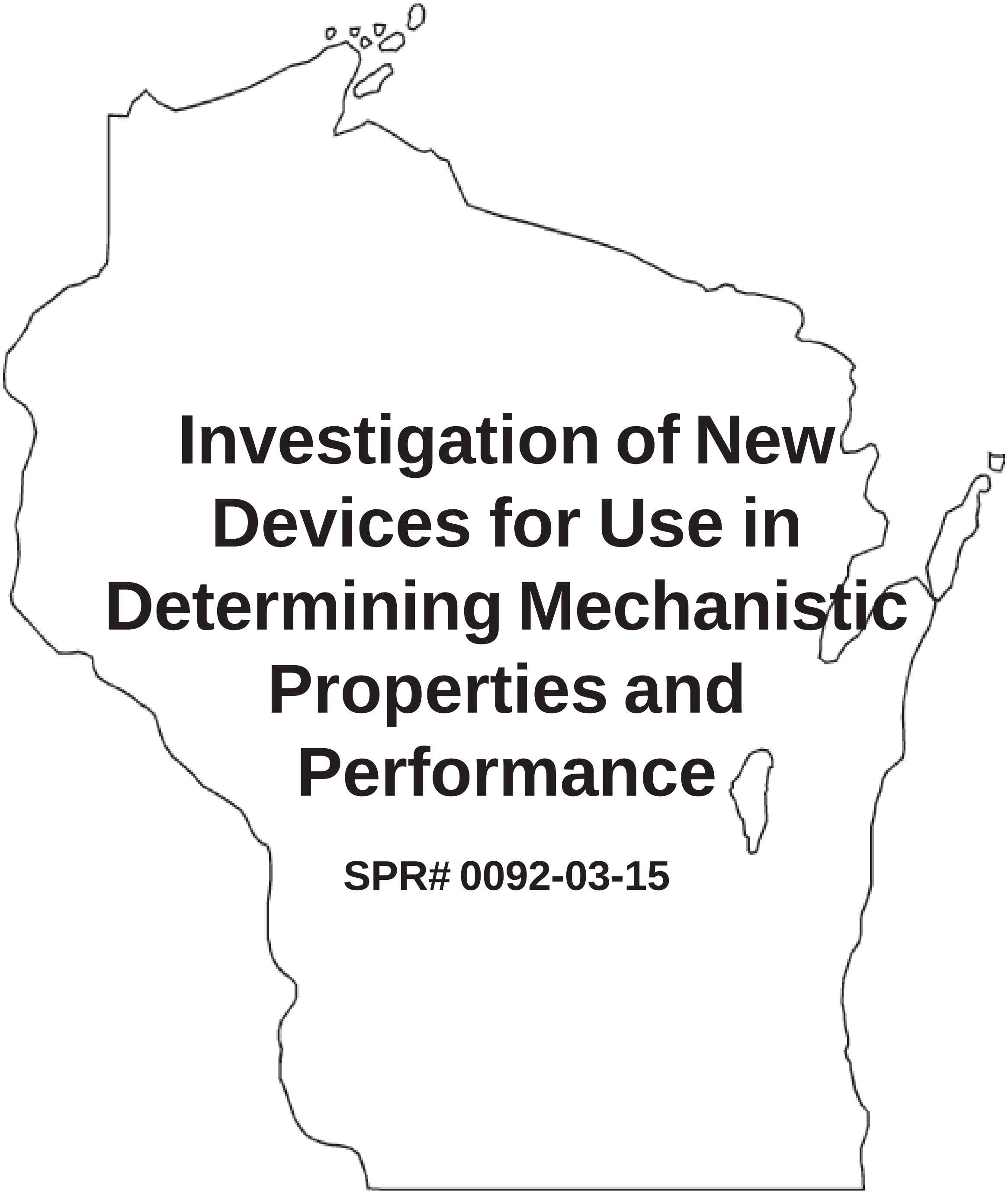
Wisconsin Highway Research Program



Investigation of New Devices for Use in Determining Mechanistic Properties and Performance

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INVESTIGATION OF NEW DEVICES FOR USE IN DETERMINING MECHANISTIC PROPERTIES AND PERFORMANCE

Final Report

by

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16. **Abstract**

The objective of this report is to provide the Wisconsin Department of Transportation (WisDOT) with an in-depth discussion of the various alternatives currently available for evaluating asphalt concrete mixtures and pavements in the field. An extensive literature review of current test methods and devices which can be used to evaluate asphalt concrete mixtures was conducted. Also, creep and recovery and indentation tests were performed at Rowan University to investigate their potentials as plant and field quality control tests, respectively. The results of these tests, as well as the results of the literature review, are presented in this report. Finally, recommendations are made to WisDOT as to which method/device would be best for evaluating asphalt concrete mixtures and pavements in the field.

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Executive Summary

Project Summary

This study provides the Wisconsin Department of Transportation (WisDOT) with the alternatives for evaluating asphalt concrete mixtures at the laboratory, plant and in the field. The recommendations of the test method and the device were based primarily on its capability of measuring accurate and repeatable properties that affect pavement performance. In addition, factors such as specimen preparation, testing time, and ease of operation were also considered.

Background

In recent years, several studies have been initiated by the National Cooperative Highway Research Program to develop a "simple" performance test for the design and optimization of asphalt concrete mixtures. As part of the NCHRP projects 1-37A and 9-19, the compressive dynamic modulus, the flow time (i.e. starting point of tertiary deformation) for the repeated test and a creep test have been proposed as mechanical properties and parameters for the American Association of State Highway Transportation Officials (AASHTO) mechanistic-empirical (ME) pavement design guide. In addition to these parameters, NCHRP 9-18 has recommended shear dynamic modulus as measured from the Field Shear Test device as a field test for quality control and quality assurance (QC/QA). However, no single device or parameters have been identified that would be suitable for use in the laboratory, field and the plant. There is a need to determine a test method and a device that will be sensitive to the critical properties of asphalt concrete mixtures, which is cost effective and can make measurements that are reasonably repeatable not only in the laboratory, but also during mixing and construction.

Based on the extensive literature review of critical mechanical parameters, current test methods, and devices used to evaluate asphalt concrete mixtures, the following tests were identified: 1) dynamic complex modulus test for characterization at the laboratory; 2) creep and recovery at the plant; and 3) indentation in the field. Subsequently, creep and recovery and indentation tests were performed at Rowan University to further investigate their potential as plant and field quality control tests, respectively. Based on the results, recommendations were made to WisDOT as to which method/device would be best for evaluating asphalt concrete mixtures and pavements in the field.

The Department of Civil and Environmental Engineering at Rowan University conducted this research project through the Wisconsin Highway Research Program. The research team includes, Dr. Yusuf Mehta (Assistant Professor), Dr. Beena Sukumaran (Associate Professor), Jeremy Stevenson and John Liddle (students).

Process

The first step of the research process was an extensive literature review covering the following topics: 1) the critical parameters of asphalt concrete that affect performance; 2) existing laboratory test devices for characterizing the mechanical behavior of asphalt concrete; and 3) density measuring devices. This was followed by a pilot experimental program at the Rowan University laboratory to evaluate the creep and recovery test and the indentation test. The entire research was conducted in 30 months. The process was consistent with the research protocol typically observed in other investigative proposals.

Findings

The findings of the study are outlined below:

1. The dynamic complex modulus (DCM) appropriately captures the viscoelastic response under dynamic mode of loading and correlates well with rutting and fatigue cracking. In addition, DCM is the required property in the mechanistic empirical design guide.

2. The creep and recovery test is simpler and quicker than the dynamic complex modulus test.

3. The creep compliance from the creep and recovery test can be used to indirectly obtain dynamic modulus values because the tests were performed within the linear viscoelastic region. Hence, creep compliance can be indirectly correlated to pavement performance.

4. Indentation, a test for field evaluation, was not found to be sensitive to changes in asphalt content. These results suggest that the indentation test would have limited applicability as a quality control and quality acceptance test in the field.

5. The nuclear density gauge is currently the most accurate method of evaluating density in the pavements.

Conclusions

Based on the findings mentioned above, the conclusions are as follows:

1. DCM would be appropriate as the primary laboratory material characterization parameter for asphalt concrete mixtures.

2. The creep and recovery test has the potential to characterize asphalt concrete mixtures at the plant. However, further research and testing is required before the test can be implemented as a quality control device at the plant.

Impact of the Findings

After an extensive investigation, the study identifies tools available to the state agency for characterization of asphalt concrete in the laboratory, plant and the field. The most significant impact would be to pursue the creep and recovery test that will detect problems in mixtures before and during construction and ensure better performing pavements. This device, if successfully implemented, will increase the life of a flexible pavement and reduce the life cycle cost of the pavement.

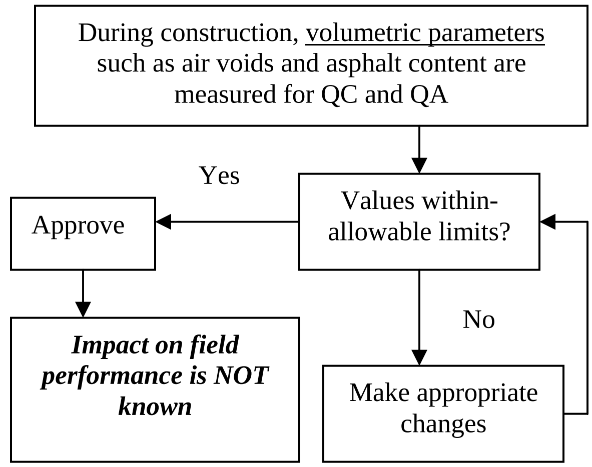

Figure 1. Current Practice in Construction Industry

During construction, the state agency measures volumetric parameters such as air voids, and asphalt content for quality control (QC) and quality acceptance (QA). Decisions about approving the job are made depending on whether these values are within the allowable deviation from the target value (Figure 1). However, even a slight change in some of the volumetric parameters may cause significant differences between in-place mechanical properties and the design values, leading to a remarkable change in long-term performance. Since the mechanical properties are not measured during construction, the impact of the changes in volumetric parameters on field performance is not known. Currently, there is no device available that can measure mechanical properties of construction material during mixing that correlates with performance. The reason for a lack of such a device is because there was no method available that can measure the mechanical response of materials during construction under varying environmental conditions which impacts performance. Due to the lack of such a method the parameters measured and controlled during construction for QC and QA do not account for performance in the field. This makes the current construction monitoring process ineffective in preventing premature failures even though the design and construction may meet all requirements.

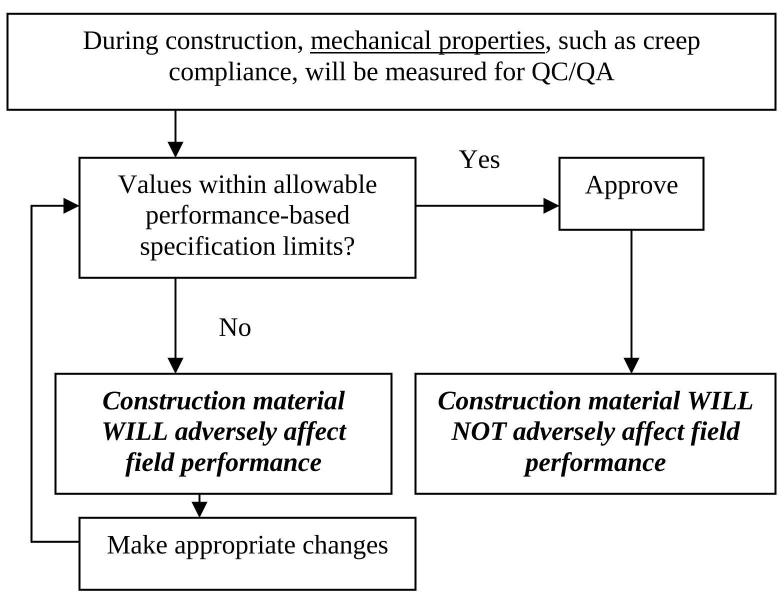

Figure 2. Impact of Study on Construction Monitoring Process in Construction Industry

The creep and recovery test will capture the interaction between the complex mechanical behavior of construction materials and construction variability in the form of fundamental mechanical properties that influence long-term field performance.

Successful development of the creep and recovery test will eventually lead to the development of a real-time evaluation device for construction materials (REDCOM). During construction of asphalt concrete pavements, the contractor or the state agency will use the device to evaluate the quality of the material as it is being laid on the road (Figure 2). Depending on the quality of the material, the contractor will have the following options: a) to continue laying the road if the quality of the material is as designed; b) make appropriate changes in the future batch if the deviation from the design is small enough to be rectified during construction; and c) to stop construction and make significant changes if the quality of material is significantly different from the design. With the development of the creep and recovery test as proposed in this study, the end-user will transcend beyond measuring just volumetric parameters that had little correlation to field performance (as previously outlined in Figure 1). The end-user will then have more confidence in the field performance of the material being constructed.

Recommendations for Further Action

The recommendations based on the findings and conclusions are as follows:

<u>Laboratory Test</u>

The research team recommends that Dynamic Complex Modulus be used as a Simple Performance Test for the laboratory characterization. The operational characteristics of the testing equipment, including specimen dimensions are specified to obtain accurate and repeatable measurements. The research team recommends that WisDOT proceed to conduct the state/regional calibration of performance models that may be included in the pavement design guide.

<u>Test Method at the Plant - Creep and Recovery Test</u>

The pilot experimental program of creep and recovery tests showed significant promise and compliment the dynamic complex modulus. The research team recommends that this test be evaluated further for characterization at the plant. To do this effectively, a more comprehensive experimental testing protocol will be necessary before guidelines can be developed.

<u>Test Method in the Field - Indentation Test</u>

The research team recommends that they hold-off on this until the creep and recovery test guidelines are developed.

<u>Density Measurement</u>

The research team recommends that WisDOT continue to use the Nuclear Density Gauge for measuring the density of pavements as an alternative to density measurement from cores.

Implementation and Training

Audiences

The primary audiences for the products outlined above are engineers and technicians responsible for the structural design of flexible pavement, and the design of asphalt concrete mixtures. Typically, these would be mid-level to senior engineers and experienced technicians working for the WisDOT, consulting engineers, paving contractors, HMA suppliers, and private testing laboratories.

Leadership

Under the leadership and support of WisDOT, the creep and recovery test can be developed for characterization at the plant, and performance models can be evaluated based on regional data to be incorporated in the pavement design guide.

Assessment Criteria

Assessing progress in the adoption of the products of this research within WisDOT will be measured by the successful integration of DCM in the design guide and the development of the creep and recovery test. Another measure of the success of the implementation is the number of organizations requesting information on the project from WisDOT or the research team.

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1.0. Introduction

Design procedures based solely on empirical methods have not sufficiently fulfilled the needs of the current asphalt paving industry. A more mechanistic method is required to properly quantify the behavior of asphalt concrete and to develop better performing pavements. The mechanistic empirical pavement design guide (design guide) has incorporated the dynamic modulus as the primary material characterization parameter for asphalt concrete mixtures. Unfortunately, the dynamic modulus test is expensive, time consuming to perform, and not suited for field evaluation. According to Brown et al. (2004) each of the diametric, uniaxial, triaxial, and shear dynamic modulus tests are overly complex and require expensive equipment to perform. Figure 3 outlines the current practice of the asphalt paving industry and illustrates where in the process the need for evaluation devices lie.

Devices currently used in the industry for measuring density are also discussed in this report. A recommendation will be made for implementation in the WisDOT mechanistic design procedures for measuring the density of asphalt concrete in pavements to ensure better performing mixtures. The recommended device must have the following characteristics:

- Makes accurate and repeatable measurements of critical mechanistic properties of asphalt concrete mixtures which can be correlated to pavement performance.
- Can be used in both the laboratory and the field.
- Produces results quickly (considering specimen preparation, testing time, and results output).
- Easily operated.
- Relatively cheap.

The dynamic modulus of asphalt concrete can also be obtained from the simpler static creep and recovery test by way of a theoretical interconversion of creep compliance with dynamic modulus. Creep and recovery, however, cannot be performed in the field without drilling cores in the newly constructed pavement. In this study, the indentation test was investigated for use as a nondestructive quality assurance test in the field. It was proposed that a correlation could be developed between the results of the creep and recovery test and the indentation test, and that the dynamic modulus of asphalt concrete can be obtained from the indentation test using this correlation.

This report begins with a discussion of various laboratory tests that are used to measure the critical parameters of asphalt concrete. This discussion also provides some insight into the theory behind asphalt concrete testing. Next, field evaluation devices currently used by the industry are discussed and compared. Results of the investigation of the creep and recovery and indentation tests, conducted at Rowan University, are then presented. Finally, a device is recommended for use in evaluating asphalt concrete pavements.

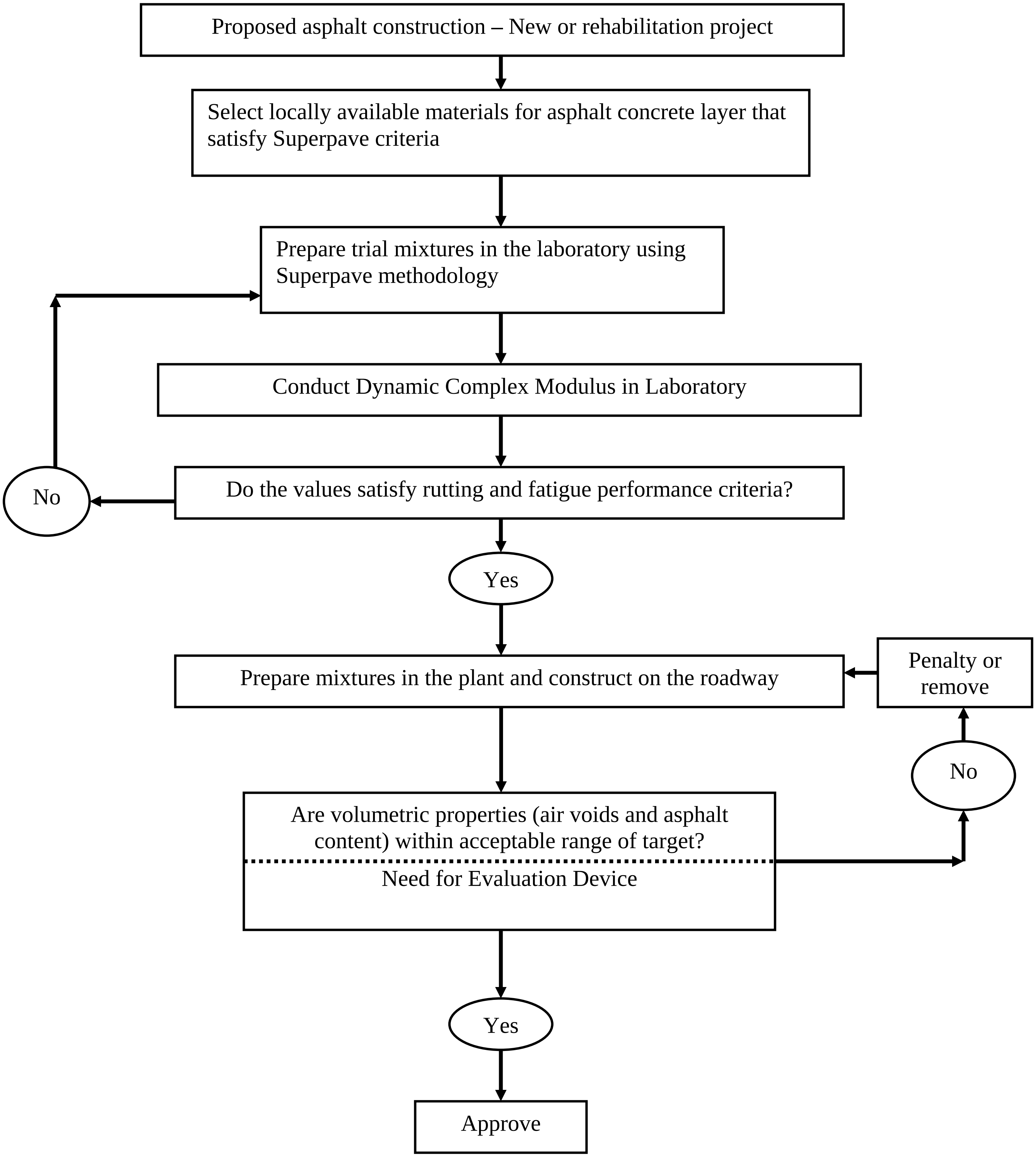

Figure 3. Current Practice in Asphalt Paving Industry.

2.0. Laboratory Tests and Critical Parameters

Table 1 lists properties and parameters of asphalt concrete along with how well they correlate with field distresses and their sensitivity to the volumetric properties of asphalt concrete. As can be seen in the table, various parameters have been correlated with pavement distresses. Among them, the one that is presently drawing much attention and is anticipated to become the test parameter of choice is the dynamic complex modulus. The tests listed in the table, as well as a few others, are discussed in this section.

Table 1. Correlations of Asphalt Concrete Properties to Pavement Performance

	Creep Compliance	**Shear Dynamic Modulus**	**Shear Strain Slope**	**Plastic Shear Strain (γ_p)**	**Flow Number (F_N)**	**Triaxial Dynamic Complex Modulus**
Test Procedure+	Indirect Tensile Test	Simple Shear Test and Field Shear Test	Unconfined Static Creep Test	SST RSCH Test	Triaxial Repeated Load Test	Dynamic Complex Modulus Test
Temperature Range+	Low	Intermediate to High	High	High	High	Intermediate to High
Distress Mode+	Fatigue Cracking, Thermal Cracking	Fatigue Cracking, Rutting	Rutting	Rutting	Rutting	Fatigue and Rutting
Correlation With Field Performance (Note: MnR = MnRoad; ALF = Accelerated Loading Facility, WsT = WesTrack.)						
Excellent+						E*/sinϕ had good (MnR, ALF) to excellent (WsT) correlation to rutting in unconfined test
Good+	Creep compliance at 1000 sec had a fair (WsT) to good (MnR) correlation to cracking	SST showed fair (WsT) to good (MnR, ALF) comparison to rutting for G* at 130°F	Fair (WsT), good (ALF), and Excellent (MnR) correlation with rutting	Best correlation to measured rut depth for accumulated shear strain was obtained at the higher test temp and higher number of life cycles	Good (MnR, ALF, WsT) correlation with rutting	E* had good correlation to rutting in unconfined test
Fair+						Fair (WsT) correlation to measured amount of cracking at lower temperatures
Very Poor+		FST showed very poor (MnR) comparison to rutting				
Sensitivity to Volumetric Parameters						
Air Void,%	Sensitive	Sensitive	Sensitive	Sensitive	Sensitive	Sensitive
AC, %	Sensitive	Sensitive	Sensitive	Sensitive	Sensitive	Sensitive
Gradation (% passing 4.75mm, 2.36mm, 0.075mm)	May not be as sensitive to gradation as to binder properties at low temperatures	Sensitive to changes in % passing 4.75mm, 2.36mm, 0.075mm				Sensitive to changes in % passing 4.75 mm and 0.075 mm

+ Information from Report #465 of the National Cooperative Highway Research Program.

2.1. Flow Time Test

The flow time test is a variation of the simple compressive creep test. In the creep test a static load is applied to a specimen and the resulting strains are recorded as a function of time. The variation introduced by the National Cooperative Highway Research Program (NCHRP) Project 9-19 is the flow time test. Flow time is defined as the time when the minimum rate of change in strain occurs during the creep test. It is determined by differentiation of the strain versus time curve (Bonaquist et al., 2003).

In NCHRP Project 9-19, the flow time correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility. For tests at a given temperature, axial stress, and confining stress, the rutting resistance of the mixture increases as the flow time increases (Bonaquist et al., 2003).

2.2. Flow Number Test

The flow number test is a variation of the repeated load permanent deformation test. In the repeated load permanent deformation test, haversine axial compressive load pulses are applied to a specimen. The duration of load pulse is 0.1 seconds followed by a rest period of 0.9 seconds. The permanent axial deformation is measured at the end of the rest periods during repeated loading and converted to strain by dividing by the original specimen length. The variation introduced by NCHRP Project 9-19 is the flow number test. Flow number is defined as the number of load pulses when the minimum rate of change in permanent deformation occurs. It is determined by differentiation of the permanent strain versus number of load cycles curve (Bonaquist et al., 2003).

As with the flow time, in NCHRP Project 9-19, the flow number correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility. For tests at a given temperature, axial stress, and confining stress, the rutting resistance of the mixture increases as the flow number increases (Bonaquist et al., 2003).

2.3. Field Shear Test

The Field Shear Test (FST) device was originally developed during NCHRP Project 9-7 as a rugged, simple device for performing quality control testing on asphalt concrete specimens in the field (Christensen, 2003). It was designed as an alternative to the complex and expensive Superpave Shear Test (SST) which was used to evaluate various performance related properties such as complex shear modulus and resistance to permanent deformation. The original FST had many desirable qualities such as small size, ruggedness, and ease of use. However, the variability of the device was found to be too high for quality control use. A new testing protocol for the FST device was developed as part of NCHRP Project 9-18 in which four modulus measurements are taken for each specimen tested and the specimen is rotated and/or flipped between each measurement, so that the specimen is sheared in a different sense and different location each time. This was intended to reduce the variability of the modulus measurements due to the non-homogeneity of the material and slight differences in test setup (Christensen, 2003).

The sensitivity and precision of the improved FST testing protocol were evaluated by Christensen (2003). Some of the main conclusions drawn from these evaluations are as follows:

- The time required for the new testing protocol, about 10 minutes per specimen, is still reasonable for a quality control device;
- The new protocol produces complex modulus data which is significantly more precise than that produced using the earlier protocol;
- Complex modulus measurements made using the new FST protocol are sensitive to changes in mixture composition;
- The overall coefficient of variation for complex modulus values at 10 Hz and 40ºC was found to be 8.0%, which is very good for modulus measurements on asphalt concrete specimens.

2.4. Rapid Triaxial Test

Crockford et al. (2002) discuss the Rapid Triaxial Test, or RaTT, which is an automated version of the triaxial test. Basically, three levels of automation are discussed: feedback control; stringing together test sequences through computerization; and specimen loading/unloading and instrumentation mounting. According to Crockford et al. (2002), the RaTT has the following advantages:

- It can be used for all flexible pavement materials including low cohesion base materials and hot mix at high temperatures.
- It can provide both engineering properties and index properties. The properties may be used as index properties in QC applications and as engineering properties for structural design and performance prediction. Testing over the past five years from at least three different sources on a range of mix designs indicates good correlation with field rut measurements.
- It minimizes technician handling time and interaction with instrumentation.
- Data analysis is embedded in the software so that the end result is immediately available with the computational details transparent to the user.
- The tests can be conducted in a reasonable amount of time using technicians with a reasonable skill level and a minimal level of computer literacy.

2.5. Indirect Tensile Test

The indirect tensile test is one of the most popular tests used for HMA mixture characterization in evaluating pavement structures. Properties measured by the indirect tensile tests that have been used for evaluating moisture damage and fracture related distresses are the resilient modulus (under repeated loadings) and indirect tensile strength and failure strain.

In the indirect tensile creep test a single load-unload cycle. A constant static load is applied to the specimen for 1000 s and the horizontal deformation is recorded. The creep compliance from the indirect tensile test showed high correlation with thermal cracking data.

2.6. Soil Stiffness Gauge (SSG)

The soil stiffness gauge measures near-surface stiffness by imparting a small dynamic force to the soil through a ring-shaped foot at 25 steady state frequencies between 100 and 196 Hz. The maximum single amplitude force produced during the SSG measurement is determined to be 10-17.3 N (Sawangsuriya et al. 2003). The stiffness is calculated as the average force per unit displacement over the measured frequencies. Due to small stress and strain levels, the stiffness measurement using the SSG is close to that required for the calculation of strain and displacement for a range of geotechnical applications including pavements.

The soil stiffness is known to change as a function of strain amplitude and stress state. A comparison of moduli of granular soils obtained from SSG with moduli obtained from tests on the basis of comparable stress and strain amplitudes indicate that SSG measures moduli at strain amplitudes lower than the strain amplitudes induced in resilient modulus, which is typically used in pavement design. Since resilient modulus is considered to be the modulus representative of the field traffic loading conditions, the SSG would provide an higher modulus values than the resilient modulus for granular soils.

2.6.1. Correlation between SSG Stiffness and Backcalculated Modulus

Backcalculated moduli of subgrades and bases from the falling weight deflectometer (FWD) test have been used extensively in pavement design, construction and maintenance. The difference between the moduli measured from the FWD and SSG tests is primarily due to in-situ variability of the material properties. Since backcalculated modulus values from the FWD test are obtained from all seven deflection measurements, which cover a distance of about 2 m, the moduli are therefore weighted over 2 meters. On the other hand, SSG only measures the near-surface soil stiffness right underneath its ring foot with the measurement influence of less than 0.3 m. Wu et al. (1991) concluded that the SSG is much more sensitive when the materials are stiffer. The relationship between backcalculated moduli (MPa) and SSG stiffness (MN/m) are given by (Wu et al. 1998, Chen et al. 1999):

$$(M_R)_{FWD} = 22.96 e^{0.12 K_{SSG}} \tag{1}$$

$$(M_R)_{FWD} = 37.65 K_{SSG} - 261.96 \tag{2}$$

2.6.2. Correlation between SSG Stiffness and Modulus from Seismic Test

Wu et al. (1998) determined that the elastic modulus obtained from SSG stiffness is about 3-times smaller than that obtained from seismic tests. The difference between the results of the two tests is explained by the difference in the stress-strain level used in these tests as well as the uncertainty of the effective depth of the SSG, which varies with stiffness, density and types of materials. The relationship between seismic modulus and SSG stiffness is given by (Chen et al. 1999):

$$(M_R)_{FWD} = 47.53 K_{SSG} + 79.05 \tag{3}$$

2.7. Load Wheel Testers (LWT)

The Load Wheel testers are performance tests on asphalt concrete primarily used to rank mixtures (Cooley et al, 2000). Several LWTs currently are being used in the United States. They include Georgia Load Wheel Tester (GWLT), Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD) and one-third scale Model Mobile Load Simulator (MMLS3). The sections below discusse the various load wheel testers.

2.7.1. Georgia Load Wheel Tester (GLWT)

The GLWT is capable of testing beams and cylindrical specimens. Testing of samples within the GLWT generally consists of applying 100 lb load on a pneumatic hose pressurized to 100 psi. The specimen can be tested at 4 or 7 percent air voids. The load is applied through an aluminum wheel on the linear hose, which resides on the sample. The testing is typically accomplished for a total of 8000 loading cycles (one cycle is forward and backward movement). The rut depth at the end of 8000 cycles is correlated to rutting.

2.7.2. Asphalt Pavement Analyzer (APA)

The APA is used to evaluate rutting, fatigue and moisture resistance of HMA mixtures. It follows the same testing protocol and loading configuration as the GLWT. Unlike GLWT, samples also can be tested while submerged in water.

2.7.3. Hamburg Wheel Tracking Device (HWTD)

The tests within the HWTD are conducted on a slab that is 260 mm wide, 320 mm long, and typically 40 mm high (10.2 in x 12.6 in x 1.6 in). These slabs are normally compacted to 7 percent air voids using a linear kneading compactor. As shown in Figure 4, results obtained from the HWTD consist of rut depth, creep slope, stripping inflection point, and stripping slope.

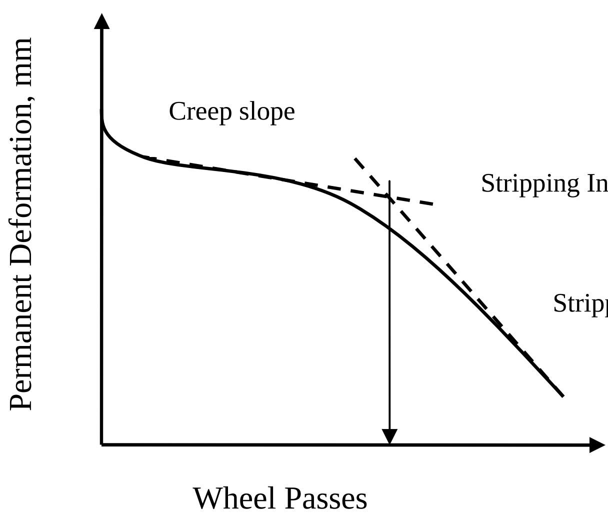

Figure 4. Typical Hamburg Wheel Tracking Test Results.

2.7.4. MMLS3 (Mobile Model Load Simulator) Pavement Testing System

The MMLS3 is a 1/3 scale machine that is mainly used to test the upper 120 mm of pavement structures. It can also test the effect of water, low temperatures, and high temperatures on the pavement. It can be used in the field as well as in the laboratory (Figure 5). The MMLS3 comes in different setups depending on the type of application.

Figure 5. Side view of MMLS3 with hot/cold air ducts on the right and water unit in the foreground.

The MMLS3 is an accelerated pavement testing device that applies realistic trafficking to the pavement. The load is scaled but tire pressures are at the same level as in full scale trucks. Accordingly, the results are transferable to conventional real life trafficking. The device can be used directly to explore performance of the upper 125 mm of asphalt pavements in the laboratory and in the field. Scaled down models of pavements can also be tested to investigate the performance of the full pavement structure. The MMLS3 can characterize a material/mix and predict actual performance if factors such as load frequency, temperature, and lateral wander of load applications and aging are taken into account. If there is a desire to evaluate pavement performance under slow trafficking in a manner similar to rut testers, it can also be done with the MMLS3, by adjusting the speed.

The MMLS3 has been used extensively in the last decade for testing of asphalt pavements and bridge joint products. There are currently 10 systems throughout the United States and several others in Europe, Africa, and Asia. Although it has been primarily used with asphalt pavements, it can be used for rigid concrete pavements research, as well as for semi-rigid concrete/asphalt pavements. Potential research topics in the area of concrete pavements include: testing of joints, moisture damage, reflective cracking, sealants, surface friction, concrete durability, and durability of reflectors, among others. The system comes with an environmental chamber to allow for low and high temperature testing. The pavement can be instrumented to measure strains, stresses, and temperature. The device can also be used for non-destructive evaluation, such as for ultrasonic, impact resonance, and GPR NDE applications to measure thicknesses and densities of pavements, among others.

2.8. Simple Performance Test

Witczak et al. (2002a) present the results of the NCHRP Project 9-19 research for developing a Simple Performance Test (SPT) for assessing the fatigue cracking and thermal cracking potential of asphalt pavements. The top SPT candidates are the dynamic modulus test and the creep test. It was found that these parameters/tests appear to have the potential to tie the Superpave volumetric mix design directly to field performance through the design guide. It was also found that the dynamic modulus test has the potential to be a unique SPT test which could predict rutting, fatigue cracking, and thermal cracking in asphalt concrete pavements (Witczak et al., 2002a). The dynamic modulus and creep and recovery tests are discussed in the next two sections.

2.9. Dynamic Complex Modulus Test

In NCHRP Project 9-19, high temperature dynamic modulus test data showed excellent correlation with rutting in field pavements, and intermeditate temperature dynamic modulus test data showed fair correlation with fatigue cracking. The complex modulus is the material property that relates stress to strain for a linear viscoelastic material (such as asphalt concrete). It has real and imaginary parts that define the elastic and the viscous response of the material. These can be determined from the dynamic modulus and phase angle measured in a controlled sinusoidal stress or strain test. Figure 6 shows schematically the response of a viscoelastic material under sinusoidal loading. The dynamic modulus and phase angle are defined below by Eqs. (4) and (5), respectively.

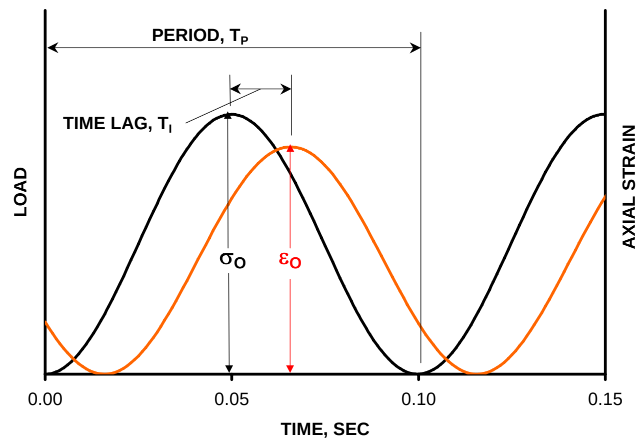

Figure 6. Typical Dynamic Modulus Test Data.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{4}$$

$$\phi = \left(\frac{T_i}{T_p}\right) \times 360 \tag{5}$$

where:

$|E^*|$ = dynamic modulus

σ_0 = amplitude of applied sinusoidal loading
ε_0 = amplitude of resulting sinusoidal strain
ϕ = phase angle in degrees
T_l = time lag, sec
T_p = period of sinusoidal loading, sec

The dynamic modulus is the overall stiffness of the material. The phase angle defines the relative magnitude of the elastic and viscous components. An elastic material has a phase angle of 0 degrees, while a viscous material has a phase angle of 90 degrees. The phase angle for asphalt concrete varies from about 5 degrees at low temperatures to about 40 degrees at high temperatures.

2.9.1. Dynamic Modulus in Pavement Design

In the mechanistic-empirical pavement models for the design guide, stresses and strains in the pavement will be computed using layered elastic theory. The dynamic modulus of the asphalt concrete is the appropriate material property for use in this analysis. Dynamic moduli for different temperatures and frequencies of loading can be combined using the principle of time-temperature superposition to form a master curve. This is shown in Figure 7 where 70°F has been selected as the reference temperature, and data for colder tempertures are shifted to the left while data for warmer temperatures are shifted to the right. Figure 8 presents the master curve and associated shift factors.

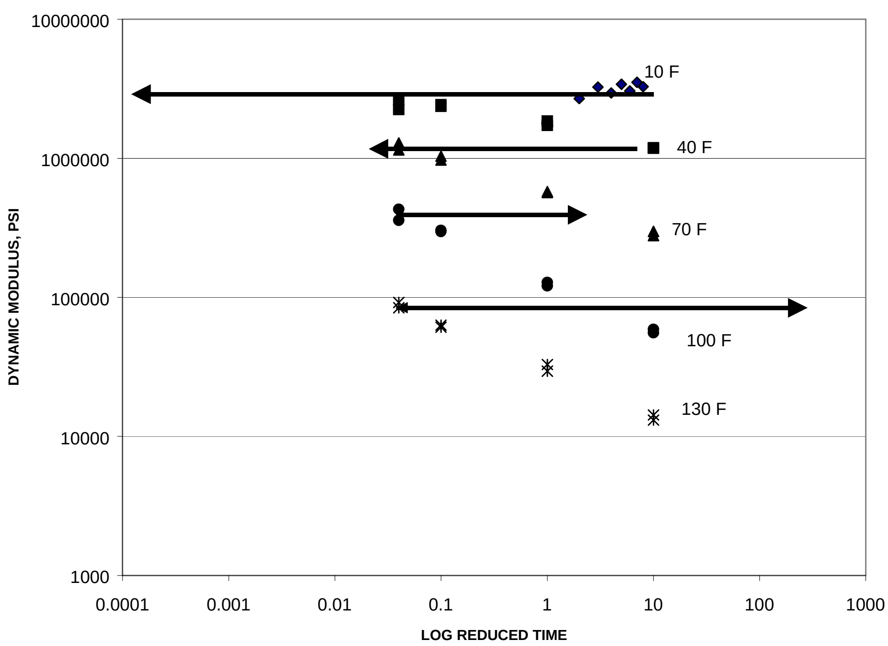

Figure 7. Schematic Representation of Time-Temperature Superposition.

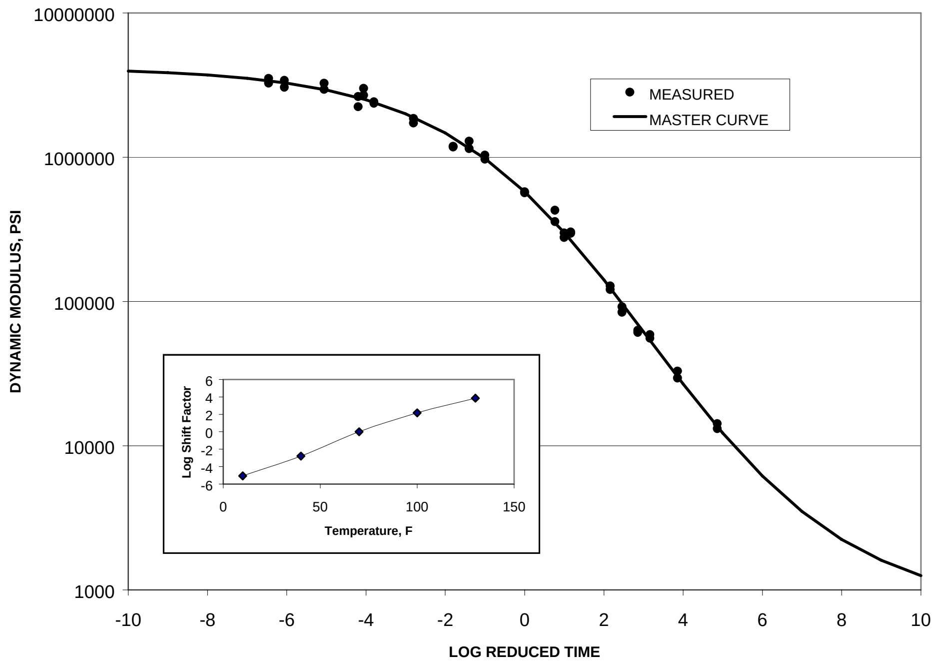

Figure 8. Typical Dynamic Modulus Master Curve for Asphalt Concrete.

Knowing the master curve and shift factors, the modulus at any temperature and loading rate can be determined. Eqs. (6) and (7) present the form of the master curve and shift factors used in the design guide for asphalt concrete, respectively. These relationships, calibrated for the design mixture, are then used to obtain appropriate moduli for all of the seasonal analyses performed in the design guide computations.

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}} \tag{6}$$

where:

E^* = dynamic modulus
t_r = time of loading at the reference temperature
δ = minimum value of E^*
$\delta+\alpha$ = maximum value of E^*
β, γ, α = parameters describing the shape of the sigmoidal function

$$\log(t_r) = \log(t) - c\left(\log(\eta) - \log(\eta_{T_r})\right) \tag{7}$$

where:

t_r = time of loading at the reference temperature
t = time of loading
η = binder viscosity at the temperature of interest
η_{Tr} = viscosity at the reference temperature

2.9.2. Dynamic Modulus As a Performance Test

In research conducted in NCHRP Project 9-19, dynamic modulus data at 37.8°C and 54.4°C correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility. Figure 9 shows an example of the relationship between rutting and dynamic modulus obtained in the Project 9-19 research for the FHWA Pavement Testing Facility sections. The rutting resistance of the mixtures increased as the dynamic modulus at high temperatures increased. Guidance on test temperatures and minimum moduli needed to achieve acceptable rutting performance are the subject of on-going research in Project 9-19. The Project 9-19 research also found a fair correlation between cracking observed in the experimental sections and the dynamic modulus at 4.4°C and 21.1°C (Bonaquist et al., 2003).

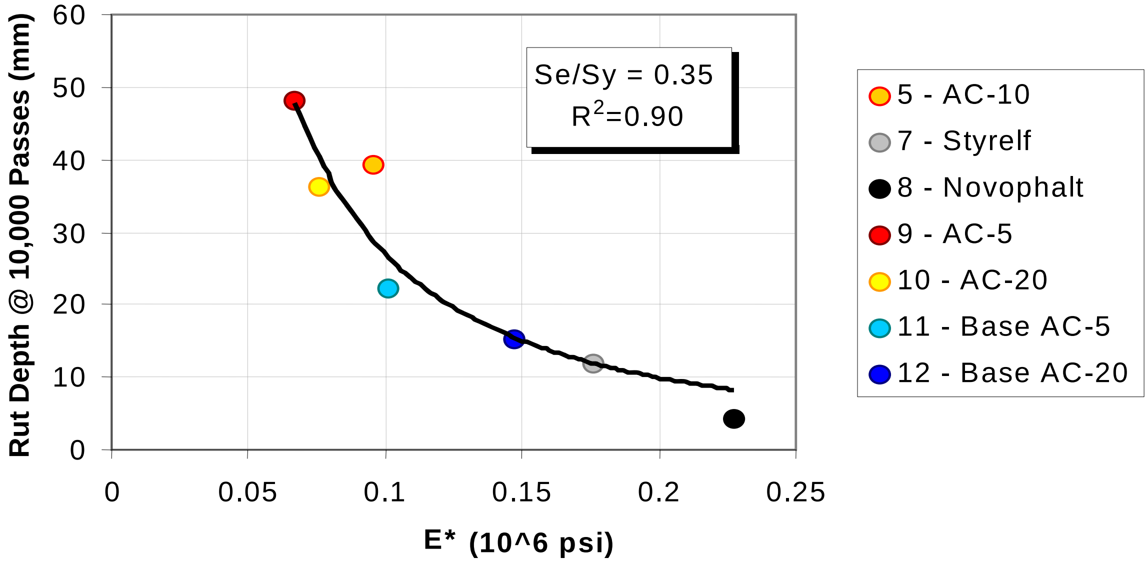

Figure 9. Relationship Between Dynamic Modulus and Rutting for the FHWA Pavement Testing Facility Sections.

2.9.3. Test Protocol

The proposed testing protocol for dynamic modulus, NCHRP 1-37A Draft Test Method DM-1, Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures, is based on ASTM D-3497. In this test a continuous haversine axial compressive load is applied to a specimen at a given temperature and loading rate. Measured stresses and strains are then used to calculate the resulting dynamic modulus and phase angle (Bonaquist et al., 2003). For the development of master curves for pavement design, tests are conducted at temperatures of 14, 40, 70, 100, and 130°F using loading frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. The resulting 30 modulus measurements are then shifted using time-temperature superposition to obtain a master curve.

Test methods for using the dynamic modulus as a simple performance test for rutting and fatigue cracking are reported in NCHRP Report 465. The primary difference between these test methods and the testing required for the design guide master curves is the number of measurements required. For the simple performance tests, the testing is done at effective temperatures for rutting and cracking that are representative of the project location. A single design loading rate is used, depending on the expected speed of traffic for the project.

NCHRP Project 9-29 places specific requirements on the size, power requirements, and noise level for the dynamic modulus test system. These operational requirements are summarized in Table 2. Table 3 summarizes the required capacities of the loading machine, and Table 4 lists the load control requirements. For the sinusoidal and pulse loads, these load control requirements are in terms of the standard error of the applied load. The standard error is a measure of how well the loading device reproduces sinusoidal loading, which is critical to the correct measurement of the dynamic modulus (Bonaquist et al., 2003).

Table 2. Operational Requirements for Dynamic Modulus Test System

Item	Specification Requirement
Assembled Size	5 ft x 5 ft x 6 ft
Component Size	Width must be less than 30 in
Electrical Power	115 or 230 VAC, 60 Hz
Air Supply	10.6 ft^3/min at 125 psi
Noise Level	70 dB at 6.5 ft

Bonaquist et al., 2003

Table 3. Compression Loading Machine Capacities

Type of Loading	Ramp, Constant, Sinusoidal
Capacity	1.35 kips
Rate	0.1 to 25 Hz

Bonaquist et al., 2003

Table 4. Load Control Requirements for Compression Loading Machine

Load Type	Requirement
Constant	± 2% of load specified
Ramp	± 2% of load specified
Sinusoidal	Standard error ≤ 5%
Pulse	Peak: ± 2% of load specified, Standard error ≤ 10%

Bonaquist et al., 2003

Deformations in the dynamic modulus test are measured using a specimen-mounted displacement measuring system. The system requirements for the displacement measuring device are listed in Table 5. Table 6 lists the specimen dimension tolerances for the test.

Table 5. Displacement Measuring System Requirements

Item	Requirement
Number of Transducers	≥ 2
Gauge Length and Position	2.75 in over middle of specimen
Range	≥ 0.04 in
Resolution	≤ 7.8 μ-in
Accuracy	error ≤ 0.0001 in when verified in accordance with ASTM D 6027
Installation	≤ 3 min to install instrumentation, insert specimen, apply confining pressure and obtain temperature equilibrium

Bonaquist et al., 2003

Table 6. Specimen Dimension Tolerances

Item	Specification
Average Diameter	3.94 in to 4.09 in
Standard Deviation of Diameter	0.0394 in
Height	5.81 in to 6.00 in
End Flatness	0.0118 in
End Parallelism	1^{o}

Bonaquist et al., 2003

NCHRP Project 9-29 (Bonaquist et al., 2003) requires the dynamic modulus test to be performed with confining pressure. The requirements of the confining pressure system are summarized in Table 7.

Table 7. Requirements for Confining Pressure System

Item	Requirement
Maximum Pressure	30 psi
Control	$\pm$ 2.0%
Pressure Sensor Resolution	0.07 psi
Pressure Sensor Accuracy	error 1% when verified in accordance with ASTM D 5720
Operation	≤ 3 min to install instrumentation, insert specimen, apply confining pressure and obtain temperature equilibrium

Bonaquist et al., 2003

An environmental chamber is also necessary to control the temperature of the specimens during the tests. The tests are conducted at different effective temperatures depending on whether the tests are for permanent deformation or for fatigue cracking. The effective temperatures are given by the following equations (Bonaquist et al., 2003):

$$T_{eff}(PD) = 30.8 - 0.12Z_{cr} + 0.92(MAAT + K_{\alpha}\sigma_{MAAT}) \tag{8}$$

$$T_{eff}(FC) = 0.8(MAPT) - 2.7 \quad (9)$$

where $T_{eff}(PD)$ is the effective temperature in ºC for permanent deformation, Z_{cr} is the critical depth in millimeters for the mix layer in question, MAAT is the mean annual air temperature in ºC, K_{α} is the value computed from the normal probability table related to the designer's selected level of reliability, σ_{MAAT} is the standard deviation of the mean annual air temperature, $T_{eff}(FC)$ is the effective temperature in ºC for fatigue cracking, and MAPT is the mean annual pavement temperature in ºC at one third the depth of the pavement layer.

For the United States, the effective temperature for permanent deformation ranges from 25 to 55ºC and the effective temperature for fatigue cracking ranges from 12 to 20ºC (Bonaquist et al., 2003). The requirements for the environmental chamber are summarized in Table 8.

Table 8. Requirements for Environmental Chamber

Item	Requirement
Range	20 to 60ºC when ambient temperature is between 15 and 27ºC
Control	± 0.5ºC
Resolution	± 0.25ºC
Accuracy	± 0.25ºC
Location of Sensor	Within 1 in of the specimen at the specimen mid-height
Operation	≤ 3 min to install instrumentation, insert specimen, apply confining pressure and obtain temperature equilibrium

Bonaquist et al., 2003

2.9.4. Variability

In NCHRP Project 9-29, two proposed dynamic modulus testing devices were compared. Tests were conducted on specimens with two different maximum aggregate sizes, at six different loading frequencies, at two different laboratories, and with three different combinations of temperature and confinement. Variability was analyzed by comparing standard deviations, coefficients of variation, and means for the dynamic modulus and phase angle values. To summarize these analyses, the general trends in the dynamic modulus data showed that the modulus and phase angle data generated by the two devices at the two laboratories appeared reasonable and in general agreement. The overall variability of the dynamic modulus data produced with the two devices was reasonable, with coefficients of variation for various conditions ranging from 5 to 15% (Bonaquist et al., 2003).

The dynamic modulus test, however, is very costly and time consuming to perform. As a result, agencies will likely be unwilling to adopt the test for quality assurance purposes. The less costly and quicker static creep and recovery test, described in the nest section, has a greater potential to be adopted for such purposes.

2.10. Creep and Recovery Test

A creep and recovery test can be conducted in unconfined uniaxial compression. Table 9 compares the setup for the dynamic modulus test and the proposed creep and recovery test. The properties measured from these tests can be interconverted within the linear viscoelastic region.

Table 9. Similarities Between the Dynamic Modulus Test and the Creep and Recovery Test

	Dynamic Modulus Test	Creep and Recovery Test	Comments
Property Measured	Dynamic Modulus, Phase Angle	Shape of Creep Compliance curve	The Creep Compliance and compliance slope is theoretically related to the dynamic modulus and phase angle.
Load Application	Dynamic	Static	Static methods are preferred for acceptable quality control testing. Dynamic methods have shown poor consistency when used in the field.
Frequency or Loading Times	25, 10, 5, 1.0, 0.5, and 0.1 Hz	Loading time(s) to be determined	
Load Control	Hydraulic	*Hydraulic	Tests that require hydraulically applied loads are used for many asphalt concrete property tests, including the dynamic modulus test. However, these types of tests are difficult to perform effectively in the field. A screw or weight type of load application is simpler and measured properties can be correlated with those of a dynamic load application.
Deflection Measurements	Three LVDTs at 120 degrees apart	Same as Dynamic Modulus Test	An LVDT hookup is necessary to measure the recovery of the specimen when the load is released.
Temperature	14, 40, 70, 100, and 130°F	To be determined	Initial investigation will perform tests at the same temperatures as those used for the dynamic modulus.
Specimen Compaction	Superpave Gyratory Compactor	Same as Dynamic Modulus Test	
Specimen Dimensions	100mm diameter, 150mm height	+Same as Dynamic Modulus Test	This size is based on the results of a comprehensive specimen size and geometry study conducted in NCHRP Project 9-19. Specimen fabrication procedures are described in NCHRP 1-37A Draft Test Method DM-1.

* A screw type machine would be used for final field testing procedure protocol. The hydraulic type is being used in the laboratory for initial investigation.

\+ Samples with diameters of 100mm will be used for the initial investigation. A 150mm diameter specimen would be used for final testing procedure protocol.

Figure 10 represents the type of load applied to specimens in a creep and recovery test. Figure 11 shows the measured creep and recovery deflection typical of viscoelastic materials under an applied constant stress. Figure 12 shows the creep compliance, D(t), which is calculated from the load magnitude and the measured deflection. Creep compliance, as measured by the static creep and recovery test can be represented by the Burger's constitutive model of viscoelastic behavior, discussed below.

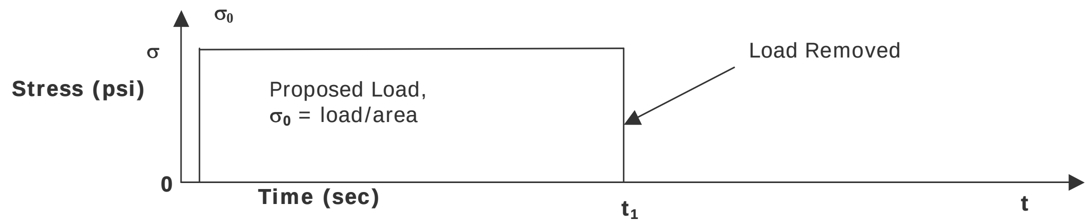

Figure 10. Load Type.

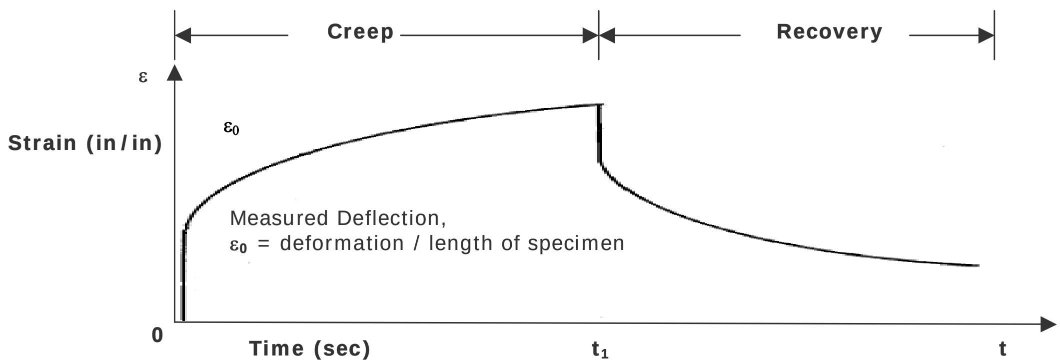

Figure 11. Typical Measured Deflection.

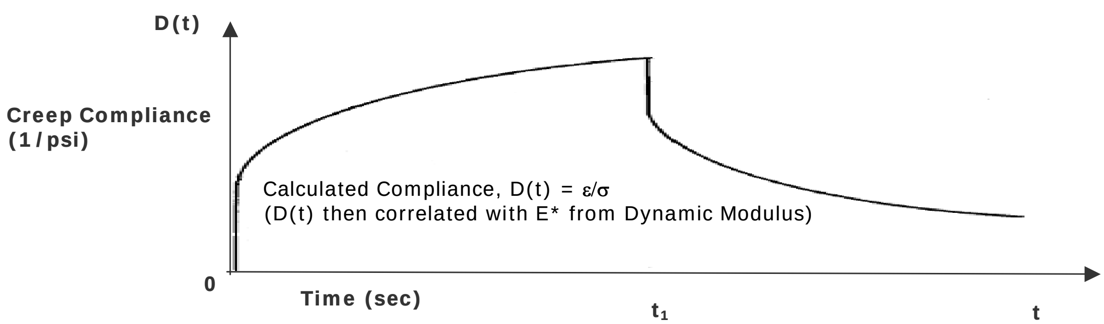

Figure 12. Calculated Compliance.

3.0.1 Burger's Model

A viscoelastic material, such as asphalt concrete, can be characterized by springs and dashpots. The springs and dashpots are rheological models that represent the elastic and viscous nature of a material, respectively. For an elastic material, the strain response is directly proportional to the stress input (Figure 13). However, if a constant stress is applied to a material that is nearly purely viscous, it would instantaneously reach a high strain level when the stress was applied, but would be permanently deformed (Figure 14).

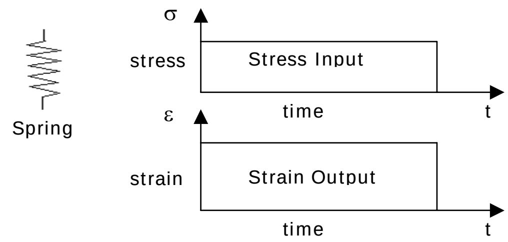

Figure 13. Spring Representing Elastic Behavior

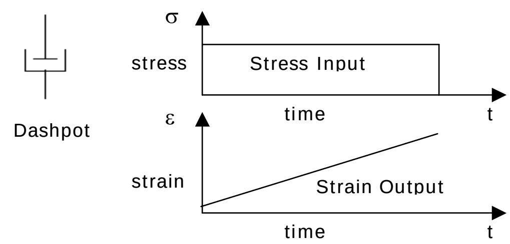

Figure 14. Dashpot Representing Viscous Behavior

The Burger's Model, shown in Figure 15, among other models, combines the spring and dashpot models to represent material behavior. The Burger's Model has been found to closely model the typical creep and recovery behavior of viscoelastic materials (Figure 16).

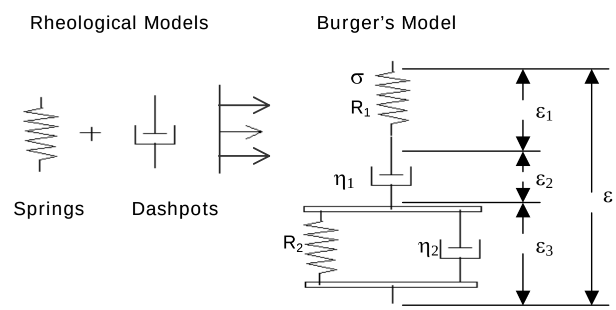

Figure 15. Burger's Model of Springs and Dashpots

The total strain, at time t, is represented by the sum of the strains in the three elements ($\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$). ε_1 is the strain in the spring and models the initial elastic jump in the curve. ε_2 is the strain in the dashpot and models the slope immediately after the elastic jump. ε_3 is the strain in the parallel spring and dashpot and models the gradual change in strain over time. Creep compliance (ε_0/σ_0), shown in Figure 17, can then be obtained from the creep and recovery deflection and load data.

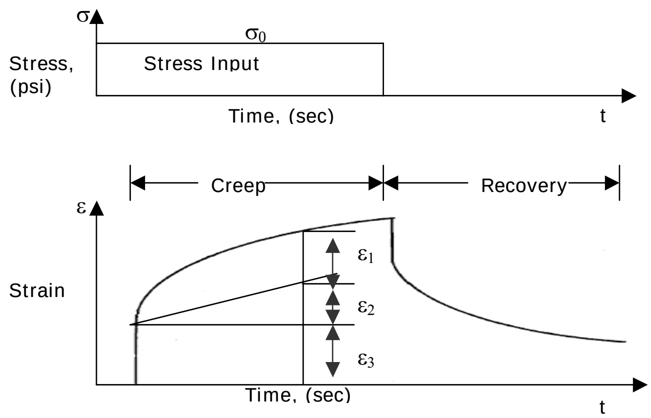

Figure 16. Typical Creep and Recovery Behavior of Viscoelastic Materials.

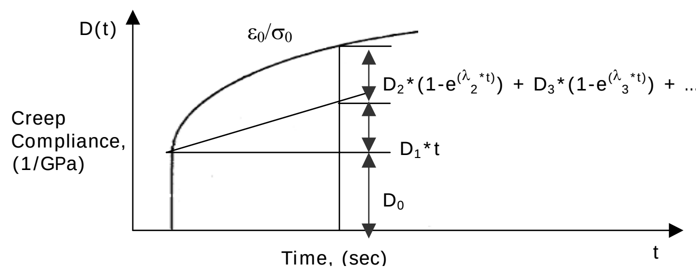

Figure 17. Creep Compliance (ε_0/σ_0).

Creep compliance can also be expressed in the following form:

$$D(t) = [D_0] + [D_1 * \text{time}] + [D_2 * (1 - e^{(\lambda_2 * \text{time})}) + D_3 * (1 - e^{(\lambda_3 * \text{time})}) + \ldots] \qquad (10)$$

where: D_0 = elastic component parameter
$D_1, D_2, D_3, \lambda_2, \lambda_3, \ldots$ = viscoelastic component parameters

The first term in Eq. (10), D_0, represents the elastic nature of the material where the curve is nearly vertical. The other terms are representative of the viscous nature of the material with respect to time. The final slope of the creep portion is mostly represented by D_1. The gradual change of slope of the curve is represented by the rest of the D and λ terms.

2.11. Indentation Test

The indentation test is another test in which creep compliance can be measured. It was proposed by the researchers that the indentation test has the potential to be used as a quality control test in the field. In the indentation test, as in the static creep and recovery test, a constant load is applied along the axis of a cylindrical specimen and the resulting deflection is measured. However, in the indentation test, a steel ball is used as the point of contact between the load and the specimen, rather than load plates. A schematic of the configuration is shown in Figure 18.

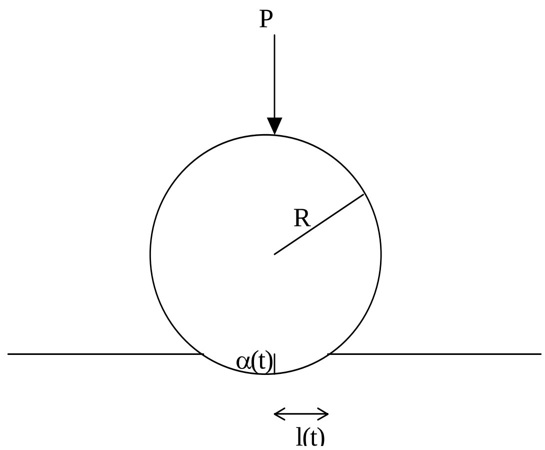

Figure 18. Indentation Configuration.

Although a constant load is applied during the indentation test, it is not a constant stress test, unlike the creep and recovery test. As the deflection of the specimen increases under the constant load, the contact area between the ball and the specimen also increases, so the applied stress decreases over time. Initially, the contact area is very small which results in high initial stresses. Due to these high initial stresses, the asphalt concrete does not stay within the linear viscoelastic region. The implications of this fact are discussed later.

Simple extension creep compliance, D(t), is the compliance measured by the static creep and recovery test and is the ratio of strain to stress over time. The compliance measured by the indentation test, however, is the simple shear creep compliance, J(t), which is given, in terms of the indentation test parameters, by (Lee and Radok, 1960):

$$J(t) = \frac{16\sqrt{R}[\alpha(t)]^{3/2}}{3P_0 H(t)} \tag{11}$$

where R is the radius of the sphere, $\alpha(t)$ is the central displacement at time t, P_0 is the applied load, and H(t) is the Heaviside step function. The following relation can be used to convert the shear creep compliance to extension creep compliance:

$$D(t) \cong \frac{J(t)}{2(1+\nu)} \tag{12}$$

where ν is Poisson's ratio, which was assumed to be 0.35, a common value for asphalt concrete mixtures.

The contact stress can also be calculated using the results of Lee and Radok (1960). They give the deflection of a point, w(r,t), at a distance r from the center of the indenting sphere at time t as:

$$w(r,t) = \frac{[l(t)]^2}{R} - \frac{r^2}{2R} \qquad \text{for } r \le l(t) \tag{13}$$

where R is the radius of the sphere and l(t) is the contact radius. So the central deflection, $\alpha(t) = w(0,t)$ is given by:

$$\alpha(t) = \frac{[l(t)]^2}{R} \tag{14}$$

The contact stress, $\sigma(t)$, depends on the projected area of contact and was therefore calculated as:

$$\sigma(t) = \frac{P}{\pi R \alpha(t)} \tag{15}$$

where P is the applied load.

As mentioned earlier, extension creep compliance can be converted to complex modulus, which correlates well with pavement performance. However, before the indentation test can be used to predict pavement performance in the field, it must be shown that the test yields extension creep compliance values which are affected by changes in volumetric properties of asphalt concrete in a manner similar to that of the creep compliance measured by the creep and recovery test. Therefore, one of the objectives of this study was to develop a correlation between the compliances obtained from the two tests.

2.12. Summary

The dynamic modulus, which correlates well with rutting and fatigue cracking, is the primary material characterization parameter for asphalt concrete mixtures in the ASSHTO mechanistic empirical pavement design guide. It has been shown that dynamic modulus tests can be performed within acceptable levels of variability, however the cost and time required for the test will likely prevent it from being widely adopted by the asphalt industry.

Therefore, there is a need for a simple and cost effective method for determining the dynamic modulus of asphalt concrete at the plant and in the field. The Simple Performance Test is currently under development in NCHRP Project 9-19. SPT will eventually contain methods for obtaining the dynamic modulus as well as some other parameters which have been shown to correlate well with pavement performance, such as the flow time and flow number.

The creep and recovery test may have potential as a simpler alternative to the dynamic modulus test as a plant device since the results of each test can be theoretically interconverted. The indentation test may have potential as a field quality control device if it can be shown to be sensitive to critical volumetric properties of asphalt concrete.

3.0. Field Devices

The density of in-place hot-mix asphalt (HMA) may be the single factor that most affects the performance of a properly designed mixture. An average, well constructed mix with good in-place air voids, will often perform better than a good mix that has been poorly constructed. In the field, density is measured as part of the quality control process by the contractors and for the quality assurance by the Wisconsin Department of Transportation (WisDOT). HMA pavement density provides the basis of the density disincentive (payment factor) and density incentive in accordance with WisDOT *Standard Specification for Highway and Structure Construction*, 2003 edition.

As mentioned above, the dynamic modulus, |E*|, test has been recommended by NCHRP Project 9-19 to be the test of choice for rutting and fatigue performance prediction of asphalt concrete mixtures. The empirical Witczak dynamic modulus equation is an extension of the dynamic modulus predictive equation used in the Asphalt Institute's MS-1 and MS-11 design procedures for highways and airfields (Witczak et al., 2002b). During the past 30 years, Witczak and several colleagues refined the equation several times as additional data became available. Equation. (16) presents the form of the dynamic modulus predictive equation included in the design guide:

$$\log |E^*| = -1.249937 + 0.029232(P_{200}) - 0.001767(P_{200})^2 - 0.00284(P_4) - 0.05809(V_a) - \frac{0.802208(V_{beff})}{V_{beff} + V_a} + \frac{3.871977 - 0.0021(P_4) + 0.00395(P_{38}) - 0.000017(P_{38})^2 + 0.005470(P_{34})}{1 + e^{(-0.603313 - 0.313351(\log f) - 0.393532(\log \eta))}} \quad (16)$$

where:

$\lvert E^*\rvert$	=	dynamic complex modulus, 0.1 million psi
η	=	bitumen viscosity, 1 million Poise
f	=	loading frequency, Hz
V_a	=	air void content, %
V_{beff}	=	effective bitumen content, % by volume
P_{34}	=	cumulative percent retained on 19 mm sieve
P_{38}	=	cumulative percent retained on 9.5 mm sieve
P_4	=	cumulative percent retained on 4.75 mm sieve
P_{200}	=	cumulative percent retained on 0.075 mm sieve

Eq. (16) can be used for pavements when dynamic modulus testing is not required. All inputs to Eq. (16) are generally known for a particular mixture with the exception of air void content. To illustrate the effects of air void content on the performance of asphalt pavements, baseline pavement structures were run through the NCHRP 9-19 ME Pavement design guide software with varying air void contents. The results of these runs are shown in Figures 19, 20, and 21. As can be seen, varying the air void content significantly affects the life and performance of a pavement.

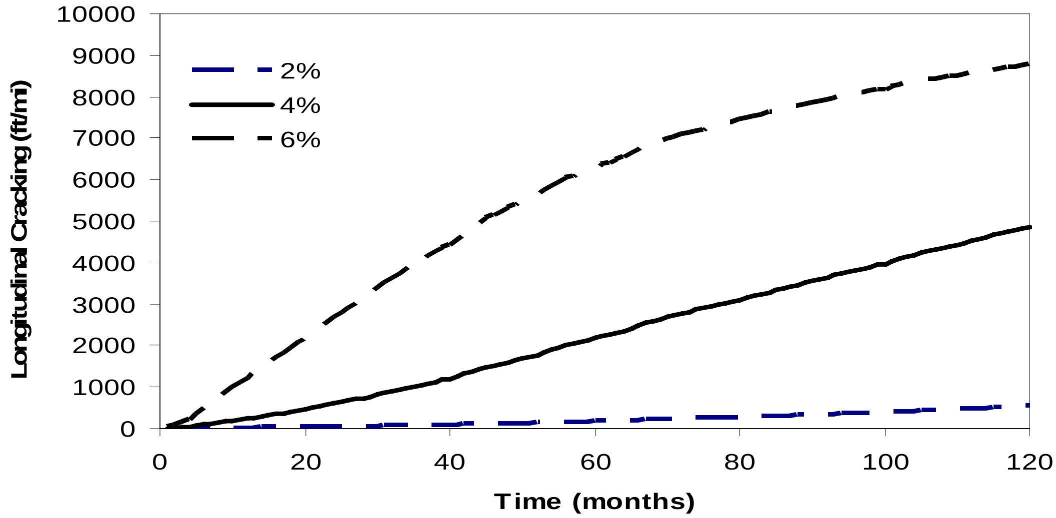

Figure 19. Longitudinal Cracking vs. Time for Varying Air Void Contents.

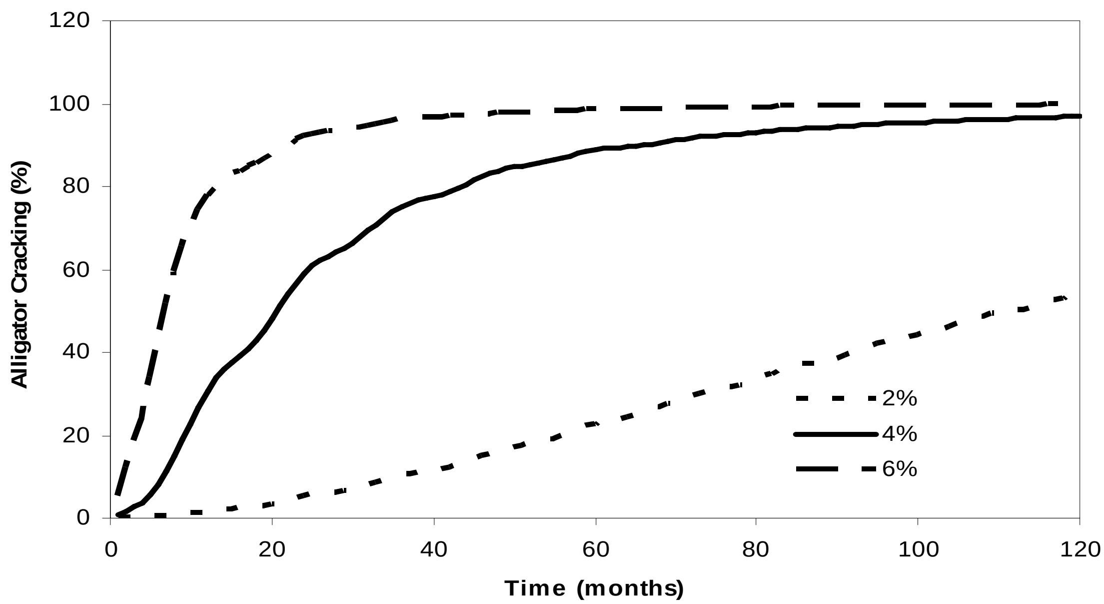

Figure 20. Alligator Cracking vs. Time for Varying Air Void Contents.

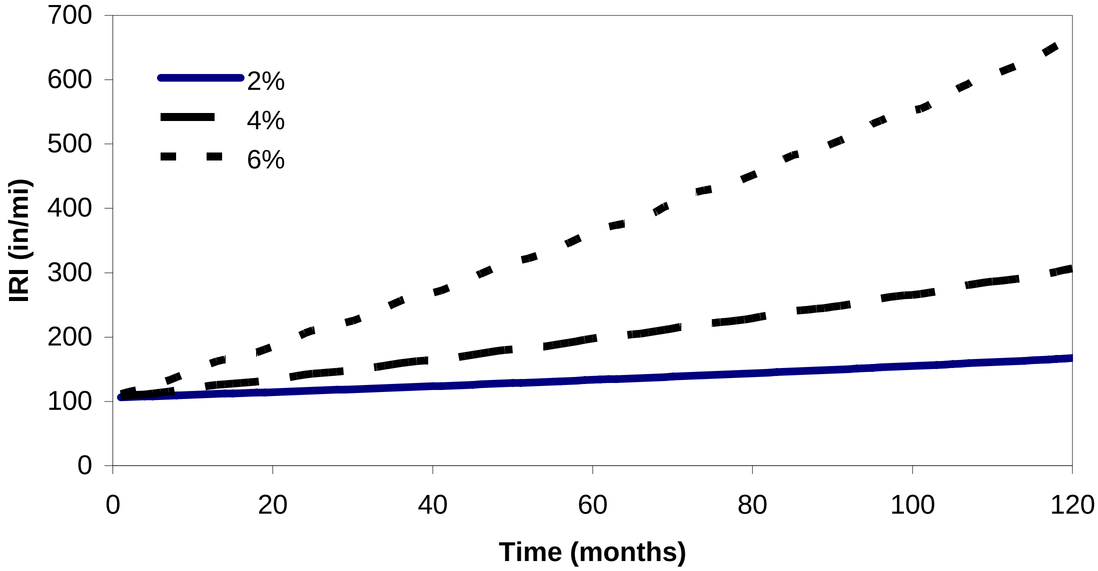

Figure 21. IRI vs. Time for Varying Air Void Contents.

In-situ air void content can be determined if the density of the compacted pavement is known. Therefore, density measurements are critical in estimating the dynamic modulus, and hence performance, of newly constructed pavements.

Currently, the asphalt concrete industry is in search of a field device that can be used to determine pavement density quickly (during rolling) and safely, while being accurate and repeatable with the capability of functioning as a method sufficient for both quality control and quality assurance (QC/QA) purposes. There are both nuclear and non-nuclear devices available that allow for quick, non-destructive density measurements. However, they vary in their accuracy, repeatability, safety, and QC/QA capabilities.

The main advantage to using the non-nuclear devices is that no radioactive handling is necessary. In initial studies, the nuclear gauge seemed to provide somewhat more accurate and repeatable measurements of pavement density than the non-nuclear devices. However, the non-nuclear technology is evolving. Nuclear and non-nuclear devices are discussed and compared below. Also discussed is the destructive method of coring.

3.1 Coring

The most common density measurement practice currently is coring, in which a core is drilled from the pavement and transported to the laboratory to undergo tests for determining density. AASHTO T 166 standardizes the procedure. The results are used for quality control (to some extent) and quality assurance. This has been practiced for many years and is widely accepted as an accurate and repeatable method of measuring density.

Two disadvantages of this method, however, are the pavement damage from the cores and the several hours of time it takes to get results, since the pavement must sufficiently cool and the testing must be done in the laboratory (Schmitt et al., 1997). If the lab results show that a core does not meet the quality control density specifications, it is too late to fix the problem in the field. It would be more desirable if those constructing the pavement could know immediately that their process is not meeting the density specifications in order to take corrective action during the compaction efforts.

3.2 Nuclear Density Gauge

Nuclear density gauges have been used in the last few decades for measuring asphalt concrete density in the field to get density results more quickly. Nuclear density devices operate by exposing the pavement to a radioactive source (such as a $Cesium^{137}$ source or a $Radium^{226}$ source (Henault, 2001)) on the bottom of the device, which emits photons, and measures the backscattered gamma radiation. The number of photons scattered back to the device over a certain time period is related to the density. As the pavement density increases, the photon count decreases. The device is calibrated using a block of known density (Troxler Electronic Laboratories, Inc., 2003b) (Romero et al., 2001).

The nuclear density gauges have not proven to be consistently comparable to core density measurements. ASTM D2950-91 standard recommends that at least seven core densities and seven nuclear densities be used to establish a conversion factor. A new conversion factor must be established at any time a change is made in the paving mixture or in the construction process. Cores are routinely taken throughout the paving project to verify that the nuclear gauge is in calibration (Schmitt et al., 1997).

Schmitt et al. (1997) addressed the concern raised by differing results between core samples and nuclear readings by providing a method for determining the number of density readings required to achieve a precise estimate of the average pavement density. Three nuclear density gauge models (Seaman C200, Seman C75, and Troxler 3440) were used in the study. Using the method developed, they determined that constructing an estimated density average of +/- 1 pcf requires a sample size of 16 cores or 24 nuclear readings.

The results showed that the nuclear gauge measures density lower than cores at low densities, and higher than cores at high densities. They concluded that the relationship between nuclear density gauges and core samples is affected by the thickness of the mat and maximum specific gravity of the asphalt mix (Schmitt et al., 1997).

Several studies conducted in the following years indicated that nuclear devices were not accurate or consistent enough to be used alone for ensuring a proper pavement density (Henault, 2001). A Maryland DOT study in 1998 indicated that results from three nuclear gauges were not comparable to each other or to core density values. In a study by Choubane and others in 1999, results indicated that Troxler Models 3401, 3440, 3450, and 4640 did not consistently correlate with the core densities. Even in 1990, Brown recommended that nuclear gauges not be used alone for acceptance testing, but should be used with cores to verify the accuracy of the gauge and ensure acceptable densities (Henault, 2001).

However, some agencies believe that a properly calibrated and properly operated nuclear gauge provides results with sufficient accuracy for acceptance testing (Schmitt et al., 1997). Buchanan et al. (2004) evaluated two different calibration methods as well as the use of surface fillers with nuclear gauges. Surface fillers are used with nuclear gauges to fill the surface voids in pavements, which provide a flat surface for the nuclear gauge to rest on and maximizes the contact area between the base of the gauge and the material being tested. The two calibration approaches studied were the 10-Point Forecast Method and the 10-Point Correction Factor approach. In the 10-Point Forecast Method, the last 10 uncorrected nuclear gauge readings and core densities are linearly regressed, using the FORECAST tool in Microsoft Excel™, to determine a predicted core density for the nuclear gauge reading. In the 10-Point Correction Factor approach, the nuclear gauge correction factor is calculated as the average of the last ten correction factors (Buchanan et al., 2004). Each of these methods were compared to the static, or one-time, calibration methods for nuclear gauges.

Some of the conclusions drawn by Buchanan et al. (2004) are as follows:

- When compared to nuclear gauge testing without surface filler, the use of surface filler improves the accuracy and precision of the nuclear gauge reading;
- Nuclear gauges with and without surface filler tended to underestimate the core density for lower core densities and overestimate the core density for higher core densities;
- The use of the 10-Point Correction Factor method provided results which were generally the same as those acquired using the static calibration value;
- The use of the 10-Point Forecast Method substantially improves the accuracy and precision of the nuclear gauge density;
- The nuclear gauge can be an extremely accurate density measurement device, provided the correct testing protocols and procedures be utilized.

3.3 Pavement Quality Indicator (Non-Nuclear Density Gauge)

WisDOT is currently utilizing non-destructive nuclear gauges as a means of measuring in-place density in accordance with ASTM D2950 (WisDOT modified). In the mid-1990s, TransTech Systems, Inc. invented and manufactured a device, called the Pavement Quality Indicator (PQI), for measuring pavement density in the field without the use of radioactivity. The PQI measures the dielectric constant of the material, which is directly proportional to the density of the pavement (TransTech Systems, Inc. 2000). Figure 22 shows a schematic of the PQI operational theory. The PQI sensing plate creates a toroidal electrical sensing field in the pavement with electrical waves. Then, a receiver on the PQI measures the impedance, which is used to determine the overall dielectric constant of the material (Henault 2001).

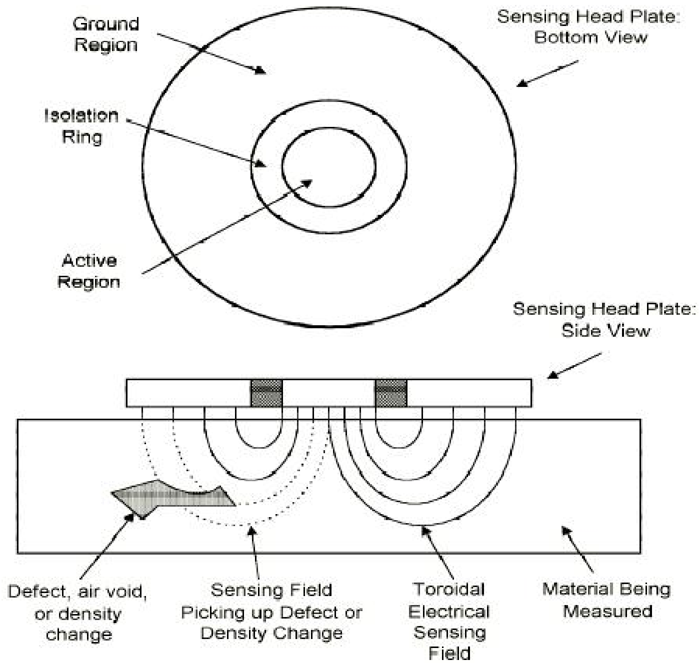

Figure 22. Schematic of PQI Operational Theory.
(Schematic from TransTech Systems, Inc. website: www.transtechsys.com.)

The non-nuclear PQI density gauge has undergone several revisions since it was first introduced to the industry. Early in the non-nuclear device development, the PQI 100, by TransTech Systems, Inc., did not have a moisture indicator. Later, the PQI 200 included larger measuring area, moisture indicator, and an on-board temperature sensor. The PQI 300 included further improvements (Hanault 2001). More recently, the PQI 301 was designed with an impedance-based measuring system (instead of capacitance-based, as in the first models), and a sensor with a multi-configuration geometry that provides an electrical field with a controllable depth of penetration (Glagola 2002). Specifications for the PQI are given in Table 10.

Various studies have been conducted on both nuclear and non-nuclear devices to further investigate their abilities to measure asphalt concrete density. Initial studies showed that the PQI technology had a good potential of being a suitable alternative to the nuclear technology. From a study by Sawchuk (1998), it was concluded that the PQI performed equally as well as or better than a nuclear density gauge (type not indicated) in accuracy and reproducibility. Also, Romero et al. (2001) indicated that the PQI device is capable of determining relative changes in asphalt concrete density under constant temperature and humidity.

Table 10. PQI Specifications

Unit Weight (with battery)	15lb, 8oz
Unit Dimensions (with handle)	10 ¾in x 10 ¾in x 11in (LxWxH)
Shipping Case Dimensions:	27 ¾in x 17 ¾in x 13in (LxWxH)
Operating Temperature and Humidity	Ambient 20F(-7C) to 110F(43C) RH 95%
Storage Temperature and Humidity	0F(-18C) to 150F(66C) RH 95% non-condensing
Max. Surface Temperature	350F (177C)
Power Supply	12 V DC 3.0 Amp Hr. Gel Cell
Current Drain	215 mA
Battery Charger	Fast charge 120V AC 60Hz 0.2A 12VDC 300mA
Recharge Time	4 hours
Output	0-10 VDC(+/- 10VDC optional); proportional to sensing gap. Includes a +/- 10VDC offset control.
Linearity	Typically +/- 2% of full scale or better. +/- .5% with limited range calibration. (+/-.2% optional)
Range	Typically 100% of probe's sensor diameter or diametrical area equivalent.
Frequency Response	232Hz standard; 3.5 kHz or 5 kHz or better optional (-3dB point)
Resolution	1 mVdc
Display	4 line alphanumeric, backlit
Scale Readings	In English lb/ft^3 or Metric kg/m^3 user selectable by keypad
Sampling time	5 seconds minimum
Measuring Depth	1-1/2 in. nominal
Continuous Operational Time (fully charged battery)	Typically greater than 13 hours
Accessories included with unit	Battery Charger: 120V AC to 12VDC Fast Charge; 12VDC Auto Adapter; Shipping Case; Operating Instructions Manual

Note: All specifications for TransTech System's PQI are from an NCHRP publication (Sawchuk 1998).

A study done by Sholar et al. (2001) compared nuclear and non-nuclear devices used to obtain material density. Nuclear devices tested were the CPN MC3, Troxler 3450, Troxler 3440, and Troxler 4640B. The non-nuclear devices tested were the TransTech PQI #100 and PQI #200. The study compared core density values to gauge density values for both coarse and fine graded Superpave mixes. The study indicated that the variability of the TransTech non-nuclear gauges were not necessarily worse than the nuclear gauges and recommended that the they be allowed for use as a quality control tool.

However, a weakness of the PQI is its sensitivity to moisture and temperature changes. In a field evaluation done by the Connecticut DOT (Henault, 2001), the density measured by a PQI Model

300 instrument showed poor correlation with density measured by cores as indicated by an average R-squared value of 0.28 for ten sites. It is suspected that substantial amounts of moisture present during HMA rolling operations may have had adverse effects on the PQI measurements. The moisture indicator in PQI 300 provides a relative moisture number (H_2O number), which is a correlation factor obtained from a phase angle reading (not the actual moisture content). In general, the low moisture levels necessary for the PQI to work properly were generally unobtainable during the paving projects done in this study (all H_2O numbers were above 5). Consequently, agency acceptance testing with PQI 300 was absolutely not recommended, agency independent assurance testing was strongly not recommended and contractor quality control testing was not recommended. Also, the nuclear gauge correlated a little better to the cores than the PQI, with an R-squared of 0.55, and the PQI did not correlate well to nuclear gauge densities (CPN Model MC-3 Portaprobe) with an R-squared of 0.24 (Henault 2001).

3.4. PaveTracker (Non-Nuclear Density Gauge)

At the turn of the millennium, Troxler Electronic Laboratories, Inc., which owns the nuclear gauges discussed above, introduced its own new version of a non-nuclear density gauge, called the PaveTracker (Romero 2002). The PaveTracker, working similarly to the PQI, measures the dielectric properties of the material which are related to density (Troxler Electronic Laboratories, Inc. 2003). Specifications for the PaveTracker are shown in Table 11.

Table 11. Model 2701b PaveTracker Specifications

Electronics Module Size	4.5in x 3.5in x 2.25in (DxWxH)
Field Case Size (with electronics module)	8in x 6in x 3.5in (DxWxH)
Electronics Module Weight	1 lb
Field Case Weight (with electronics module)	2 lb
Display	Pavement density in lb/ft^3
Probe	Non-nuclear, electromagnetic
Probing Depth	1.75 in
Measurement Time	1 second
Repeatability	+/- 0.5 pcf
Power	Rechargeable battery, run time 8 hours
Calibration	To asphalt cores, unit will sit on a 6” core or puck
Handle	Telescoping, detachable
Transport Case	Water resistant with built-in reference standard “test plate”

Note: All specifications for PaveTracker are from an application brief by Troxler (Troxler Electronic Laboratories, Inc., 2003b).

Romero (2002) prepared the final report of a pooled fund study that included six state highway agencies and the Federal Highway Administration’s Turner-Fairbank Highway Research Center to evaluate if the PQI Model 300 or the newly introduced PaveTracker could be used to determine pavement density. Both devices were compared to accepted density values. Several improvements were made to the PQI-300 following a laboratory study in 1999 and a field study in 2000 that showed it to be not adequate to measure density changes in the field. Following these improvements and the introduction of the PaveTracker, another field study was conducted in 2001. It was concluded that “in order to use non-nuclear gauges to obtain absolute pavement density, calibration using the same materials is needed.” Neither device was considered suitable for quality acceptance purposes or to determine pay factors. However, it was suggested that “the devices were accurate for quality control applications.” The devices were also considered useful for locating and correcting for low-density sections found in the pavement.

Other conclusions and recommendations from Romero’s study (Romero 2002) are as follows:

- The Nuclear Gauge method has higher correlation with core measurements than PQI with core measurements in most of the projects.
- The Nuclear Gauge method has higher correlation with core measurements than PaveTracker with core measurements in most of the projects.
- The PQI has higher variability than the core measurements and Nuclear Gauge.
- Calibration of these devices [PQI and PaveTracker] to local materials and conditions is critical to obtain accurate results. Whenever practical, the calibrations should be done using a test section. However, assumptions made based on knowledge and experience of local materials can greatly improve the results.
- Both the PQI300+ (the plus indicates changes made after the 2000 construction season) and the PaveTracker are suitable devices to control density of hot-mix asphalt during construction. Both devices can provide immediate feedback so that irregular spots can be located and corrective actions taken.
- Even though neither the PQI300+ nor the PaveTracker is as accurate as existing nuclear gauges, the advantage of not having to deal with regulations associated with the radioactive source of nuclear gauges and the ability to take multiple measurements in short periods of time makes them attractive devices for quality control of pavement density during construction.
- The only accurate method to obtain absolute pavement density for acceptance or pay factor determination is by taking cores and analyzing them in the laboratory.

4.5. State Efforts on Mixture Design Catalog

Various state agencies, such as Maine, Massachusetts, Missouri, New Jersey, New York, Texas, Virginia and Washington have initiated efforts to develop a mixture catalog as a step towards implementation of the Mechanistic Empirical design guide. This section summarizes the effort by the various state agencies.

Maine

The Maine DOT is collecting material characterization data to get sufficient inputs for ME PDG. They are expecting it to be a low level design for their roadways. Standard mixtures that cover a broad range of gradation, aggregate sources and binder type have been selected for dynamic complex modulus testing being conducted by Worcester Polytechnic Institute. In addition, resilient modulus testing is being conducted on subgrade soils. The state agency has instrumented weigh-in-motion (WIM) sites for traffic data collection. They will provide more detailed data from their database.

New Jersey
The state of New Jersey has spearheaded the effort of collecting data for material characterization of both bound and unbound material in 2002 in anticipation of the pavement design guide. They initiated a project of collecting seasonal material property of various roadways in New Jersey. The final report will be released by the end of 2005. A database has been developed that will be eventually used for the pavement design guide.

New York
The state of New York is a lead state in various NCHRP and AASHTO studies. They are conducting local calibration using performance monitoring sites as part of a pooled funds study. Annually approximately ten sites are selected for pavement monitoring. The sites are selected based on geographical and environmental conditions and traffic level. Among these sites, a subset is selected based on available resources and logistical issues. The plant material of these sites is then sent to Kansas State University for detailed material characterization as part of the pooled fund study. The report will be available when it is finished.

Texas
The state agency is currently not sure if they can implement the design guide. They feel that the rehabilitation section of the design guide is weak and trenches may be necessary. They may develop their own ME design guide by refining their current semi-mechanistic design procedure. They are developing a database for volumetric, aggregate sources and mixture design process and using spreadsheets.

Virginia
The state agency of Virginia has collected a sufficient amount of pavement material characterization data for rigid pavements. The state agency has initiated a research project with Virginia Transportation Research Center (VTRC) to collect dynamic complex modulus data for a few mixtures consisting of a selected aggregate type, nominal maximum size and binder type. They mainly use 9.5-mm and 12.5-mm - nominal maximum size and only change the binder grade depending on the truck traffic. The state uses 9.00mm finer mixes for urban roadways.

Due to this simplified array of mixtures, the first phase is primarily focused on observing the sensitivity of the parameters to DM, the second phase may be initiated based on the results of the first phase. The state agency may not have a distinct levels as maintained in the original ME Pavement design guide. Based on the results, they might have a combination of detailed levels of data requirements, i.e. elements of Level 1, Level 2 and Level 3 may be combined to create their own hierarchy for the design guide. .

Washington
As a first step towards developing a mixture catalog, typical mixtures from typical sites will be selected and samples will be selected from production sites. The mix as well as the aggregates and the binder will be sent to Washington State University for Dynamic Complex Modulus testing. The gradation will then be varied from the production mix (keeping within the Superpave gradation guidelines) and its sensitivity to DCM will be determined.

If a significant change in DCM is observed (in the order of magnitude), the recommendations for a change in gradation may be made. These changes will not affect their structural design, since they already have thin sections and may be uneconomical for thinner sections due to multiple passes necessary for compaction of thin layers.

3.6. Summary

When dynamic modulus testing is not required, the dynamic modulus of asphalt concrete can be estimated by using the dynamic modulus predictive equation. The inputs to the predictive equation are all known with the exception of air void content. The air void content in newly constructed pavements can be determined by way of density measurements. Until the Simple Performance Tests are developed under the NCHRP projects, it appears that the most accurate device for measuring the density of pavements is the nuclear gauge using the results of Buchanan et al. (2004). Table 12 summarizes the key aspects of each of the devices discussed in this section.

Table 12. Summary of Devices

	Nuclear Gauge	PQI	PaveTracker
Type	Nuclear	Non-nuclear	Non-nuclear
Source	Radioactive	Electromagnetic	Electromagnetic
Density Value	Absolute density value	Relative value to reference density	Relative value to reference density
Calibration	Calibration with cores is needed for each specific project		Calibration with cores is needed for each specific project
Measuring Depth	93% reading is affected by top 4 inches. Offer thin-layer measurement.	1-4 inches	1.75 inches
Ease of Use	Fairly easy to use. May take a few minutes per measurement.	Easy to operate. Makes very quick measurements.	Easy to operate. Makes very quick measurements.
Accuracy, Repeatability	Good accuracy. Less variability and better correlation to core density measurements than PQI.	Fair accuracy / repeatability when properly operated.	Fair accuracy when properly operated.
Moisture Sensitivity	Can read moisture content and not affected by moisture	Can read moisture index and correct internally.	Not affected by moisture
Temperature Sensitivity	Not affected by temperature	Can read temperature and correct internally.	Not affected by temperature
Sensitive to Aggregate Source	Not sensitive to aggregate source	Sensitive to aggregate source and offers internal correction.	Sensitive to aggregate source and offers internal correction.
Nominal Maximum Aggregate Size	Not sensitive to nominal maximum aggregate size	Sensitive to nominal maximum aggregate size and needs calibration with cores.	Sensitive to nominal maximum aggregate source and needs correction
Aggregate Gradation	Not sensitive to aggregate gradation	Sensitive to aggregate gradation and offers internal correction.	Works well for fine-graded mixes, not good for coarse or gap graded mixes
Core Density Measurement	Can not measure the density of cores.	Can measure density of 6” diameter core	Can measure density of 6” diameter core
Segregation Mode	No	Yes, offers segregation mode	Yes, offers segregation mode
Quality Control	Useful for QC because it measures densities accurately, fairly quickly, and non-destructively.	Suitable for QC. Can detect relative pavement densities, corrective procedures can be taken during construction to limit poorly compacted sections.	Suitable for QC.
Quality Acceptance		Not suitable for QA in current form. For absolute pavement density, need to take a core to a laboratory.	Not suitable for QA in current form. For absolute pavement density, need to take a core to a laboratory.
Special Training	Yes	No	No

4.0. Testing Conducted at Rowan University

This report has focused on the review of past and contemporary research conducted on the mechanical parameters and properties that are studied within the framework of the design guide. It has also focused on the devices used to determine these critical mechanical properties of asphalt concrete. It was found that the mechanical property which correlates best with pavement performance is the dynamic complex modulus. Three tests which can be used to measure the dynamic modulus (directly or indirectly) of asphalt concrete are: the dynamic modulus test, the static creep and recovery test, and the indentation test. The later two measure the dynamic modulus indirectly by means of an interconversion between creep compliance and dynamic modulus, which is only valid within the linear viscoelastic region.

As mentioned previously, the static creep and recovery test is less costly and less time consuming than the dynamic modulus test. And since the results of the two tests can be interconverted within the linear viscoelastic region, it is believed that the static creep and recovery test may eventually be used at the plant as a quality control test. Similarly, the indentation test may have the potential to be used in the field for quality control purposes.

A pilot study was conducted in which static creep and recovery tests and indentation tests were performed at Rowan University in order to investigate their potential as plant and field quality control tests, respectively. The static creep and recovery tests were performed in order to determine under what conditions creep compliance could produce repeatable measurements while remaining within the linear viscoelastic region. The initial objective of the indentation tests was to establish a correlation between the creep compliances measured by the indentation test and the static creep and recovery test. It was first necessary, however, to demonstrate that the indentation test is sensitive to the critical volumetric properties of asphalt concrete. The results of these investigations are discussed below.

5.1. Creep and Recovery Test

As outlined in Section 2.7., the creep and recovery test can be utilized for characterization of asphalt concrete. In this study, experimental tests were conducted to evaluate the creep and recovery test.

4.1.1. Test Setup

An MTS machine, which is a servo-hydraulic feedback compression machine, was used to perform the unconfined uniaxial compression tests. The MTS data acquisition system is capable of measuring and recording the time history of the applied load and axial deformations. Three transducers, 120 degrees apart, also measured deformation during the tests. The time history of the applied load was predetermined and the MTS machine ran the tests automatically. An environmental chamber was used for temperature control. The specimens were loaded between two metal plates. The bottom plate was a steel plate, resting on two aluminum plates. The top plate was a thin aluminum plate. The transducers were mounted to the two larger aluminum plates. The specimen was visually centered with the load actuator in order to avoid eccentric loading. The experimental setup is shown in Figure 23.

The loading magnitude, loading time, and temperature all affect the mechanical response of asphalt concrete. The starting protocol focused on selecting these factors so that the maximum strain in the specimen was within the linear viscoelastic region.

Figure 23. MTS Load Machine, Load Plates, and LVDTs.

4.1.2. Specimen Preparation

Asphalt concrete specimens were prepared in the laboratory. The specimens were 4-inches in diameter and 6-inches in length cut from gyratory compacted specimens. If test are to be conducted on 6-inch diameter specimens, the interconversion must be evaluated for those specimens. Specimens were mixed from prepared aggregate blends created to meet Superpave aggregate gradation requirements. Aggregate gradation, type, and source; asphalt binder type; and specimen size remained the same for all test specimens. The aggregate gradation was defined based on the Superpave limits and control points, having a gradation with a smooth S-shaped curve, as shown in Figure 24.

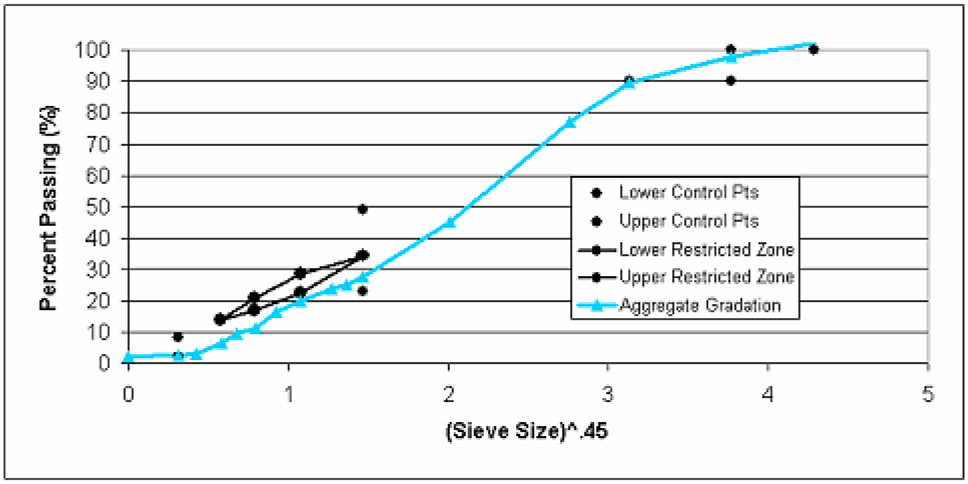

Figure 24. Aggregate Gradation

Two specimens had 6% binder content (design content), and two had 8% binder content. Higher than design was selected to evaluate the sensitivity of creep compliance on asphalt content. The specimens were compacted in the gyratory compactor in 6 inch molds to approximately 7% air void contents. Once specimens were compacted, they were cored and cut with a diamond blade saw to have 6-inch lengths with flat, smooth, and parallel ends. These dimensions are the same as those used in the dynamic modulus test. The volumetric properties of the prepared specimens are shown in Table 13.

Table 13. Asphalt Concrete Specimen Volumetric Properties

Specimen	Height (mm)	Diameter (mm)	Gradation*	Asphalt Content (%)	Air Voids (%)	Bulk Specific Gravity	Maximum Specific Gravity
CR01	150	100	#1	6.00	8.24	2.230	2.430
CR02	150	100	#1	6.00	8.26	2.229	2.430
CR11	150	100	#1	8.01	7.21	2.174	2.343
CR12	150	100	#1	8.01	7.17	2.175	2.343

*Gradation #1 is represented by Figure 24.

4.1.3. Results and Discussion

Based on the literature reviewed, the researchers tested the specimens under the conditions shown in Table 14. Figure 25 shows a typical plot of load versus time. A summary of the load behaviors can be found in Table 15. The load was applied for 600 seconds in each experiment. The load magnitudes for each experiment were consistent. The load stabilized after about 30 to 120 seconds. The researchers believe that the stability of the load could improve with tuning the MTS gains and/or performing experiments at lower load magnitudes. The range of the load was about +/-5 lbs from 512 lbf for all four tests.

Table 14. Experimental Conditions

Specimens	Load Type	Temperature (°C)	Loading Magnitude (lbf)	Loading Time (s)	Recovery Time (s)
CR01, CR02, CR11, CR12	Static, axial compression	20	512	600	3600

Table 15. Summary of Loading Behaviors

Specimen	Loading Time (sec)	Loading Magnitude (lbf)	Stabilization (sec)	Range (lbf)
CR01	600	512	30	+/-5
CR02	600	512	120	+/-5
CR11	600	512	30	+/-5
CR12	600	512	120	+/-5

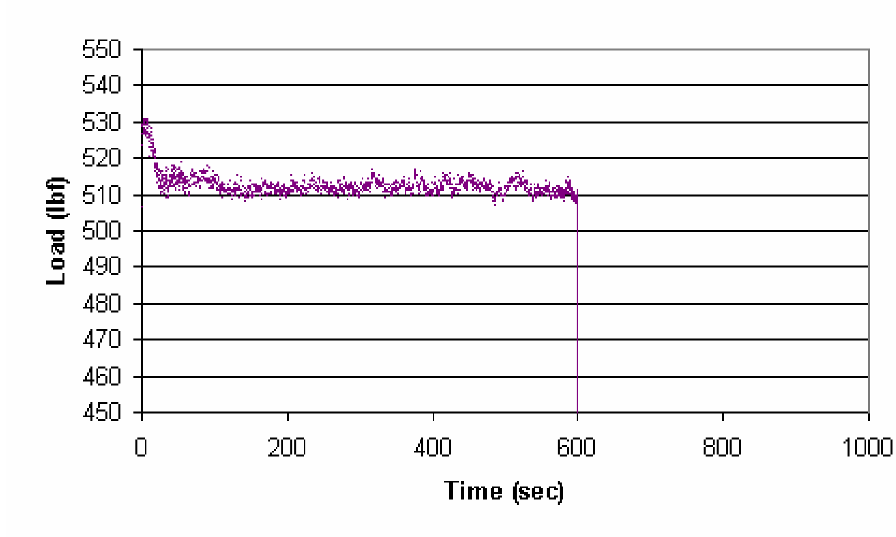

Figure 25. Load Applied on Specimen CR01

The measured strain, which is calculated from the measured deflection over time (based on the average of the actual creep and recovery measurements from the three transducers), is shown for each specimen in Figures 26 through 29. Also shown in these figures is the predicted (theoretical) strain (based on Burger's equation for viscoelastic materials).

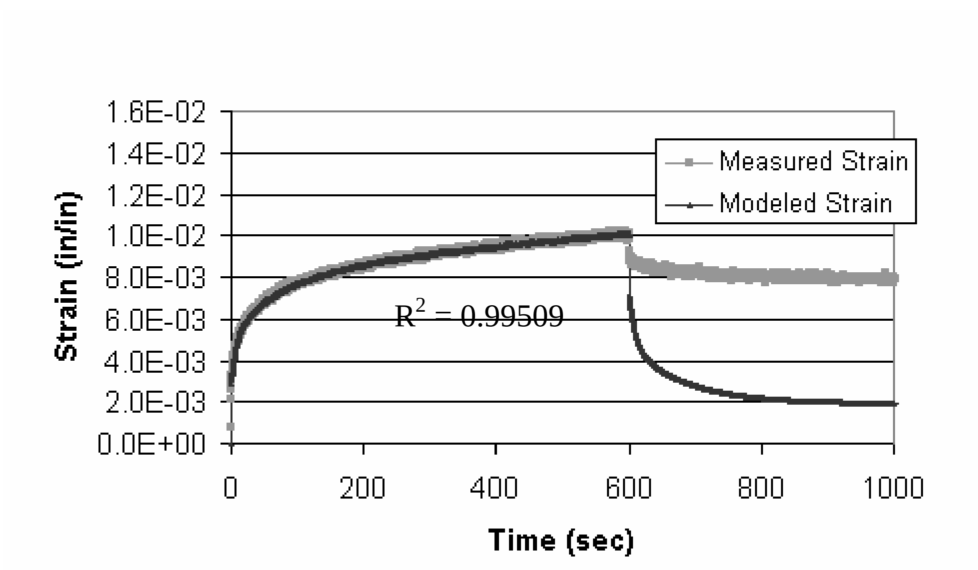

Figure 26. Measured (actual) and Modeled (theoretical) Strain, ε(t), for CR01

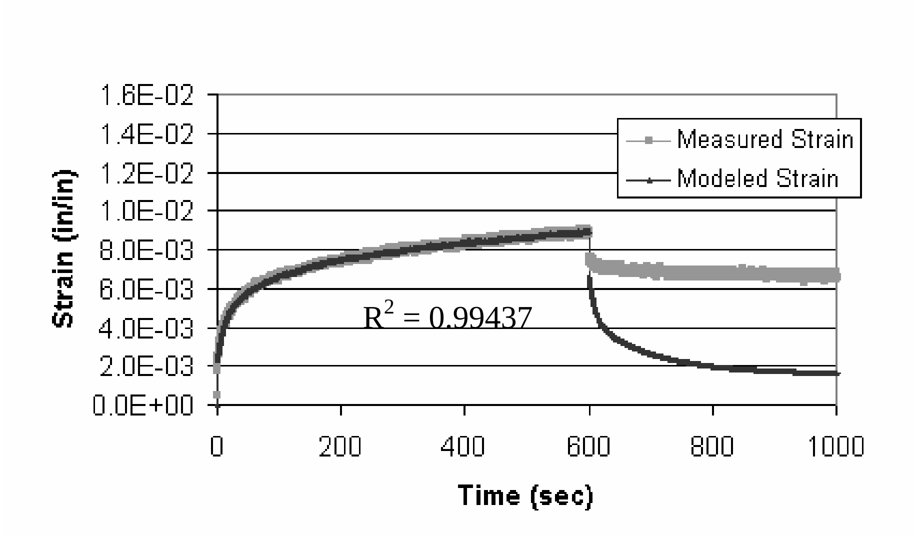

Figure 27. Measured (actual) and Modeled (theoretical) Strain, ε(t), for CR02.

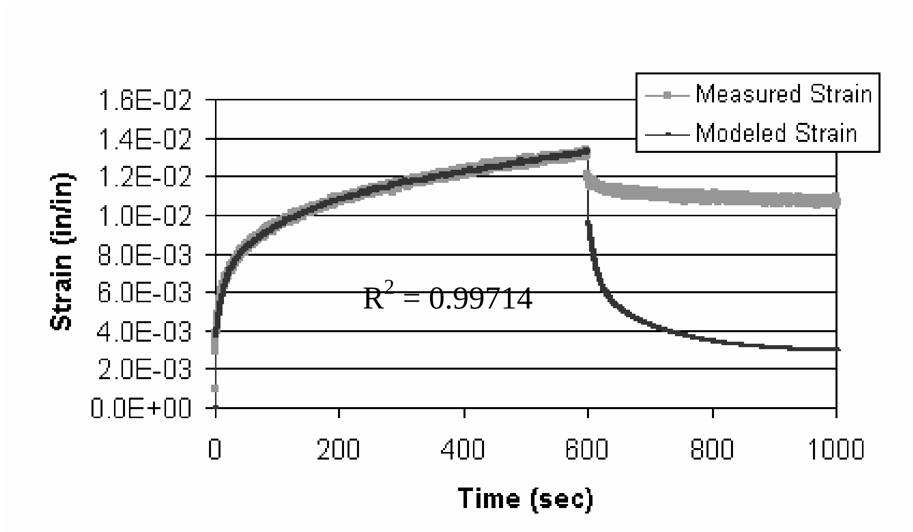

Figure 28. Measured (actual) and Modeled (theoretical) Strain, ε(t), for CR11.

The terms used in Burger's equation for quantifying the creep strain and predicting the recovery strain are shown in Table 16. The strain versus time plots show readings only to 1000 seconds. Measurements were recorded for longer than 1000 seconds, however the trend of the recovery curve is evident.

The 8% asphalt content specimens produced a maximum strain of about 14% at 600 seconds, whereas the 6% asphalt content specimens produced a maximum strain of about 12%. All other testing conditions and volumetric variables were constant. This difference appears to represent the more viscous nature of the higher asphalt content mixtures.

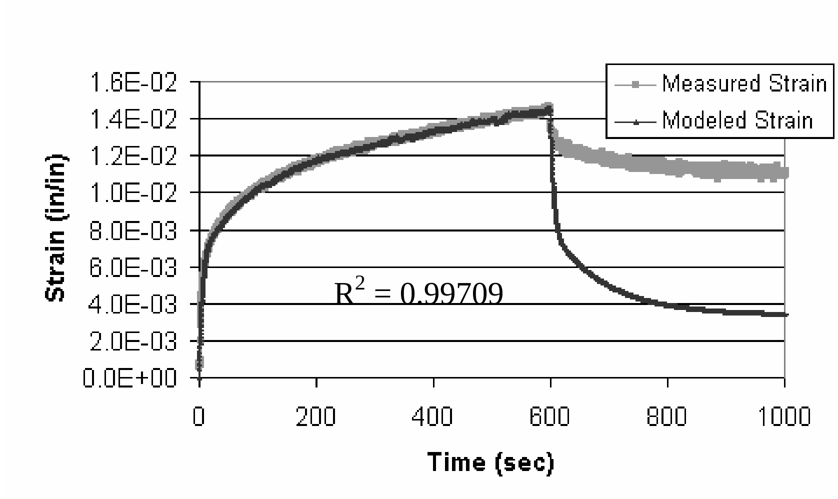

Figure 29. Measured (actual) and Modeled (theoretical) Strain, ε(t), for CR12.

Table 16. Terms Used in Burger's Expression to Model D(t)

Specimen	D_0	D_1	D_2	λ_2	D_3	λ_3
CR01	7.04E-05	7.85E-08	6.07E-05	1.07E-01	7.01E-05	1.19E-02
CR02	5.56E-05	6.43E-08	5.68E-05	9.25E-02	6.79E-05	9.62E-03
CR11	8.88E-05	1.17E-07	8.05E-05	7.74E-02	8.62E-05	9.08E-03
CR12	9.75E-19	1.37E-07	1.58E-04	1.97E-01	1.16E-04	1.08E-02

The dynamic modulus test recommends that the total strain should not exceed 1500 microstrains (1.5%). The maximum strains were as much as 10 times that value. However, the loads applied were within the typical stress levels used at a frequency of 0.1 Hz (10 sec). Therefore, this seems to indicate that the material may have entered the non-linear viscoelastic region shortly after the load was applied.

The diamond blade saw produces nearly, but not perfectly parallel specimen ends. Non-parallel ends can cause the LVDTs to register erratic measurements if the specimen wobbles slightly as it is loaded. To reduce this wobbling effect, several cycles of loading were applied and a seating load of 5 lbf was maintained between each cycle. After the third or fourth cycle, the measurements became more repeatable, as shown in Figures 30 and 31.

The measured creep compliance curve for the first cycle did not match the modeled curve, as shown in Figure 32 for specimen CR01, and as discussed above. However, the measured and modeled creep compliance curve for each subsequent cycle compared reasonably well, as shown in Figure 33, which suggests that the specimen was within the linear viscoelastic region after the first cycle, and that the model was accurate. Similar plots are included for specimen CR11 (Figures 34, 35, and 36), in which case the measured and modeled curves matched after the second cycle. Figure 37 shows the repeatability of the creep and recovery test and its sensitivity to asphalt content. The numbers are also consistent with the work conducted by Mehta et al 2000.

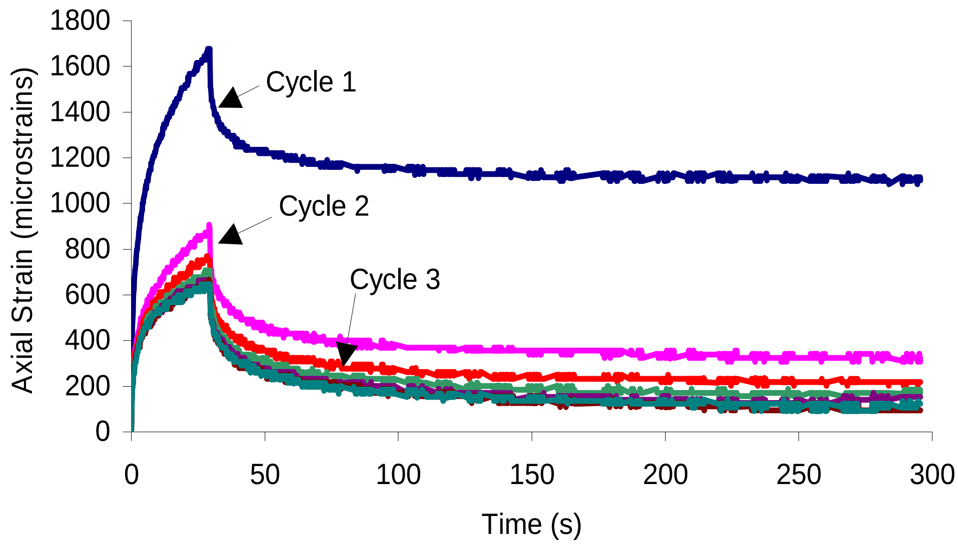

Figure 30. Deformations from Creep Test Cycles for Specimen CR01.

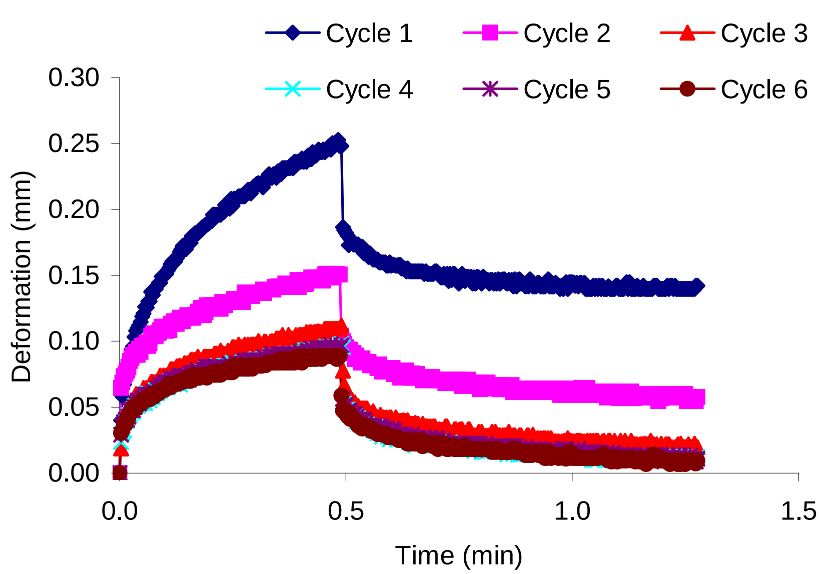

Figure 31. Deformations from Creep Test Cycles for Specimen CR11.

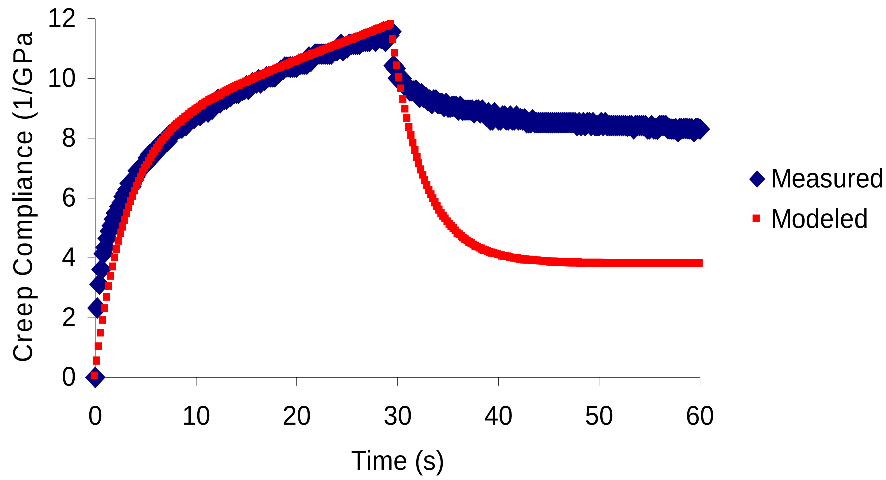

Figure 32. Measured and Modeled Creep Compliance from First Cycle, CR01.

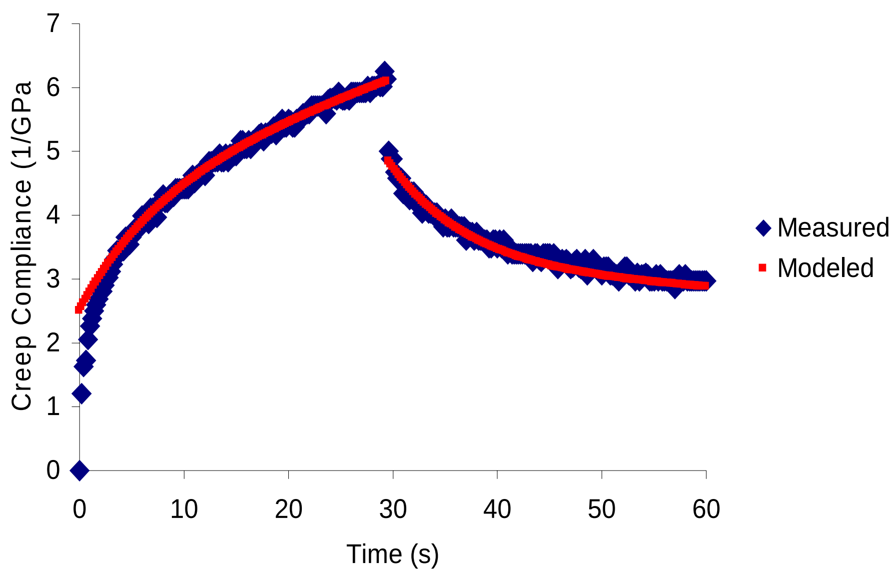

Figure 33. Measured and Modeled Creep Compliance from Second Cycle, CR01.

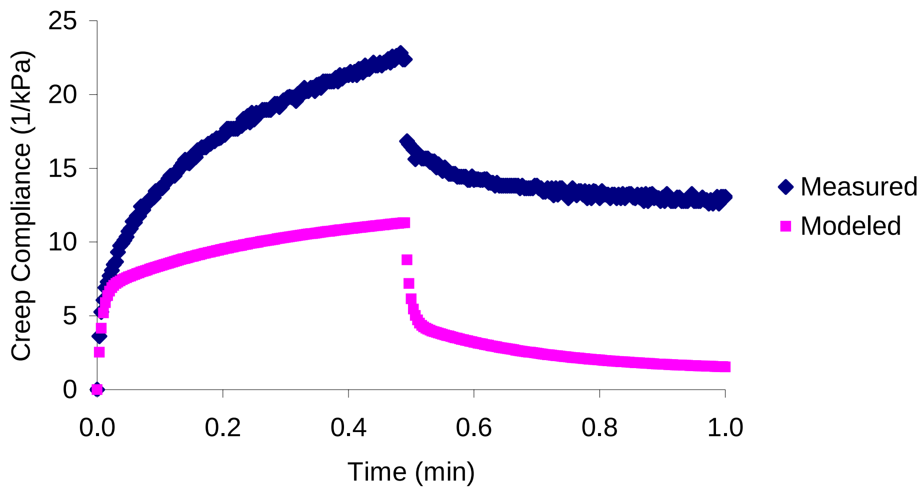

Figure 34. Measured and Modeled Creep Compliance from First Cycle, CR11.

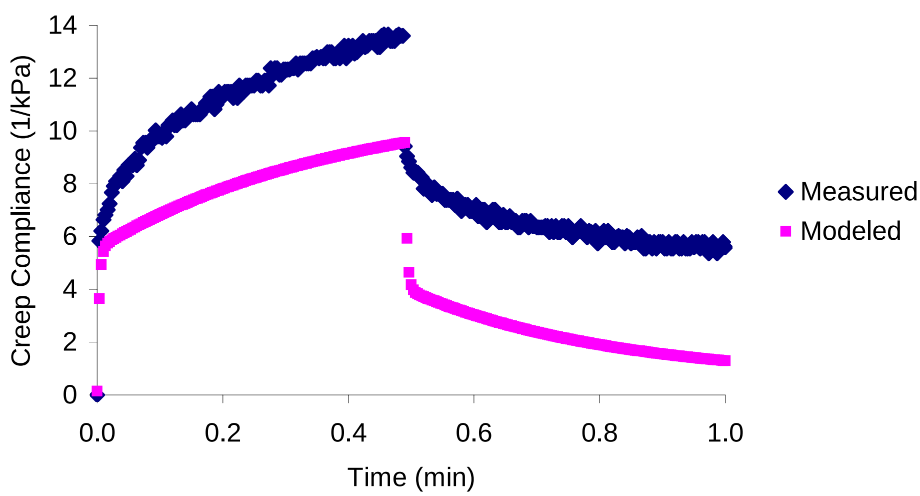

Figure 35. Measured and Modeled Creep Compliance from Second Cycle, CR11.

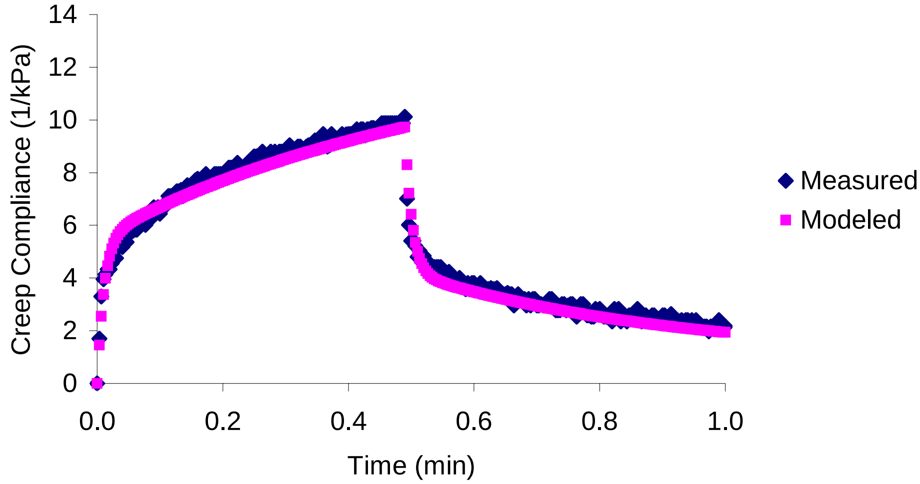

Figure 36. Measured and Modeled Creep Compliance from Third Cycle, CR11

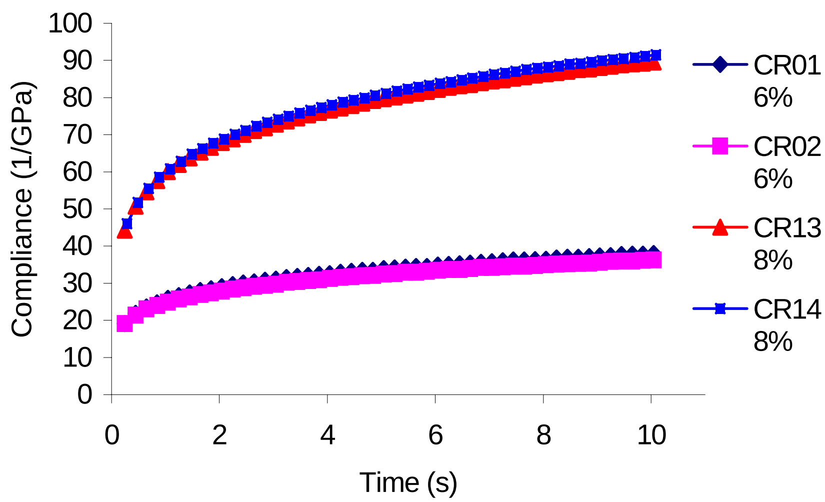

Figure 37. Creep and Recovery Results

4.1.4. Plant Implementation Issues

The gyratory compacted specimen ends will most likely not be sawed at the plant. Therefore, the effects of having non-parallel ends (i.e. the wobbling of specimens during loading) may be significantly greater than in this study. As many as five to ten loading cycles may be required to obtain reliable data. This will increase the total testing time for each specimen at the plant. Higher loads may be used to reduce the number of cycles required, but this increases the risk of being in the non-linear viscoelastic range.

4.1.5. Summary

The creep and recovery test has been successfully used to characterize asphalt concrete. However, several cycles of loading were required to obtain repeatable data. Because of these loading cycles, a device based on this testing protocol may be complex and time consuming. More importantly, the specimen ends will likely not be sawed at the asphalt plant. Therefore, further research and testing is required before the test can be implemented as a quality control device at the plant.

4.2 Indentation Test

The indentation tests, as discussed in the June 2004 Quarterly Progress Report, were repeated on a greater number of specimens. The specimens used in this second round of testing were fabricated with varying percentages of asphalt concrete and air voids. These tests and their results are discussed below.

4.2.1 Specimen Preparation

The specimens tested were fabricated from asphalt concrete mixtures which were based on a mixture commonly used by the New Jersey Department of Transportation (NJDOT). The same binder grade, PG64-22, and aggregate gradation were used for all specimens. The relative amounts of aggregates used are shown in Table 17. The overall aggregate gradation (Figure 38) conforms to the Superpave requirement of respecting the control points and restricted zone.

Table 17. Percentages of Aggregate Sources Used in Indentation Mixtures

Aggregate	Percentage by Weight
12.5 mm Gneiss	20.8
9.5 mm Gneiss	44.2
Gneiss screenings	24.0
Wash Sand	10.0
Filler	1.0

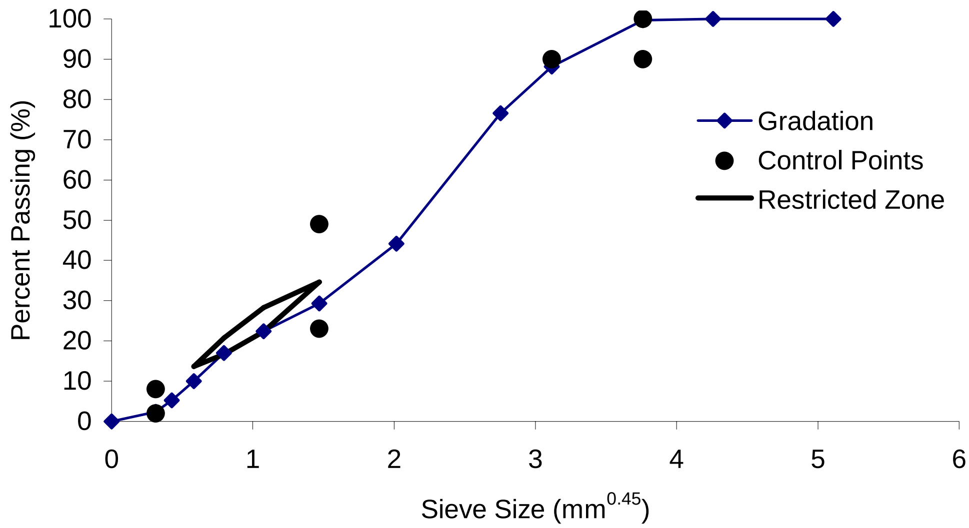

Figure 38. Aggregate Gradation

The design asphalt content for the NJDOT mixture is 4.2% with 4% air voids at N_{des}. Specimens were tested with the design asphalt content and air voids as well as with 3.7 and 4.7% asphalt and 7% air voids. The complete matrix of the specimens tested in this study is shown in Table 18.

Table 18. Number of Replicates Tested for Each Mixture

Target Air Voids (%)	Asphalt Content (%)		
	3.7	4.2	4.7
4	3	3	3
7	3	3	3

Specimens with 7% air voids were tested since pavements are generally compacted to 93% of the maximum specific gravity during construction. The specimens were compacted in a Superpave gyratory compactor to a height of 150 mm (6 in) using a 100 mm (4 in) diameter mold.

4.2.2 Testing Conditions

A constant load of 178 N was applied for 30 seconds to each specimen through a 50 mm diameter steel sphere. The resulting deflections were measured during the 30 seconds at 0.2 second intervals. An MTS load machine was used to apply this load and record deflections. The MTS ramp-up time to the desired load was set to zero so that the applied load was as close to instantaneous as possible. In applying this load, however, the MTS machine overshot the desired load considerably if there was no initial contact with the load cell. To avoid this problem, a 22 N load was applied to the specimen as a seating load before the 178 N load was applied. The 22 N load was the smallest load which resolved the overshooting problem. In effect, the applied load for compliance calculation purposes was 156 N. Also, the deflections were zeroed at the time when the 156 N load was applied. The 178 N load was chosen since it was the smallest load which produced a smooth creep curve. A small load was desirable to prevent excessive damage to the specimen. All specimens were heated to 60ºC and tested in an environmental chamber. This temperature was chosen since the indentation test is intended to be conducted on pavements immediately after construction. A photograph of the indentation test setup is shown in Figure 39.

Figure 39. Indentation Test

4.2.3 Results and Discussions

When fabricating asphalt concrete specimens in the laboratory, it is difficult to accurately achieve specific values for some volumetric parameters, this is especially true for air voids. The actual asphalt contents and air voids of the specimens tested in this study are shown in Table 19 along with the shear compliance values at 10 and 20 seconds as calculated from the indentation tests using Eq. (11). To account for small fluctuations in compliance values, which result from small fluctuations in the MTS load and measured deflections, the compliance values shown are averages of five data points around 10 and 20 seconds, respectively. The shear compliance versus time curves for each specimen are shown in Figures 40-45. Also shown in the figures are the contact stress values over time.

Table 19. Specimen Fabrication and Testing Results

Specimen	Asphalt Content (%)	Air Voids (%)	Average Shear Compliance, 10s (1/GPa)	Average Shear Compliance, 20s (1/GPa)
3.7-4-1	3.71	3.38	25.5	27.0
3.7-4-2	3.70	3.61	32.2	34.4
3.7-4-3	3.70	3.30	25.4	27.3
3.7-7-1	3.70	6.45	27.4	30.2
3.7-7-2	3.70	6.33	33.0	35.4
3.7-7-3	3.70	6.37	30.0	32.2
4.2-4-1	4.19	4.11	28.0	29.8
4.2-4-2	4.20	4.46	27.9	30.1
4.2-4-3	4.19	4.35	26.0	28.0
4.2-7-1	4.21	7.14	30.6	35.1
4.2-7-2	4.20	6.60	28.6	31.7
4.2-7-3	4.20	6.83	30.6	34.2
4.7-4-1	4.70	5.04	55.0	60.1
4.7-4-2	4.70	5.00	52.4	55.1
4.7-4-3	4.71	5.43	35.8	40.7
4.7-7-1	4.70	6.86	109.4	111.4
4.7-7-2	4.71	6.79	45.7	48.3
4.7-7-3	4.71	6.59	171.5	171.5

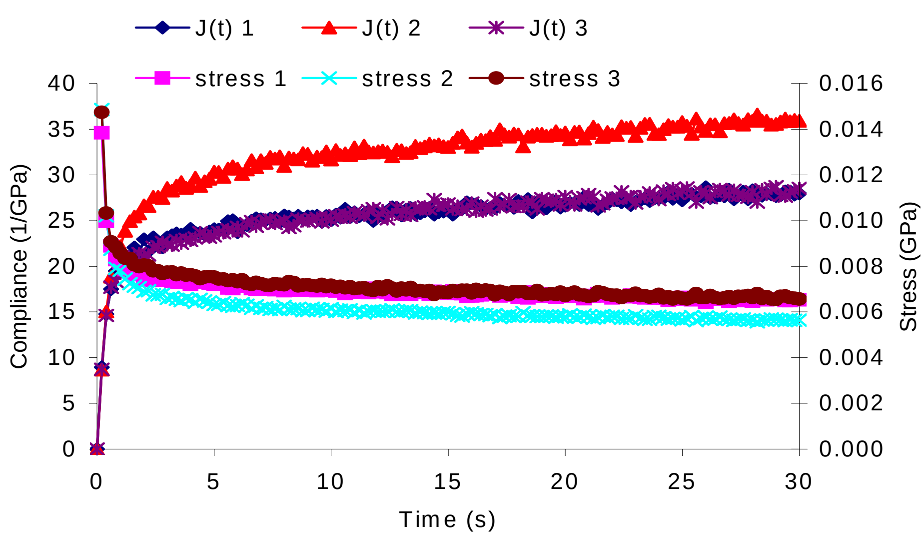

Figure 40. Compliance and Stress vs. Time for 3.7% Asphalt Content, 4% Air Voids.

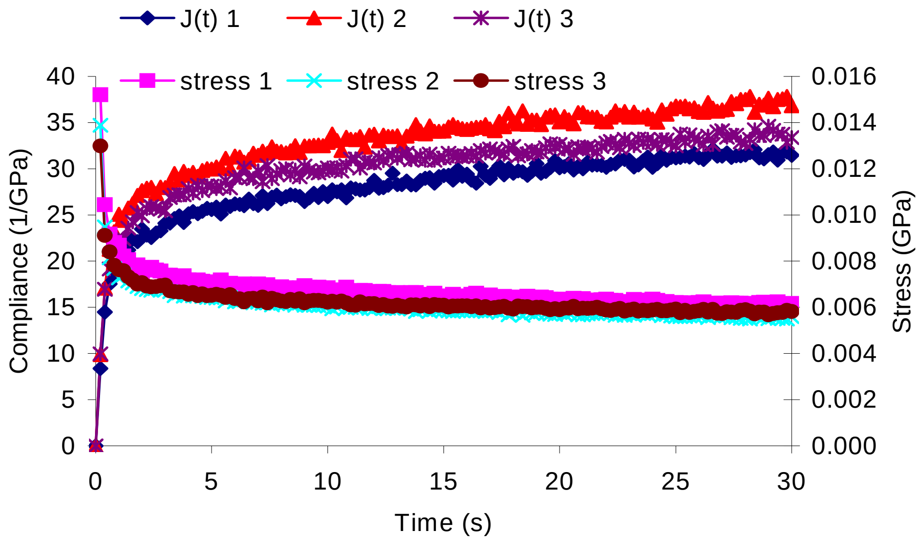

Figure 41. Compliance and Stress vs. Time for 3.7% Asphalt Content, 7% Air Voids

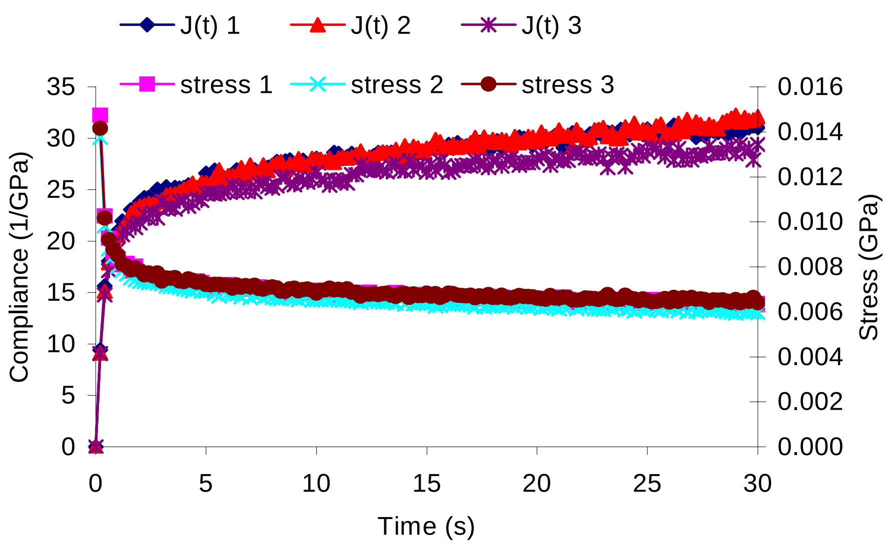

Figure 42. Compliance and Stress vs. Time for 4.2% Asphalt Content, 4% Air Voids

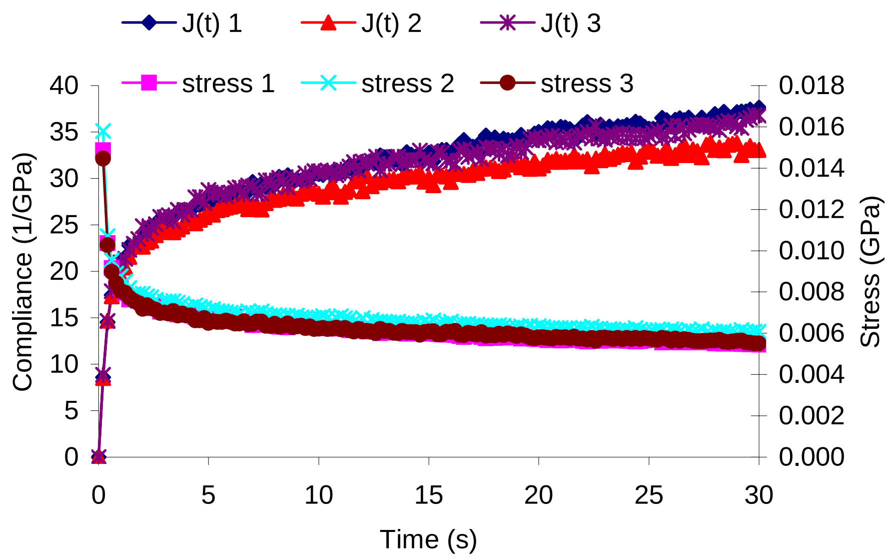

Figure 43. Compliance and Stress vs. Time for 4.2% Asphalt Content, 7% Air Voids

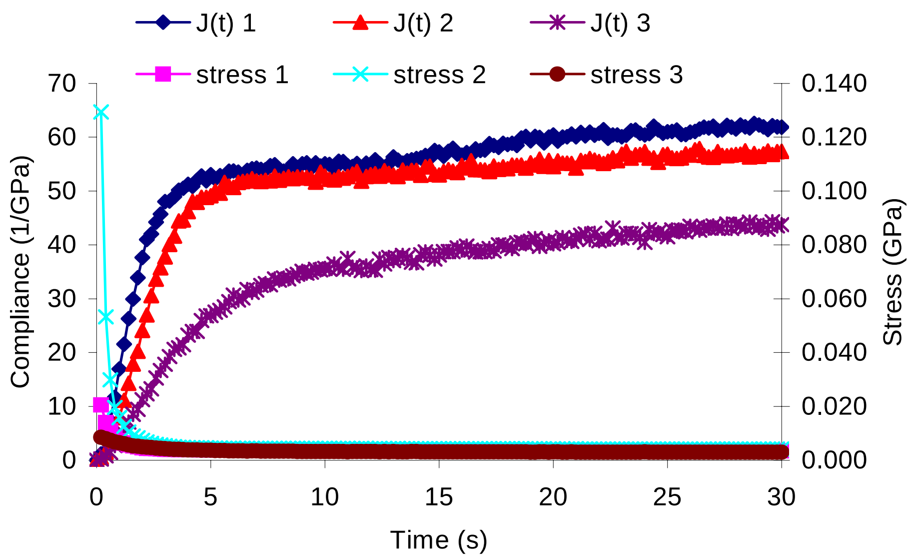

Figure 44. Compliance and Stress vs. Time for 4.7% Asphalt Content, 4% Air Voids

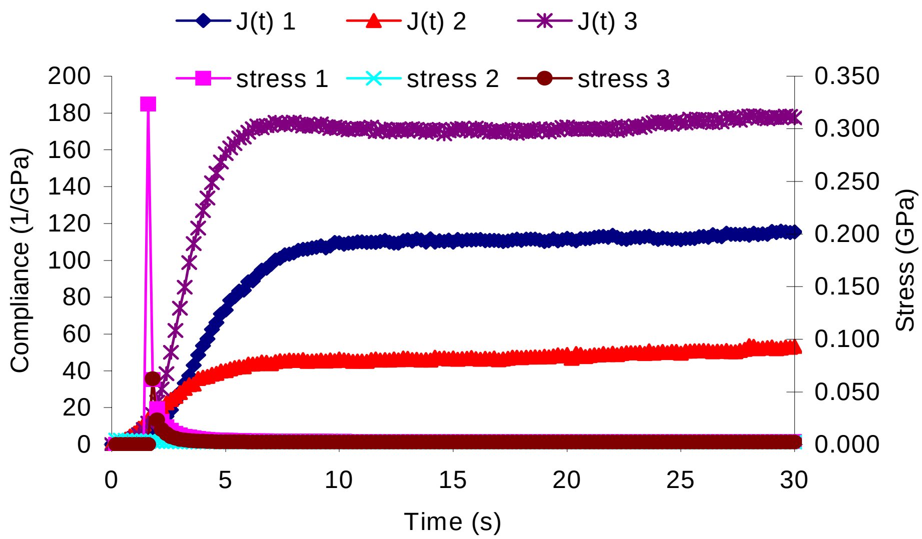

Figure 45. Compliance and Stress vs. Time for 4.7% Asphalt Content, 7% Air Voids

Table 20 shows the average shear compliance values at 10 and 20 seconds for each mixture. Specimen 3.7-4-2 was removed from this analysis since a loss of data during testing required it to be retested. It is felt that the results of the second test may have been affected by damage caused by the first test. The standard deviations and coefficients of variation are also shown in the table.

For the 3.7 and 4.2% asphalt content cases, the coefficients of variation are all below 10%, which are acceptable levels of repeatability for asphalt concrete testing. The coefficients of variation are much higher, however, for the 4.7% asphalt content case. Visual representations of the data for 10 and 20 seconds are provided as Figures 46 and 47, respectively. In these cases the compliance values (as in Table 20) were averaged for each mixture. As stated above, specimen 3.7-4-2 was removed as an outlier. The error bars at the top of each data bar represent the 95% confidence intervals.

Table 20. Descriptive Statistics of Shear Creep Compliance

	Average (1/GPa)		Standard Deviation (1/GPa)		Coefficient of Variation (%)	
Mixture	10 s	20 s	10 s	20 s	10 s	20 s
3.7-4	25.4	27.1	0.10	0.21	0.39	0.78
3.7-7	30.1	32.6	2.83	2.61	9.39	8.02
4.2-4	27.3	29.3	1.12	1.14	4.12	3.90
4.2-7	29.9	33.7	1.18	1.79	3.93	5.31
4.7-4	47.7	52.0	10.43	10.08	21.86	19.39
4.7-7	108.9	110.4	62.90	61.61	57.78	55.80

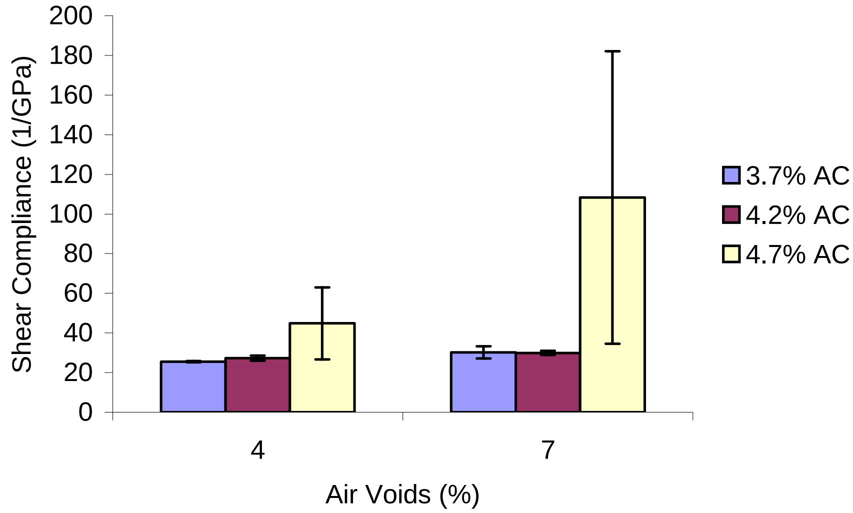

Figure 46. Average Shear Compliance Values at 10s

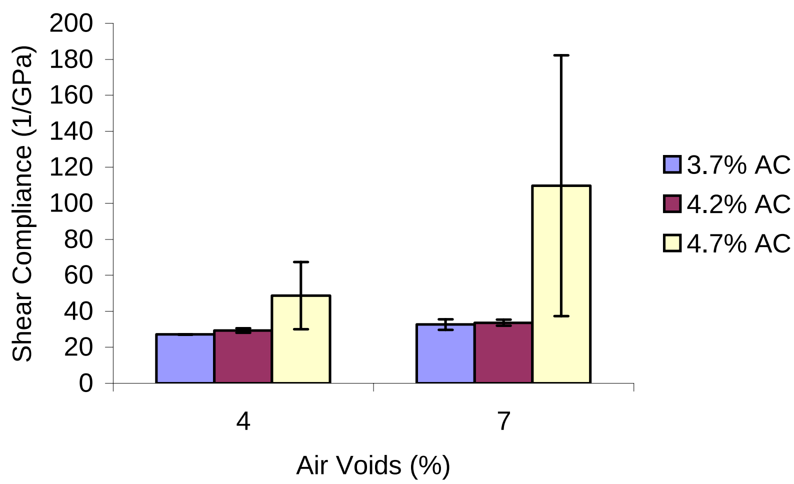

Figure 47. Average Shear Compliance Values at 20s

<u>Air Voids</u>

For the case of 3.7 and 4.2 % asphalt content, although the confidence intervals do not overlap, the difference between the 95% confidence upper limit for 4% air voids and the lower limit for 7% air voids is very small, about 0.3 GPa^{-1} at 10 seconds and 1.4 GPa^{-1} at 20 seconds. This is about a 1 and 4% difference at 10 and 20 seconds, respectively. In the case of 3.7% asphalt content, these differences are about 5 and 8% for 10 and 20 seconds, respectively. Therefore, although the difference in shear compliance values between 4 and 7% air voids for 3.7 and 4.2% asphalt content was statistically significant, this difference was taken to be practically insignificant. The error bars for the case of 4.7% asphalt content clearly overlap, and so there was no significant difference in compliance values in this case either. The air-voids for 4.7% asphalt content was one percent above the target of 4%, which would partly explain the similarity (overlapping 95% confidence interval) in compliance between the two levels of air-voids.

Asphalt Content
Statistical analysis of the data revealed no significant relationship between shear compliance and asphalt content. The 95% confidence intervals, as shown in Figures 46 and 47, do not overlap for the case of 4% air voids. However, with reference to the discussion above in regards to the sensitivity to air voids, the 95% confidence limits differ by only 1 and 3% for 10 and 20 seconds, respectively. Further, in the case of 7% air voids, the 95% confidence intervals clearly overlap. For these reasons it is concluded that the indentation test did not significantly detect a change in asphalt content in this study.

As stated earlier, the stresses caused by the indentation test are localized stresses and the response depends only on the local properties at the point of contact. It is believed that this fact prohibits the indentation test from being able to detect a change in asphalt content. As the asphalt content increases, the aggregates are coated with a thicker film of asphalt. There is a cumulative effect of this increase in aggregate coating over the whole specimen which may allow asphalt content to be detected by a test in which the entire specimen is in compression. However, when measuring the response of only a small area of the specimen, it is believed that the effects of this increased coating are not great enough to be detected.

4.2.4. Summary

The results of the indentation tests are summarized as follows:

- The results of the indentation tests were found to be repeatable for the 3.7 and 4.2% asphalt content cases. The coefficients of variation for shear compliance were below 10% for these cases. However, repeatable results were not found for the 4.7% asphalt content case.
- The shear compliance was not found to be sensitive to a change in air void level from 4 to 7%.
- The shear compliance was not sensitive to a change in asphalt content between 3.7, 4.2, and 4.7%. This appears to be due to the localized nature of the indentation test.

5.0. Conclusions and Recommendations

The dynamic modulus, which correlates well with rutting and fatigue cracking, is the primary material characterization parameter for asphalt concrete mixtures in the ASSHTO mechanistic empirical pavement design guide. It has been shown that dynamic modulus tests can be performed within acceptable levels of variability, however the cost and time required for the test will likely prevent it from being widely adopted by the asphalt industry.

Devices for Measuring Density
It appears that the most accurate device for measuring the density of pavements is the nuclear gauge using the results of Buchanan et al. (2004).

Creep and Recovery

Creep and recovery is simpler and quicker than the dynamic modulus test and can be used to obtain dynamic modulus values. In the current study, the creep and recovery test produced repeatable results which were sensitive to a change in asphalt content while remaining within acceptable limits of the linear viscoelastic region. Since the test was performed within acceptable limits of the linear viscoelastic region, the interconversion of the obtained compliance values to dynamic modulus is valid. In this way, the creep and recovery test has been successfully used to characterize asphalt concrete mixtures with respect to the requirements of the design guide.

In order to achieve these results, however, it was necessary perform the tests in three to four creep and recovery cycles. This was done in order to remove the effects of eccentric loading on the specimen. Also, in these tests, the specimen ends were sawed in an attempt to create smooth and parallel surfaces. Although the loading cycles will increase the total testing time required for each specimen, it is believed that this increase in testing time would not reduce the potential for the creep and recovery test to be used as a quality control test at the plant. However, the specimens tested at the plant will most likely not be sawed as they were in these tests. Therefore, further testing under conditions more likely to be found at the plant is required.

Indentation

Indentation was not found to be sensitive to changes in air void level nor to changes in asphalt content. These results suggest that the indentation test would have limited applicability as a quality control and quality acceptance test in the field. Therefore, no attempt was made to establish a correlation between the compliances obtained from the indentation test and the creep and recovery test.

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Appendix 2: Implementation Plan

WisDOT Research	Wisconsin Department of Transportation 4802 Sheboygan Ave., Rm. 451 P.O. Box 7965 Madison, WI 53707-7965 www.dot.state.wi.us/dtid/research	Nina McLawhorn, Research Ann Pahnke, Program Analyst Linda Keegan, Program Louis Bearden, Program Pat Casey, Communications

Implementation of Research Results

Project Information	
Project Title:	**Project ID:** **Today's Date:**
Technical Oversight Committee (WHRP or COR):	**TOC Chair and Phone number:**
Project Start Date: February, 01 2003	**Approved Contract Amount:**
Project End Date: September 01, 2006	**Final Project Expenditures:**
Reference Final Report Draft Dated:	
Principal Investigator: Mehta, Y. **Organization: Rowan University**	**Phone: 856-256-5327** **E-Mail: mehta@rowan.edu**

Technical Oversight Committee Recommendations	
1. Check one of the two choices below: ☐ *Yes. We recommend changes to current practice based on some or all of the results of this report. The research was sound, and the report's conclusions appear to offer an advance over current practice.* ☐ **No. We do not recommend changes to current practice at this time. This approach does not appear fruitful OR future study is needed OR our objectives have changed, etc.**	
2. If implementation is not recommended, we suggest the following actions instead:	
3. If implementation is recommended, we suggest the following specific changes to current practice, detailed on the attached work plan and timeline (check applicable items): ☐ **Standard Specifications** ☐ **Quality Management Program (QMP) Specifications** ☐ **Facilities Development Manual (FDM)** ☐ **Highway Maintenance Manual** ☐ **Training, outreach** ☐ **Other (describe):**	
4. Approval of this implementation plan by the Technical Oversight Committee (chair on behalf of entire committee):	**Signature:** **Date:**
5. Approval of this implementation plan by the Council on Research (for COR approved projects):	**Signature(s):** **Date:**

6. Referral for development of detailed work plan and timeline to (check one):	**☐ WisDOT/Industry Technical Committee on:** ______________________________ **☐ Other WisDOT policy body:** ______________________________
7. Approval of work plan and timeline by the WisDOT Bureau Director(s) responsible for the policies described in item #3 above:	**Signature(s):** **Date**
8. Acceptance by a project manager of the responsibility for completing these implementation efforts according to the attached work plan and timeline:	**Signature:** **Date:**

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Implementation Work Plan	
1. Project Title:	**2. Prepared by:**
1. Scope and objectives of implementation, including specific changes to WisDOT procedures.	
2. Estimated cost (if any) to implement.	

4. Expected benefits and how they will be measured (dollar savings, time savings, other).
5. Possible pitfalls and how they will be avoided.

Implementation Timeline (Gantt Chart)												
Tasks/Person Responsible												