Development and Evaluation of the Strategic Highway Research Program Measurement and Analysis System for Indirect Tensile Testing at Low Temperatures

WILLIAM G. BUTTLAR AND REYNALDO ROQUE

The indirect tensile testing mode is a practical method for obtaining tensile properties of bituminous mixtures from cylindrical specimens. An indirect tensile creep testing and analysis system is shown analytically to be superior to conventional methods in obtaining fundamental properties of asphalt mixtures at low temperatures in a previous study. Before extensive testing of a wide range of mixtures, however, the ability of the system to obtain accurate, reliable results was unknown. Since the introduction of the new measurement and analysis system, hundreds of field cores and laboratory compacted specimens have been tested and analyzed. Improvements to the system resulting from the testing experience are described, including how analyses of data collected from these tests were used to evaluate the accuracy of the system. Poisson's ratio values obtained with the new system were found not only to be reasonable but also necessary for the accurate determination of creep compliance of the asphalt mixtures tested—a result consistent with analytical findings. In addition, creep compliances obtained from mixtures of well-known components were found to agree with expected values and trends. Input of properties measured on 20 field sections with the new system into a mechanics-based thermal cracking model resulted in accurate predictions of thermal cracking in the field. The measurement and analysis system presented is part of the test selected by the Strategic Highway Research Program to support new mixture specifications for thermal cracking; it has been incorporated into the SUPERPAVE software.

A measurement and analysis system was developed by Roque and Buttlar (*1*) to obtain accurate, fundamental mixture properties at low temperatures in the indirect tensile testing mode (Figure 1). Finite element analyses of diametrally loaded cylindrical specimens have indicated that properties cannot be accurately determined from measurements obtained on the perimeter of the specimen. Stress concentrations near loading heads do not allow the accurate determination of Poisson's ratio, which is required for accurate interpretation of the deformation response. This and other problems were overcome by obtaining vertical and horizontal measurements in the center of flat faces of cylindrical specimens (Figure 1). This measurement system is an extension of the system developed by Anderson [see Hussain (*2*)]. Other advantages of the system include (*a*) reduction or elimination of measurement errors caused by specimen rotation and (*b*) nearly uniform stresses in the measurement zone.

It was determined that analyses of stresses and deformations within the specimen are clearly needed to interpret accurately deflections obtained from the test. Finite element analyses showed that deformations and stresses on flat faces of cylindrical specimens are dependent upon specimen thickness and Poisson's ratio. Roque and Buttlar (*1*) developed a set of correction factors to perform a pseudo–three-dimensional analysis based upon conventional, two-dimensional plane-stress solutions.

Pennsylvania Transportation Institute, Pennsylvania State University, Research Office Building, University Park, Pennsylvania 16802.

The final step in developing the system was to evaluate its practicality and accuracy by testing a broad range of asphalt mixtures. This paper describes the results of testing and analyzing hundreds of field cores and laboratory-compacted specimens, from efforts associated with the thermal cracking validation work of the Strategic Highway Research Program (SHRP) A005 research program.

OBJECTIVES

- To report developments in specimen preparation, testing, and data reduction procedures for the SHRP measurement and analysis system for indirect tensile testing at low temperatures.
- To determine whether reasonable and accurate values of creep compliance and Poisson's ratio can be obtained using this system.

SCOPE

- Four mixtures were tested and analyzed by using materials having well-known properties from the SHRP Materials Reference Library (MRL). Measurements taken from these mixtures were used to compare measured properties with expected trends.
- Cores from 20 test sections across the United States were tested and analyzed as part of the SHRP A005 project to validate the SHRP binder and mixture tests for thermal cracking.
- The present study is limited to procedures and analysis methods related to creep testing, even though the system is often used to obtain the creep and strength properties of bituminous mixtures.

Because of the wide range of properties represented by the mixtures described, it was possible to develop and refine universal testing protocols for the new measurement and analysis system. In addition, measured properties were used in a mechanics-based model developed at Pennsylvania State University (PSU) to predict

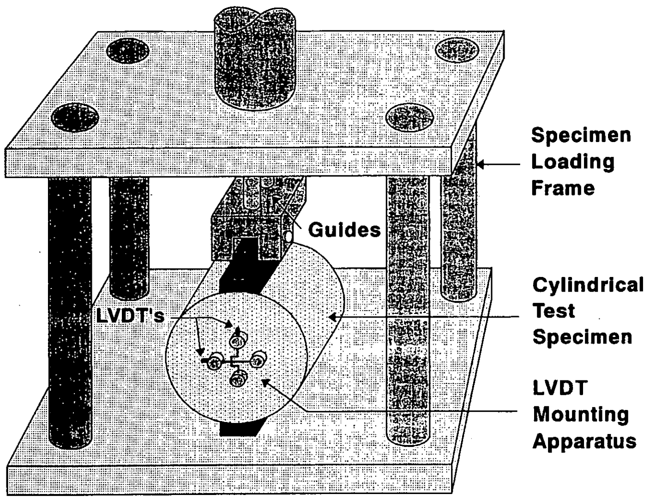

FIGURE 1 Testing arrangement of the new measurement and analysis system.

thermal cracking pavement performance. Comparisons between predicted and observed cracking were used to help evaluate the quality of properties obtained by the new system.

DEVELOPMENT OF TEST EQUIPMENT AND TESTING METHODS

Since its introduction in 1991, the measurement and analysis system developed at PSU has been used to test and analyze hundreds of field cores and laboratory compacted specimens. The test experience has led to substantial developments in test equipment, test procedures, and analysis methods. Such developments, in turn, have led to a system that is more accurate, reliable, and practical.

Development of Test Equipment

The following modifications to test equipment have led to enhanced testing efficiency, longer equipment life, and superior measurements.

1. Round gauge points help produce a simpler, more effective mounting system. Gauge points are small, brass pieces that are glued symmetrically about the centers of both flat faces of test specimens, at a spacing of one-fourth of the diameter. The function of the linear variable differential transformers (LVDT) mounting apparatus (Figures 1 and 2) is to secure LVDT coils and cores onto gauge points at 6.4 mm (0.25 in.) above the surface of the specimen, in such a manner that LVDT core alignment can be manually adjusted to avoid scraping against the inner surface of the coil.

Square gauge points were used originally; however, it was found that they had two disadvantages: (*a*) any substantial misalignment of gauge points makes it difficult to center LVDT cores within the coil, and (*b*) square gauge points do not allow an LVDT mounting apparatus to pivot upon specimen rupture in a failure test, thus increasing the potential for bending or even breakage of the core assembly. Round gauge points, 7.9 mm in diameter by 3.2 mm $^5/_{16}$ in. in diameter by $^1/_8$ in. now are being used effectively to alleviate these problems.

2. A specimen loading frame should be used inside the testing frame. A specimen load frame (Figure 1) should be used to help deliver loads that are in good alignment, with minimal friction in guides or bearings—22.2 N (5 lb) or less—even when eccentric loads occur because of slightly uneven specimens or temperature changes, for example.

3. A transducer mounting station can be used to expedite testing. Because creep testing often allows time for the operator to perform other tasks during each test, a separate temperature-controlled container can be used to mount and "zero" LVDTs during this free time. As a result, tests can be run consecutively without the additional time required to mount and align LVDTs safely within their linear range before each test.

4. A transducer diagnostics program can help ensure proper LVDT operation. Before deflection data are collected, a diagnostics program should be used to examine the electrical signals of all LVDTs. Checking signals before each test will greatly reduce prob-

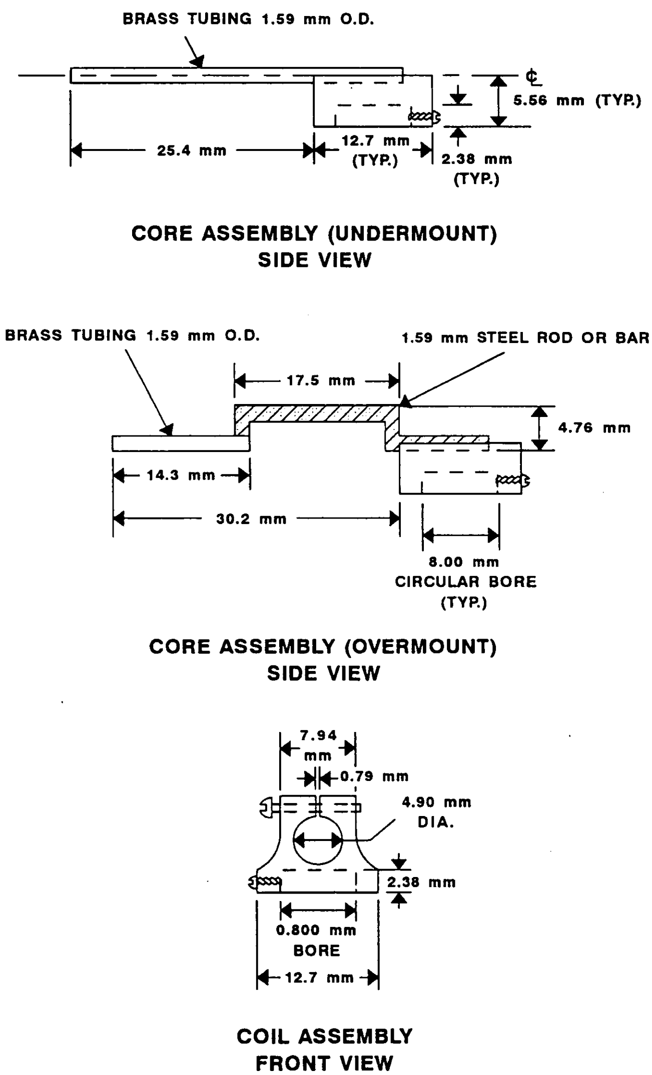

FIGURE 2 New LVDT mounting apparatus.

lems associated with substandard transducers, cables, or connections, as well as help identify temperature or electrical drift. Such monitoring is especially critical because transducers and cables are subject to wear and tear as a result of the explosive nature of failure testing at low temperatures. Signals should be checked for noise levels and signal stability (drift) and to verify that LVDTs have remained safely within their linear range after the specimen is moved into the test chamber. Signal noise should be no greater than $\pm 125 * 10^{-6}$ mm, and signal drift should be negligible. In addition, the diagnostics program should alert the operator if any of the four LVDTs are connected out of order in the test chamber.

5. Use of a data acquisition system is recommended. Because the new measurement and analysis system involves collecting and analyzing large amounts of data, the use of a data-acquisition system to collect deflections and loads is highly recommended and preferable to simply using a chart recorder. One system successfully used in this study collected conditioned LVDT signals using a personal computer with an A/D board and a data-acquisition program. To minimize the size of data files, a 10 Hz sampling rate should be used for the first 10 sec to permit accurate determination of the beginning of the test, followed by a slower rate for the remainder of the test. For example, a 100-sec creep test might consist of 10 Hz for 10 sec and 1 Hz for 90 sec.

Developments in Testing Methods

Strain Limits Established To Keep Specimens in the Linear Range

The analysis system presented later in this study is valid only for specimens tested at temperatures and loading times at which the material exhibits linear elastic or linear viscoelastic behavior. Testing experience indicates that specimens tested at 0°C or lower generally exhibit linear behavior for tests up to 1,000 sec in duration, if creep loads are kept low enough. Additional research is underway, and one finding indicates that choosing loads that limit horizontal tensile strains to 300 microstrains or less helps to keep asphalt mixture behavior safely within the linear range.

Although keeping strains low is desirable, a lower limit on strains must be imposed to ensure the signal to noise ratio is high enough. A lower limit of 50 microstrains has been used successfully with equipment in this study. Because choosing the correct loads to keep strains within these limits requires some trial and error (material properties are not known a priori), a deflection window can be set at some specified time near the beginning of the test. One window that has been used successfully requires that horizontal strains remain within 40 and 120 microstrains at $t = 30$ sec for a 1,000-sec creep test. An operator should stop a test immediately if strains exceed these limits. Specimens should be allowed to recover for at least 3 min before they are reloaded at a different level. Although deflections are not converted into corrected strains until a three-dimensional analysis is performed, for this purpose, strains can be approximated as measured deflection divided by the gauge length.

Specimen Conditioning Recommendations

As with any test method, observing consistent specimen conditioning techniques leads to more accurate and repeatable results. The most critical concerns for this test with respect to specimen conditioning are temperature, humidity, and preloading or seating loads.

Specimens should be cooled at test temperature for 3 to 12 hr before testing. The minimum cooling time recommended is 3 hr, which is determined by embedding thermocouples in the middle of Marshall-sized test specimens and cooling them from room temperature (20°C) to very low test temperatures (−25°C). The maximum recommended cooling time has been established to avoid the effects of low-temperature physical hardening, a phenomenon observed by Bahia (*3*) in asphalt cements. The effects of this phenomenon on the properties of asphalt mixtures are not thoroughly understood at this time.

Tests have clearly shown that variation in moisture within specimens may have a dramatic effect on low-temperature mixture compliance. Thus, humidity conditioning of specimens is highly recommended. A humidity-conditioning procedure that has been used successfully at Pennsylvania State University requires storing specimens at 30 percent relative humidity and 20°C for at least 3 days before testing to ensure uniform and consistent moisture content.

To reduce problems associated with incompatibility between the specimen and loading heads, seating loads should be applied to all specimens before creep tests are performed. A procedure was developed to seat specimens at room temperature (20°C) without introducing large permanent deformations. The procedure involves applying 100 cycles of load pulses and rest periods. Each cycle consists of a 0.1 sec inverted haversine load pulse, with an amplitude of approximately 70 kPa tensile stress (Equation 1), followed by a rest period of 0.9 sec.

$$P_{\text{SEAT}} = 0.110(D)(t) \qquad (1)$$

where

P_{SEAT} = target seating load (kN),
D = specimen diameter (mm), and
t = specimen thickness (mm).

Test Chamber Temperature Tolerance

Because asphalt concrete properties are particularly temperature-dependent, careful control of test chamber temperatures is required to obtain accurate material properties. A test chamber temperature tolerance of ± 0.5°C is practical and generally acceptable. However, because low temperature measurements on asphalt concrete are extremely small, large temperature fluctuations within this range during testing can lead to significant drift in deflection measurements. Thus, it is recommended that once a test is initiated (where the actual temperature is within ± 0.5°C of the target temperature) the test chamber should not fluctuate more than 0.2°C from this initial test temperature during the entire test.

DEVELOPMENTS IN ANALYSIS PROCEDURES

Simplified Analysis Procedures

Review of Existing Analysis Procedures

A brief review of the measurement and analysis system as presented elsewhere (*1*) aids understanding of newer analysis methods. A finite element study of diametrally loaded cylindrical specimens indicated that measurements obtained with the new system needed to be corrected to account for three-dimensional effects. Bulging of specimens, as illustrated in Figure 3 (top), affects horizontal and vertical measurements. Bulging correction factors dependent on Poisson's ratio and specimen geometry were developed to account for this phenomenon. In addition, three-dimensional stress states differ dramatically from those predicted by conventional two-dimensional plane-stress theory, as illustrated in Figure 3 (bottom). Stress correction factors, also dependent on Poisson's ratio and specimen geometry, were presented in tabular form. Finally, it was found that horizontal and vertical deformations measured over finite gauge lengths were related to point strains at the center of the flat face by a constant. After two-dimensional stresses and strains were corrected to account for three-dimensional effects, creep compliance was obtained by applying Hooke's law. Because several correction factors were functions of Poisson's ratio, which is not known a priori, the original analysis scheme involved a somewhat tedious iterative solution scheme.

The following sections present a simple set of equations that can be used to obtain creep compliance directly, as well as Poisson's ratio and other quantities of interest. These equations were obtained by presolving the iterative analysis scheme and fitting simple functions through the results.

Creep Compliance

Tensile creep compliance, $D(t)$, is usually the primary quantity to be obtained from the creep test. Poisson's ratio is indirectly very important because it strongly influences the three-dimensional behavior of the specimen and thus plays an important role in the calculation of creep compliance. Poisson's ratio, by definition, is a function of X/Y, where

X/Y = absolute value of ratio of measured horizontal deflection to measured vertical deflection (2)

The absolute value is taken for convenience to avoid the negative ratio that occurs because x and y deflections are always of opposite sign (tensile deflections versus compressive deflections). Thus, creep compliance adjusted for three-dimensional effects can be expressed as a function of X/Y. A method for calculating a representative X/Y from the creep test will be presented later.

Creep compliance for the biaxial stress state that exists on the specimen face ($\sigma_z = 0$) is obtained through Hooke's law.

$$D(t) = \frac{\epsilon_x}{\sigma_x - \upsilon\sigma_y} \tag{3}$$

Substituting correction factors to account for three-dimensional effects (*1*).

$$D(t) = \frac{\frac{H_M{}^{(t)}}{GL} * 1.071 * C_{BX}}{\frac{2P}{\pi t D}(C_{SX} + 3\upsilon\, C_{SY})} \tag{4}$$

where

ϵ_x = horizontal strain,
σ_x = horizontal stress,
σ_y = vertical stress,
υ = Poisson's ratio,
$H_M(t)$ = measured horizontal deflection at time t,
GL = gauge length (25.4 mm for 101.6 mm diameter, 38.1 mm for 152.4 mm diameter),
C_{BX} = horizontal bulging correction factor,
P = creep load,
C_{SX} = horizontal stress correction factor,
C_{SY} = vertical stress correction factor, and
t,D = as defined before.

Rearranging Equation 4, we obtain Equations 5 and 6.

$$D(t) = \frac{H_m{}^{(t)} * D * t}{P * GL} * (C_{CMPL}) \tag{5}$$

where

$$C_{CMPL} = \frac{1.071 * \pi * C_{BX}}{2(C_{SX} + 3\upsilon\, C_{SY}} \tag{6}$$

C_{CMPL} is a nondimensional creep compliance factor that varies linearly with $(X/Y)^{-1}$, as illustrated in Figure 4. This relationship is given by Equation 7.

$$C_{CMPL} = 0.6354\left(\frac{X}{Y}\right)^{-1} - 0.332 \tag{7}$$

This factor is restricted to the following limits (Equations 8 and 9):

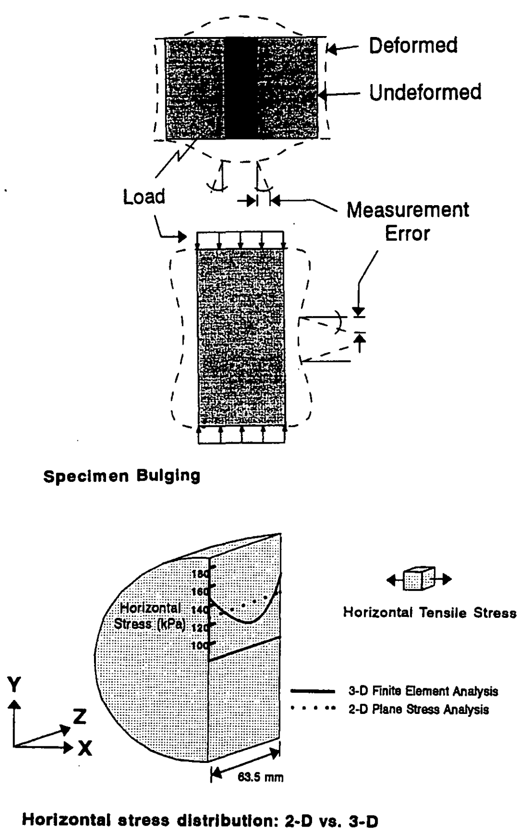

FIGURE 3 Three-dimensional behavior of indirect tensile specimens.

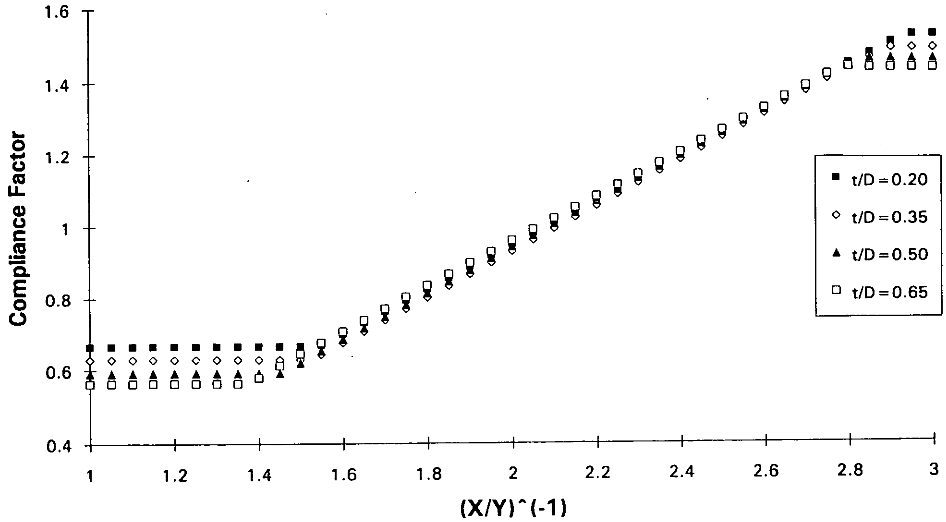

FIGURE 4 Compliance factor versus $(X/Y)^{-1}$ and *t/D*.

$$\left[0.704 - 0.213\left(\frac{t}{D}\right)\right] \leq C_{CMPL} \leq \left[1.566 - 0.195\left(\frac{t}{D}\right)\right] \tag{8}$$

$$0.20 \leq \frac{t}{D} \leq 0.65 \tag{9}$$

The above limits define the horizontal portions of the data in Figure 4. These limits are a direct consequence of the limits imposed on Poisson's ratio, as described in the following section.

Poisson's Ratio

The calculation of creep compliance presented in the previous section had Poisson's ratio inherently built into the solution via the $(X/Y)^{-1}$ term and did not require the direct solution of Poisson's ratio. However, if a measure of Poisson's ratio of the mixture is desired, it can be easily computed through a family of curves (Figure 5). Poisson's ratio was determined to be related to *X/Y* and specimen aspect ratio (*t/D*). The curves were fit with a single function (Equation 10) using linear regression and least squares estimators.

$$\upsilon = -0.10 + 1.480\left(\frac{X}{Y}\right)^2 - 0.778\left(\frac{t}{D}\right)^2\left(\frac{X}{Y}\right)^2 \tag{10}$$

where

$$0.05 \leq \upsilon \leq 0.50 \tag{11}$$

Here, the regression variables reflect the quadratic form of the relation between *X/Y* and Poisson's ratio and account for the effect of *t/D* on the relation.

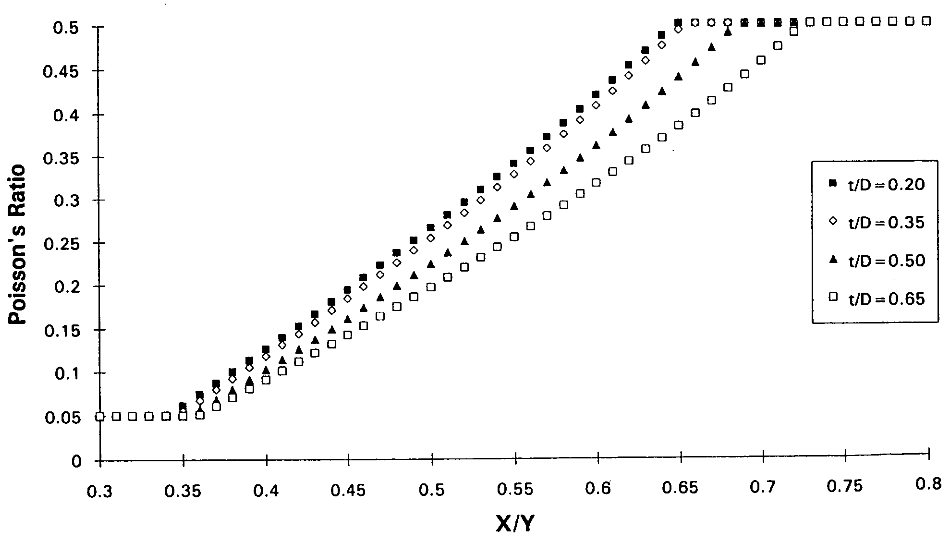

FIGURE 5 Poisson's ratio versus *X/Y* and *t/D*.

As seen in the previous limits (Equation 11), Poisson's ratio is restricted between 0.05 and 0.50. These limits were imposed to prohibit unrealistic values of Poisson's ratio from entering into other computations. The upper limit of 0.50 was selected to coincide with the upper bound of Poisson's ratio for elastic materials. Although the lower bound of 0.05 is seldom approached, it was instituted to help keep compliance factors within reasonable limits for unrealistic X/Y values. An analysis method aimed at using replication to arrive at a more statistically stable estimate of Poisson's ratio is presented later in this section.

Other Quantities

Other quantities that may be useful in other pavement-response or prediction models are presented in the following equations. The maximum tensile stress, corrected to account for three-dimensional effects, can be obtained by Equations 12 and 13.

$$\sigma_X = \frac{2 * P}{\pi * t * D}(C_{SX}) \tag{12}$$

where

$$C_{SX} = 0.948 - 0.01114\,(t/D) - 0.2693(\upsilon) + 1.436(t/D)(\upsilon) \tag{13}$$

The maximum compressive stress, also corrected for three-dimensional effects is where

$$\sigma_Y = -\frac{6 * P}{\pi * t * D}(C_{SY}) \tag{14}$$

$$C_{SY} = 0.901 + 0.138(\upsilon) + 0.287(t/D) - 0.251(\upsilon)(t/D) - 0.264\,(t/D)^2 \tag{15}$$

Finally, maximum tensile strain, corrected for specimen bulging and conversion to point strain, is obtained by Equations 16 and 17.

$$\epsilon_X = \frac{H_M}{GL} * 1.072 * C_{BX} \tag{16}$$

where

$$C_{BX} = 1.03 - 0.189(t/D) - 0.081(\upsilon) + 0.089(t/D)^2 \tag{17}$$

The advantage of the new analysis system is readily apparent. For example, if creep compliance is the only parameter to be obtained from the creep test (as in SUPERPAVE), it can be easily obtained through Equations 7–9. The new system does not involve an iterative set of equations or require interpolation of tables to obtain correction factors. Instead, the iterative solution is presolved and correction factors are built into the simple relations.

Obtaining Reliable Measures of Poisson's Ratio and Creep Compliance

Accurate measures of Poisson's ratio are necessary to obtain reasonable values of creep compliance (*1*). However, because of variability in asphalt mixtures, unreliable measures of Poisson's ratio may be obtained when using measurements from a single face. Several approaches that use replication to arrive at more reliable values were considered. Of all methods considered, the most reliable results were obtained by taking a trimmed mean of deflections measured on replicate specimens and calculating a single Poisson's ratio and creep compliance for the mixture.

The trimmed mean involves ranking observations numerically, that is, "trimming" the highest and lowest values and averaging the remaining observations. Trimmed observations, although not directly used to calculate the mean, influence the mean and should not be considered wasted data. By using the trimmed mean technique to obtain average horizontal and vertical strains for the mixture, a single, representative Poisson's ratio is determined for the mixture on the basis of measured deflections from all the replicate specimens.

Because replicate specimens may have different thicknesses, creep loads, and possibly diameters, deflections must be normalized so that they can be ranked and trimmed properly. The first step is to find the average thickness, diameter, and creep load of the specimens (Equations 18–20), in which the summation for i varies from 1 to the n number of specimens.

$$t_{AVG} = \frac{\sum t_i}{n} \tag{18}$$

$$D_{AVG} = \frac{\sum D_i}{n} \tag{19}$$

$$P_{AVG} = \frac{\sum P_i}{n} \tag{20}$$

Where n equals the number of specimens.

Each of the ith horizontal and vertical deflection arrays are then multiplied by the following normalization factor (Equation 21) to obtain normalized deflections (Equations 22 and 23).

$$C_{NORM_i} = \left(\frac{t_i}{t_{avg}}\right) * \left(\frac{D_i}{D_{avg}}\right) * \left(\frac{P_{avg}}{P_i}\right) \tag{21}$$

$$H(t)_{NORM_i} = H_M(t)_i * C_{NORM_i} \tag{22}$$

$$V(t)_{NORM_i} = V_M(t)_i * C_{NORM_i} \tag{23}$$

The trimmed mean of the normalized deflection arrays is then obtained by ranking each of the horizontal and vertical arrays according to its normalized deflection values in a window around the middle of the test. For example, consider a 1,000 sec creep test with three replicates and horizontal and vertical measurements taken on both sides of each specimen (Figure 6). Because the data arrays contain measurements taken every 10 sec, and some small level of noise is present in the data, a "noise-insensitive" approximation of the normalized deflection at $t = 500$ sec is obtained by averaging the nine values in a window between $t = 460$ and $t = 540$ sec. These "mid-test" averages of the six horizontal and six vertical deflection arrays are then ranked numerically to identify the middle four horizontal and middle four vertical deformation arrays (the trimmed mean discards the upper and lower observations) to be used in subsequent steps.

The horizontal and vertical deflection arrays remaining after trimming are averaged to obtain the trimmed mean deflection arrays (Equations 24 and 25), where the summation on j

$$H(t)_{TRIM} = \frac{\sum H(t)_{NORM_j}}{2n - 2} \tag{24}$$

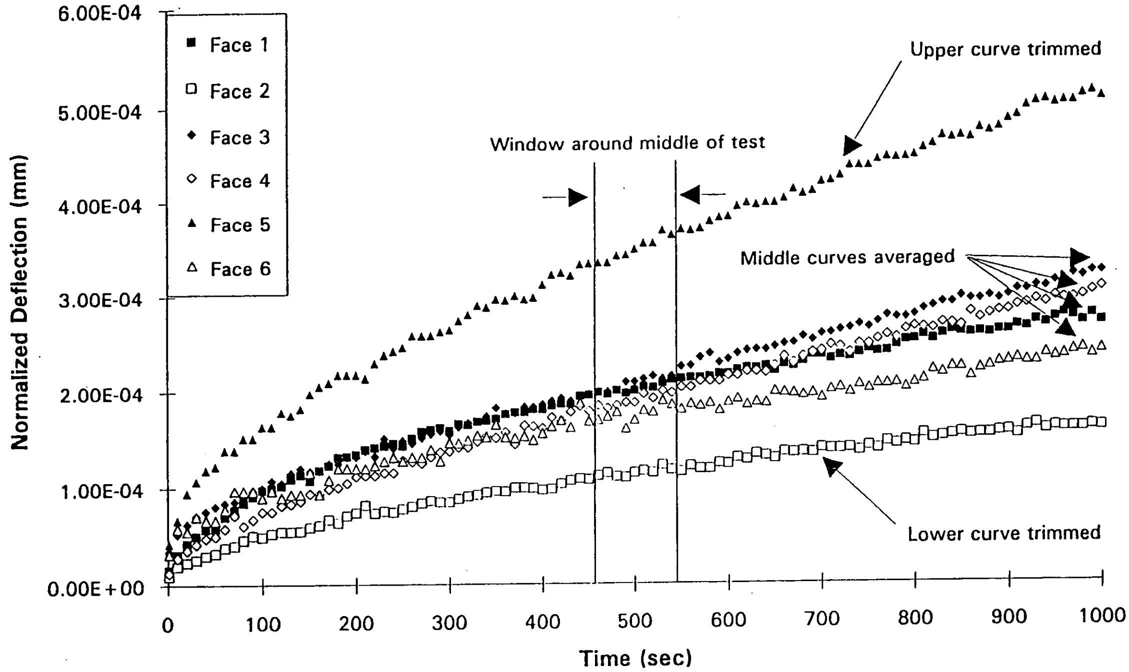

FIGURE 6 Trimmed mean approach for obtaining $H(t)_{AVG}$ and $V(t)_{AVG}$.

$$V(t)_{TRIM} = \frac{\sum V(t)_{NORM_j}}{2n - 2} \tag{25}$$

varies from 1 to the $2n - 2$ sorted deflection arrays.

The scalar quantity $(X/Y)_{TRIM}$ is then calculated for the entire test (Equation 26),

$$\left(\frac{X}{Y}\right)_{TRIM} = \frac{\sum H(t)_{TRIM}}{\sum V(t)_{TRIM}} \tag{26}$$

where the summation is taken over all elements in the array. The remainder of the analysis can be performed using Equations 1 through 17, after making the following substitutions:

$$t = t_{AVG}$$
$$D = D_{AVG}$$
$$P = P_{AVG}$$
$$X/Y = (X/Y)_{TRIM}$$
$$H_M(t) = H(t)_{TRIM}$$

SYSTEM EVALUATION

Although the previous sections described the evolution of the testing and analysis system in terms of test protocols, equipment, and analysis methods, there is one major issue that must still be addressed, namely: Does the new system give reasonable values of creep compliance and Poisson's ratio? There is no simple answer to this because fundamental properties of asphaltic mixtures at low temperatures are not thoroughly documented. In the following section, two separate experiments will show that (*a*) the Poisson ratio values obtained from the new system are reasonable and necessary if creep compliances are to be computed correctly and (*b*) creep compliances obtained from the new system were used successfully to predict thermal cracking performance of field sections when used in a mechanics-based model developed for SHRP at PSU.

MRL Materials Testing Program

Specimens were prepared by using rolling wheel compaction and MRL materials at Oregon State University. Four mixtures were prepared, consisting of two binders (AAG-1 and AAK-2), two air-void levels (approximately 4 percent and 8 percent, and one aggregate (RB). The two binders selected are known to have extremely different properties. The AAG-1 binder is very hard (low compliance), whereas the AAK-2 binder is very soft (high compliance).

Because well-known values of Poisson's ratio for the selected mixtures do not exist, one way to evaluate the reasonableness of values obtained was to compare measured values against expected trends. It is clear that measured Poisson's ratios (Table 1) for mixtures with low air voids (about 4 percent) are higher than those obtained from mixtures with high air voids (about 8 percent). Values range from 0.18 to 0.33 for low-void mixtures, whereas high-void

TABLE 1 Measured Poisson's Ratios in Study on MRL Mixtures

Mixture	Temp. (°C)	Air Voids	
		High	Low
Hard Asphalt (AAG-1)	-5	0.20	0.46
	-15	0.30	0.50
Soft Asphalt (AAK-2)	-5	0.18	0.49
	-15	0.33	0.50

mixtures range from 0.46 to 0.50, following the expected trend. Poisson's ratio is a measure of compressibility, where $\upsilon = 0.5$ for incompressible materials and $\upsilon \leq 0.5$ for compressible materials. A less significant difference is seen between Poisson's ratios obtained at −5°C and those obtained at −15°C for specimens having similar air-void levels. For mixtures with high voids, the differences in Poisson's ratios at the two temperatures range from 0.10 and 0.15; whereas for low-void mixtures the differences range from 0.01 to 0.04.

The importance of using these values of Poisson's ratio measured directly from the specimen, as opposed to the commonly accepted practice of using default values (e.g., $\upsilon = 0.35$), can be seen by comparing compliances obtained using measured Poisson's ratios with those obtained using a default value (Table 2). For mixtures with identical constituents, specimens compacted to a lower level of air voids logically should exhibit lower compliance than specimens compacted to a higher level of air voids. This trend is observed to be true for all four mixtures by comparing compliances computed using measured values of Poisson's ratio (Table 2). In contrast, when a default value of Poisson's ratio ($\upsilon = 0.35$) was used in computing compliances, the expected trend was less prominent. In fact, in two of the four mixtures the expected trend was reversed when the default value of Poisson's ratio was used.

Therefore, measured values of Poisson's ratio appear both reasonable and necessary for the accurate computation of creep compliance. This confirms the analytical findings of Roque and Buttlar (*1*). Other expected trends, such as higher compliance at higher temperatures and higher compliances for the mixture containing the softer AAK-2 binder were also observed (Table 2).

Comprehensive Field Core Testing Program

The new system can be used to obtain fundamental mixture properties at low temperatures that appear to be reasonable. The advantage of obtaining fundamental mixture properties is that the measured values can be used directly in mechanics-based performance prediction models. Such models can be used to predict pavement response and performance for a broad range of conditions and assist efforts to control thermal cracking in performance-based mixture specifications. Additional details on this subject were reported by Lytton et al. (*4*).

A mechanics-based thermal cracking model was developed at PSU under the SHRP A-005 contract. This model was incorporated into the SUPERPAVE software, which was designed to support the new SHRP binder and mixture specification (*5*). A complete description of this model is beyond the scope of this paper. However, the strong correlation between cracking predicted by the mechanics-based model using properties measured from the new system with thermal cracking observed in the field also provides evidence that the method presented here provides reasonable and accurate estimates of low-temperature mixture properties.

In the final calibration of the PSU thermal cracking model, 20 GPS sections from around the United States were used. Site-specific environmental and pavement structure data were used along with information obtained from field-cored specimens using the new testing and analysis system. Rheological properties (i.e., compliances) were obtained by testing each section at three temperatures with three replicates; thus, 180 specimens were tested and analyzed.

Predicted and observed cracking for this comparison were categorized as follows:

- *Zero cracking:* 0 to 7.6 m of cracking per 152-m section (< 1 crack per 76 m) [0 to 25 ft of cracking per 500-ft section (< 1 crack per 250 ft)],
- *Low cracking:* 7.6 to 23 m of cracking per 152-m section (from 1 crack per 76 m to 1 crack per 26 m) [25 to 75 ft of cracking per 500-ft section (from 1 crack per 250 ft to 1 crack per 85 ft)],
- *Medium cracking:* 23 to 46 m of cracking per 152-m section (from 1 crack per 26 m to 1 crack per 12 m) [75 to 150 ft of cracking per 500-ft section (from 1 crack per 85 ft to 1 crack per 40 ft)], and
- *High cracking:* greater than 46 m of cracking per 152-m section (> 1 crack per 12 m) [greater than 150 ft of cracking per 500-ft section (> 1 crack per 40 ft)].

The development of this grouping system is described elsewhere (*4*).

Predicted and observed cracking of the 20 sections were correlated fairly strongly ($R^2 = 0.84$). These results were arranged (Table 3) so that accurate predictions would fall on a diagonal line. As displayed, only one prediction was off the diagonal by two cells and no prediction deviated by three cells. Of the other 19 predictions, 16 were on the diagonal, indicating an excellent prediction, and only three were off the diagonal by one cell, suggesting a fairly good prediction. Thus, the correspondence between predicted and observed cracking was excellent or good for 19 of the 20 test sections. Additional details concerning these predictions may be found elsewhere (*4,5*).

TABLE 2 Compliances from Measured and Assumed Poisson's Ratios in Study on MRL Mixtures

		Compliance @ 1000 sec (1/mPa) x 10^6			
		Measured Poisson's Ratio		Poisson's Ratio = 0.35	
		Air Voids		Air Voids	
	Temp °C	High	Low	High	Low
Hard Asphalt (AAG-1)	-5	251	147	190	231
	-15	60	41	55	55
Soft Asphalt (AAK-2)	-5	3220	1260	2350	1600
	-15	432	247	425	353

TABLE 3 Observed Versus Predicted Cracking Using PSU Thermal Cracking Model and Properties Obtained with New Measurement and Analysis System

		Observed Cracking			
		Zero	Low	Med	High
Predicted Cracking	Zero	4	2	1	
	Low		1		
	Med			3	
	High			1	8

Considering the inherent variability of bituminous mixtures and the potential problems in obtaining properties from field-cored specimens, the quality of measurements obtained with the new system appears to be suitable for use with a mechanics-based thermal cracking model in a performance-based specification test.

SUMMARY AND CONCLUSIONS

Suitable test methods, test equipment, and analysis procedures for the new indirect tensile creep measurement and analysis system were presented in this paper. Developments in test methods help keep specimen behavior in the linear range and allow for consistent temperature, humidity, and load conditioning of specimens. Round gauge points led to an improved transducer mounting system, and the use of a transducer diagnostics program improved the quality of data acquired. Simplified analysis equations were developed that incorporate the solutions of more complicated iterative equations. A trimmed mean data-reduction approach was presented that can be used to obtain more reliable estimates of Poisson's ratio and creep compliance by using data from replicate tests.

It appears that reasonable and accurate estimates of creep compliance and Poisson's ratio can be obtained using the new measurement and analysis system presented. Tests on four MRL mixtures showed the importance of obtaining Poisson's ratio for each mixture. Expected trends between the mixtures were detected by the new system. Performance of 20 field sections was predicted with good accuracy ($R^2 = 0.84$) when properties obtained with the new system were used in a mechanics-based thermal cracking prediction model developed at PSU.

REFERENCES

1. Roque, R., and W. G. Buttlar. Development of a Measurement and Analysis Method to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Mode. *Proc., Association of Asphalt Paving Technologists,* Vol. 61, 1992.
2. Hussain, S. R. *Evaluation of Low Temperature and Pavement Deformation Characteristics of Some Polymer Modified Asphalts.* Master of science thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta, Canada, spring 1990.
3. Bahia, H. *Low Temperature Isothermal Physical Hardening of Asphalt Cements.* Ph.d. thesis, Pennsylvania State University, University Park, Pa., 1991.
4. Lytton, R. L., R. Roque, J. Uzan, D. R. Hiltunen, E. Fernando, and S. M. Stoffels. *Performance Models and Validation of Test Results.* Draft Final Report to Strategic Highway Research Program, Project A-005, Washington, D.C. 1993.
5. Roque, R., D. R. Hiltunen, and S. M. Stoffels. *Field Validation of SHRP Asphalt Binder and Mixture Specification Tests to Control Thermal Cracking Through Performance Modeling.* Presented at the Annual Meeting of the Association of Asphalt Paving Technologists, 1993.

Publication of paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures To Meet Structural Requirements.