Development of a Flattened Indirect Tension Test for Asphalt Concrete

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ABSTRACT

The Indirect Tension Test (IDT) is frequently used in civil engineering because of its benefits over direct tension testing. During the Strategic Highway Research Program (SHRP), in the mid-1990's, an IDT protocol was developed for evaluating tensile strength of Hot Mix Asphalt (HMA) mixtures. However, with the increased use of finer aggregate gradations and polymer modified asphalt binders in HMA mixtures, the IDT results can be misleading because of crushing failure under the narrow loading heads. For such mixtures the 150-mm diameter, 50-mm thick, cylindrical specimens tends to fail in crushing beneath the loading heads versus the desired indirect tension at the center of the specimen. Therefore, a new specimen configuration is proposed for strength testing of HMA. In place of the loading heads at the top and bottom, the specimen is 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 3 different HMA mixtures. This integrated modeling and testing study shows that for the HMA mixtures with fine aggregate gradations and compliant asphalt binders used in this study, the flattened IDT eliminates the severe crushing observed in the regular IDT. It is recommended that further testing and analysis be performed on the flattened IDT arrangement, leading to a revision of the current AASHTO standard for IDT testing as asphalt mixtures.

INTRODUCTION

Tensile strength of Hot Mix Asphalt (HMA) is an important design parameter used in various flexible pavement design procedures. The recently developed AASHTO Mechanical Empirical Pavement Design Guide uses tensile strength as an important design parameter to predict the low temperature cracking in flexible pavements. Recently, a number of pavement cracking prediction models have been explored and tensile strength is a key parameter in most of these sophisticated fracture and/or damage models. Thus, it is important to accurately measure the tensile strength of HMA in laboratory.

The indirect tensile testing mode is a very practical configuration for testing of asphalt concrete, as HMA samples are often cylindrical in shape. When samples are taken from the field, a core barrel is utilized, producing cylindrical specimens. In addition, the laboratory equipment used to produce HMA samples uses a cylindrical shaped mold during compaction. The HMA mixtures exhibit a wide verity of tensile strengths depending on asphalt binder grade and aggregate gradation. Due to dependence of tensile strength on number of factors it is important that each mixture be individually tested to properly characterize the asphalt mixture.

LITERATURE REVIEW

The Indirect Tension Test (IDT) was fully developed for HMA in the mid 1990's [1, 2] through the research efforts put together during SHRP. The research was finalized in form of an AASHTO standard for testing and analysis [3], namely AASTHO T-332.

The evaluation of tensile strength of both field and lab samples within the AASHTO standard was derived as an extension of the simple plane stress formula first developed by Hertz in 1881[4]. The latter is given by:

$$S_t = \frac{2 \times P}{\pi \times b \times D} \quad \text{.........} \quad \textbf{(1)}$$

where S_t is the tensile strength of specimen, P is the failure load for specimen, b is the thickness of specimen, and D is the diameter of specimen. Hondros [5] provided the refinement to above shown form by solving the problem for loads applied in form of a finite-width strip.

In the AASHTO T332 standard, a "first failure load" is used in the calculation of the tensile strength of HMA instead of peak load. This concept was proposed by Buttlar and Roque [1, 2] in effort to define tensile strength as the stress state at the threshold of material failure in tension, which does not necessary occur at the same load as the peak load during the IDT test. In addition, a correction factor was introduced to account for 3D stress states and the effect of the strip loading.

The IDT setup developed for HMA uses a 19mm wide loading strip on the top and bottom of the testing specimen. With the increased use of finer aggregate gradations and polymer modified asphalt binders in HMA mixtures, the IDT results can be suspect, particularly at testing temperatures above 0 °C because of crushing under the narrow loading heads. Figure 1 illustrates one such example from the current study. Wagoner et al. [6] briefly discussed this problem for an HMA interlayer mixture manufactured with heavily modified polymer asphalt binder and fine aggregate gradation, specially designed to reduce reflective cracking of HMA overlay pavements. One solution to this crushing problem is to increase the contact area between the loading heads and sample.

In the area of rock mechanics, the idea of a flattened Brazilian disc specimen has been studied [7, 8, and 9]. This testing configuration increases the surface area between the loading heads and sample, thus reducing the shear failures in the specimen, and increasing the purity of tensile failure within the sample. However, flatter ends reduces the tensile stress in the middle of the specimen. Thus, it is important to identify an optimum test geometry that minimizes the crushing and failures near the loading heads, and at the same time provides sufficient tension in the middle of specimen for a global tensile failure. A closed form solution does not exist that imitates the exact specimen geometry and loading conditions. Finite element (FE) simulation is a powerful tool that can be used to solve a boundary value problem such as one studied. FE analysis was adopted as the method of choice to determine optimum specimen geometry.

Figure1 - Crushing Failure under Regular IDT Loading Head (Mix-40)

APPROACH

For determining suitable test geometry an integrated testing and modeling approach was adopted. The process can be divided into following steps:

- Selection and laboratory characterization of suitable HMA mixtures
- Numerical simulations to determine the most favorable test geometry
- Manufacture and test the flattened IDT test specimens on basis of findings from numerical simulations

The first step in the experimental plan was selection and testing the three HMA mixtures in the regular IDT testing configuration. The three HMA mixtures were chosen to bracket the anticipated crushing failure. Therefore, one mixture used a large aggregate structure with a stiff asphalt binder. We anticipated that this mixture, called Mix-22, would not crush during the regular IDT test. The second mixture used a small aggregate structure with a semi-stiff binder. We anticipated that this mixture, called Mix-28, had a chance of crushing during the regular IDT test. The third mixture used a small aggregate structure with a soft binder. We anticipated that this mixture, called Mix-40, would crush during the regular IDT test. Table 1 shows each HMA mixture's properties.

Table 1 – Mixture Characteristics

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

Creep data and strength data were obtained from the regular IDT testing protocol. This data will be reviewed in a following section.

The second step in the experimental plan was to perform numerical simulations. The range of simulation model geometries were obtained on basis of the existing closed form solutions, particularly the Hondros Solution. This is an elastic solution, that assumes the load is applied normal to the surface of the specimen, and that the specimen is circular, not flattened. Approximate optimal values for alpha were obtained from this solution. Once the approximate value of alpha was obtained, viscoelastic FE simulations of flattened IDT samples were performed at different alpha values, where the different alpha values bracketed the approximate alpha value found in the Hondros solution. These simulations will be reviewed in more detail in the section on modeling.

The third and final step was to fabricate the specimens as per the findings from simulation results and test the three HMA mixtures in the flattened IDT configuration. Again, creep and strength data were collected for specimens tested in this configuration.

REGULAR IDT TEST RESULTS

As mentioned early, most HMA samples are cylindrical in shape with a diameter of 150-mm, whether from field core samples or the Superpave Gyratory Compactor. In order to fabricate regular IDT specimens, one simply slices a core into 50-mm thick disks. The sample is then ready for regular IDT testing.

Three HMA mixtures were tested to obtain creep properties and indirect tensile strength in the AASHTO T-332 testing configuration. Relaxation moduli of the three mixtures were obtained from creep tests, and relaxation modulus master curves for three mixtures are plotted in Figure 2. The time-temperature superposition principle was used to build the relaxation modulus master curves from the 1000-second creep tests conducted at three temperatures. At low temperatures (below 0°C) HMA behaves as a linear viscoelastic material, thus for modeling purpose it is important to characterize its time and temperature dependent properties.

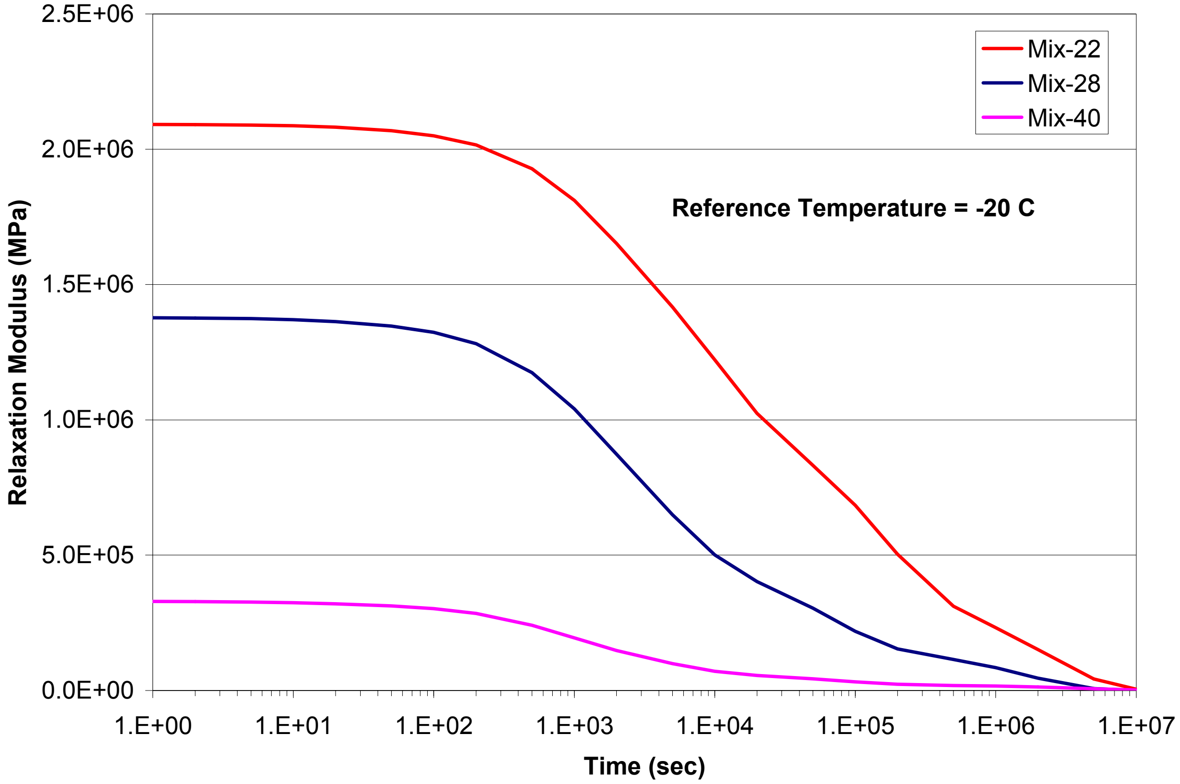

Figure 2 – Relaxation Modulus Mastercurves for Mix-22, Mix-28, and Mix-40 in the Regular IDT Configuration

In addition to the creep data, strength data was collected. The strength tests were run with a constant loading head displacement of 12.5-mm/min. Vertical and horizontal strain gages are placed on each side of the specimen, and the load is recorded throughout the test. Four different techniques were used in analyzing the tensile strength data. The tensile strength is summarized in Table 2.

Table 2 – Tensile Strengths in Regular IDT Configuration (MPa)

	IDT First Failure	IDT Peak Load	Hondros Solution First Failure	Hondros Solution Peak Load
Mix-22	2.30	2.62	4.21	4.80
Mix-28	4.12	4.13	7.55	7.56
Mix-40	1.26	1.48	2.31	2.72

IDT first failure is the point when tensile induced damage begins to occur on the face of the HMA specimens. When running the test, both horizontal and vertical displacements are recorded at the center on each side of the specimen. Taking the difference of the horizontal and vertical displacement, a peak value of this difference is generally reached before the peak load is achieved. The load is recorded at this time, and denoted as the IDT first failure load. This load, and the peak load, is used to determine the tensile strength. The Hondros Solution was also used to calculate tensile strengths at the first failure and peak load.

MODELING

A set of FE simulations were performed to optimize the flattened IDT specimen geometry. As explained earlier Hondros solution was used to identify the suitable bracket for optimum flattened IDT geometry. Figure 3(a) shows the schematic for Hondros solution. An equivalent schematic for the flattened IDT is as shown in figure 3(b).

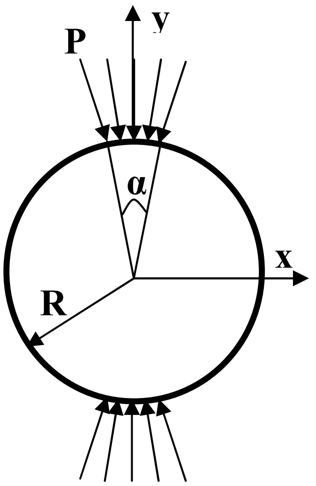

Figure - 3(a) Hondros Solution Schematic

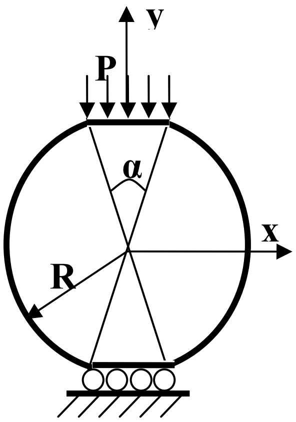

Figure - 3(b) Flattened IDT Schematic

Figure 4 shows the plot for stress ratio versus angle α for Hondros solution. The stress ratio is defined as the ratio of peak compressive stress (under loading head) to the peak tensile stress (at the middle of specimen). One of the main objectives of this study is to reduce the amount of compressive stresses in the asphalt concrete in vicinity of loading heads and yet obtain sufficient tensile stresses in the center. From Figure 4, it can be observed that the ratio minimizes at around $\alpha = 60^o$ Based on this result a set of FE models were generated with angle α ranging from 10^o to 70^o. In addition to flattened IDT setup a regular IDT was also modeled.

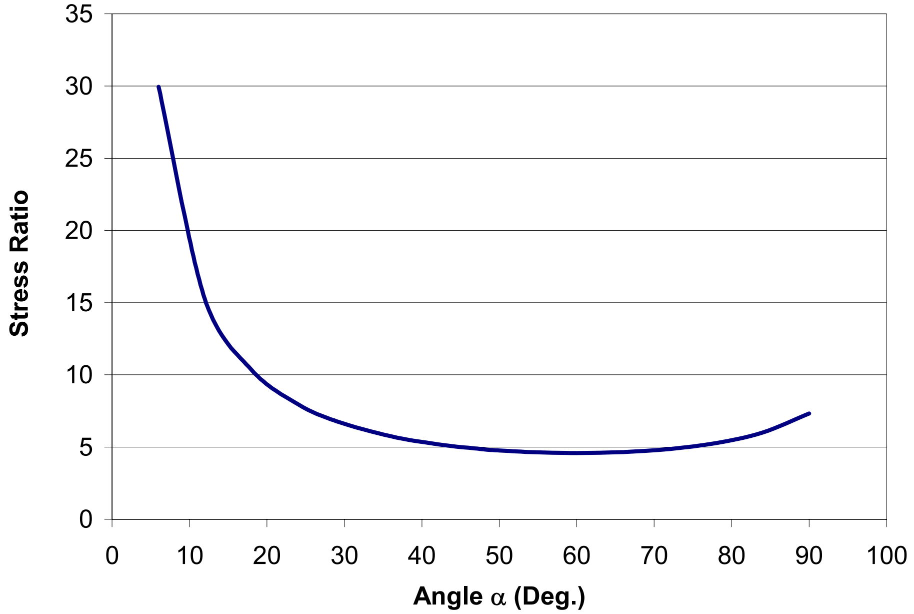

Figure 4 – Compressive/Tensile Stress Ratio versus Internal Angle Alpha, Hondros Solution

All the FE simulations for this study were performed using commercially available FE software ABAQUS. The first set of three dimensional FE models were generated using 8-node brick elements with average element side lengths of 4-mm. Due care was taken to control the element size for various meshes. The simulations were performed to imitate the laboratory testing conditions. A 10-parameter generalized Maxwell model was used to model the relaxation modulus of asphalt concrete. The material parameters were obtained using the creep tests, which were performed as part of regular IDT. The FE simulations indicated that the peak compressive stresses were located along the edge of loading head in x-direction, whereas the peak shear stresses were located along the edge of loading head in thickness direction of the specimen. The highest tensile stresses are at the center of specimen with peak stresses at the surface. This is illustrated through various stress contours shown in Figure 5.

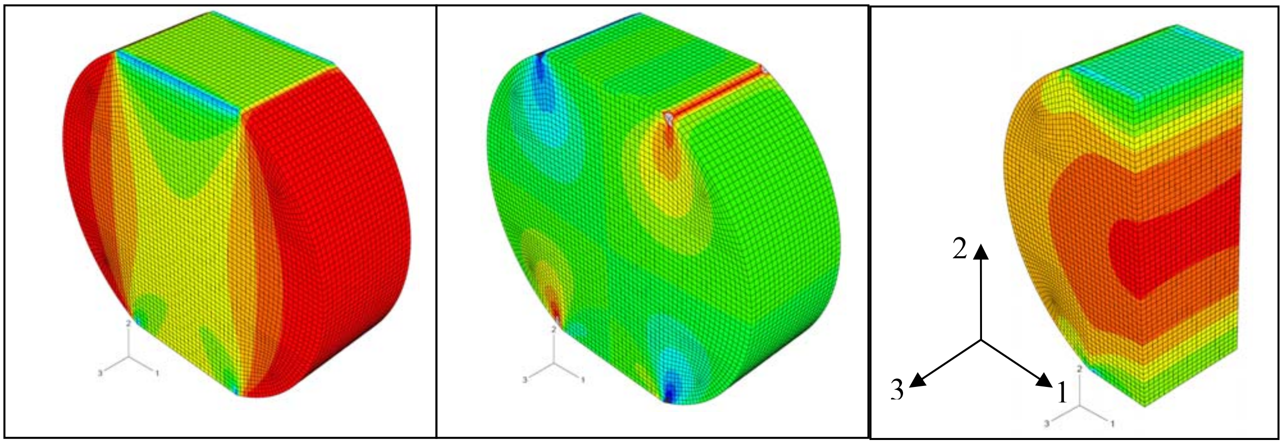

Figure 5 – Stress in 2-2 Direction, Shear Stress in 1-2 Direction, Stress in 1-1 Direction

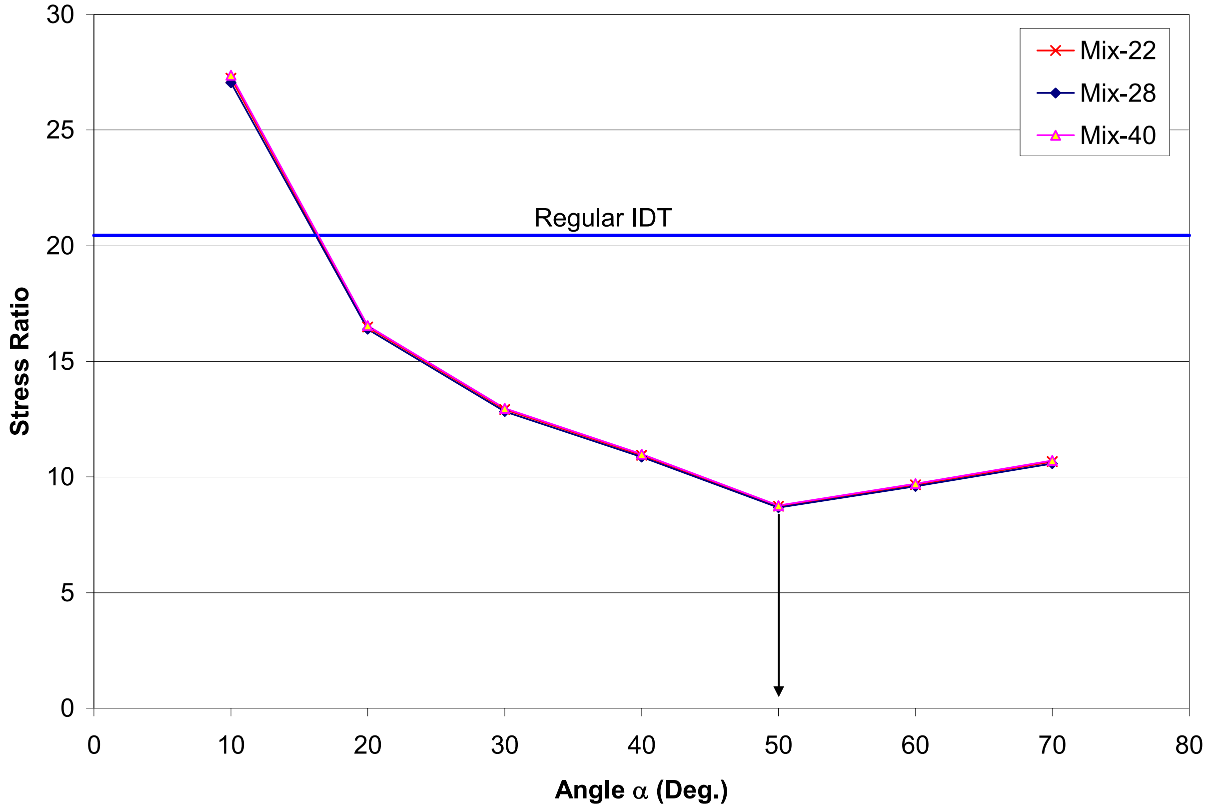

Figure 6 – Compressive/Tensile Stress Ratio versus Angle α from FE Analysis

Figure 6 shows the plot of stress ratio versus angle α. 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 specimen). Here, we can see that the minimum compressive stress to tensile stress ratio occurs at α angle of 50°. The stress ratio for regular IDT has also been shown on the plot. The stress ratio for regular IDT was found to be approximately 21. These results are in accordance with the findings found in literature on rock mechanics.

The region of the peak compression has very high stress gradients. In the plain FE simulations the accuracy of results in this region can be highly dependent on the mesh size as well as type of element. In order to further verify that the stress ratio minimizes at $\alpha = 50^{o}$ a second set of FE simulations were performed. This time the simulation were performed for: (1) FE models made with 8-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 these set of meshes also indicated that the stress ratios minimize at $\alpha = 50^{o}$.

It is important to note that the FE analyses performed in this study were limited to linear material behavior. The test itself however has number of non-linear material phenomenon such as cracking (fracture), damage, plasticity etc. These phenomena have not been modeled in this initial study. However as the next iteration step it has been planned that some of these non-linear material behaviors will be studied to better optimize the flattened IDT test.

FLATTENED IDT TEST and RESULTS

The flattened IDT specimens are fabricated exactly the same as the regular IDT, with the addition of one more step. A tile saw was used to cut the parallel faces on the top and the bottom of the specimen. With careful measuring, a standard deviation of less than three tenths of a millimeter between the height of the two edges of the flat faces was achieved. Figure 7 shows a flattened IDT sample after fabrication, with the gage points attached for the vertical and horizontal strain gages.

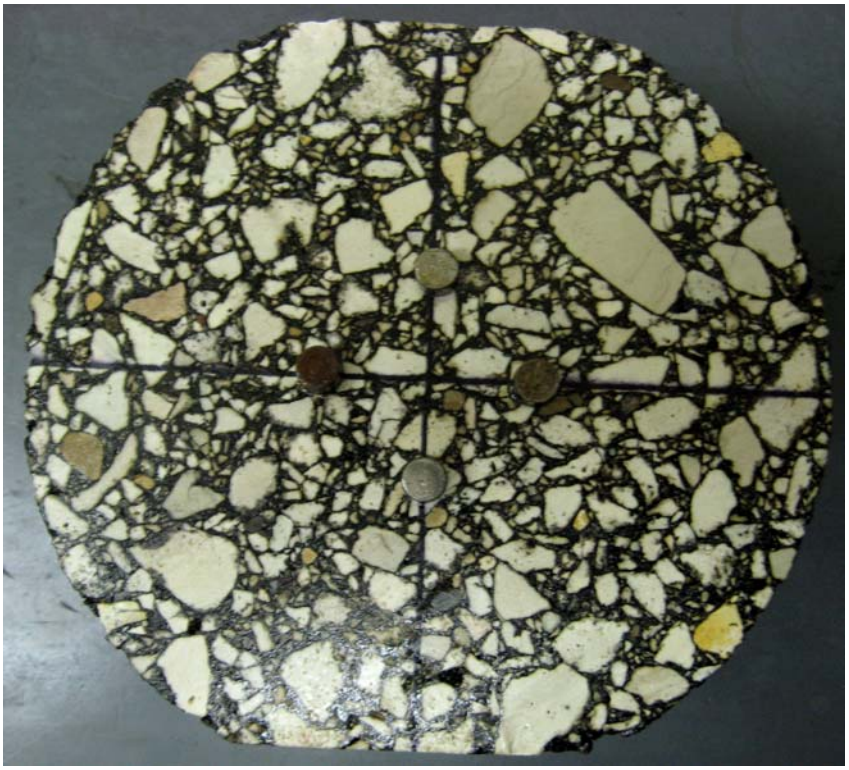

Figure 7 – Flattened IDT Specimen

Figure 8 – Flattened IDT Test Setup

Although creep data was collected for the flattened IDT mixtures, we do not currently have an analysis technique for the calculation of creep compliance. Therefore, we will only present the tensile strengths. Since we do not have an exact solution for the flattened IDT configuration's tensile strength, we found the tensile strengths using the same calculations as the regular IDT. These tensile strengths are summarized in Table 3.

Table 3 – Tensile Strengths in Flat IDT Configuration

	IDT First Failure	IDT Peak Load	Hondros Solution First Failure	Hondros Solution Peak Load
Mix-22	4.08	7.21	6.17	10.89
Mix-28	6.79	7.35	10.25	11.11
Mix-40	2.77	3.04	4.21	4.63

Figure 9 compares the three HMA mixtures, in both the regular and flattened IDT configuration, with all four strength techniques.

It is interesting to note that the flattened IDT (the circles in Figure 9) gave a higher tensile strength than the regular IDT (the squares in Figure 9). All mixtures, except Mix-22 in the flattened state, showed a consistent increasing strength trend from left to right going through the different analysis techniques.

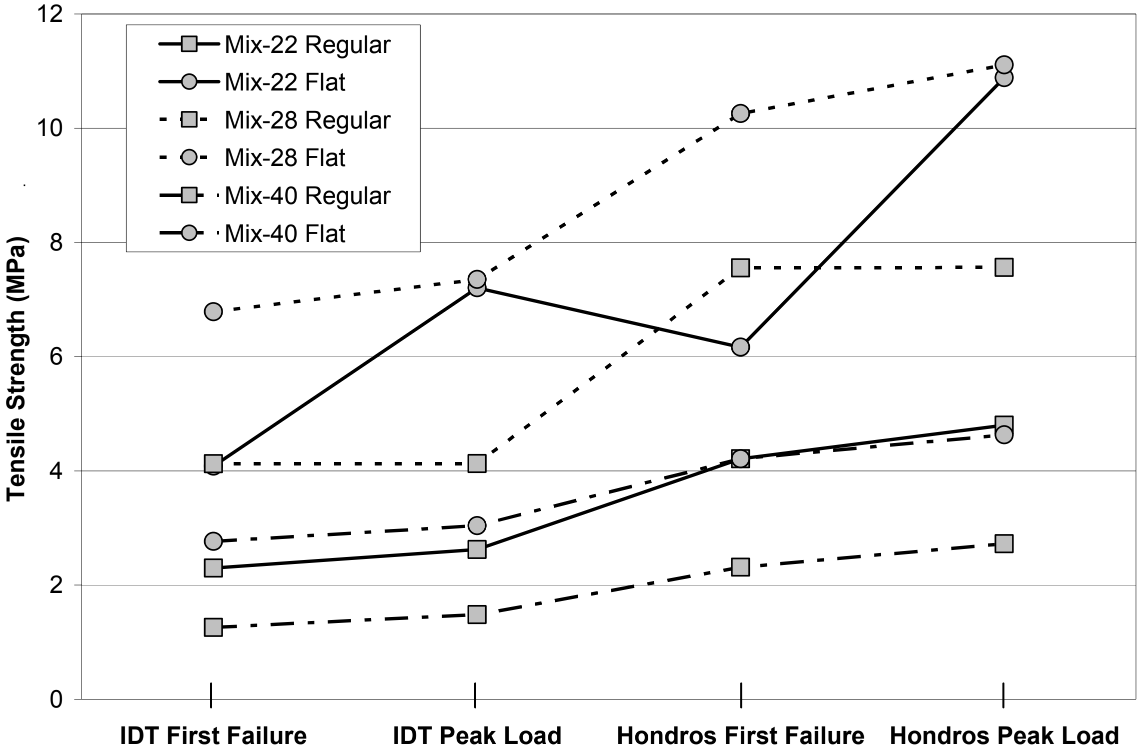

Figure 9 – Tensile Strength Comparison (the lines do not have any numerical significance, they are only used to connect each mixture's tensile strength with each method)

CONCLUSIONS

A new specimen configuration has been proposed for tensile strength testing of Hot Mix Asphalt. The flattened IDT configuration was developed with an integration of numerical analysis and laboratory testing. The following conclusions can be inferred from the study:

- Flattened IDT setup is compatible with HMA mixtures consisting of small aggregate structures and soft binders as it reduces the amount of crushing under the loading heads
- The FE simulations indicate a minimum ratio of compressive stresses near the loading head and to the tensile stresses in middle of IDT specimen at angle $\alpha = 50^o$
- Using the same data analyses procedures as regular IDT, the tensile strength predictions for flattened IDT are greater than regular IDT
- Viscoelastic analysis for evaluating creep and relaxation material behavior in this flattened IDT geometry was successful

FUTURE RESEARCH

A set of assumptions were made during the course of this study, therefore, a set of future studies are planned to eliminate these assumptions. The findings from this study also generated a number of recommendations that will guide the direction of future research. The future research topics anticipated on basis of this study are:

- Validation studies for various class of HMA mixtures to ensure the success of flattened IDT approach
- FE simulations performed using sophisticated material behavior to account for crushing near the loading heads and tensile cracking in the middle of specimen
- Development of tensile strength and creep analysis procedure for flattened IDT through an integrated modeling and testing program

It is recommended that further testing and analysis be performed on the flattened IDT arrangement, and if successful, leading to a revision of the current AASHTO standard for IDT testing as asphalt mixtures.

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