Hollow-Cylinder Tensile Tester for Asphaltic Paving Mixtures

GHAZI G. AL-KHATEEB AND WILLIAM G. BUTTLAR

Obtaining fundamental mechanical properties of asphalt paving mixtures is a key component of performance-related mixture design and production control. Different testing modes, including the Superpave Indirect Tensile Test (IDT) and the direct tension mode, are used to obtain fundamental properties of asphalt mixtures, such as creep compliance and tensile strength. In this study, a hollow-cylinder tensile tester (HCT) was developed and used to obtain such properties for asphalt mixtures at low temperatures. The HCT is a compact, portable, and operationally simple surrogate test device for the IDT. In the HCT test mode, an internal pressure is applied to the inner cavity wall of the hollow cylinder through a flexible membrane, which produces a hoop (tangential) tensile stress in the cylinder. Closed-form equations are presented to determine creep compliance and tensile strength for thick-walled cylinders under ideal conditions. In the event of eccentrically-cored specimens (non-uniform wall thickness) or partial loading of inside hollow cylinder wall, three-dimensional finite element correction factors are presented, which can be used to obtain accurate measures of creep compliance and tensile strength from raw measurements.Two asphalt mixtures, a dense-graded surface course mixture (9.5-mm top aggregate size typical Illinois limestone) and a polymer-modified (PG70-34) sand-asphalt mixture, were tested in this study using both the HCT and IDT. Delrin plastic was also tested as a reference material using the HCT for validation purposes. Although the HCT is still in the early prototype stage, the preliminary results seem very reasonable when compared to the IDT. As expected, differences in tensile strengths between the IDT and HCT were observed due to differences in specimen geometry, size, and stress states. Key words: hollow cylinder, creep compliance, tensile strength, Superpave IDT, tensile test mode.

INTRODUCTION

Flexible pavements compose about 94% of the over two million miles of paved roadways in the United States. Asphalt mixture design must consider both climatic effects and vehicular loading. Asphalt mixtures behave very differently across the typical range of in-service pavement temperatures. Its behavior ranges from elasto-viscoplastic behavior at higher temperatures to nearly elastic, brittle behavior at very low temperatures. Accordingly, different pavement cracking is obtained at different temperature ranges, which require specific fundamental properties for each range, to serve as inputs for performance-related mixture design systems, such as Superpave. At low temperatures, creep compliance and tensile strength are the main fundamental properties of the asphalt mixture required by Superpave. Asphalt mixture creep compliance at low in-service pavement temperature (<0 C) is known to be strongly related to pavement cracking (*1*).

Department of Civil Engineering, University of Illinois at Urbana-Champaign, 205 North Mathews Avenue, MC-250, Urbana, Illinois 61801.

The Superpave IDT (*2, 3*) was developed in the Strategic Highway Research Program (SHRP) to obtain creep compliance and tensile strength for asphalt mixtures at low temperatures. However, the Superpave IDT is not a truly practical mixture design tool due to its cost and lack of portability. Therefore, the HCT device was developed to address these disadvantages by providing a simple, inexpensive, and portable test method for obtaining creep compliance, tensile strength, and dynamic modulus at low and intermediate temperatures.

OBJECTIVES

The main objectives of this study are:

- To evaluate the feasibility of the HCT as a surrogate test device for the IDT in obtaining fundamental properties for asphalt mixtures
- To assess the accuracy and repeatability of a prototype HCT

LITERATURE REVIEW

Previous studies dealing with the hollow cylinder testing mode have been reported in the literature. Most of these studies were conducted in the geotechnical field and mostly to obtain compressive, shear and torsional properties for granular materials. Richardson et al. (*4*) developed the Nottingham Repeated Load Hollow-Cylinder Apparatus (NRLHCA) to characterize the inherent anisotropy and the anisotropic shear strength properties of fine-grained Leighton Buzzard sand. They concluded that the inherent anisotropy due to the preferred particle distribution induced during the sample preparation procedure affects the ultimate shear strength properties of the material.

Hight and Saada (*5, 6*) used hollow cylinders to determine compressive, shear, and torsional properties of asphalt concrete. Alavi and Monismith (*7*) tested hollow cylinders of 228.6 mm (9 in.) and 177.8 mm (7 in.) outer and inner diameters, respectively, under compression along the axis of symmetry. The testing was conducted at moderate and high in-service temperatures (4º, 25º, and 40º C) to evaluate the viscoelastic response characteristics of asphalt-aggregate mixes under dynamic axial and shear loads. The general conclusions from the evaluation were that asphalt concrete can be treated as a linear viscoelastic material for the stress range investigated, the stiffness moduli in both axial and shear loading are essentially independent of stress, and that the interchangeability of time and temperature can be used to define the stiffness response of mixes at a specific temperature over a wide range of time. Crockford (*8*) also tested hollow-cylindrical specimens under shear and compressive loading to study the effect of principal-plane rotation on permanent deformation in flexible pavements.

From the literature search conducted, it is clear that the hollow cylinder test mode has never been used to specifically determine the tensile properties of asphalt paving mixtures at low temperatures.

CONCEPT AND KEY ISSUES OF THE HCT

In the HCT test mode, an internal pressure is applied to the inner cavity of a hollow-cylinder specimen to obtain fundamental tensile properties (creep compliance and tensile strength) for the asphalt mixture (Figure 1). The constitutive equations for thick-walled cylinders found in Timoshenko et al. (*9*) or Ugural et al. (*10*) are given below. The use of thick-walled cylinders is necessary for asphalt paving mixtures since aggregate size-to-wall thickness ratio is of concern.

$$\sigma_t = \frac{a^2 p_i}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right) \qquad (1)$$

$$\sigma_r = \frac{a^2 p_i}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right) \qquad (2)$$

Where:

ρ_i	=	Internally-applied pressure
σ_t	=	Tangential (hoop) stress, which is tensile
σ_r	=	Radial stress, which is compressive
a	=	Inner radius of the hollow-cylinder
b	=	Outer radius of the hollow-cylinder

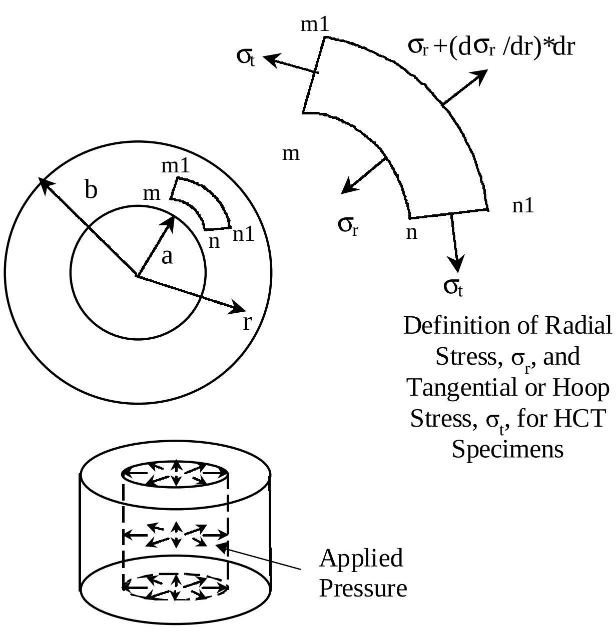

FIGURE 1 Concept of the Hollow-Cylinder Tensile Test (HCT)

Tensile properties of asphalt paving mixtures can be obtained using different test modes including direct tension, indirect tension (such as the Superpave IDT-Figure 2), beam testing, and finally the HCT test mode presented in this paper. The only mode with pure tensile stress state is the direct tension mode. However, the direct tension mode has several disadvantages including difficulty in gripping and testing brittle materials in tension, which sometimes results in failure near grips (at the ends) due to stress concentrations. A fundamental measure of tensile strength is a difficulty in beam testing due to neutral axis shifting and stress redistribution after crack initiation. The use of beams instead of cylindrical specimens is also a disadvantage shared by both direct tension and beam testing modes.

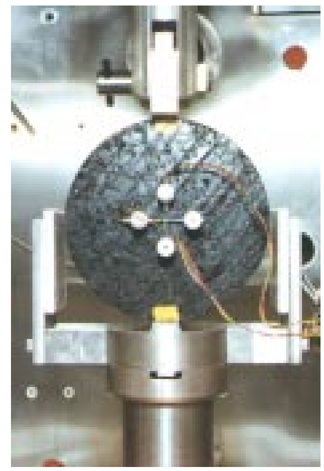

FIGURE 2 The Superpave IDT

The HCT test mode has several advantages over other tensile test modes. One of these advantages is the simplicity and portability of the test device. Utilization of gyratory specimens is also an advantage of the HCT mode. Another advantage of the HCT is the lack of stress concentration at the point of load application, since the HCT involves the application of a uniform internal pressure to produce tension. Some key issues, however, have to be considered in the HCT test mode including: (1) particle size-to-wall thickness ratio; (2) density gradients and broken particles in gyratory-compacted specimens; (3) tensile strength determination; and (4) containing the pressurizing bladder and accounting for compressibility of the membrane, fittings, and fluid. Some of these key issues have been discussed in details in a previous study (*11*). In this paper, the validity and repeatability of a prototype HCT test device (Figure 3) is addressed through testing of two asphalt mixtures and a Delrin plastic reference material.

MATERIALS AND EXPERIMENTAL METHODS

Materials

Two asphalt mixtures were produced in this study. The first was a modified sand-asphalt mixture, which was designed for an upcoming demonstration project at the Peoria Regional Airport in central Illinois, to serve as a strain-tolerant reflective crack control interlayer. A PG70-34 polymer-modified binder and a 4.75 mm (No.4) maximum aggregate size gradation were used to prepare this mixture. The second mixture was designed to resemble a standard highway sur-

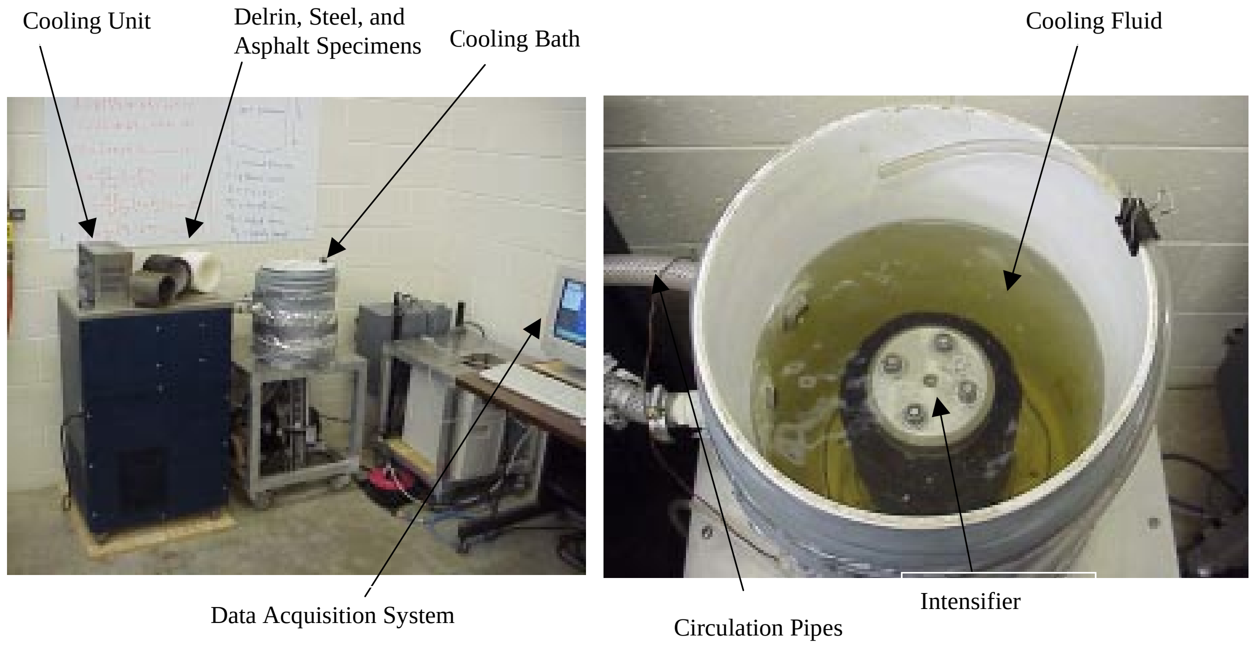

FIGURE 3 Prototype HCT

face mixture used in Illinois. An AC-20 (PG64-22) binder and a 9.5 mm top aggregate size limestone gradation were used to produce this mixture. Specimens were compacted to design air void levels (3% for the sand-asphalt interlayer, and 4% for the surface mixture) using a Brovold/TestQuip Superpave gyratory compactor (SGC). Three hollow cylinder replicate specimens were produced for each mixture at each temperature from the SGC specimens, using a coring machine that produces specimens of 4.025 inch (102.24 mm) inner diameter. The outer diameter is 5.906 inch (150 mm), which is standard for SGC specimens. A Delrin plastic hollow cylinder with the same dimensions was also fabricated to serve as a reference standard.

Testing Methods

Creep tests were conducted at three low temperatures, -20º C, -10º C, and 0º C for a duration of 100 seconds, following Superpave IDT test protocols outlined in AASHTO TP-9 specifications. Strength tests were conducted at –10º C for asphalt mixtures. For Delrin, testing was performed at room temperature (22.2º C). Only creep testing was performed on the Delrin material. Piston movement and applied pressure were monitored in the HCT mode. In the creep tests, a constant internal pressure was applied to the inner wall of the hollow cylinder using a control pressure mode, and the vertical movement of the loading ram was monitored throughout the 100-second test. Two-inch strain gages for testing of asphalt mixtures and 0.5-inch strain gages for testing of Delrin were used as a secondary measure of the tensile strains at the midpoint of the inner wall of the specimen. A constant rate of ram displacement was applied to the specimen in strength tests until failure occurred. Pressure of the cavity pressurizing fluid was monitored throughout the test with a pressure transducer.

Formulas presented in Buttlar et al. (*11*) were used to obtain creep compliance and tensile strength from raw test measurements. In short, the hoop stress on the inner wall of the HCT specimen is a function of applied pressure in the inner cavity and specimen geometry. The ratio of hoop stress to applied cavity pressure is approximately 2.65; however, the aforementioned formulas allow a more accurate computation of hoop stress based upon the specimen dimensions, eccentricity of the inner cavity, and percent of the inner wall loaded pertaining to each specimen.

Strain was measured using two methods. One method involves estimating hoop strain on the inner wall by virtue of the increase in cavity volume in response to pressure. The increase in cavity volume causes the loading to charge piston. Of course, it is necessary to account for the amount of ram displacement caused by bulk fluid compression, compression of the pressurizing membrane, and movements of fittings, seals, etc. This is accomplished by periodically running a companion test on a very rigid cylinder to determine the magnitude of these effects. A steel hollow cylinder was fabricated for this purpose.

PRELIMINARY RESULTS

Creep Compliance

Initial validation of the HCT was performed using the Delrin plastic reference cylinder. Creep results for Delrin were used to compare strain-gage-based tensile strains and volume-based tensile strains for a material with well-defined properties. Volume-based strains were found to be consistent with strain gage measurements over a range of applied cavity pressures (Figure 4) and loading times (Figure 5). Both measurement systems yielded realistic estimates of Delrin modu-

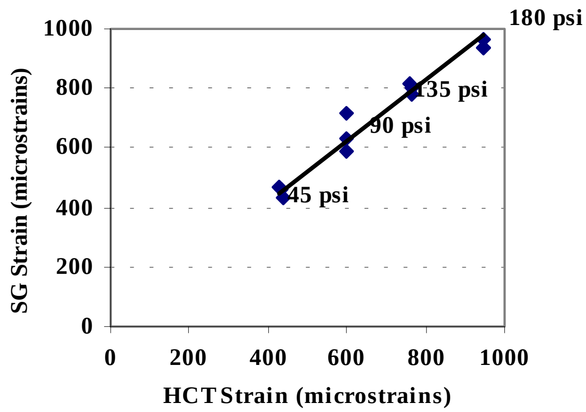

FIGURE 4 Strain-gage tensile strain vs. volume-based tensile strain for Delrin at 100-sec. and 22.2 degrees C on outer wall over range of cavity pressures

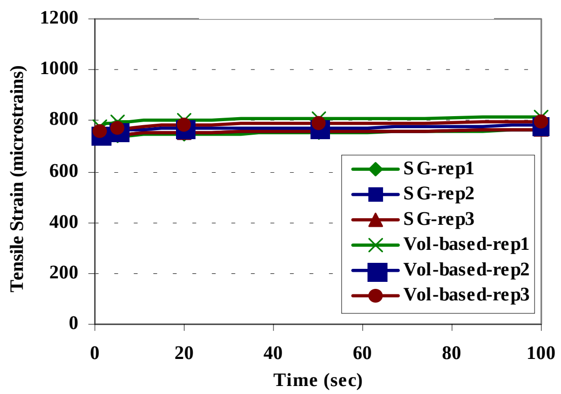

FIGURE 5 Volume-based tensile strains and strain-gage tensile strains vs. tine for pressure of 135 psi and at 22.2 degrees C

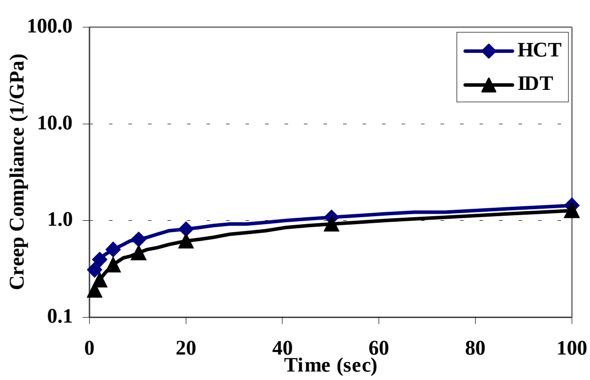

FIGURE 6 HCT/IDT creep compliances vs. time at 0 degrees C for polymer-modified sand mixture

lus at 22º C (approximately 3 GPa). However, this series of tests indicated a problem in the flexible seals used to contain the pressurizing membrane, which could lead to more significant errors in tests performed on asphalt concrete specimens. Since the new seal design was not completed at the time of this phase of the test program, specimen strain via strain gage measurements were reported in the ensuing analysis.

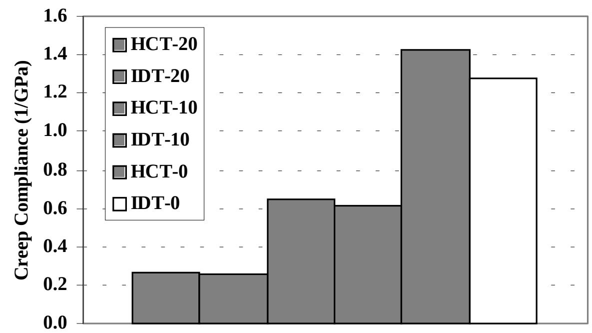

FIGURE 7 HCT compliance vs. IDT compliance at 100-sec loading time for polymer-modified sand mixture

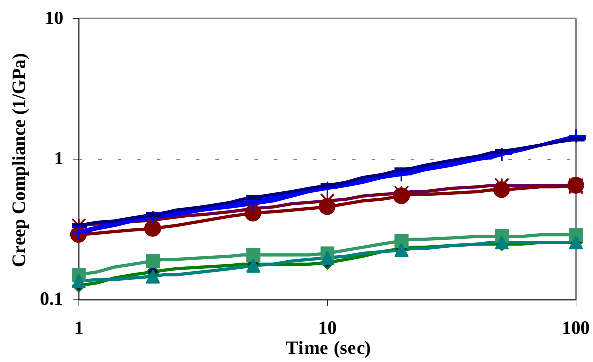

FIGURE 8 HCT creep compliance vs. time for polymer-modified sand mixture (3 replicates per temperature)

Figures 6 and 7 present a comparison of creep test results performed on the polymer-modified mixture using the HCT and IDT. The HCT creep compliances were found to match closely with IDT creep compliances at higher loading times, while a slight, yet consistent over-prediction of compliance was noted at shorter loading times. Follow-up testing is planned to study this effect in greater detail. One possible explanation for the differences noted would be that the shape of the applied creep load (step function) for the IDT and HCT tests performed were in fact different. Figure 8 shows increasing creep compliance with higher temperatures and longer loading times from HCT measurements, as would be expected. As shown in Figure 8, creep compliance measurements on replicate specimens showed good repeatability at each of the three test temperatures.

Tensile Strength

Unlike fundamental measures of modulus or compliance, which are, by definition, independent of test mode, tensile strength is generally dependent upon specimen geometry, size, and stress states. For instance, the ratio of direct tensile strength of Portland cement concrete (PCC) to flexural strength ranges from 0.30 to 0.77, and the ratio of the direct tensile strength to splitting strength can be as low as 0.41

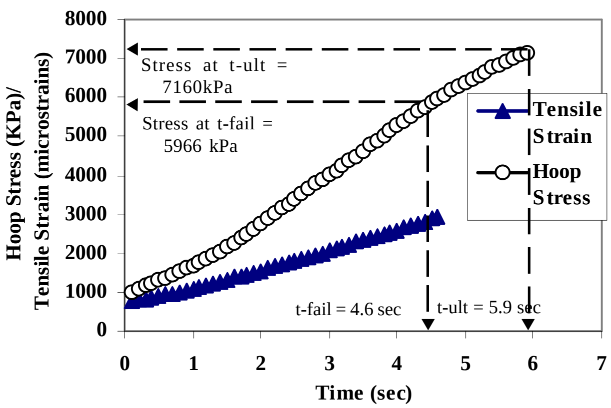

FIGURE 9 Hoop stress and tensile strain vs. time at -10 degrees C for polymer-modified sand mixture

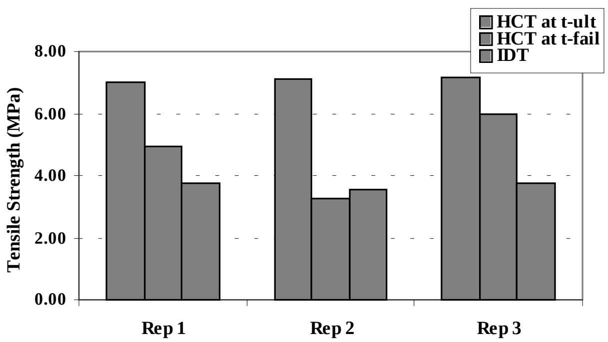

FIGURE 10 Comparison between HCT and IDT tensile strength at -10 degrees C for polymer-modified sand mixture

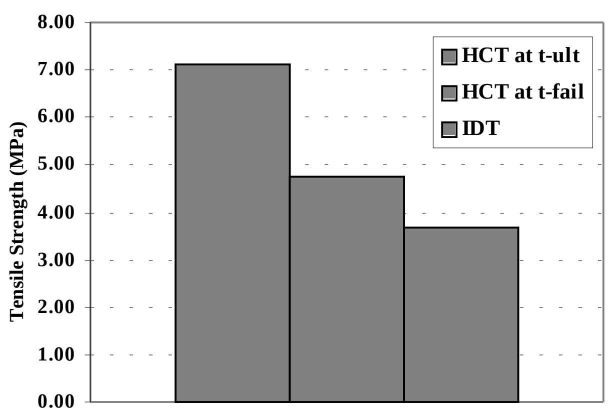

FIGURE 11 Comparison of average tensile strength at -10 degrees C between HCT and IDT

for PCC (*13*). In the IDT, a distinction is made between ultimate tensile strength and true tensile strength. The surface mounted sensors on IDT specimens are used to determine the time of "first failure," by identifying the time and corresponding load at which the maximum difference between vertical and horizontal deformations on each side of the specimen is reached (*12*). True tensile strength is found to be, on average, about 80 percent of the strength based upon ultimate load.

Similarly, it was found that first failure does indeed occur on the inner wall of HCT specimens, where tensile stresses are highest (Figure 9), and additional pressure is required to completely fracture the HCT specimen. After failure, HCT specimens are typically split vertically on one side. Figure 9 shows typical data from an HCT strength test. For this specimen, the ultimate pressure occurred at 5.9 seconds (t-ult), while the failure time from the strain-gage measurement on the inner wall was 4.6 seconds (t-fail). An average value of 7.11 MPa for the HCT tensile strength was obtained when the pressure at t-ult was used, whereas, a 4.73 MPa average tensile strength was obtained when the stress at the t-fail was used. Figures 10 and 11 present comparisons between HCT and IDT strengths. The HCT strengths taken at t-fail are closer in magnitude to IDT strengths than those taken at t-ult, yet are still higher in magnitude. However, the HCT strengths taken at t-ult show better repeatability. This is probably because the strain gages used on the inside wall of the HCT specimens only spanned across 1/6th of the inner circumference.

A comprehensive testing program is underway, which will employ crack detection foils, additional strain gages, and a greater variety of materials in an effort to gain a better understanding of failure behavior in the HCT. The testing program will also seek to quantify the accuracy and precision of the HCT device, particularly as a function of maximum aggregate size. In addition to creep and strength tests, the HCT will also be used to measure dynamic modulus over a range of temperatures.

SUMMARY AND CONCLUSIONS

A hollow-cylinder tensile tester (HCT) was developed to obtain fundamental tensile properties for asphalt paving mixtures at low and intermediate temperatures. The HCT was designed to be a simple and portable surrogate test for the Superpave IDT. Preliminary tests have now been performed on asphalt concrete and Delrin plastic reference specimens. The following conclusions can be drawn based upon the findings of this study:

1. The HCT device has many potential advantages over conventional tensile test modes for obtaining fundamental tensile properties of asphalt mixtures. The HCT test mode is capable of inducing tension on brittle materials, such as asphalt mixtures at low temperatures, with relatively minimal stress concentrations.
2. HCT tests conducted to date suggest that accurate, fundamental measures of creep compliance are achievable with the HCT.
3. The HCT yields tensile strengths that are higher than the IDT, particularly when the breaking pressure (at t-ult) is used to compute tensile strength.
4. More testing is still needed to validate the accuracy and repeatability of the HCT. In particular, a new bladder sealing system and a better understanding of the failure behavior are needed.

ACKNOWLEDGEMENT

The authors of this paper would like to acknowledge the significant contribution and support of Mr. Tom Brovold and Mr. Jim Adams in the design, assembly, and calibration of the prototype HCT device. Their expertise, help, and dedication are greatly appreciated.

REFERENCES

1. Lytton, R.L., R.L. Roque, J. Uzan, D. R. Hiltunen, E. Fernando, and S. M. Stoffels. *Performance Models and Validation of Test Results*. Final Report to Strategic Highway Research Program; Asphalt Project A-005, SHRP Report A-357, 1993.
2. Roque, R.L., and W.G. Buttlar. Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Test. *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992.
3. Buttlar, W.G., and R.L. Roque. Development and Evaluation of the Strategic Highways Research Program Measurement and Analysis System for Indirect Tensile Testing at Low Temperatures. *Transportation Research Record.1454,* TRB, Washington, D.C., 1994.
4. Richardson, I.R., D.N. Chapman, and S. Brown. Relating Failure Tests Performed in Hollow Cylinder Apparatus to Inherent Anisotropy, *Transportation Research Record 1526,* TRB, Washington, D. C., 1996, pp. 149-156.
5. Hight, D. W., A. Gens, and M. J. Symes. The Development of a New Hollow Cylinder Apparatus for Investigating the Effects of Principal Stress Rotation in Soils. *Geotechnique* Vol. 33, 1983, pp. 355-383.
6. Saada, A. S. Hollow Cylinder Torsional Devices: Their Advantages and Limitations. *ASTM STP 977,* American Society for Testing and Materials, Philadelphia, 1988, pp. 766-795.
7. Alavi, S. H., and C. L. Monismith. Time and Temperature Dependent Properties of Asphalt Concrete Mixes Tested as Hollow Cylinders and Subjected to Dynamic Axial and Shear Loads. *Journal of the Association of Asphalt Paving Technologists*, Vol. 63, 1994, pp. 152-181.
8. Crockford, W. W. Role of Principle-Plane Rotation in Flexible Pavement Deformation. *Journal of Transportation Engineering*, the American Society of Civil Engineers, Washington, D. C., Vol. 119, No. 1, 1993.
9. Timoshinko, S. and S. Woinowsky-Krieger. *Theory of Plates and Shells*. Mc Graw-Hill, New York, NY, 1959.
10. Ugural, A.C., and S.K. Fenster. *Advanced Strength and Applied Elasticity*. Second Edition. Elsevier Science Publishing Co., Inc., New York, 1987.
11. Buttlar, W.G., G.G. Al-Khateeb, and D. Bozkurt. Development of a Hollow-Cylinder Tensile Tester to Obtain Mechanical Properties of Bituminous Paving Mixtures. *Journal of the Association of Asphalt Paving Technologists,* Vol. 68, 1999.
12. Buttlar, W.G., R. Roque, and N. Kim. Accurate Asphalt Mixture Tensile Strength. *Proceedings of 4th Materials Engineering Conference, Materials for the New Millenium*, American Society of Civil Engineers, Washington D.C., 1996, pp. 163-172.
13. Popovics, S. *Strength and Related Properties of Concrete: A Quantitative Approach.* John Wiley and Sons, Inc., New York, 1998.