Analysis of creep properties using a flattened indirect tension test for asphalt concrete

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ABSTRACT: The Indirect Tension Test (IDT) is frequently used for evaluation of asphalt material viscoelastic creep properties. With the increased use of finer aggregate gradations and polymer modified asphalt binders in asphalt materials, crushing can occur under the narrow loading heads. The new specimen configuration proposed has a trimmed area under the loading heads, creating a "flattened-IDT." This integrated modeling and testing study shows that the flattened IDT reduces the crushing observed in the regular IDT. This study shows that the flattened configuration alters creep properties approximately 10-16% within typical experimental variability.

1 INTRODUCTION AND MOTIVATION

The Indirect Tension Test is frequently used in the evaluation of asphalt materials due to its convenience for capturing both viscoelastic properties and tensile strength. The indirect tensile testing mode is a very practical configuration for testing of asphalt concrete, as Hot Mix Asphalt (HMA) samples are often cylindrical in shape. When samples are taken from the field, a core barrel is utilized, producing cylindrical specimens, as illustrated in Figure 1. In addition, the laboratory equipment used to produce HMA samples uses a cylindrical shaped mold during compaction. During the Strategic Highway Research Program (SHRP), in the mid-1990's, a test protocol was developed for evaluating creep and strength properties of HMA mixtures (Buttlar, Roque, 1992) in indirect tension. The test was, somewhat arbitrarily, dubbed with the acronym "IDT" during the SHRP program. 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 HMA 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. In place of the traditional 150-mm diameter, 50-mm thick, cylindrical specimen, a previous study introduced a new specimen configuration for strength testing of HMA (Dave *et al*., 2007). 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." It was shown that the flattened IDT significantly reduced crushing in the vicinity of loaded areas. The study, however, did not whether or not tensile creep compliance could be accurately measured with the new system. This is a key issue, because in practice, creep compliance and tensile strength are often measured on the same sample.

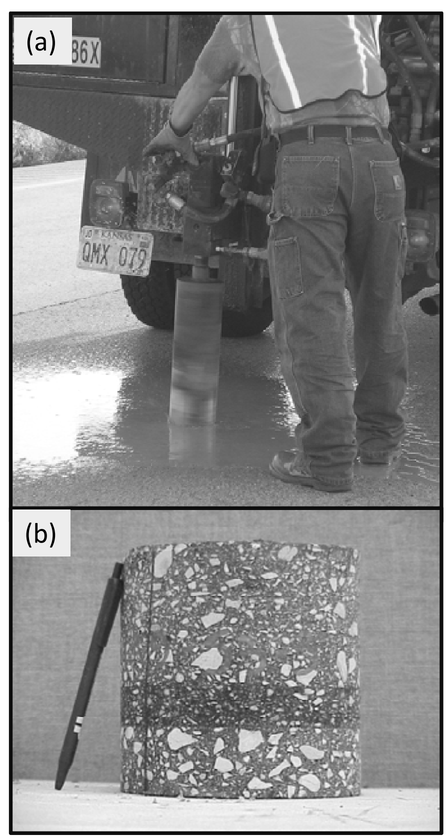

Figure 1. (a) Coring Operation, (b) Field sample procured through coring.

2 BACKGROUND

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 during the strength testing. Figure 2 illustrates one such example from the current study.

Figure 2. Crushing under loading heads.

Wagoner *et al.* 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.

Towards this end, it is important to identify a test geometry that minimizes the material damage near the loading heads while providing sufficient tension in the middle of specimen for a global tensile failure. In the area of rock mechanics, the idea of a flattened Brazilian disc specimen has been studied (Wang *et al.,* 2004). This testing configuration increases the surface area between the loading heads and sample; thereby reducing localized crushing and increasing the predominance of failure in tension within the sample.

A closed-form solution does not appear to exist, which considers the exact specimen geometry and loading condition present in the flattened IDT arrangement. Finite element (FE) simulation was employed in this study in an effort to optimize specimen geometry. With the geometry determined, the creep analysis should be performed to see if the analysis is reasonable.

3 APPROACH

In an effort to determine 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 HMA mixtures
- Numerical simulation to determine the most favorable test geometry
- Manufacture and testing of flattened IDT specimens for validation of concept

3.1 *Material Characterization*

The first step in the experimental plan was the selection and testing of three HMA mixtures in the regular IDT configuration. The three HMA mixtures were chosen in an attempt to elicit differing amounts of crushing failure, which is thought to be related to maximum aggregate size and binder stiffness. Therefore, one mixture was designed to have a large aggregate structure and was combined with a relatively stiff asphalt binder. It was anticipated that this mixture, labeled Mix-22, would not exhibit significant crushing during strength testing in the AASHTO T322 IDT test (2004). The second mixture was designed to have a small aggregate structure and a semi-stiff binder. It was 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 soft binder. It was anticipated that this mixture, labeled Mix-40, would experience significant crushing during the regular IDT test. Table 1 and Table 2 summarize aggregate and binder characteristics for the three mixes used in this study.

Table 1. Aggregate Characteristics.

	Nominal Maximum Aggregate Size	Aggregate Structure
Mix-22	9.5 mm	Large
Mix-28	4.75 mm	Small
Mix-40	4.75 mm	Small

Table 2. Binder Characteristics.

	Binder Type	Binder Characteristics
Mix-22	PG64-22	Stiff
Mix-28	PG58-28	Semi-Stiff
Mix-40	PG58-40	Soft

The second step in the study was to perform numerical simulations. Before conducting numerical analyses, the Hondros closed form solution (Hondros, 1959) was applied to obtain an estimate of the optimal length of the flattened ends, as described by an interior angle alpha. This is an elastic solution, which assumes that the load is applied normal to the surface of the specimen and that the specimen is circular, not flattened. That notwithstanding, an approximate optimal value for alpha was obtained from this solution. Next, viscoelastic FE simulations of flattened IDT samples were performed at different alpha values, ranging in the vicinity of the value suggested by the elastic solution..

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

3.2 *The Hondros Solution*

The Hondros (1959) solution used an elastic closed-form solution, where the load is assumed to be applied normal to the cylindrical specimen. By changing the alpha value, the width of the simulated flattened face can be increased. Figure 3 illustrates this concept.

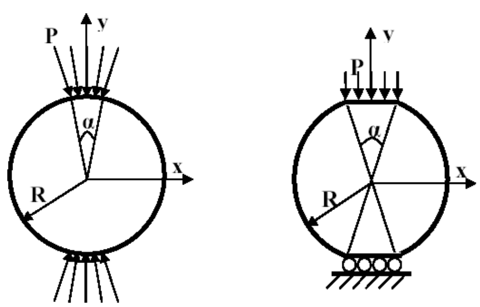

Figure 3. Comparison of Hondros solution assumptions (left) and flattened-IDT configuration (right).

Equations 1 and 2 present the Hondros solution:

$$\sigma_{xx}(x,0)=\frac{2P\left(-ArcTan\left[\dfrac{\left(1-\frac{x^2}{R^2}\right)Tan\left(\frac{\alpha}{2}\right)}{1+\frac{x^2}{R^2}}\right]+\dfrac{\left(1-\frac{x^2}{R^2}\right)Sin(\alpha)}{1+\frac{x^4}{R^4}+\frac{2x^2Cos(\alpha)}{R^2}}\right)}{a\pi w} \tag{1}$$

$$\sigma_{yy}(0,y)=\frac{-2P\left(ArcTan\left[\dfrac{\left(1+\frac{y^2}{R^2}\right)Tan\left(\frac{\alpha}{2}\right)}{1-\frac{y^2}{R^2}}\right]+\dfrac{\left(1-\frac{y^2}{R^2}\right)Sin(\alpha)}{1+\frac{y^4}{R^4}-\frac{2y^2Cos(\alpha)}{R^2}}\right)}{a\pi w} \tag{2}$$

where w = specimen thickness and a = width of loading strip.

Using the Hondros solution, the horizontal and vertical deformations are presented in Equation 3.

$$H=\frac{P}{E\,w}(I_1-\nu I_2);\quad V=\frac{P}{E\,w}(I_4-\nu I_3) \tag{3}$$

where I_j (j=1, 2, 3, 4) are dimensionless factors that depend on specimen dimensions and gage length, GL, as shown in Equation 4.

$$\begin{aligned} I_1&=\frac{w}{P}\int_{-GL/2}^{GL/2}\sigma_{xx}(x,0)\,dx; \quad I_2=\frac{w}{P}\int_{-GL/2}^{GL/2}\sigma_{yy}(x,0)\,dx \\ I_3&=\frac{w}{P}\int_{-GL/2}^{GL/2}\sigma_{xx}(0,y)\,dy; \quad I_4=\frac{w}{P}\int_{-GL/2}^{GL/2}\sigma_{yy}(0,y)\,dy \end{aligned} \tag{4}$$

3.3 *Viscoelastic Solution*

The Hondros Solution is an elastic solution. Asphalt concrete, however, is a visco-elastic material. Zhang *et al,* (1997) have extended Hondros solution using the elastic-viscoelastic correspondence principle (see, for example, Christensen 1982). The corresponding viscoelastic solution is as shown in Equation 5.

$$\begin{aligned} H(t)&=\frac{K_1}{w}\int_0^t P(t-t')\frac{\partial J(t)}{\partial t'}dt'+\frac{K_2}{w}\int_0^t P(t-t')\frac{\partial V(t)}{\partial t'}dt' \\ &\quad+\frac{K_1}{w}J_0P(t)+\frac{K_2}{w}V_0\,P(t) \\ V(t)&=\frac{K_3}{w}\int_0^t P(t-t')\frac{\partial J(t)}{\partial t'}dt'+\frac{K_4}{w}\int_0^t P(t-t')\frac{\partial V(t)}{\partial t'}dt' \\ &\quad+\frac{K_3}{w}J_0P(t)+\frac{K_4}{w}V_0\,P(t) \end{aligned} \tag{5}$$

where *J(t)* denotes deviatoric creep compliance and *V(t)* denotes volumetric creep compliance. The geometric coefficients K_j are calculated from I_j *(j=1, 2, 3, 4)*, which depend on specimen geometry and gage length.

For the creep testing performed, the load history can be approximated in Equation 6.

$$P(t)=P_oH(t) \tag{6}$$

where *H(t)* is a heaviside function. Therefore, Equation 5 becomes:

$$\begin{aligned} H(t)&=\frac{K_1}{w}P_0\,J(t)+\frac{K_2}{w}P_0\,V(t) \\ V(t)&=\frac{K_3}{w}P_0\,J(t)+\frac{K_4}{w}P_0\,V(t) \end{aligned} \tag{7}$$

By means of Equation 7, *J(t)* and *V(t)* can be solved at each data point. It should be noted that the applicability of the correspondence principle is limited to linear viscoelastic materials.

4 TESTING AND ANALYSIS

For this study, both regular and flattened IDT specimens were tested. For comparison, Figure 4 shows regular and flattened IDT specimens side-by-side. Notice the metal gage points glued near the center of the specimens, used for mounting the displacement gages.

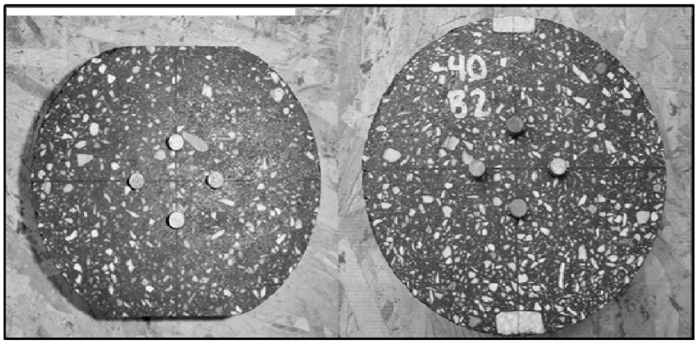

Figure 4. Flattened (left) and Standard (right) IDT Test Specimens.

Creep tests were performed for 1000 seconds at three test temperatures, 0, -10, and -20°C, following the AASHTO T322 procedure (2004). Three replicates were tested, with displacement gages mounted in both horizontal and vertical directions on specimen faces. Compliances were calculated using the viscoelastic solution outlined in section 3.3, and time-temperature superposition was performed to generate creep-compliance master curves (Roque *et al.*, 1995), again using T322. Finally, a generalized Kelvin model was fit to the master-curve.

The AASHTO procedure describes the limit for linearity criteria of asphalt concrete as 500-microstrains. More recent work by Airey and Rahimzadeh, 2004, suggest a linear viscoelastic limit for asphalt mixtures as low as 100-microstrains. These criteria were visited during the data analysis, since the validity of elastic-viscoelastic correspondence principle is limited to linear viscoelastic conditions (Papagiannakis and Masad, 2008). Test results for Mix-22 and Mix-28 showed that the peak strain response near the center of the test specimens were limited to 100-microstrains or lower in most instances. For tests performed at 0°C at very long loading times (> 500-seconds) a level of 200-microstrains was reached. In the case of Mix-40, the strains exceeded 500-microstrains at a test temperature of 0°C. As the test data obtained for Mix-40 at 0°C was beyond the range of linearity, it was excluded from further analysis.

The creep compliance mastercurves for Mix-22, Mix-28 and Mix-40 are presented in Figures 5, 6, and 7. Note that the markers represent the test data and the lines represent the generalized Kelvin model representing the mastercurve. All mastercurves are plotted at a reference temperature of -20°C.

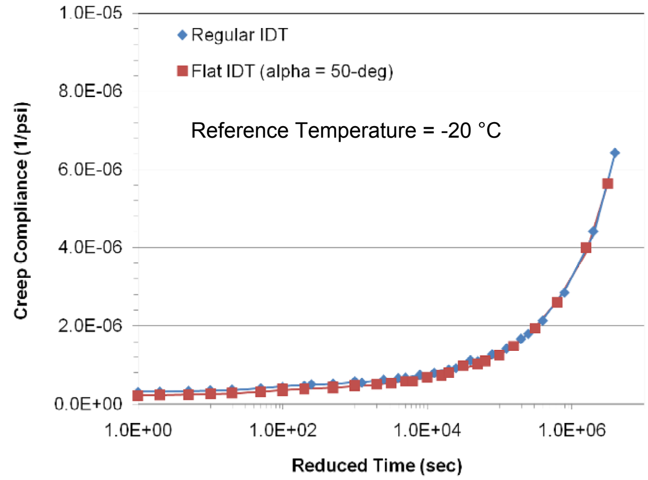

Figure 5. Mix-22 Creep Compliance.

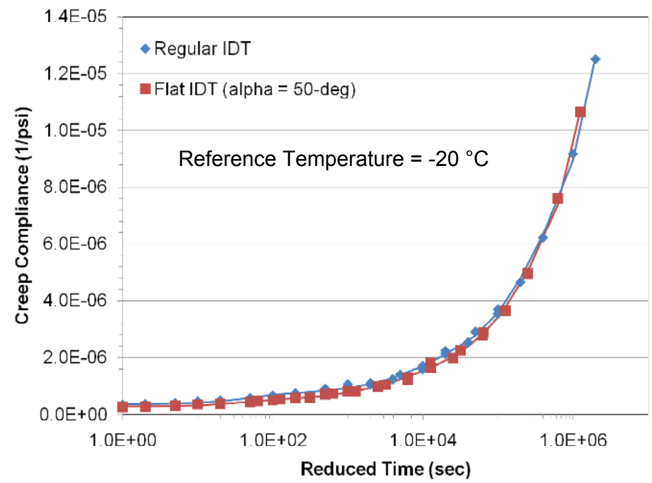

Figure 6. Mix-28 Creep Compliance.

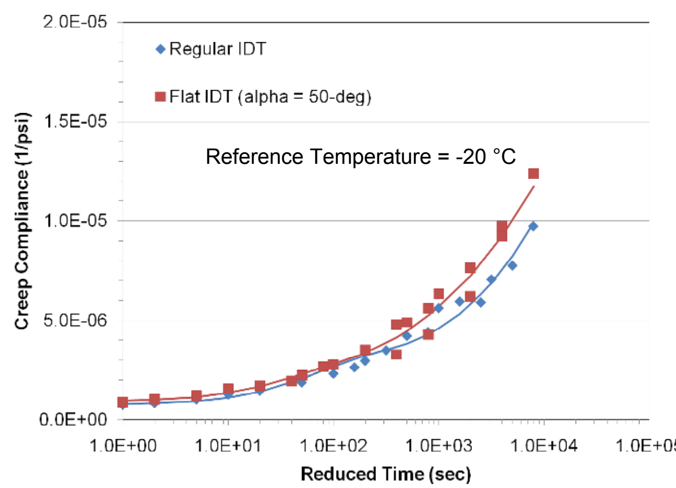

Figure 7. Mix-40 Creep Compliance.

The data from figures 5, 6, and 7 were also placed on unity plots, as shown in Figures 8, 9, and 10. In general, reasonably good agreement was found between the two testing approaches, suggesting that the flattened IDT arrangement may be a viable alternative to the standard IDT testing arrangement described in AASHTO T-332. More work will be needed to further develop and validate this method. For instance, the AASHTO T-322 procedure acknowledges the limitations of plane stress assumptions and presents correction factors based upon inverse, 3D finite element (FE) analysis techniques that can be used to interpret test results to obtain realistic estimates of creep compliance and tensile strength (Roque and Buttlar, 1992). A similar approach is being adopted for the interpretation of results from the flattened IDT arrangement. It is hoped that through improved analysis and addition experimental validation, the flattened IDT arrangement will serve as a versatile test for obtaining creep compliance and tensile strength of a broad range of asphalt-aggregate mixtures.

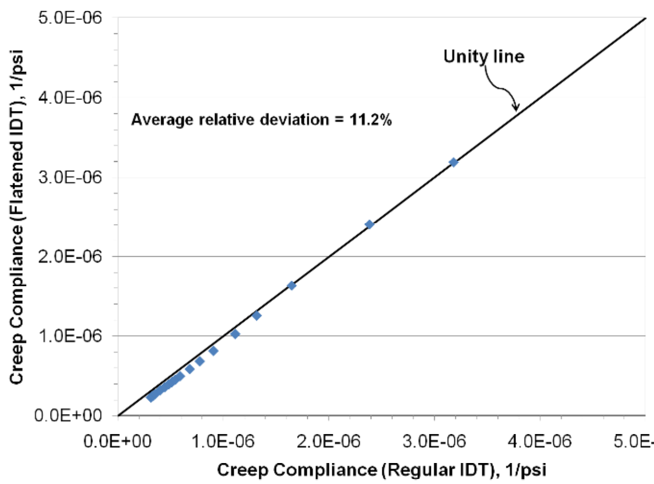

Figure 8. Comparison of Regular and Flattened IDT Creep compliances for Mix-22.

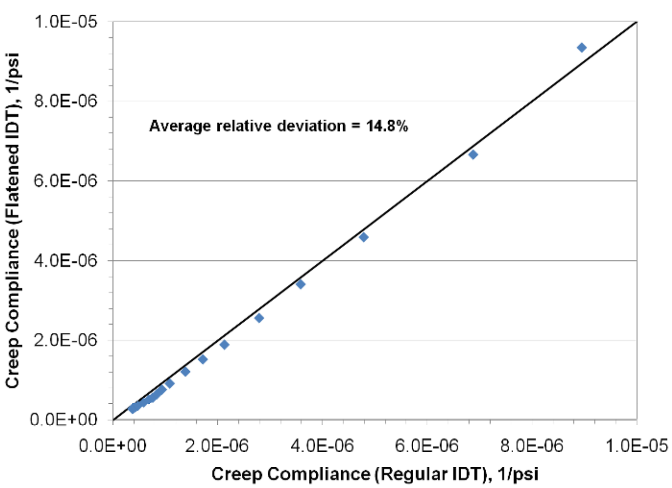

Figure 9. Comparison of Regular and Flattened IDT Creep compliances for Mix-28.

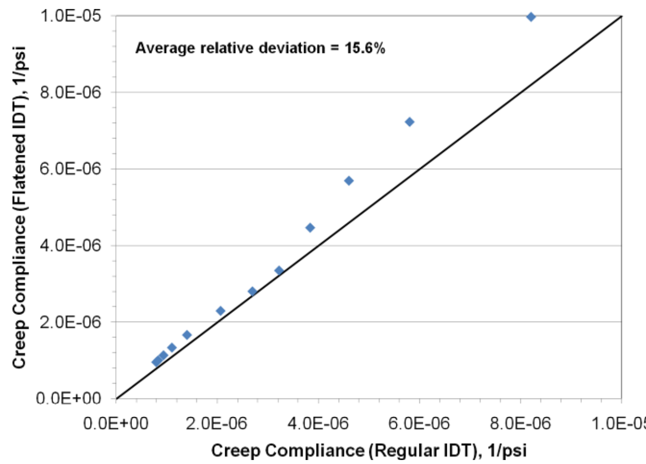

Figure 10. Comparison of Regular and Flattened IDT Creep compliances for Mix-40.

5 SOME FINDINGS

Creep testing of three asphalt concrete mixtures was performed using the AASHTO T322 (2004) test protocol on regular cylindrical test specimens as well as for the flattened geometry. Test data was analyzed for both configurations based on the extension of Hondros solution proposed by Zhang *et al*., 1997. For analysis of the flattened IDT geometry, it was assumed that the Hondros solution would provide enough accuracy to assess the feasibility of the proposed testing configuration.

Comparison of regular and flattened IDT results showed maximum variations ranging from 10% to 16%. The sources of variation between the creep compliances determined from regular and flattened IDT specimens could include the assumptions made in the data analysis, e.g., the applicability of the Hondros solution for the flattened geometry, as well as testing and measurement variability associated with testing of asphalt mixtures with relatively small specimen dimensions.

Based on this limited study it can be inferred that the flattened IDT geometry may be a viable alternative to the current AASHTO procedure for low temperature viscoelastic characterization of asphalt concrete material, and especially advantageous when indirect tensile strength testing is required. The next step in the work will involve the development of more rigorous analysis techniques based upon inverse, 2D FE analysis and additional experimental validation.

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