the standard AASTHO T322 configuration.

FIG. 2—*Field samples (left) and laboratory samples (right); both sets of these samples are 150 mm diameter samples of asphalt concrete.*

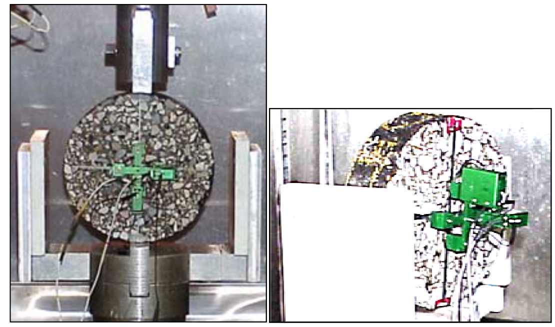

FIG. 3—*Traditional IDT setup (AASHTO T322).*

Approach

In an effort to identify a suitable test geometry for the flattened IDT test for asphalt concrete, an integrated testing and modeling approach was adopted. The process can be summarized as follows:

- Selection and laboratory characterization of several different asphalt concrete mixtures;
- Numerical simulations to evaluate suitable flattened IDT geometry; and
- Manufacture and testing of flattened IDT specimens for validation purposes.

Selection and Characterization of Asphalt Concrete Mixtures

The first step in the experimental plan was the selection and testing of three asphalt concrete mixtures in the regular IDT configuration. The three asphalt concrete mixtures were chosen in an attempt to elicit differing amounts of crushing failure, which related to maximum aggregate size and binder stiffness. Table 1 summarizes the aggregate and binder characteristics for the three mixes used in this study.

The first mixture was designed to have a relatively large aggregate structure and was combined with a relatively stiff asphalt binder (conforming to the AASHTO MP-1 PG64-22 binder grade). It was anticipated that this mixture, labeled Mix-22, would not exhibit significant crushing during strength testing in the AASHTO T322 IDT test [10]. The second mixture was designed to have a small aggregate structure and a less stiff binder (PG58-28). It was

FIG. 4—*Undesirable crushing failure under regular IDT loading head (Mix-40).*

TABLE 1—*Mixture characteristics.*

	Nominal Maximum Aggregate Size (mm)	Aggregate Structure	Binder Type	Binder Characteristics	Anticipated Regular IDT Performance
Mix-22	9.5	Large	PG64-22	Stiff	No crushing
Mix-28	4.75	Small	PG58-28	Semi-stiff	Possible crushing
Mix-40	4.75	Small	PG58-40	Soft	Probable crushing

anticipated that this mixture, termed Mix-28, would experience a moderate level of crushing during the regular IDT strength test. The third mixture used a small aggregate structure with a very soft binder (PG58-40). It was anticipated that this mixture, labeled Mix-40, would experience significant crushing during the regular IDT test. All strength testing was performed at −10 °C. The PG binder grade provides two temperatures to describe the behavior of the mixture, with the second temperature providing low temperature applicability. As the testing temperature moves further towards the warmer side from this second temperature, the mixture will be more susceptible to crushing under the loading heads versus preferred tensile straining at the center of the specimen. Therefore, at −10°C, Mix-22 (where the second temperature is −22°C) will have greater indirect tensile failure tendency versus Mix-28 (−28°C) and Mix-40 (−40°C). When mixtures are more compliant, there is a higher probability of crushing. Before starting the experimental campaign, numerical simulations were performed in order to reduce the amount of testing required to optimize the flattened IDT geometry (e.g., to determine an optimal extent of end flattening as described by the interior angle, α).

Numerical Simulations

The next step was to conduct numerical simulations of the flattened IDT specimen to provide input towards optimal specimen geometry, as described by angle α. The practical range of model geometries to be simulated was estimated from the closed-form Hondros solution. Although this is an elastic solution (and asphalt concrete is a viscoelastic material), approximate optimal values for α were obtained. More details on this analysis can be found in Braham et al. [5]. Figure 5 shows the schematics of the boundary value problems for the flattened IDT geometry and the Hondros solution.

Figure 6 shows the plot for stress ratio versus angle α for the elastic Hondros solution. The stress ratio is defined as the ratio of peak compressive stress (under the loading head) to the peak tensile stress (in the middle of the specimen), which is a useful parameter since the reduction of the amount of compressive stresses in the asphalt concrete in the vicinity of loading heads was desired, but ideally without compromising the magnitude of tensile stresses in the center. From Fig. 6, it can be observed that the stress ratio is minimized at around α=60°. Based on this result, a set of viscoelastic FE models was generated with angle α ranging from 10° to 70°.

The first set of three-dimensional FE models was generated using eight-node brick elements with average element side lengths of 2 mm. A ten-parameter generalized Maxwell model was used to model the relaxation modulus of asphalt concrete [3]. The material parameters were obtained using the creep tests, which were performed using the regular IDT. The simulations were performed with prescribed displacements to simulate a ramp-type loading head displacement of 12.5 mm/min. The simulated load reached a peak value of 32 kN at a loading time of 3.5 s. This loading condi-

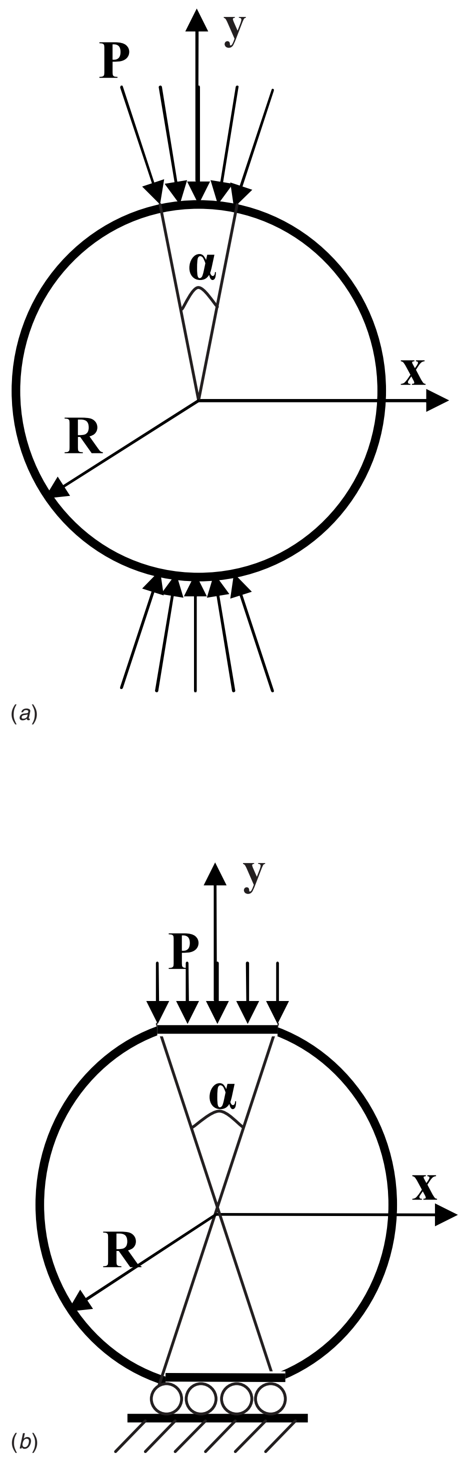

FIG. 5—*(a) Hondros solution schematic. (b) Flattened IDT schematic.*

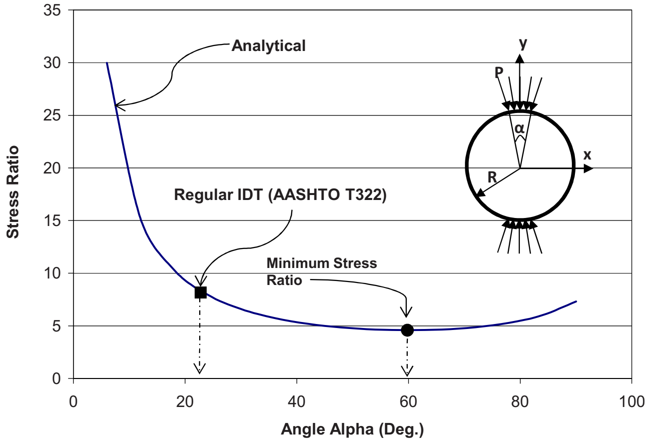

FIG. 6—*Compressive/tensile stress ratio versus internal angle α (elastic Hondros solution).*

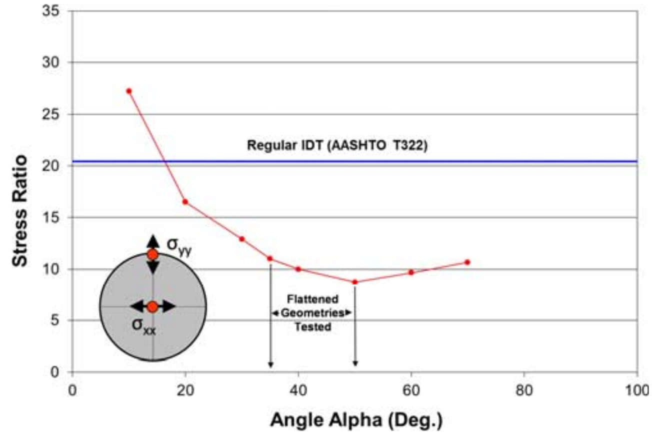

FIG. 8—*Compressive/tensile stress ratio versus angle α from FE analysis.*

tion was used to replicate typical loading conditions in the standard IDT test. The same loading conditions were utilized for all simulations and the results presented herein are those occurring at peak load. The numerical simulations indicated that the peak compressive stresses were located along the edge of loading head in the *X* direction (Fig. 5), whereas the peak shear stresses were located along the edge of the loading head in the thickness direction of the specimen. The highest tensile stresses were at the center of the specimen with peak stresses occurring at the surface, which concurs with the findings of Roque and Buttlar [2]. This is illustrated through various stress contours as shown in Fig. 7.

Figure 8 shows the plot of stress ratio (σ_{xx}/σ_{yy}) versus angle α as predicted by the FE models. Once again, the stress ratio is defined as the ratio of peak compressive stress (near the loading head) to the peak tensile stress (near the center of the specimen). The minimum compressive stress to tensile stress ratio occurs at an angle of $\alpha=50°$. The stress ratio for the regular IDT has also been shown on the plot. These results are in general agreement with the literature review findings.

In order to verify the regions with high stress gradients, a second set of FE simulations were performed with smaller element side lengths as well as with higher order elements. This time the simulations were performed for (1) FE models made with eight-node brick elements with average element side lengths of 2 mm and (2) FE models generated using a 20-node brick element with average element side length of 4 mm.

Simulation results with this set of meshes also indicated that the stress ratios are minimized at $\alpha=50°$.

The loading head on the regular IDT (with an arc of 19 mm) creates an α angle of ~14.3°. A third angle of 35° was chosen to fall approximately between the minimized stress ratio and the regular IDT. Therefore, three α angles were studied both numerically and in the laboratory: 14.3°, 35°, and 50°. Three-dimensional simulations were performed on the three mixtures; however, in this paper, only the Mix-40 results are presented. Figure 9 shows the peak normal stresses in the *Y* direction directly under the loading head in the middle of the specimen.

In Fig. 9, the regular IDT configuration showed the highest normal stresses in the *Y* direction. The narrow loading head created high stresses, which could translate into compressive crushing forces on the sample. Peak compressive stresses contributing towards crushing failure were ~2.5 and 3 times higher for regular IDT compared to flattened IDT with $\alpha=35°$ and $\alpha=50°$, respectively. As expected, as α increased, the crushing stresses decreased.

Figure 10 shows the stress distribution from three-dimensional FE analysis for three values of α. The first plot in the series, the regular IDT configuration ($\alpha=14.3°$), shows that the maximum compressive stress occurs in the middle of the sample but quickly reduces and eventually reaches zero as the side of the sample is approached. The simulations of $\alpha=35°$ and $\alpha=50°$ showed similar trends but with increased stress uniformity across the sample as α was increased. In the regular IDT configuration, the peak compressive stresses were near the middle of the loading head, while compressive stresses were relatively constant along the loaded area for the flattened IDT configurations. This variation was due to the

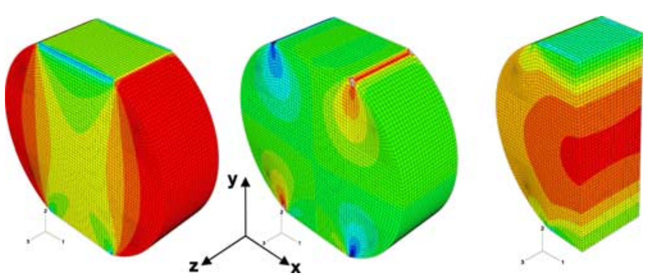

FIG. 7—*Normal stress in the Y direction, shear stress in the XY plane, and normal stress in the X direction.*

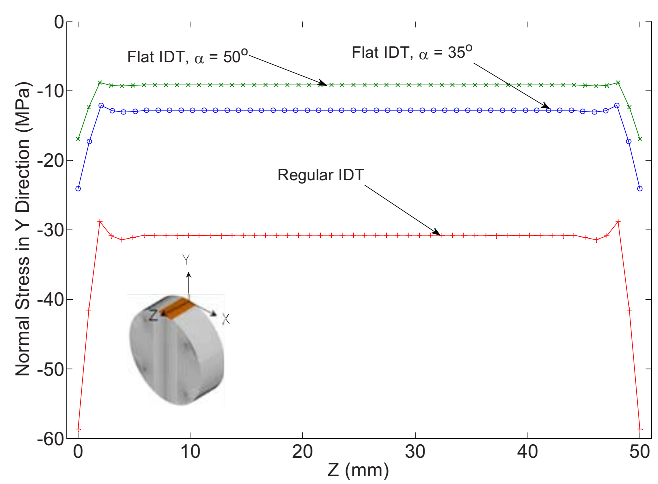

FIG. 9—*Peak normal stresses in the Y direction, Mix-40.*

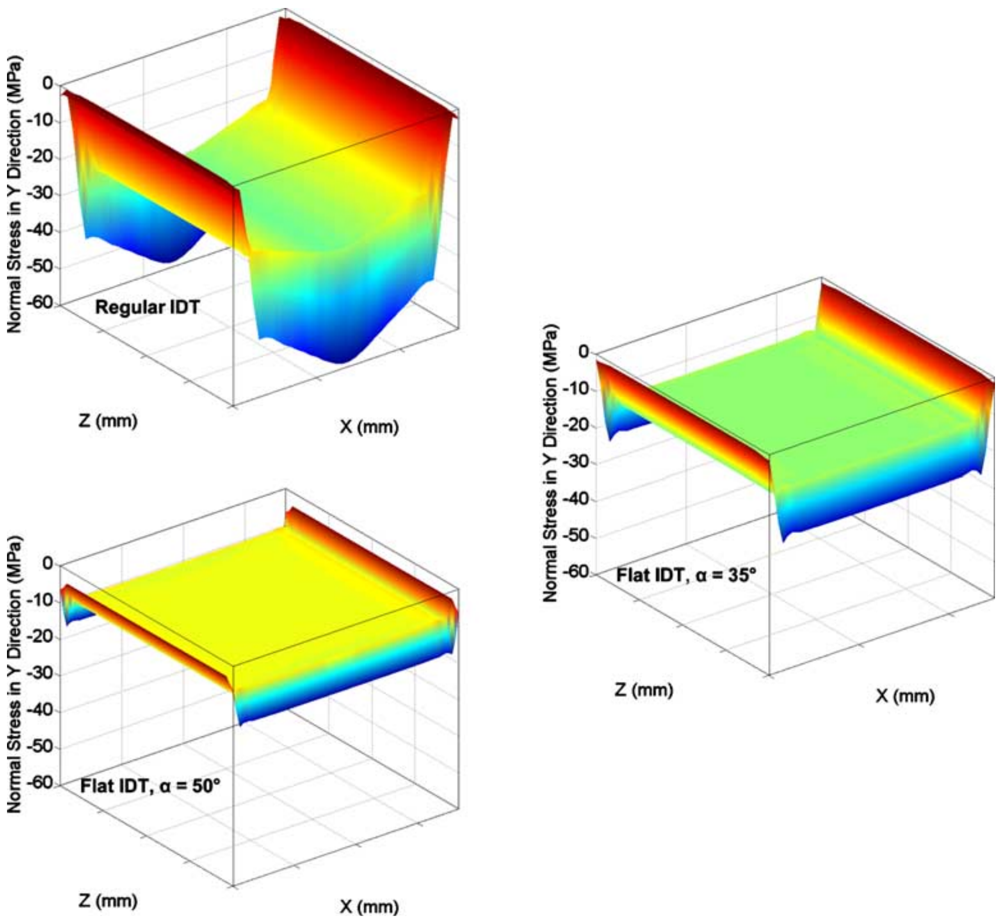

FIG. 10—*Three-dimensional peak normal stresses in the Y direction, Mix-40.*

curved shape of the loaded area for the regular IDT versus the flat loading faces for the flattened IDTs.

Figure 11 presents the computed tensile stress distribution (σ_{xx}) along the anticipated failure plane for the IDT test. Figure 11 clearly shows that as the value of α is increased, the zone of tension along the vertical axis of symmetry is decreased. This confirmed the assumption that as the α value increased, the region of indirect tension was reduced. However, the peak tensile stresses were not significantly different for the three specimen configurations. Hence, when coupled with lower crushing stresses in flattened geometries, the simulations indicated that the primary mode of failure will continue to be indirect tension for the flattened IDT configurations investigated.

Finally, Fig. 12 shows peak shear stresses in the *XY* plane directly under the loading head. The shape of the curves in Fig. 12 is similar to that in Fig. 9, with rapidly increasing stress values ap-

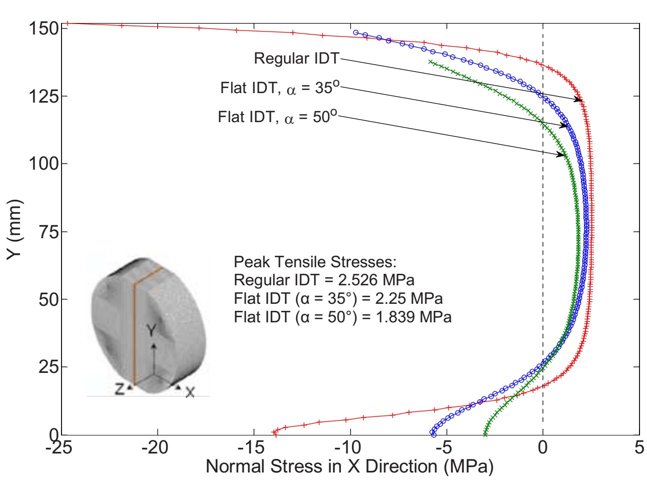

FIG. 11—*Normal stress in the X direction, Mix-40.*

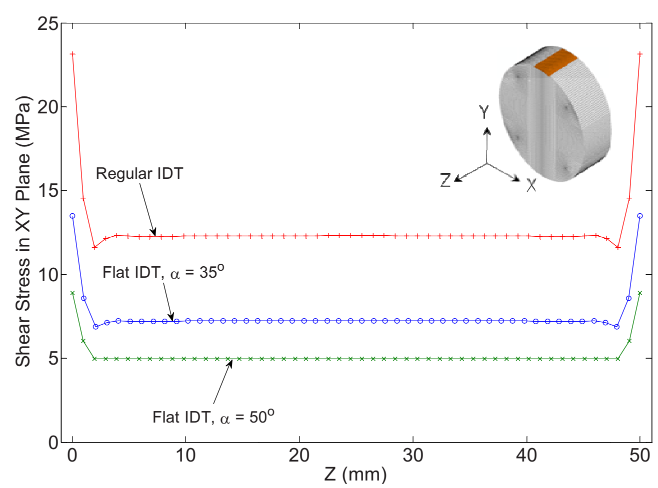

FIG. 12—*Peak shear stresses in the XY plane, Mix-40.*

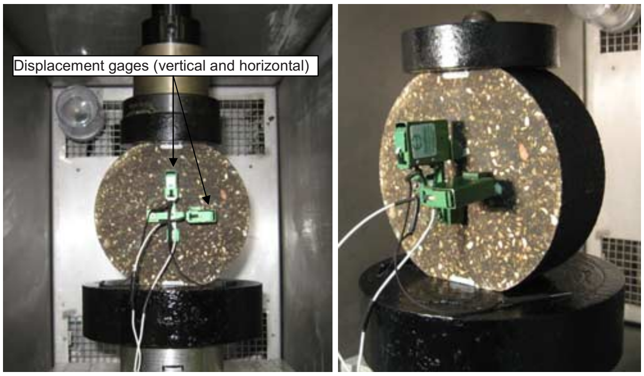

FIG. 13—*Flattened IDT test setup.*

proaching the two faces of the sample. In the *XY* plane, the shear stresses decreased with an increase in the angle α; this further demonstrates the reduced potential for crushing damage in flattened IDT configurations.

Laboratory Testing

Both the flattened IDT and the regular IDT specimens are fabricated using the same protocols. An extra step is added to the flattened IDT fabrication, which consists of using a tile saw to cut the parallel faces on the top and the bottom of the specimen. With careful trimming and measuring, it was found that a standard deviation of less than three tenths of a millimeter between the heights of the two edges of the flat faces was achieved. Figure 13 shows the flattened sample in the load frame, while Fig. 14 shows a flattened sample in comparison with the standard IDT sample. Notice the metal gage points glued near the center of the specimens, used for mounting the displacement gages.

Two sets of tests were conducted on the samples, creep tests and strength tests. Since the strength test is a destructive test, the creep tests were run first. Creep tests were performed for 1000 seconds at three test temperatures: 0, −10, and −20°C, following the AASHTO T322 procedure [10]. Three replicates were tested, with displacement gages mounted in both horizontal and vertical directions on the specimen faces. Creep compliances were calculated using a viscoelastic solution and time-temperature superposition was performed to generate creep compliance master curves [3], again using AASHTO T322. Finally, a generalized Kelvin model was fit to the master curve.

The validity of the elastic-viscoelastic correspondence principle, used in this analysis, is limited to linear viscoelastic conditions [11]. The AASHTO procedure describes the limit for linearity criteria of asphalt concrete as 500 microstrains. A more recent work

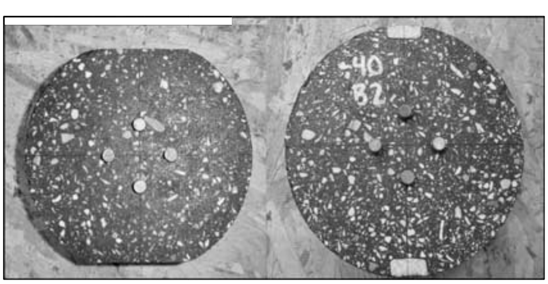

FIG. 14—*Flattened (left, α = 50°) and regular (right) IDT test specimens.*

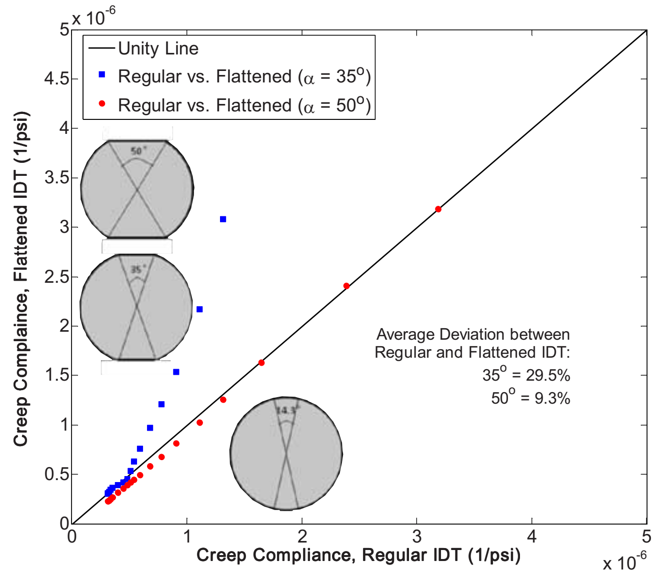

FIG. 15—*Creep compliance for Mix-22.*

by Airey and Rahimzadeh [12] suggests a linear viscoelastic limit for asphalt mixtures as low as 100 microstrains. While the test results for Mix-22 and Mix-28 showed that the maximum strain response at the center of the test specimens was limited to between 100 and 200 microstrains, Mix-40 exceeded 500 microstrains at a test temperature of 0°C. As the test data obtained for Mix-40 at 0°C was well beyond the range of linearity, it was excluded from further analysis.

The creep compliances for Mix-22, Mix-28, and Mix-40 are presented in Figs. 15–17 through unity plots. Note that the markers represent the test data and the lines represent the line of equality. All unity plots contain data at a reference temperature of −20°C.

The trends across the three sets of creep compliance curves were not straight forward. These diverse trends instigate many questions. What is an acceptable range of data before the difference between creep compliance becomes significant? The testing of a material,

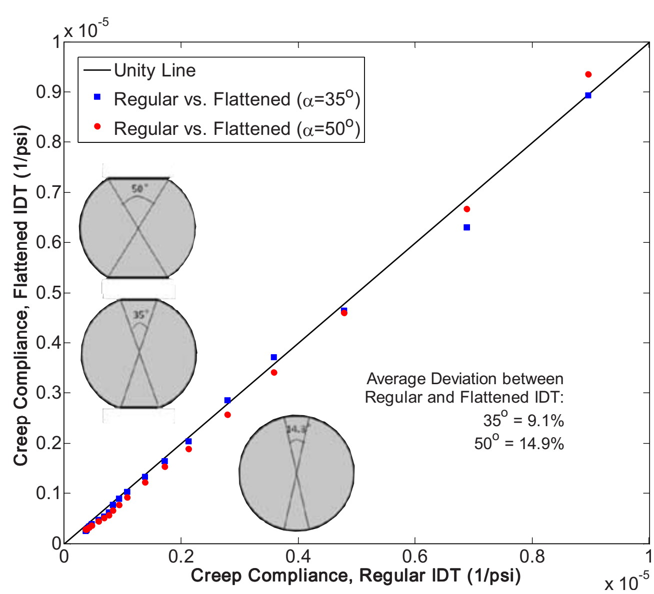

FIG. 16—*Creep compliance for Mix-28.*

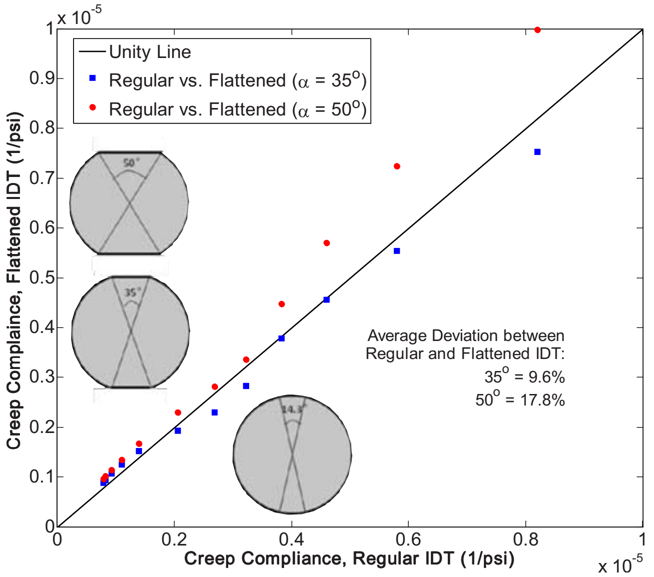

FIG. 17—*Creep compliance for Mix-40.*

especially a heterogeneous material such as asphalt concrete, often produces testing variability over 20 %, so the deviation of Alpha 35 for Mix-22 (29.5 %) may be out of testing variability, while the deviation of Alpha 50 for Mix-40 (17.8 %) may be within testing variability. Another question is the influence of shifting the data. The spread of data became larger in Mix-22 and Mix-40 as the reduced time increased, which is further away from the physical data collected. In addition, the higher reduced times lie at warmer testing temperatures, which brings into question the validity of the elastic-viscoelastic correspondence principle, as asphalt becomes more viscoelastic as the testing temperature increases. Although this creep data represents a preliminary analysis of the flattened IDT configuration, it is obvious that more work needs to be done in this area.

The strength tests were run with a constant loading head displacement of 12.5 mm/min at −10°C. Vertical and horizontal strain gages were placed on each side of the specimen, and the load was recorded throughout the test. In the AASHTO T322 standard [10], a "first failure load" was used in the calculation of the tensile strength of hot mix asphalt instead of a peak load. This concept was proposed by Buttlar and Roque [2] in an effort to define tensile strength as the stress state at the threshold of material failure in tension, which does not necessarily occur at the same load as the peak load during the IDT test. In addition, a correction factor was introduced to account for three-dimensional stress states and the effect of the strip loading. Table 2 summarizes the first failure tensile strength loads for the three mixtures and three α angles.

For all three mixtures, there was an increase of tensile strength as the value of α increased. This is reasonable, as the region of tensile stress states in the specimen decreases as the angle α increases; therefore, a larger load is needed to produce a tensile failure. Mix-40 is the most compliant mixture, so this mixture was expected to have the lowest strength values. It is interesting to note that the stiffest mixture, Mix-22, did not have the highest tensile strength. Often, the stiffer an asphalt concrete mixture, the higher its tensile strength. However, such was not the case with the mixtures investigated in this limited experimental study.

TABLE 2—*Indirect tensile strength at first failure (MPa).*

	Regular Configuration (α=14.3°)	Flattened Configuration (α=35°)	Flattened Configuration (α=50°)
Mix-22	2.30	3.67	4.08
Mix-28	4.12	5.19	6.79
Mix-40	1.26	2.41	2.77

Conclusions

A new specimen configuration has been proposed for creep compliance and tensile strength testing of asphalt concrete. The flattened IDT configuration was developed with an integrated study involving numerical analysis and laboratory testing. The following conclusions can be inferred from the study.

- The flattened IDT configuration is compatible with asphalt concrete mixtures consisting of small aggregate structures and soft binders as it reduced the amount of crushing under the loading heads.
- The FE simulations indicated that a minimum ratio of maximum compressive stress near the loading head to the maximum tensile stress in middle of the IDT specimen occurs at α=50°.
- FE simulations showed that as α increased, the zone of peak indirect tensile stresses decreased. However, the drop in peak tensile stress was not prohibitively large (11 % reduction for α=35° and 25 % reduction for α=50°).
- Using the same data analysis procedures as the regular IDT, the experimentally determined tensile strengths for the flattened IDT geometry were greater than the regular IDT.

Flattened indirect tensile testing of asphalt concrete appears to be promising, as the larger loading area reduces compressive stresses, thereby reducing the amount of crushing under loading platens and the amount of energy consumed in the damaged region. While the strength data followed expectations, the creep compliance data collected in this study was not conclusive. Between flattened geometries with angles α=35° and α=50°, the geometry with α=35° seems more promising due to the relatively low reduction in maximum tensile stress and the relatively large drop in crushing stresses. With additional work directed towards obtaining three-dimensional correction factors for the interpretation of creep compliance data, this configuration may become a viable alternative to the current AASHTO procedure for low temperature viscoelastic characterization of asphalt concrete material. This test becomes more salient as the difference between the testing temperature and the low temperature binder grade increases. Other extensions of this work could be in the areas of moisture damage evaluation and cyclic testing, as the reduced stress intensity and damage under the loading heads in the flattened configuration would likely improve the repeatability and quality of measurements obtained.

Acknowledgments

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