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REPORT 513

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Simple Performance Tester for Superpave Mix Design: First-Article Development and Evaluation

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Simple Performance Tester for Superpave Mix Design: First-Article Development and Evaluation

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SUBJECT AREAS
Materials and Construction

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in Cooperation with the Federal Highway Administration

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Ramon Bonaquist, Chief Operating Officer for Advanced Asphalt Technologies, LLC, served as Principal Investigator for the project. William Stump, III, President of Calibration Services Incorporated was Co-Principal Investigator. Donald W. Christensen, Senior Engineer for Advanced Asphalt Technologies, LLC, and Dr. Charles Antle, consulting statistician, performed the statistical analyses that compose a significant portion of the evaluation included in this report. The report was written by Dr. Bonaquist, Mr. Stump, and Dr. Christensen.

Work on this project was performed under the general supervision of Ramon Bonaquist. Mr. Kevin Knechtel, Laboratory Manager for Advanced Asphalt Technologies, LLC, and Mr. Donald Jack, Chief Engineering Technician for Advanced Asphalt Technologies, LLC, supervised the laboratory work performed during the project. Work in the Federal Highway Administration Mobile Asphalt Laboratory was performed by Dr. Leslie Myers, Mr. Charles Paugh, and Dr. Roustam Djoumanov.

FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents the findings of a research project to develop a practical, economical simple performance tester for use in routine Superpave mix design and possibly in the characterization of hot mix asphalt (HMA) materials for pavement structural design. In the phase of the work reported here, first-article simple performance testers (SPTs) procured from two different manufacturers were evaluated, and both units were found to meet the requirements of the performance-based purchase specification. Based on these results, the Federal Highway Administration (FHWA) is coordinating a pooled-fund purchase of production units for evaluation by the state highway agencies. Four of these units will be immediately purchased in the next phase of this project for use by state highway agencies and FHWA to test the ruggedness of candidate simple performance tests. Thus, the report will be of particular interest to materials engineers in state highway agencies, as well as to materials suppliers and paving contractor personnel responsible for design and production of hot mix asphalt and the specification and purchase of laboratory test equipment.

The Superpave volumetric mix design procedure developed in the Asphalt Research Program (1987–1993) of the Strategic Highway Research Program (SHRP) does not include a simple, mechanical "proof" test analogous to the Marshall stability and flow tests or the Hveem stabilometer method. Instead, the original Superpave method relied on strict conformance to the material specifications and volumetric mix criteria to ensure satisfactory performance of mix designs intended for low-traffic-volume situations (defined as no more than 10^6 equivalent single axle loads [ESALs] applied over the service life of the pavement). For higher trafficked projects, the original SHRP Superpave procedures[1] required a check for tertiary creep behavior with the repeated shear at constant stress ratio test (AASHTO TP7) and a rigorous evaluation of the mix design's potential for permanent deformation, fatigue cracking, and low-temperature cracking using several other complex test methods in AASHTO TP7 and TP9.

User experience with the Superpave mix design and analysis method, combined with the long-standing problems associated with the original SHRP Superpave performance models supporting what was then termed "level 2 and 3" analyses, demonstrated the need for simple performance tests (SPTs) to quickly and easily proof-test candidate mix designs. In 1996, work sponsored by FHWA (Contract DTFH61-95-C-00100) began at the University of Maryland at College Park (UMCP) to identify and validate SPTs for permanent deformation, fatigue cracking, and low-temperature cracking. In 1999, this effort was transferred to Task C of NCHRP Project 9-19, "Superpave Support and Performance Models Management," with the major portion of the task conducted by a research team headed by UMCP subcontractor Arizona State University (ASU). In *NCHRP Report 465*, the UMCP-ASU team recommended three candidate

[1] *The Superpave Mix Design Manual for New Construction and Overlays,* Report SHRP-A-407, Strategic Highway Research Program, National Research Council, Washington DC (1994).

test-parameter combinations as SPTs for permanent deformation: (1) the dynamic modulus, E^*, determined from the triaxial dynamic modulus test; (2) the flow time, $F_{T,}$ determined from the triaxial static creep test; and (3) the flow number, $F_{N,}$ determined from the triaxial repeated load test.

Under NCHRP Project 9-29, "Simple Performance Tester for Superpave Mix Design," Advanced Asphalt Technologies, LLC, was assigned the task of designing, procuring, and evaluating first-article SPTs for their potential use in Superpave mix design and in HMA materials characterization for pavement structural design. The first-article SPTs would be capable of conducting all three simple performance tests above; the units would further be evaluated for their capability to perform the dynamic modulus master curve determination required for HMA materials characterization in the pavement design guide developed in NCHRP Project 1-37A, "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II."

In the first stage of this work, the research team reviewed the draft test protocols prepared by the Project 9-19 research team. This review included a 1-day workshop attended by the project panel, key members of the research team, and invited materials testing experts to discuss the requirements for the simple performance test devices. The team then developed draft equipment specifications and cost estimates for each of the three candidate simple performance tests; these were then combined to specify a single device capable of performing all three tests.

The team conducted a workshop with the project panel and potential manufacturers to review the draft specifications and cost estimates; comments from the workshop participants were incorporated into the first-article purchase specification. Finally, the team prepared a work plan for evaluation of the first-article equipment.

In the second stage of the work, proposals for procurement of first-article SPTs were solicited from several equipment manufacturers. Four proposals were received; purchase orders for first-article SPTs were awarded to Interlaken Technology Corporation and Shedworks, Inc. Upon delivery, these units were extensively evaluated through a joint effort of Advanced Asphalt Technologies, LLC, and the Federal Highway Administration to (1) ensure they were in compliance with the specifications and properly calibrated, (2) evaluate HMA mechanical properties measured with the two devices, and (3) assess their overall functionality.

Both first-article SPTs were found to meet all requirements of the performance-based purchase specification and to be reasonably user-friendly. The overall variability of the simple performance test based on E^* conducted with either first-article unit was found acceptable for purposes of HMA mix design or quality control testing; however, the variability of the test based on the F_N parameter was judged too high for either purpose.

As presently configured, the SPT cannot reach the lowest test temperature specified for determination of the dynamic modulus master curve according to the protocol developed in NCHRP Project 1-37A, "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II." In the next phase of the project, alternative methods for estimating limiting low temperature modulus will be evaluated to determine the minimum required testing temperature range for equipment to measure the dynamic modulus master curves. Based on these results, a production SPT fully capable of accurately measuring the master curve will be procured.

This report describes the development of the first-article purchase specification, procurement and evaluation of the two SPTs, and the ensuing revision of the purchase specification for future procurement of production SPT units. In addition, it contains four supporting appendixes:

- Appendix A: First-Article Equipment Specifications;
- Appendix B: Materials and Laboratory Methods;
- Appendix C: Evaluation Test Data; and
- Appendix D: Revised Equipment Specification.

CONTENTS

SIMPLE PERFORMANCE TESTER FOR SUPERPAVE MIX DESIGN: FIRST-ARTICLE DEVELOPMENT AND EVALUATION

SUMMARY

In Phase II of NCHRP Project 9-29, a detailed purchase specification was developed for equipment to perform the three Project 9-19 simple performance tests: dynamic modulus, flow number, and flow time. The specification was used to procure two simple performance test systems from Interlaken Technology Corporation and Shedworks, Incorporated. These two systems were similar in several critical design areas. Both are relatively small bottom-loading, servo-hydraulic devices with an automated test chamber that serves as both the confining pressure cell and the environmental chamber. The primary differences between the devices are (1) the specific methods used to heat and cool the chamber and (2) the specimen-mounted deformation measuring system used exclusively in the dynamic modulus test. The Interlaken device uses heating elements and an air-driven vortex cooler to control temperature in the chamber. The specimen deformation measuring system is a unique extensometer system held against the specimen with small pneumatic actuators. The Shedworks device circulates conditioned air through the test chamber. The specimen deformation measuring system is a refined version of the glued contact point system used in the original Project 9-19 research.

An extensive evaluation of these two devices was undertaken in Phase II of Project 9-29. This evaluation included (1) specific testing to ensure that the devices were in compliance with the specifications and properly calibrated and (2) an extensive mixture testing program to evaluate mechanical properties measured with the two devices and to assess the functionality of the devices. The overall findings from the evaluation were as follows:

1. Both devices meet the requirements of the first-article specifications and are reasonably user-friendly. Both have functional deficiencies that need to be addressed in future production units.
2. For the dynamic modulus test, the evaluation testing revealed significant differences in both the mean and the variability of dynamic modulus data collected with the two devices. These differences appear to be associated with differences in the specimen-mounted deformation measuring system.
3. The overall variability of the dynamic modulus test was found acceptable for specification testing, and the variability is expected to decrease as limits are placed on the quality indicators developed in this project for the dynamic modulus test.

4. For the flow number test, the evaluation testing showed no significant difference in flow numbers obtained with the two devices.
5. The overall variability of the flow number test was found to be too high for specification testing. One probable source of variability that could be improved is the algorithm used to select the flow point.

The equipment specification was revised based on these findings. The most significant revision addressed the specimen deformation measuring system for the dynamic modulus test. A generic glued gage point system was included in the specification as the standard system with the option to use other systems if they can be shown to produce the same measured specimen responses. Test methods for performing the flow time, flow number, and dynamic modulus tests with the Simple Performance Test System were developed. The test methods are adaptations of the Project 9-19 test methods to the specific capabilities of the Simple Performance Test System.

Based on the findings of the evaluation testing and the revised specification requirements, the Interlaken Simple Performance Test System did not receive approval. The performance of the unique extensometer system was the primary deficiency with this system. The Shedworks Simple Performance Test System was conditionally approved. This device requires minor improvements in several functional areas.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

1.1 PROBLEM AND PURPOSE

NCHRP Project 9-19, Superpave Support and Performance Models Management, recommended three candidate simple performance tests to complement the Superpave volumetric mixture design method. These are flow time, flow number, and dynamic modulus. The recommended tests are conducted in uniaxial or triaxial compression on cylindrical specimens that are sawed and cored from over-height gyratory compacted samples. Data from all three candidates were shown to correlate well with observed rutting in field pavements. The dynamic modulus was also shown to have potential as a simple performance test for fatigue cracking. In NCHRP Project 1-37A, Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II, the dynamic modulus was recommended as the primary material characterization test for asphalt concrete layers. The use of this test for both mixture evaluation and structural design offers a potential link between mixture design and structural analysis that was one of the goals of the original Superpave mixture analysis system.

Although additional work is being done in NCHRP Project 9-19 to further evaluate the candidate tests and develop acceptance limits, the test methods were defined to the point that equipment development could be conducted in parallel with the remaining Project 9-19 and Project 1-37A activities. The objective of Project 9-29 is to stimulate the development of commercial equipment that can be used for two purposes:

1. For simple performance testing to complement Superpave volumetric mixture design, and
2. For the asphalt concrete material characterization required by future pavement structural design methods.

This project is the first in a series of equipment development efforts that will lead to a national procurement for state highway agencies and ultimately to the widespread adoption and use of the equipment by the hot-mix asphalt (HMA) industry.

1.2 SCOPE AND RESEARCH APPROACH

The project consisted of eight tasks assembled into two phases. The first phase comprised the following five tasks aimed at the development of detailed equipment purchase specifications and a plan for evaluating the first-article devices that were purchased during Phase II:

1. Review the draft test protocols prepared by the Project 9-19 research team. This review included a 1-day workshop attended by the project panel, key members of the research team, and invited materials testing experts to discuss the requirements for the simple performance test devices.
2. Develop draft equipment specifications and cost estimates for the three candidate tests. Individual draft equipment specifications were developed for the three candidate tests. These were then combined to specify a device capable of performing all three tests.
3. Conduct a workshop with the project panel and potential manufacturers to review the draft specifications and cost estimates. This workshop was attended by 10 manufacturers who provided several comments on the draft equipment specifications that were incorporated into the first-article equipment specifications.
4. Develop a work plan for evaluation of the first-article equipment. The work plan included the methods for verification that the first-article equipment met the specifications as well as a laboratory experiment to evaluate the performance of the first-article equipment and the repeatability/reproducibility of data obtained with it.
5. Prepare and submit an interim report documenting the work completed in the first phase of the project.

The second phase of the project comprised three tasks associated with the procurement and evaluation of two first-article devices and the revision of the equipment specifications and draft test protocols based on the evaluation. These tasks were as follows:

6. Solicit manufacturers, evaluate proposals, and procure two first-article devices from different manufacturers. First-article devices were procured from Interlaken Technology Corporation and Shedworks, Incorporated.
7. Perform the first-article evaluation in accordance with the plan developed in Task 4. Analyze the data and develop

recommendations concerning the equipment evaluated and revise the equipment specifications, cost estimates, and Project 9-19 Draft Test Protocols as needed.

8. Prepare and submit a final report documenting the work performed during Phase II. The report includes stand-alone appendices presenting the final equipment specifications, and recommended changes to the Project 9-19 Draft Test Protocols.

Details of the Phase I work were documented in the Interim Report submitted on October 10, 2001. This report documents the work completed during Phase II of the project.

CHAPTER **2**

FINDINGS

In this section of the report, the key findings of NCHRP Project 9-29 are summarized. Detailed documentation of the each of the various project activities is presented in the appropriate appendix to this report. Discussion of the practical ramifications of these findings is given in Chapter 3 of this report, while extension of the findings to general conclusions and recommendations are presented in Chapter 4.

2.1 KEY ELEMENTS OF THE FIRST-ARTICLE SPECIFICATION

The basic philosophy behind the first-article specifications was to produce performance type specifications that would allow manufacturers to propose innovative design concepts to address issues associated with user-friendliness, cost, and reliability. The specifications described how the test must be conducted, what needed to be measured, and the accuracy and resolution of the measurements. Manufacturers were then permitted to propose various alternatives that met the specification requirements. Four first-article equipment specifications were developed during Phase I of the project. The following specifications were included as appendices in the Interim Report:

- First-Article Equipment Specification for Specimen Fabrication Equipment,
- First-Article Equipment Specification for the Flow Time Test,
- First-Article Equipment Specification for the Flow Number Test, and
- First-Article Equipment Specification for the Dynamic Modulus Test.

Draft specifications were first prepared by the Project 9-29 research team based on the findings from the review of the Project 9-19 and 1-37A Draft Test Protocols and the workshop conducted with materials testing experts in Task 1. These draft specifications were then sent to 13 potential manufacturers for review and comment and were reviewed in detail with 10 of the potential manufacturers at the manufacturer's workshop conducted in Task 3. The draft equipment specifications were revised based on comments obtained from the manufacturers and presented in the Interim Report. The Interim Report also included the recommendation that Phase II be directed at the procurement and evaluation of equipment capable of performing the flow time, flow number, and dynamic modulus test over a temperature range of 20 to 60 °C. This recommendation was approved by the project panel, and a final first-article equipment specification was prepared by combining elements from the test-specific specifications listed above. The final specification, "First-Article Equipment Specification for the Simple Performance Test System," is included in this report as Appendix A. The sections that follow summarize key elements of this specification.

2.1.1 Test Capabilities

The simple performance test system can perform the three candidate uniaxial and triaxial compression tests recommended in NCHRP Project 9-19 (*1*): flow time, flow number, and dynamic modulus. These three tests are variations on tests that have been used for many years by various researchers to characterize asphalt concrete materials (*2*). The tests are performed on nominal 100-mm (4-in) diameter, 150-mm (6-in.) high cylindrical specimens cut and cored from over-height 150-mm (6-in.) diameter gyratory specimens. The simple performance test system includes a confining pressure system and environmental control over the temperature range of 20 to 60 °C. The tests are briefly described below.

2.1.1.1 Flow Time Test

The flow time test is a variation on the simple compressive creep test that has been used by several researchers to measure the rutting potential of asphalt concrete mixtures (*3*). In this test, a static load is applied to the specimen, and the resulting strains are recorded as a function of time. The variation introduced by the Project 9-19 research is the concept of flow time, which 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. Figure 1 presents an example of a typical creep response and the computation of the flow time. In this case, the flow time is

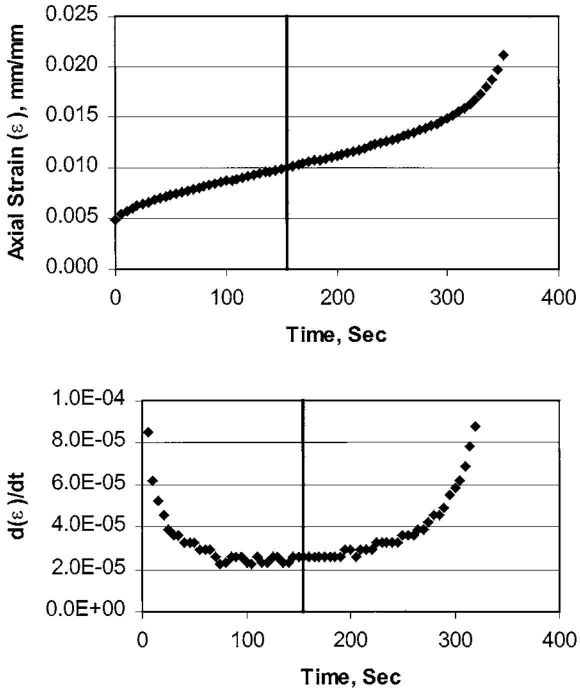


Figure 1. Typical creep test response and flow time.

approximately 155 sec, and the axial strain at the flow time is approximately 1.0 percent.

In 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 (*2*). For tests at a given temperature, axial stress, and confining stress, the rutting resistance of the mixture increases as the flow time increases. Guidance on temperatures, stress levels to be used in the testing, and the minimum flow time needed to achieve acceptable rutting performance are the subject of ongoing research in Project 9-19.

2.1.1.2 Flow Number

The flow number test is a variation on the repeated load permanent deformation test that has been used by several researchers to measure the rutting potential of asphalt concrete mixtures (*3*). Figure 2 shows a schematic of the repeated loading used in this test. Haversine axial compressive load pulses are applied to the specimen. The duration of the load pulse is 0.1 sec followed by a rest period of 0.9 sec. The permanent axial deformation measured at the end of the rest period is monitored during repeated loading and converted to strain by dividing by the original gauge length. The variation introduced by the Project 9-19 research is the concept of flow number, which is defined as the number of load pulses when the minimum rate of change in permanent strain occurs during the repeated load test. It is determined by differentiation of the permanent strain versus the number of load cycles curve. Figure 3 presents an example of a typical permanent axial strain response and the computation of the flow number. In this case, the flow number is 1300 and the permanent axial strain at the flow number is approximately 1.0 percent.

In 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 (*2*). For tests at a given temperature, axial stress, and confining stress, the rutting resistance of the mixture increases as the flow number increases. Guidance on temperatures, stress levels to be used in the testing, and the minimum flow

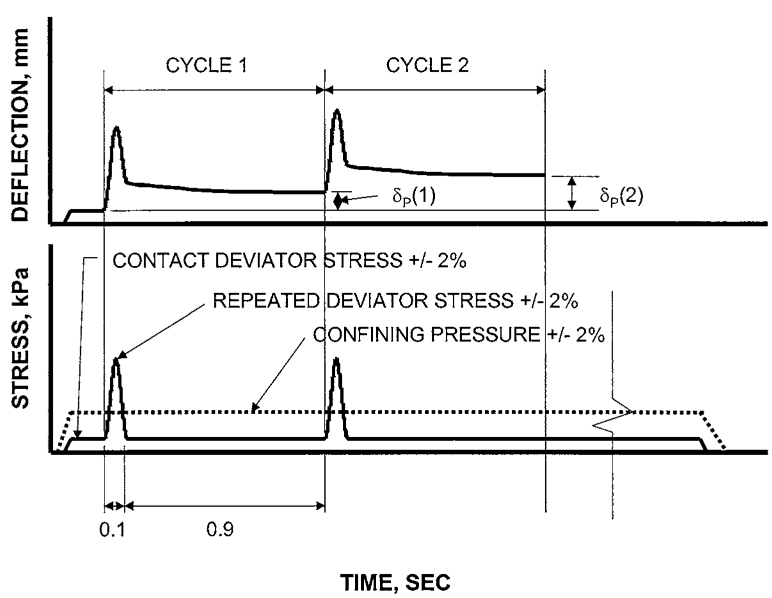


Figure 2. Schematic of flow number test loading.

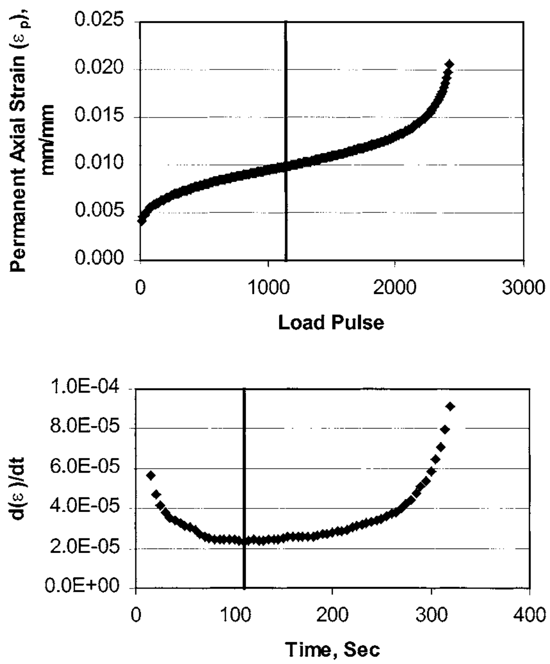


Figure 3. Typical repeated load test response and flow number.

number needed to achieve acceptable rutting performance are the subject of ongoing research in Project 9-19.

2.1.1.3 Dynamic Modulus Test.

The dynamic modulus simple performance test recommended by the NCHRP Project 9-19 team is a variation on ASTM D3497. 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 used to calculate the resulting dynamic modulus and phase angle. Figure 4 presents a schematic of typical data from the dynamic modulus test. The dynamic modulus and phase angle are defined by Equations 1 and 2, respectively.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{1}$$

$$\phi = \left(\frac{T_i}{T_p}\right) \times 360 \tag{2}$$

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

Two dynamic modulus test procedures were recommended in Project 9-19: one for permanent deformation and one for fatigue cracking. The primary difference in the tests is the temperature for measuring the dynamic modulus. For permanent deformation, tests will be performed at high temperatures while an intermediate temperature will be used for the fatigue tests. In Project 9-19, dynamic modulus test results at 37.8 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 (*1*). The rutting resistance of the mixtures increased as the dynamic modulus at high temperatures increased. Guidance on test temperatures and the minimum moduli needed to achieve acceptable rutting performance are the subject of ongoing research

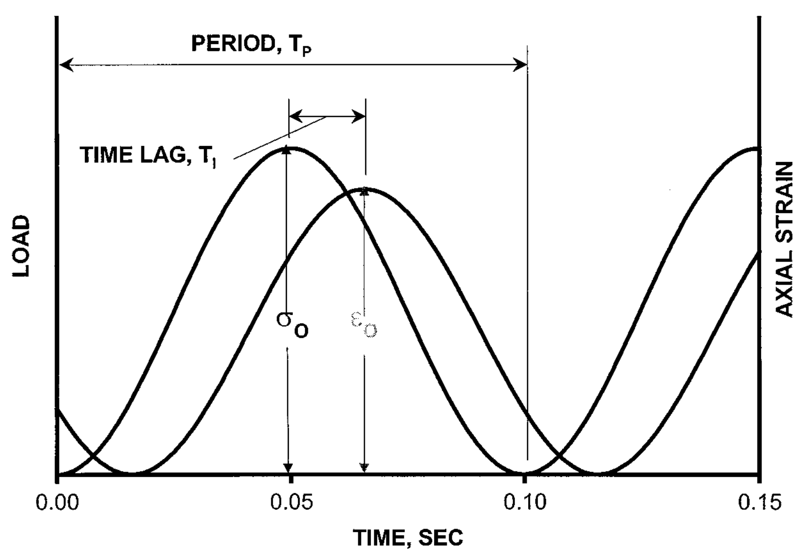


Figure 4. Typical dynamic modulus test data.

in Project 9-19. The Project 9-19 research found only a fair correlation between cracking observed in the experimental sections and the dynamic modulus at 4.4 and 21.1 °C (*1*). Guidance on test temperatures and moduli needed to achieve acceptable fatigue performance are also the subject of ongoing research in Project 9-19.

2.1.2 Overall Test System Requirements

The first-article specifications place specific requirements on the size, power requirements, and noise level for the simple performance test system. These were included in the specifications to promote future implementation of the equipment in HMA plant laboratories. Table 1 summarizes key operational requirements included in the specification.

2.1.3 Compression Loading Machine

The first-article specifications require a compression loading machine with closed loop control that can apply constant, ramp, sinusoidal, and pulse loads. Table 2 summarizes the required capacities of the loading machine. The specifications do not specify the type of loading machine, but place specific requirements on the machine's ability to control the loading. Table 3 summarizes the load control requirements. For sinusoidal and pulse loads, a control requirement was placed on the standard error of the applied load, defined by Equation 3. 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.

$$se(P) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n-1}}\left(\frac{100\%}{\hat{x}_o}\right) \quad (3)$$

where

se(P) = Standard error of the applied load
x_i = Measured load at point *i*
$\hat{x}_i$ = Predicted load at point *i* from the best fit sinusoid
$\hat{x}_o$ = Amplitude of the best fit sinusoid
n = Total number of data points collected during test.

Two types of loading machines were proposed by manufacturers who responded to the Project 9-29 request for proposals: servo-hydraulic, and a unique linear motor based on electromagnetic control technology. As discussed in a later section of this report, both of the machines selected as the first-article equipment were servo-hydraulic.

TABLE 1 Key operational requirements for the simple performance test system

Item	First-Article Specification Requirement
Assembled Size	1.5 m (5 ft) by 1.5 m (5 ft) by 1.8 m (6 ft) high.
Component Size	Width must be less than 76 cm (30 in.).
Electrical Power	115 or 230 VAC, 60 Hz.
Air Supply	0.005 m^3/s (10.6 ft^3/min) at 850 kPa (125 psi).
Noise Level	70 dB at 2 m (6.5) ft.

The first-article specifications required two configurations for the loading platens. For the flow time and flow number tests, the loading platens are required to remain parallel. For the dynamic modulus test, the loading platens must include a ball or swivel joint on one platen to allow that platen to conform to the contour of the specimen end.

Finally, loads must be measured with an electronic load cell. To minimize the potential for damage, the full-scale range of the load cell was specified to be at least equal to the stall force of the actuator. The accuracy of the load cell was specified to be ±1 percent over a load range of 2 to 100 percent of the capacity of the machine. The resolution of the load cell was specified to be that required by ASTM E4 *(4)*, which is 1/100 of the lowest calibrated load. For the simple performance test devices with 10 kN capacity, the first-article specifications require a resolution of 2 N (0.5 lb).

2.1.4 Deformation Measuring Systems

Two separate deformation measuring systems are required by the first-article specifications. The first, used in the flow time and flow number tests, measures the movement of the loading actuator. Measuring the flow time and flow number using an actuator-mounted system is a departure from the specimen-mounted instrumentation specified in Project 9-19 (*1*). Given that the flow time and flow number are determined from the derivative of the strain history, the Project 9-29 research team suggested that an actuator-mounted deformation measuring device could be used to detect flow in these tests. Such instrumentation would simplify the equipment and technician skill level required to perform the flow tests. As long as machine compliance errors are not a function of time, they do not affect the computation of the flow time or flow number. This hypothesis was verified by additional test-

TABLE 2 Compression loading machine capacities

Test	Type of Loading	Capacity	Rate
Flow Time	Ramp, constant	10 kN (2.25 kips)	0.5 sec ramp
Flow Number	Ramp, constant, pulse	8 kN (1.80 kips)	10 Hz pulse with 0.9 sec dwell
Dynamic Modulus	Ramp, constant, sinusoidal	6 kN (1.35 kips)	0.1 to 25 Hz

TABLE 3 Load control requirements

Load Type	Requirements
Constant	± 2 percent of specified
Ramp	± 2 percent of specified
Sinusoidal	Standard error, se(P), ≤ 5%
Pulse	Peak: ± 2 percent of specified
	Standard error, se(P): ≤ 10%

ing conducted in Project 9-19, which compared flow times and flow numbers measured with three systems:

- The specimen-mounted LVDTs specified in the Project 9-19 test protocol,
- The radial LVDTs specified as an alternate in the Project 9-19 test protocols, and
- An actuator-mounted LVDT.

Figure 5 shows data presented in the Project 9-19 June 2001 Quarterly Progress Report (*5*). This data confirmed that flow times and flow numbers from an actuator-mounted deformation system were the same as those from the specimen-mounted deformation system. The primary concerns in conducting the two flow tests are (1) whether or not the range of the actuator-mounted deformation measuring system is sufficient to obtain flow and (2) whether or not the resolution is adequate to allow detection of flow through numerical differentiation of the strain versus time curve. A minimum range of 12 mm (0.5 in.) and resolution of 0.0025 mm (0.00001 in.) was included in the first-article specifications.

The second deformation measuring system is a specimen-mounted system used in the dynamic modulus test. The system specified in the first-article specifications differs from that described in the Project 9-19 test protocols in two ways. First, the gauge length was reduced from 100 mm (4 in.) to 70 mm

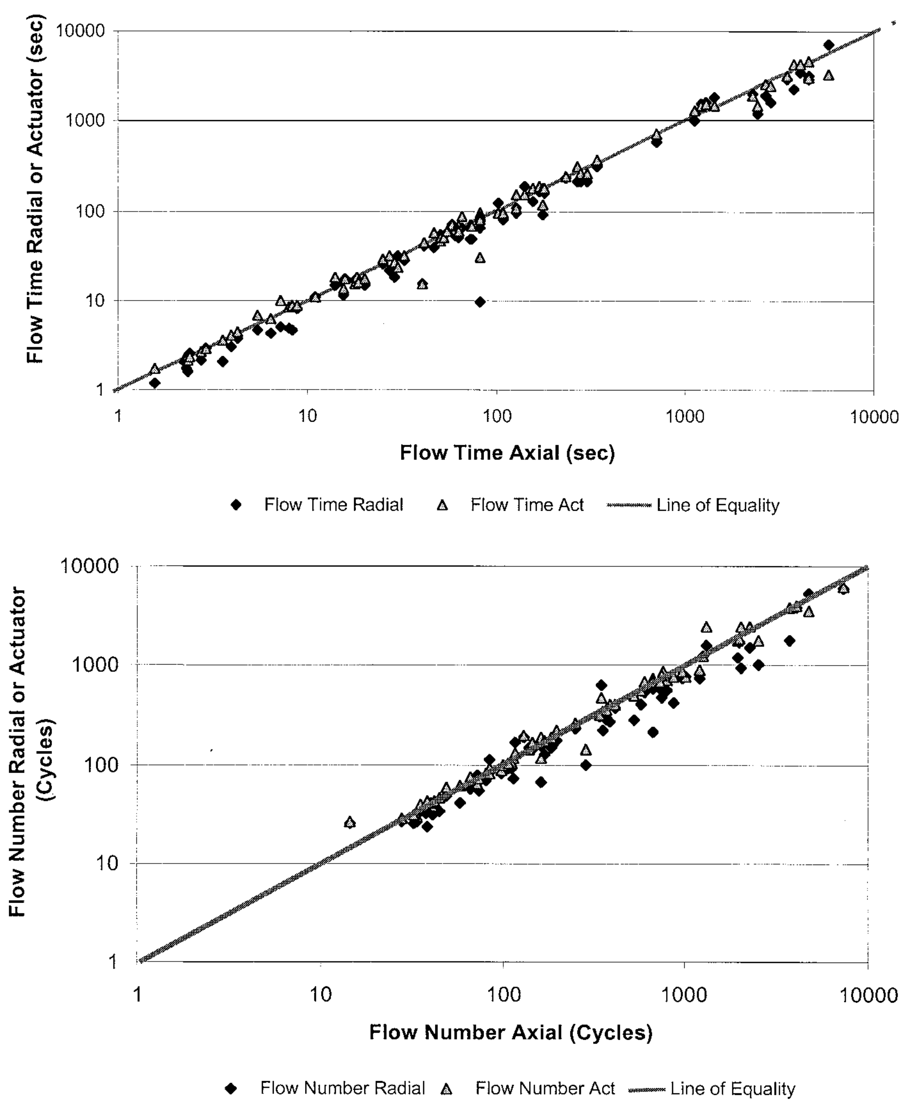


Figure 5. Comparison of flow from different instrumentation systems (5).

(2.75 in.). The shorter gauge length was specified for the simple performance test system in an attempt to reduce variability caused by the instrumentation being mounted close to the ends of specimens with ends that are not perfectly smooth and parallel. In Phase I, measurements on a large number of specimens showed that some of the specimen dimensional tolerances included in the Project 9-19 test protocols could not be achieved with standard laboratory saws and drills. The tolerances in the Project 9-19 test protocols were based on those presented in AASHTO T231(*6*) for capping concrete cylinders. The revised tolerances listed in Table 4 were recommended and incorporated in the first-article specifications for an automated sawing and coring device. The use of a shorter gauge length in the dynamic modulus test is supported by the findings of a large specimen size and geometry study conducted as part of Project 9-19 (*7*). This study concluded that 70-mm (2.75-in.) diameter specimens with 70-mm (2.75-in.) gauge length could be used to measure the dynamic modulus of mixtures with nominal maximum aggregate sizes up to 37.5 mm.

The second difference between the first-article specifications and the Project 9-19 test protocols is the first-article specifications do not require the specific mounting system shown in the Project 9-19 test protocols *(1)*, although the Project 9-19 mounting system can meet the requirements of the first-article specifications. This change was made to encourage the consideration by equipment manufacturers of alternative mounting systems that may simplify the equipment and technician skill level required to perform the dynamic modulus test. To further encourage simplification of the instrumentation and the possible use of noncontact sensors, the first-article specifications require rapid installation of the specimen-mounted measuring system so that specimen instrumentation, installation in the testing machine, application of confining pressure, and temperature equilibration can be completed in 3 minutes. Other requirements of the specimen-mounted deformation measuring system are listed in Table 5.

2.1.5 Confining Pressure

The simple performance test system includes a confining pressure system for performing the tests with confinement. Table 6 summarizes the requirements of the confining pressure system. As discussed in the previous section, a time limit of 3 minutes for specimen instrumentation, installation, application of confining pressure, and temperature equilibrium was included in the first-article specifications to encourage manufacturers to use automated pressure cells.

2.1.6 Environmental Chamber

The simple performance test system includes modest environmental control over a temperature range from 20 to 60 °C. This temperature range is based on the Project 9-19 recom-

TABLE 4 Project 9-29 specimen dimension tolerances

Item	Specification	Remarks
Average Diameter	100 mm to 104 mm	
Standard Deviation of Diameter	1.0 mm	See note 1
Height	147.5 mm to 152.5 mm	
End Flatness	0.3 mm	See note 2
End Parallelism	1 degree	See note 3

Notes:

1. Measure the diameter at the center and third points of the test specimen along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 1.0 mm. The average diameter, reported to the nearest 1 mm, shall be used in all material property calculations.

2. Check this requirement using a straight edge and feeler gauges.

3. Check this requirement using a machinist's square and feeler gauges.

TABLE 5 Specimen-mounted deformation measuring system requirements

Item	Requirement
Number of Transducers	≥ 2
Gauge Length and Position	70 mm (2.75 in.) over middle of specimen
Range	≥ 1 mm (0.04 in.)
Resolution	≤ 0.0002 mm (7.8 micro-inch)
Accuracy	Error ≤ 0.0025 mm (0.0001 in.) when verified in accordance with ASTM D 6027 *(8)*.
Installation	≤ 3 min to install instrumentation, insert specimen, apply confining pressure, and obtain temperature equilibrium.

TABLE 6 Confining pressure system requirements

Item	Requirement
Maximum Pressure	210 kPa (30 psi)
Control	± 2.0 percent
Pressure Sensor Resolution	0.5 kPa (0.07 psi)
Pressure Sensor Accuracy	Error ≤ 1 percent when verified in accordance with ASTM D 5720 *(9).*
Operation	≤ 3 min to install instrumentation, insert specimen, apply confining pressure and obtain temperature equilibrium.

mendation that the simple performance tests for permanent deformation and fatigue cracking be conducted at the effective temperatures for these distresses as defined by Equations 4 and 5 (*10*).

$$T_{eff}(PD) = 30.8 - 0.12Z_{cr} + 0.92(MAAT + K_{\alpha}\sigma_{MAAT}) \qquad (4)$$

where

$T_{eff}(PD)$ = effective temperature in °C for permanent deformation
Z_{cr} = critical depth in mm for the mix layer in question
MAAT = mean annual air temperature in °C
K_{α} = value computed from normal probability table related to designers selected level of reliability.
σ_{MAAT} = standard deviation of the mean annual air temperature.

$$T_{eff}(FC) = 0.8(MAPT) - 2.7 \qquad (5)$$

where

$T_{eff}(FC)$ = effective temperature in °C for fatigue cracking
MAPT = mean annual pavement temperature in °C at one third of the depth of the pavement layer

For the United States, the effective temperature for permanent deformation ranges from 25 to 55 °C and the effective temperature for fatigue cracking ranges from 12 to 20 °C.

Table 7 summarizes the requirements of the environmental chamber. As discussed in previous sections, a time limit of 3 minutes for specimen instrumentation, installation, application of confining pressure, and temperature equilibrium was included in the first-article specifications to encourage manufacturers to use environmental chambers with sufficient capacity to reach equilibrium quickly.

2.1.7 Computer Control and Data Acquisition

Computer control and electronic data acquisition were specified for the simple performance test system. The first-article specifications require the control software to include logic that prompts the user through each of the tests. The software includes on-line help and allows the user to choose either SI or US Customary units. For each of the simple performance tests, the first-article specifications include requirements on the following:

- **Test control:** the sequence of operations, parameters to be controlled during the test and their tolerances, and actions to be taken if control parameter tolerances are exceeded;
- **Data acquisition:** data to be acquired and sampling rates;
- **Operator input:** test identification information, test control information, and remarks; and
- **Data storage and output:** format for data files and hard copy reports.

The first-article specifications also require real-time graphical display of information that will be useful to the operator. Displays for the flow time test include time histories of stress, strain, and the rate of strain. The flow number test includes a digital oscilloscope for real-time display of stress and strain as a function of time and histories of the peak stress, permanent strain, and permanent strain rate as a function of the number of load cycles. Finally, the dynamic modulus test

TABLE 7 Environmental chamber requirements

Item	Requirement
Range	20 to 60 °C (68 to 140 °F) when ambient temperature is between 15 and 27 °C (60 to 80 °F)
Control	± 0.5 °C (1 °F)
Resolution	± 0.25 °C (0.5 °F)
Accuracy	± 0.25 °C (0.5 °F)
Location of Sensor	Within 25 mm (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.

includes a digital oscilloscope for real-time display of the stress and strain measured during the test.

2.1.8 Computations

The first-article specifications provide detailed algorithms for computation of the flow time, flow number, and dynamic modulus. The algorithms are much more specific than the general descriptions for data analysis included in the Project 9-19 test protocols (*1*). Important computational issues are summarized below for the three tests.

2.1.8.1 Flow Time

The flow time is defined as the time corresponding to the minimum rate of change of axial strain during a creep test. The computational procedure for the flow time included in the first-article specifications includes three steps: (1) numerical calculation of the creep rate; (2) smoothing of the creep rate data; and (3) identification of the point at which the minimum creep rate occurs as the flow time. The numerical calculation of the creep rate uses a simple finite difference calculation using data one sampling point ahead and one sampling point behind the point of interest. Smoothing of the creep rate is done using a five-point moving average filer. Finally, the flow time is reported as the time at which the minimum value of the smoothed creep rate occurs. If there is no minimum, then the flow time is reported as being greater than or equal to the length of the test. If more than one point shares the minimum creep rate, the first such minimum is reported as the flow time. Details of the calculations are included in the first-article specifications in Appendix A.

2.1.8.2 Flow Number

The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test. The computational procedure for the flow number included in the first-article specifications is the same as that for the flow time, except the derivatives are taken with respect to the number of load cycles instead of with respect to time. The same smoothing and reporting as described above for the flow time is used with the flow number.

2.1.8.3 Dynamic Modulus

The dynamic modulus test data is the most complex data to analyze. The material properties computed from this test are the dynamic modulus, |E*|, which is a measure of the material stiffness, and the phase angle, δ, which is a measure of the viscous properties of the material. Various methods are available for reducing data collected during the dynamic modulus test and computing the material properties. These include peak search algorithms, Fourier transform, and regression. The approach included in the first-article specifications is the regression approach (*11*). Regression was used because it is a relatively simple, direct approach that most engineers and technicians in the paving industry can understand and apply. This approach also lends itself to the computation of data quality measures, which can be used in evaluating the reliability of test data. A step-by-step description of the regression approach is included in the first-article specifications in Appendix A. This approach is general and can be adapted to any number of specimen deformation transducers.

In addition to the dynamic modulus and phase angle, the computations described in the first-article specification include four measures of data quality. As experience is gained with the dynamic modulus test, these data quality measures will be useful to engineers and test technicians in identifying the reliability of test data. The four data quality measures are described briefly below.

1. **Standard Error of the Load.** The standard error of the load is a measure of how well the applied loading approximates a sine wave. It is calculated from the difference between the measured data and the best-fit sine wave using Equation 6. High values of standard error indicate poor sinusoidal loading, and such data should not be used for computing viscoelastic material properties. The first-article specification limits the standard error of the load to 5 percent.

$$se(P) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n-1}}\left(\frac{100\%}{\hat{x}_o}\right) \tag{6}$$

where

se(P) = Standard error of the applied load
x_i = Measured load at point *i*
$\hat{x}_i$ = Predicted load at point *i* from the best fit sinusoid
$\hat{x}_o$ = Amplitude of the best fit sinusoid
n = Total number of data points collected during test.

2. **Standard Error of the Deformations.** The standard error of the deformations is a measure of how well the specimen response approximates a sine wave. It is calculated individually for each deformation sensor using Equation 7, then averaged over the number of deformation sensors. High values of deformation standard error indicate poor specimen response or high amounts of signal noise. Such data should not be used for the computation of viscoelastic material properties.

$$se(Y_j) = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_{ji} - Y_{ji}\right)^2}{n-1}}\left(\frac{100\%}{\left|Y_j^*\right|}\right) \quad (7)$$

where

$se(Y_j)$ = Standard error for transducer j, %
$|Y_j^*|$ = Amplitude for transducer j
$\hat{Y}_{ji}$ = Predicted response for transducer j at point i
Y_{ji} = Measured response for transducer j at point i.

3. **Uniformity Coefficient for the Deformation Amplitude.** This parameter is a measure of the difference in deformations on the same specimen by the various deformation transducers. It is defined as the coefficient of variation of the deformation amplitudes measured by the individual transducers. Large differences in deformation measured on the same sample indicate suspect data. These differences may be caused by poor transducer mounting, poor specimen end preparation, a faulty transducer, and inherent variability in the specimen.
4. **Uniformity Coefficient for the Phase Angle.** This parameter is a measure of the difference in phase angle measured on the same specimen by the various deformation transducers. It is defined as the standard deviation of the phase angles measured by the individual transducers. Large differences in phase angle measured on the same specimen indicate suspect data. These differences may be caused by poor transducer mounting, poor specimen end preparation, a faulty transducer, and inherent variability in the specimen.

Values of the data quality measures for good and poor quality data were not available before the laboratory testing phase of Project 9-29. The specification requirement that the machines be capable of operating with a load standard error of 5 percent or less was based on discussions with equipment manufacturers. An analysis of the data quality measures collected during the laboratory evaluation is included in Section 2.3 of this chapter.

2.1.9 Calibration

The first-article specifications address both static and dynamic calibration of the simple performance test system. The specifications require the device to have a calibration mode and clearly marked access points for calibration by third-party services. The static calibration requirements and methods are summarized in Table 8. Neither AASHTO nor ASTM has a standard method for verification of temperature calibration. The first-article specifications include a method that uses a National Institutes of Standards and Technology (NIST) traceable thermal detector to compare temperatures measured with this device and the simple performance test system temperature sensor at six temperatures over the range of the environmental chamber.

Dynamic calibration is also not addressed by current AASHTO or ASTM methods. The first-article specifications require a verification of dynamic performance to be performed after static calibration is complete. The approach is similar to that described in the laboratory start-up procedure for the Long Term Pavement Performance (LTPP) resilient modulus testing (*12*). This verification involves loading an elastic device, such as a proving ring, under static and dynamic conditions and recording loads and deformations. The first-article specifications require static and dynamic measurements to agree to within 2 percent and the phase angle between load and displacements be less than 1 degree.

2.1.10 Documentation and Warranty

The first-article specifications include requirements for online and hard copy documentation. The specifications also include a 1-year warranty period for the first-article devices.

TABLE 8 Static calibration requirements

Subsystem	Requirements	Method
Load	Range: 0.2 to 10 kN (0.04 to 2.25 kips)	ASTM E4
	Resolution: ≤ 2 N (0.4 lb)	
	Accuracy: error ≤ 1 percent	
Actuator Mounted Deformation	Range: 12 mm (0.5 in.)	ASTM D 6027
	Resolution: ≤ 0.0025 mm (0.0001 in.)	
	Accuracy: error ≤ 0.03 mm (0.001 in.)	
Specimen-Mounted Deformation	Range: 1 mm (0.04 in.)	ASTM D 6027
	Resolution: ≤ 0.0002 mm (7.8 micro inch)	
	Accuracy: error ≤ 0.0025 mm (0.0001 in.)	
Confining Pressure	Range: 35 to 210 kPa (5 to 30 psi)	ASTM D 5720
	Resolution: ≤ 0.5 kPa (0.07 psi)	
	Accuracy: error ≤ 1 percent	
Temperature	Range: 20 to 60 °C (68 to 140 °F)	NIST traceable sensor readable and accurate to 0.1 °C (0.2 °F)
	Resolution: ≤ 0.25 °C (0.5 °F)	
	Accuracy: ≤ 0.25 °C (0.5 °F)	

2.2 FIRST-ARTICLE EQUIPMENT

2.2.1 Background

A key component of NCHRP Project 9-29 was the involvement of equipment manufacturers early in the specification development process. Equipment manufacturers were asked to review and comment on the draft specifications developed by the research team. Thirteen equipment manufacturers were provided the draft specifications developed during Phase I of the project. Ten of those manufacturers also attended the manufacturers' workshop held on July 30, 2001. At this workshop, the draft equipment specifications were reviewed in detail with the manufacturers. Comments from the manufacturers were then incorporated in the First-Article Equipment Specification for the Simple Performance Test System. Table 9 lists the manufacturers who participated in the development of the first-article equipment specifications.

2.2.2 Request For Proposals

A request for proposals (RFP) for the Simple Performance Test System was issued on November 12, 2001, to the 13 manufacturers listed in Table 9. The RFP required the manufacturers to provide information on their capabilities, a detailed description of their proposed simple performance test system, and information on pricing for the first-article and subsequent production units. The following four manufacturers submitted proposals in response to the RFP:

1. EnduraTec
2. Instron Corporation
3. Interlaken Technology Corporation
4. Shedworks, Inc.

MTS Systems Corporation, and James Cox and Sons, Inc., responded that they could provide equipment to meet the specification, but declined to propose. Both companies indicated that they intended to monitor the market and might be interested in providing equipment in the future.

2.2.3 Proposal Evaluation Process

This section summarizes the evaluation of the four proposals for the Simple Performance Test System. The four proposals were evaluated by five senior members of the research team. The evaluation panel and their particular areas of expertise relevant to the evaluation are summarized in Table 10.

The proposals were evaluated independently by each panel member based on the criteria presented in Table 11. The first criteria addressed the first-article specification requirements. The RFP requested that the manufacturers describe their equipment in sufficient detail to document that the proposed equipment met the requirements of the first-article specification. The second criteria addressed advantages of the equipment in the areas of user-friendliness and reliability. The RFP informed the manufacturers that the primary use of the equip-

TABLE 9 Equipment manufacturers

Manufacturer	Address	Phone	Contact	Workshop
Bohlin Instruments, Inc.	1004 Eastpark Blvd. Cranbury, NJ 08612	(609) 655-447	John Casola	Yes
EnduraTec Systems Corporation	5610 Rowland Road Minnetonka, MN 55343	(612) 933-7742	Kent Vilendrer	Yes
Instron Corporation	100 Royall Street Canton, MA 02021-1089	(800) 564-8378	Anatoly Perlov	Yes
Interlaken Technology Corporation	7600 Golden Triangle Drive Eden Prairie, MN 55344	(612) 942-7499	Tom Driggers	Yes
ShedWorks Inc. Industrial Process Controls, LTD	1501 FM 2818, Suite 320 College Station, TX 77840	(979) 695-8416	Bill Crockford	Yes
James Cox and Sons, Inc.	1085 Alpine Way Colfax, CA 95713	(530) 346-8322	Jim Cox	No
MTS Systems Corporation	14000 Technology Drive Eden Prairie, MN 55344	(952) 937-4000	Scott Johnson	Yes
Pavement Technology, Inc.	P.O. Box 1184 Covington, GA 30015	(770) 388-0909	Ron Collins	Yes
Pine Instrument Company	101 Industrial Drive Grove City, PA 16127	(724) 458-6391	Frank Dalton	Yes
Precision Machine and Welding	2231 D1 Centennial Road Salina, KS 67401	(785) 823-8760	Jeff Harris	Yes
Rainhart Company	604 Williams Street Austin, TX 78752	(512) 452-8848	Ray Alexander	No
Test Quip, Inc.	105 Old Highway 8, Suite 4 New Brighton, MN 55112	(651) 636-5510	Tom Brovold	No
Troxler Electronic Laboratories, Inc.	3008 Cornwallis Road Research Triangle Park, NC 27709	(919) 549-8661	Mike Bienvenu	Yes

TABLE 10 **Evaluation panel and expertise**

Member	Expertise
Dr. Ramon Bonaquist, Principal Investigator	Mechanical property characterization
Dr. Donald Christensen, Senior Engineer	Mechanical property characterization
Mr. Kevin Knechtel, Laboratory Manager	Mixture design, equipment operation
Mr. Donald Jack, Chief Engineering Technician	Mixture design, equipment operation
Mr. William Stump, Co-Principal Investigator	Testing equipment calibration

ment would be routine specification compliance testing by technicians in state highway agency, hot-mix producer, and consultant testing laboratories. The third criteria addressed the cost of the proposed system. As part of their proposal, the manufacturers were asked to provide a firm fixed price for the first-article equipment and estimates of the cost of future production units. Finally, the fourth criteria addressed the capabilities and experience of the manufacturer. Of particular interest was documentation of the results of past prototype development projects.

Each panel member was also asked to provide written comments and a recommendation of the two manufacturers who should be awarded contracts for the first-article equipment. A meeting to reconcile differences between evaluation panel ratings was planned, but was not required because of the consistency of the initial ratings.

2.2.4 Proposal Evaluation Results

Three of the four manufacturers: EnduraTec, Interlaken, and Shedworks, proposed relatively compact equipment specifically designed to perform the three simple performance tests. The Instron proposal was essentially an assembly of standard and optional components for a general purpose load frame with customized software to perform the three simple performance tests. The similarities in the designs provided by EnduraTec, Interlaken, and Shedworks were striking. All proposed fairly compact bottom-loading equipment with a chamber that is both a pressure cell and temperature control chamber. They also proposed automatic or semi-automatic methods for opening the vessel for insertion of the test specimen. The primary differences in the designs were the loading system, the specimen deformation measuring systems, and the temperature control system.

The results of the evaluation are summarized in Table 12. Although there are significant differences between evaluators in scores on individual criteria, there was overall agreement on the two highest ranking proposals. Additionally, the evaluators unanimously recommended that the Interlaken and Shedworks designs be selected for the first-article equipment. These two proposals were rated near the highest by all evaluators on all of the evaluation criteria. The sections below summarize key elements of the equipment proposed by each manufacturer.

2.2.4.1 Instron

The Instron approach was not well received by four of the five evaluators. The proposed approach offered some advantages for laboratories interested in using the equipment to perform a variety of tests in addition to the simple performance tests. The evaluators unanimously agreed that evaluation of this type of equipment would not provide significant benefit to future efforts to implement the simple performance tests. Although the cost of production units of this equipment, estimated by Instron at $65,000 to $70,000, is high for the market envisioned for the simple performance test, it suggests that equipment capable of performing the dynamic modulus master curves proposed by the Project 1-37A team for structural design may be available for approximately $100,000. A wider temperature range and higher load capacity than specified for the simple performance test are needed to perform the dynamic modulus test at the lower temperatures required for construction of master curves for structural design.

2.2.4.2 EnduraTec

EnduraTec proposed a very innovative design based on the linear motor technology that they have developed in cooperation with Bose Corporation. The linear motor is an electromagnet that operates using standard electrical power available in all laboratories and has the potential to be very reliable and require minimal maintenance. Apparently this technology is not capable of providing both static and dynamic loads; therefore, the design included a pneumatic actuator and

TABLE 11 **Evaluation criteria**

Criteria	Weight
Ability of Proposed Equipment to Meet the Specification Requirements	30
Advantages of the Proposed Equipment	30
Cost of First-Article Equipment and Production Units	20
Capabilities and Experience of the Manufacturer	20

TABLE 12 Summary of evaluation

Maximum Score		300	300	200	200	1000	
Manufacturer	**Evaluator**	**Ability of Proposed Equipment to Meet the Specification Requirements**	**Advantages of the Proposed Equipment**	**Cost of First Article Equipment and Production Units**	**Capabilities and Experience of the Manufacturer**	**Total**	**Recommeded Manufacturers**
EnduraTec	Bonaquist	150	270	100	160	680	
	Christensen	201	219	106	152	678	
	Knechtel	240	150	80	80	550	
	Jack	300	150	60	100	610	
	Stump	240	240	60	200	740	
	Average	**226**	**206**	**81**	**138**	**652**	
Instron	Bonaquist	240	60	100	100	500	
	Christensen	285	219	88	152	744	
	Knechtel	150	30	20	60	260	
	Jack	150	0	100	100	350	
	Stump	120	120	80	160	480	
	Average	**189**	**86**	**78**	**114**	**467**	
Interlaken	Bonaquist	180	270	160	140	750	**X**
	Christensen	252	228	142	156	778	**X**
	Knechtel	240	240	180	100	760	**X**
	Jack	300	150	180	200	830	**X**
	Stump	180	300	160	200	840	**X**
	Average	**230**	**238**	**164**	**159**	**792**	
Shedworks	Bonaquist	240	240	200	180	860	**X**
	Christensen	225	210	200	144	779	**X**
	Knechtel	240	210	180	180	810	**X**
	Jack	300	150	200	200	850	**X**
	Stump	300	240	200	200	940	**X**
	Average	**261**	**210**	**196**	**181**	**848**	

a load-sharing mechanism to provide the haversine loading required by the dynamic modulus and flow number tests and the static loading required by the flow time test. Three of the evaluators were concerned about whether this system could be controlled within the tolerances specified, and EnduraTec provided no data to support their claim that it could. EnduraTec also proposed an innovative temperature control system. The system uses heating bands to provide heat, a solid-state thermoelectric cooling (Peltier) device for cooling, and an internal circulating fan. Again, no data were provided to support the claim that the system could reach the specified temperature in the 3-minute time limit and control temperatures within the tolerances specified. The combined pressure vessel and environmental chamber has a locking flange to facilitate specimen insertion and a counter balance to enable the chamber to be easily lifted. The specimen deformation system consisted of two strain gauge extensometers with unique spring-loaded holders to keep them in contact with the specimen. This specimen deformation system combined with the counterbalanced, locking flange vessel has the potential to greatly simplify specimen installation. Control of the entire system is provided through EnduraTec's standard WinTest Control system, programmed for the three applications. EnduraTec has had limited experience with asphalt testing equipment. They have attempted to market the Field Shear Test device and redesigned equipment in support of NCHRP Project 9-18. The EnduraTec proposal received low ratings primarily because of concerns about the loading and temperature control systems and the overall cost of the equipment. The cost of the first-article, at $89,480, was well above the Project 9-29 budget. EnduraTec's estimated cost of production units at $55,000 to $63,000, depending on the market size, is somewhat above the Project 9-29 target of $50,000.

2.2.4.3 Interlaken

Interlaken proposed a hydraulic-powered device that is a variation on two of their standard product lines: the Universal Soils and Asphalt Test System and the ServoPress, which is used for quality control in the metal-forming industry. The Interlaken Simple Performance Test System, shown in Figure 6, is a small self-contained unit that includes the actuator and testing fixture, hydraulic supply, system control electronics, and computer interface in a small bench that is on casters to provide mobility in the laboratory. The adaptation of proven reliable technology to the Simple Performance Test System is one of the reasons that the Interlaken proposal received high scores from all of the evaluators. In Interlaken's design, the combined pressure and temperature enclosure is automated using pneumatic cylinders to raise and lower the enclosure and latches to hold it in place during testing. Heating of the chamber is provided by an electrical resistance heater inside the enclosure. Cooling uses a heat exchanger inside the chamber that is cooled by a vortex chiller mounted outside of the enclosure. A small blower is included to provide circulation within the chamber. The use of an automated, combined pressure and temperature vessel greatly simplifies equipment operation.

Interlaken also proposed an automated system for measuring deformations in the dynamic modulus test. The system, shown in Figure 7, uses LVDTs that are mounted on guide brackets, and the brackets are pressed against the specimen by small pneumatic actuators. This specimen deformation system combined with the automated enclosure greatly simplifies specimen installation.

Control of the test system is provided through Interlaken's digital controller and their UniTest software programmed for the three specific applications. An interesting aspect of the Interlaken software is the ability to provide access levels to different users. Using this, a technician may be given only the ability to run an application. The laboratory manager, on the other hand, would have greater access and might be able to modify the control or data analysis.

The Interlaken system was selected for the adaptation of proven technology, user considerations in the design, the experience building asphalt testing equipment, and cost. The cost of the first-article at $49,900 was at the NCHRP Project 9-29 target of $50,000. It is interesting that Interlaken's estimated production unit costs remain within 10 percent of the first-article costs even for a very large number of units. This may be the result of cost savings already included in the first-article from the use of the same platform for the Simple Performance Test System and other standard product lines.

2.2.4.4 Shedworks

Shedworks proposed to provide a user-friendly system that is an improvement on the equipment used at the Arizona State University in Project 9-19. The Shedworks Simple Performance Test System is a hydraulic powered unit that is a variation of their compact, automated rapid triaxial test equipment. The unit, shown in Figure 8, includes two separate parts: a hydraulic power supply and the simple performance test equipment. The system is controlled by Industrial Process Controls' (IPC's) control and data acquisition system (CDAS2) that has already been programmed for the three simple performance test applications.

Figure 6. Overview of Interlaken simple performance test system.

Figure 7. Interlaken dynamic modulus test instrumentation.

The Shedworks Simple Performance Test System includes a combined pressure and temperature chamber that is automatically lifted and lowered to facilitate installation of the specimens. The unique concept proposed by Shedworks is to control the temperature inside the chamber by supplying air at the required temperature. The system uses a refrigerated dryer to produce cool dry air that is then heated to the desired temperature with a process heater controlled by a sensor inside the cell. The use of thermally conditioned air for temperature control is an interesting concept that simplifies the equipment operation.

The Shedworks specimen deformation measuring system, shown in Figure 9, is an improvement on the system used in NCHRP Project 9-19. It uses three LVDTs spaced equally around the circumference of the specimen. The LVDTs are held by a unique clip holder that allows rapid attachment of the LVDTs. Figure 9 shows an LVDT attached to the specimen. The holder attaches to small disks that are glued to the specimen prior to conditioning them to the test temperature. The Shedworks Simple Performance Tester includes the device shown in Figure 10 to accurately position the glue-on disks on the specimen.

The Shedworks system was selected for their adaptation of proven technology, user considerations in their design, and their experience building asphalt testing equipment, particularly that used by the Arizona State University in Project 9-19 and cost. The cost of the first-article at $39,000 was well below the NCHRP Project 9-19 budget. The estimated cost

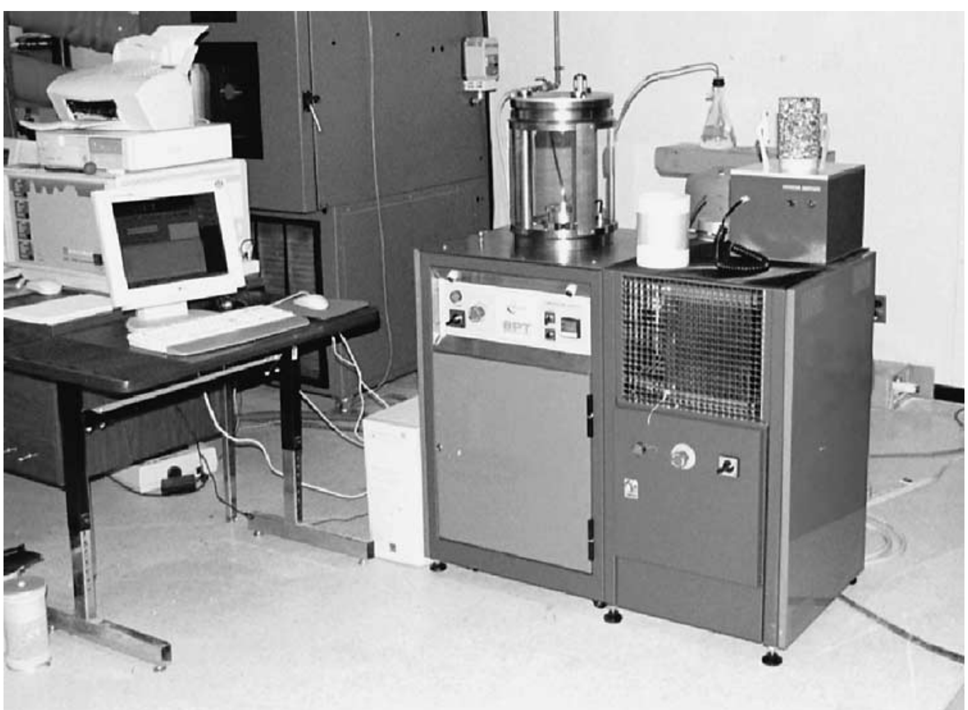


Figure 8. Shedworks simple performance test system.

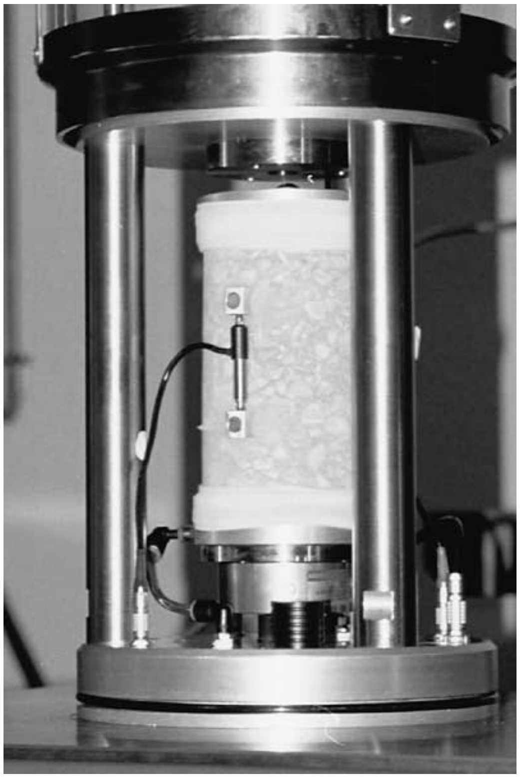


Figure 9. Shedworks dynamic modulus test instrumentation.

of production units at $25,000 is also well below the NCHRP Project 9-19 target of $50,000.

2.3 FIRST-ARTICLE EQUIPMENT EVALUATION

The evaluation of the first-article equipment had several objectives. The first was to assess the specific equipment procured in Phase II of the project, make recommendations concerning the acceptability of this equipment to perform the specified testing, and evaluate the functionality of the equipment for use in routine laboratory testing. The second objective was to evaluate the repeatability and reproducibility of material properties measured with equipment manufactured to the same specification by two vendors and to compare that with data from two laboratories. The third objective was to identify possible revisions to the first-article equipment specification that will enhance the functionality of future equipment or reduce variability in measured material properties. Finally, the fourth objective was to identify possible revisions to the Project 9-19 Draft Test Protocols to simplify testing and reduce variability in measured material properties. To accomplish these objectives, the first-article equipment evaluation included two major components: specification compliance testing and mixture testing.

The specification compliance tests were developed to document that the equipment meets the requirements of the first-article specifications. The tests were included in the first-article specification and successful completion of these tests was a requirement of the purchase orders issued to Interlaken and Shedworks. The objective of the mixture component of the first-article evaluation was to evaluate the repeatability and reproducibility of material properties measured with equipment manufactured to the same specification by two vendors. Given that this component involved the preparation and testing of a large number of specimens, the functionality, and to a certain degree, the durability of the equipment was also evaluated. Finally, this component of the first-article evaluation provided the opportunity for the evaluation of the Project 9-19 test protocols by practicing technicians.

2.3.1 Specification Compliance Testing

Authorization to proceed with fabrication of the Simple Performance Test System was given to Interlaken and Shedworks on January 18, 2002. Both systems were completed and delivered within the specified time frame. The Shedworks device was completed first and delivered to Advanced Asphalt Technologies' (AAT's) laboratory on July 10. The Interlaken device was delivered to the FHWA Turner-Fairbank Highway Research Center on July 22. Upon delivery, representatives of the manufacturers set up the equipment and participated in the specification compliance testing, which was designed to verify that the equipment met the specification requirements. Table 13 summarizes the items included in the specification compliance testing.

The specification compliance testing for the Shedworks device was performed from July 15 through July 19. The equipment was found to be in compliance with the specification. Some minor software issues were noted. Shedworks provided revised software addressing the software issues before the start of the evaluation testing in November, 2002.

The specification compliance testing for the Interlaken device was initially performed from July 23 through July 26. The equipment failed several of the specification compliance tests. Table 14 presents a summary of the deficiencies initially found in the Interlaken equipment. The research team worked with representatives of Interlaken throughout August and early September to resolve these deficiencies. Representatives from Interlaken visited the Turner-Fairbank Highway Research Center twice during this period to make substantial changes to the hardware and software. Interlaken completed resolution of the deficiencies on September 13, 2002, and on September 16 and 17, the research team verified that the equipment met all of the specification compliance tests.

Figure 10. Shedworks glue-on gauge point system.

2.3.2 Mixture Testing

2.3.2.1 Experimental Design

Although the first-article simple performance devices are capable of performing three tests (i.e., dynamic modulus, flow number, and flow time), only two of these tests were included in the mixture testing component of the evaluation because of budget constraints. The dynamic modulus and flow number were the tests selected for evaluation because these were the two tests for which criteria differentiating between good and poor performance were being developed in Project 9-19. Research in Project 9-19 found a good correlation between flow number and flow time, allowing flow time to be used as a surrogate test for flow number, but the criteria differentiating between good and poor performance will be based on the flow number test and the performance of in-service sections.

Tables 15 and 16 present the experimental design for the dynamic modulus and flow number tests. Data for the two simple performance test devices were collected in two laboratories (AAT and FHWA) on two mixtures (9.5 mm and 19.0 mm). Eight independent tests were included in each cell to provide sufficient replication to evaluate differences in means and differences in variances between devices, laboratories, and testing conditions. The dynamic modulus tests were conducted for three conditions selected to exercise the range of the equipment capabilities:

- Unconfined dynamic modulus at 25 °C, a representative condition for evaluating mixtures for fatigue cracking potential;
- Unconfined dynamic modulus at 45 °C, a representative condition for evaluating mixtures for rutting potential; and
- Confined dynamic modulus at 45 °C, a representative condition for possibly evaluating open- or gap-graded mixtures for rutting potential.

The flow number was evaluated only at 45 °C for unconfined and confined conditions. The levels of confinement and deviatoric stress were selected to provide a relatively short test, fewer than 1000 cycles, and a relatively long test, greater than 5000 cycles.

2.3.2.2 Mixtures

Two mixtures that exhibited different levels of variability in mechanical properties when tested in NCHRP Project 9-18,

TABLE 13 Summary of specification compliance tests

Item	Specification Section	Method
Assembled Size	4.4 & 4.6	Measure
Specimen and Display Height	4.4	Measure
Component Size	4.7	Measure
Electrical Requirements	4.5 & 4.6	Documentation and trial
Air Supply Requirements	4.8	Documentation and trial
Limit Protection	4.9	Documentation and trial
Emergency Stop	4.10	Documentation, visual inspection, trial
Loading Machine Capacity	5.1	Independent force verification
Load Control Capability	5.2 - 5.4	Trial tests on asphalt specimens and manufacturer provided dynamic verification device.
Platen Configuration	5.5	Visual
Platen Hardness	6.1	Test ASTM E10
Platen Dimensions	6.2	Measure
Platen Smoothness	6.3	Measure
Load Cell Range	7.1	Load cell data plate
Load Accuracy	7.2	Independent force verification
Load Resolution	7.3	Independent force verification
Configuration of Deflection Measuring System	8.1	Visual
Transducer Range	8.2	Independent deflection verification
Transducer Resolution	8.3	Independent deflection verification
Transducer Accuracy	8.4	Independent deflection verification
Load Mechanism Compliance and Bending	8.5	Measure on steel specimens with various degrees of lack of parallelism
Configuration of Specimen Deformation Measuring System	9.1	Visual
Gauge Length of Specimen Deformation Measuring System	9.1	Measure
Transducer Range	9.2	Independent deflection verification
Transducer Resolution	9.3	Independent deflection verification
Transducer Accuracy	9.4	Independent deflection verification
Specimen Deformation System Complexity	9.5	Trial
Confining Pressure Range	10.1 & 10.5	Independent pressure verification
Confining Pressure Control	10.2	Trial tests on asphalt specimens
Confining Pressure System Configuration	10.3 & 10.4	Visual
Confining Pressure Resolution and Accuracy	10.5	Independent pressure verification
Temperature Sensor	10.6 & 11.4	Independent temperature verification
Specimen Installation and Equilibration Time	9.5, 10.7 & 11.3	Trial
Environmental Chamber Range and Control	11.1	Independent temperature verification
Control System and Software	12	Trial
Data Analysis	13	Independent computations on trial test
Initial Calibration and Dynamic Performance Verification	14	Certification and independent verification
Calibration Mode	14.6	Trial
Verification of Normal Operation Procedures and Equipment	15	Review
On-line Documentation	16.1	Trial
Reference Manual	16.2	Review

"Field Shear Test for Hot-Mix Asphalt," were used in the evaluation testing. The first was a 9.5 mm mixture with low variability, having a shear modulus coefficient of variation of approximately 5 percent when tested in NCHRP Project 9-18 (*13*). The second was a 19.0 mm mixture that had a shear modulus coefficient of variation of approximately 17 percent (*13*). Volumetric properties for the mixtures are provided in Table 17. Both are coarse-graded Superpave mixtures. The 9.5 mm mixture was made with limestone coarse and fine aggregates. Granite aggregates were used in the 19.0 mm mixtures. Both mixtures were made with the same PG 64-22 binder. AASHTO M320 properties for the binder are summarized in Table 18.

TABLE 14 Summary of initial specification test deficiencies for the Interlaken equipment

Item	Section	Deficiency
Electrical and Pressure Documentation	4.0	Label plates documenting electrical and pressure requirements not provided.
Compression Loading Machine	5.0	The proposed system provides only the parallel platen arrangement. A ball or swivel joint is require for the Dynamic Modulus Test
Specimen Deformation Measuring System	9.0	The proposed system does not always attach properly to asphalt specimens. Transducers often went out of range due to slippage during the attachment process.
Confining Pressure System	10.0	Installation of the specimen membrane is difficult. There is not enough space behind the specimen to install the membrane and the technician can not see the membrane to ensure proper seal. This combined with slow temperature response results in equipment exceeding 3 minute specimen installation requirement.
Environmental Chamber	11.0	1. The environmental chamber was not able to return to the specified temperature within 3 minutes over the complete range of 20 to 60 °C. 2. The temperature sensor was not mounted within 25 mm of the test specimen. During the specification compliance testing, it was bent to meet the specification
Flow Time Test Control and Data Acquisition	12.3	Unable to demonstrate that this test could be performed as described. Deficiencies that were noted included failure to zero strain at the start of the test and improper computation of creep rate.
Flow Number Test Control and Data Acquisition	12.4	Unable to demonstrate that this test could be performed as described.
Calibration and Verification of Dynamic Performance	14.0	Certificate of calibration not provided. Unable to verify dynamic performance. Errors may be associated with non-linearity in the verification device.
Documentation	16.0	Operations manual that was provided is incomplete. It does not address all items listed in Section 16.2.

2.3.2.3 Laboratory Methods

Preparation and testing of the simple performance tests specimens was performed in accordance with the Project 9-19 test protocols (*1*). Appendix B provides a detailed description of the laboratory methods.

The simple performance test specimens were prepared to a target air void content of 4.0 percent. First 150-mm diameter by 165-mm high gyratory specimens were prepared to air void contents of approximately 5.5 percent. From these, 100-mm diameter by 150-mm high specimens were cored and sawed using the portable core drilling machine shown in Figure 11 and the double-bladed saw shown in Figure 12. All coring and sawing was done using water to cool the cutting tools.

After all cutting was complete, the bulk specific gravity of the finished specimen was determined in accordance with

TABLE 15 Experimental design for dynamic modulus testing

			Dynamic Modulus and Phase Angle		
Device	Lab	Mix	Unconfined, 25 °C	Unconfined, 45 °C	Confined, 45 °C
Interlaken	AAT	9.5 mm	8	8	8
		19.0 mm	8	8	8
	FHWA	9.5 mm	8	8	8
		19.0 mm	8	8	8
Shedworks	AAT	9.5 mm	8	8	8
		19.0 mm	8	8	8
	FHWA	9.5 mm	8	8	8
		19.0 mm	8	8	8

TABLE 16 Experimental design for flow number testing

Device	Lab	Mix	Flow Number Unconfined, 45 °C	Flow Number Confined, 45 °C
Interlaken	AAT	9.5 mm	8	8
		19.0 mm	8	8
	FHWA	9.5 mm	8	8
		19.0 mm	8	8
Shedworks	AAT	9.5 mm	8	8
		19.0 mm	8	8
	FHWA	9.5 mm	8	8
		19.0 mm	8	8

AASHTO T166 by first measuring the immersed mass, then the saturated surface dry mass, and finally the dry mass. The cores were measured for compliance with the NCHRP Project 9-29 specimen tolerances, which are summarized in Table 19.

The dynamic modulus and flow number tests were performed with the simple performance test devices in accordance with the Project 9-19 test protocols (*1*). Test specimens were conditioned in a separate environmental chamber prior to testing. Dummy specimens with thermocouples were used to ensure that the test specimens were within the specified 0.5 °C tolerance of the target test temperature. The test chamber of the simple performance test device was also equilibrated to the target testing temperature. Once the specimens and the test chamber reached the target temperature, the specimens were removed from the separate environmental chamber, placed in the test chamber, and instrumented if required. The test chamber was then closed and allowed to equilibrate to the test temperature before the testing began.

The three dynamic modulus tests, 25 °C unconfined, 45 °C confined, and 45 °C unconfined, were performed on the same test specimen. For each condition, dynamic moduli and phase angles were measured at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. Stress levels were varied automatically by the simple performance testers to achieve a target strain level of 100 µstrain. A confining pressure of 138 kPa was used in the confined testing. Separate test specimens were used for each of the flow time tests. Table 20 summarizes the confining and deviatoric stresses used in the flow number testing for the two mixtures.

The evaluation testing program required fabrication and testing of 192 specimens. Sample fabrication and testing were split into two phases, as shown in Table 21. In the first phase, the Interlaken equipment was operated in the FHWA laboratory and the Shedworks equipment was operated in AAT's laboratory. In the second phase, the location of the equipment was switched. Each phase was divided into two blocks, and all of the testing for a given block in both laboratories was completed before the next block began. To allow reasonable productivity during specimen fabrication, the over-height gyratory specimens were fabricated on a regular schedule of four specimens per day. To minimize aging of the test specimens, the simple performance test specimens were sawed and cored from the over-height gyratory specimens when

TABLE 17 Volumetric properties of evaluation mixtures

Property	9.5 mm	19.0 mm
N_{design}	65	96
Coarse Aggregate Angularity One Face/ Two Face	100/100	100/100
Fine Aggregate Angularity	45.0	52.1
Flat & Elongated, % (Ratio 5 : 1)	1.6	1.9
Sand Equivalent, %	83	80
Binder Content, %	6.2%	4.4%
Gyratory Compaction, % Gmm		
N_{ini}	85.2%	85.9%
N_{des}	96.0%	95.8%
N_{max}	97.8%	97.2%
Voids in Mineral Aggregate (VMA), %	17.2	14.5
Voids in Total Mixture (VTM), %	4.0	4.2
Voids Filled with Asphalt (VFA), %	76.7	71.0
Fines to Effective Binder Ratio (F/A)	1.2	1.1
Gradation, % passing Sieve Size, mm		
37.5	100	100
25	100	100
19	100	94
12.5	100	73
9.5	97	52
4.75	62	33
2.36	42	24
1.18	27	17
0.6	18	14
0.3	11	10
0.15	8	6
0.075	6.8	3.6

TABLE 18 Binder properties for evaluation mixtures

Condition	Test	Method	Result
Unaged Asphalt	Specific Gravity at 25 °C	AASHTO T228	1.032
	Viscosity at 135 °C	ASTM D4402	0.38 Pa·s
	G*/sinδ at 10 rad/sec, 64 °C	AASHTO T515	1.58 kPa
RTFO Aged Residue	Mass Change, %	AASHTO T240	-0.32
	G*/sinδ, at 10 rad/sec, 64 °C	AASHTO T315	5.27 kPa
PAV Aged Residue	G*sinδ, at 10 rad/sec, 25 °C	AASHTO T315	2800 kPa
	Creep Stiffness, at 60 sec, -12 °C	AASHTO T313	138 MPa
	m-value at 60 sec, -12 °C	AASHTO T313	0.331

needed. All of the simple performance test specimens for a specific mixture for a block were cored, sawed, and measured at the same time. They were then distributed to the two laboratories based on their air void contents to obtain approximately the same average and range of air void contents.

2.3.3 Statistical Analysis

2.3.3.1 General

This section presents key findings from the statistical analysis of the mixture testing component of the first-article evaluation. The data collected during the first-article evaluation are presented in Appendix C. The primary objectives of the statistical analysis were as follows:

1. To evaluate the general overall quality and reasonableness of the data generated with the two devices under different conditions;
2. To evaluate the variability in the data and what differences in variability occur with different devices and test conditions; and
3. To evaluate significant differences in the mean response produced using the devices under different conditions.

The dynamic modulus and flow number experimental designs presented earlier represent analysis of variance experiments with four factors:

- Device (Two levels: Shedworks (IPC), Interlaken (ITC));
- Laboratory (Two levels: AAT and Federal Highway Administration (FHWA));
- Mixture (Two levels: 9.5-mm and 19-mm); and
- Test conditions (Dynamic modulus test, three levels: 25 °C unconfined, 45 °C unconfined, and 45 °C confined) (Flow number test, two levels: 45 °C unconfined and 45 °C confined)

Because it is well known that changes in temperature and confinement will produce substantial changes in the mechanical properties of asphalt concrete and because changes in temperature and confinement probably produce differences in variance that might render a statistical analysis invalid, the analysis was performed separately for each test condition. Thus, the experiment design for practical purposes involved a full 2^3 factorial, that is, an analysis of variance including three factors (i.e., device, laboratory, and mixture), each at two levels. Because one of the primary purposes of these experiments was to evaluate and compare the variances among the different factors, a large number of replicates was tested—eight for each cell. Thus each of the experiments included 64 independent measurements.

As will be seen in the following discussion, there were many cases where statistically significant differences in standard deviation occurred, depending on the specific test conditions. For this reason, analysis of variance techniques were not used in the analysis. This did not severely handicap the results, because the objectives of the analysis could just as easily be achieved by a combination of simple com-

Figure 11. Portable core drilling machine and stand.

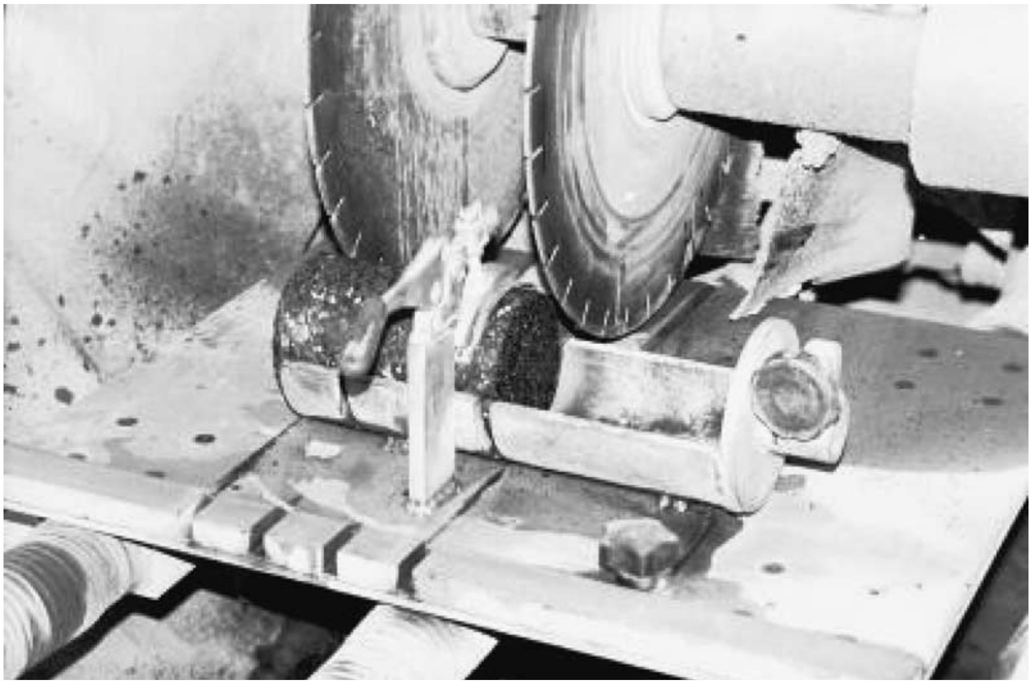


Figure 12. Double-bladed saw.

parisons between standard deviations and mean response values.

2.3.3.2 Dynamic Modulus

Each test in the dynamic modulus experiment included a frequency sweep using six frequencies: 25, 10, 5, 1, 0.5, and 0.1 Hz. Given that the responses at different frequencies tend to be similar and closely related, a rigorous statistical analysis was not performed at each frequency. Only the data from the 10, 1, and 0.1 Hz frequencies were included in the analysis. The analysis proceeded in the following order. First, various plots were constructed to observe general trends in the modulus and phase angle data. Second, a detailed analysis of the equality of variances between the various cells of the experiment was performed. This second step was critical to the selection of appropriate methods to evaluate differences in mean response. The third step was an analysis of differences in mean response for the two devices and laboratories.

TABLE 19 Project 9-29 specimen dimension tolerances

Item	Specification	Remarks
Average Diameter	100 mm to 104 mm	
Standard Deviation of Diameter	1.0 mm	See note 1
Height	147.5 mm to 152.5 mm	
End Flatness	0.3 mm	See note 2
End Parallelism	1 degree	See note 3

Notes:

1. Measure the diameter at the center and third points of the test specimen along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 1.0 mm. The average diameter, reported to the nearest 1 mm, shall be used in all material property calculations.
2. Check this requirement using a straight edge and feeler gauges.
3. Check this requirement using a machinist's square and feeler gauges.

TABLE 20 Flow number test conditions

Mixture	Condition	Deviatoric Stress, kPa	Confining Pressure, kPa
9.5 mm	Unconfined	400	0
9.5 mm	Confined	600	20
19.0 mm	Unconfined	600	0
19.0 mm	Confined	900	20

TABLE 21 Evaluation testing program

Phase	Block	Device	Lab	Mix	Dynamic Modulus			Flow Number	
					25 °C Unconfined	45 °C Confined	45 °C Unconfined	45 °C Unconfined	45 °C Confined
1	1	Interlaken	AAT	9.5 mm		4		4	4
				19.0 mm		4		4	4
		Shedworks	FHWA	9.5 mm		4		4	4
				19.0 mm		4		4	4
	2	Interlaken	AAT	9.5 mm		4		4	4
				19.0 mm		4		4	4
		Shedworks	FHWA	9.5 mm		4		4	4
				19.0 mm		4		4	4
2	1	Shedworks	AAT	9.5 mm		4		4	4
				19.0 mm		4		4	4
		Interlaken	FHWA	9.5 mm		4		4	4
				19.0 mm		4		4	4
	2	Shedworks	AAT	9.5 mm		4		4	4
				19.0 mm		4		4	4
		Interlaken	FHWA	9.5 mm		4		4	4
				19.0 mm		4		4	4
Total						64		128	

The final step was an analysis of quality statistics from the tests to determine overall levels of variability for the dynamic modulus test and to recommend limits for the quality indicators to be included in the test protocol. The sections that follow present and discuss pertinent findings from these four analyses.

2.3.3.2.1 General Trends. Figures 13 and 14 show the relationship between dynamic modulus (|E*|) data generated using the two devices and at the two laboratories, respectively. Note that at intermediate- to high-modulus values, the two devices appear to agree closely, although at lower modulus values, the Interlaken device seems to produce higher values for |E*|. Modulus data generated at AAT and FHWA appear to be similar, regardless of the mixture stiffness (see Figure 14). Given that both devices were calibrated to the same standards before testing, and the same testing protocol was used in both laboratories, the likely cause of the differences in |E*| shown in Figure 13 is the specimen deformation measuring system. Recall, the Interlaken device has an automated extensometer system that uses air actuators to hold the deformation measuring system against the specimen. The Shedworks device uses a refined glued-on gauge point system similar to that used in the original Project 9-19 research. As discussed later, additional statistical analyses were performed to determine if the discrepancy shown in Figure 13 is statistically significant.

Figure 15 shows a comparison of phase angle values generated using the two simple performance test devices. Note

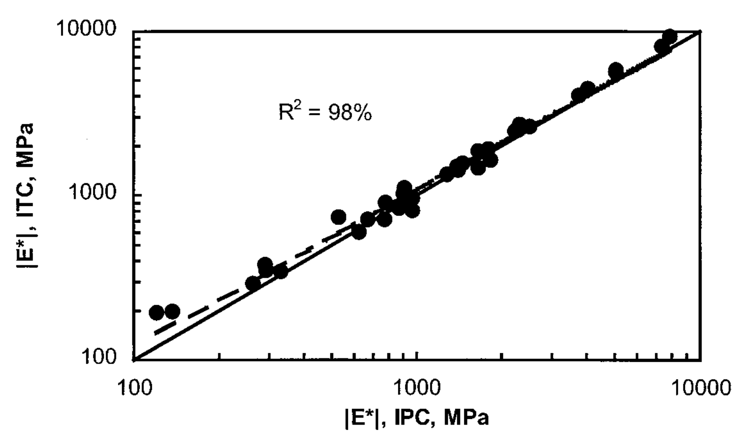


Figure 13. Comparison of dynamic modulus values generated using the Interlaken (ITC) and Shedworks (IPC) simple performance test devices (dashed line represents fit, solid line equality).

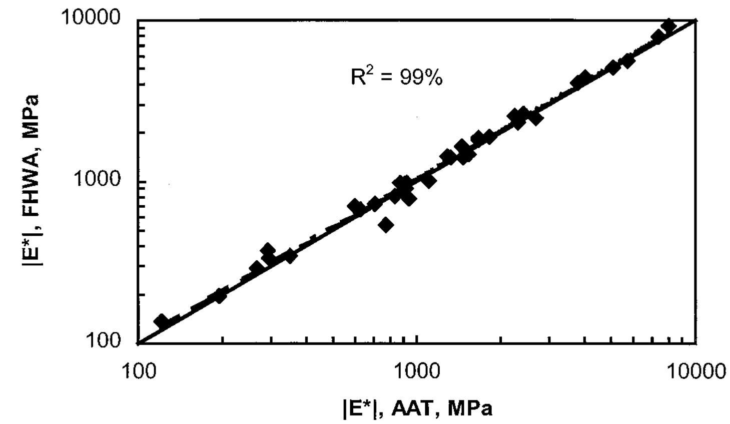


Figure 14. Comparison of complex modulus values generated at FHWA and at AAT using the two simple performance test devices (dashed line represents fit, solid line equality).

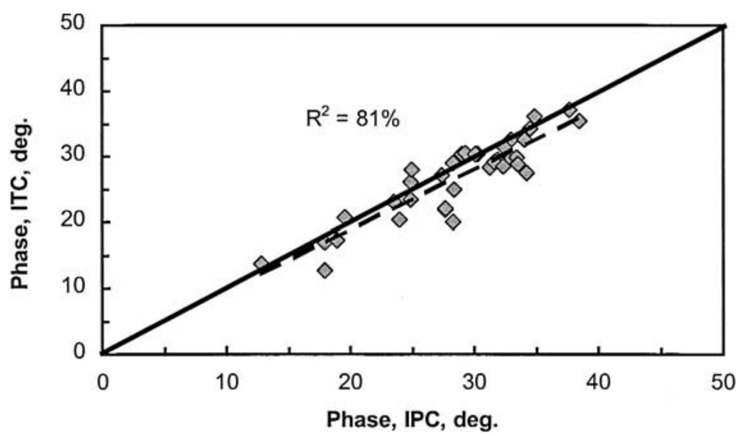
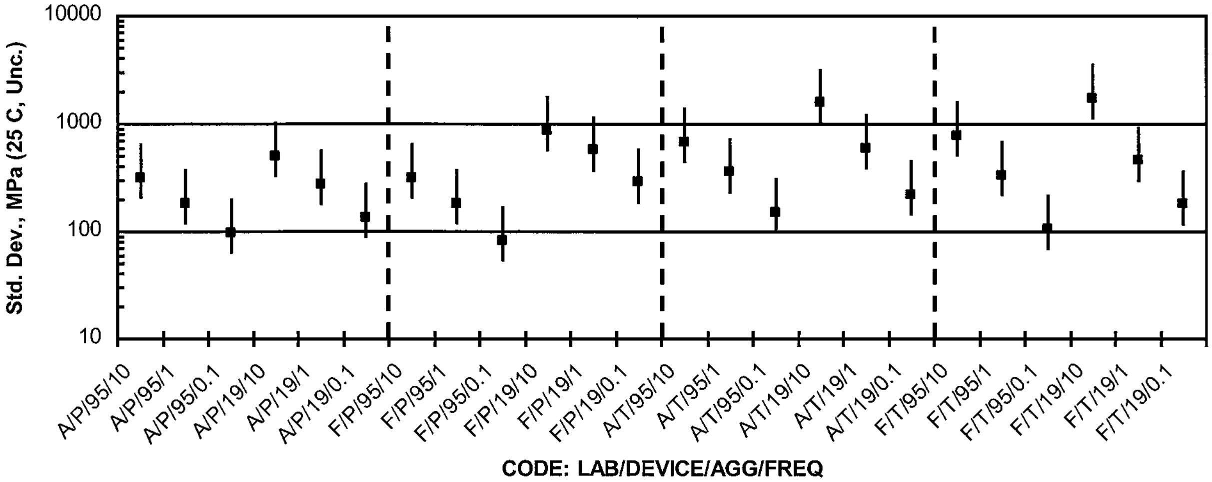


Figure 15. Comparison of phase angle values generated by the Interlaken (ITC) and Shedworks (IPC) simple performance test devices (dashed line represents fit, solid line equality).

that, as with modulus, the relationship appears to deviate from equality, though the statistical significance of the deviation cannot be judged from this figure. In general, the Interlaken device appears to generate somewhat lower phase angles than the Shedworks device at high phase angles, corresponding to low modulus values. This difference is consistent with that observed for |E*|, where the Interlaken device produced higher modulus values than the Shedworks device for low mixture stiffness values.

Figure 16 shows 95-percent confidence limits for the standard deviation of |E*| for the 25 °C tests for 24 combinations of laboratory, device, mixture, and frequency. These are not joint confidence limits, but single confidence limits calculated using $n = 7$ degrees of freedom and $\alpha = 0.05$—that is assuming a 5-percent risk of failure to capture the true value for the standard deviation (*14*). It is clear in this figure that the standard deviation decreases significantly with decreasing frequency. However, it should be remembered that |E*| also decreases with frequency, so that the variability relative to the modulus value is probably relatively constant. To evaluate the change in variance relative to modulus value, the confidence limits were converted to confidence limits in coefficient of variation (C.V.), by expressing them as a percentage of the measured |E*| value, and plotted in Figure 17. The variability expressed in these terms appears independent of frequency. It is difficult to evaluate other aspects of the changes in variability with test conditions from these figures, though it appears that the overall level of variability is relatively low for measurements of mixture modulus.

In summary, the general trends in the dynamic modulus data show that the modulus and phase angle data generated by the two devices at the two laboratories appear reasonable and are in general agreement. The Interlaken device appears to produce higher |E*| values and lower phase angles than the Shedworks device for low stiffness conditions. The overall variability of the dynamic modulus data produced with both

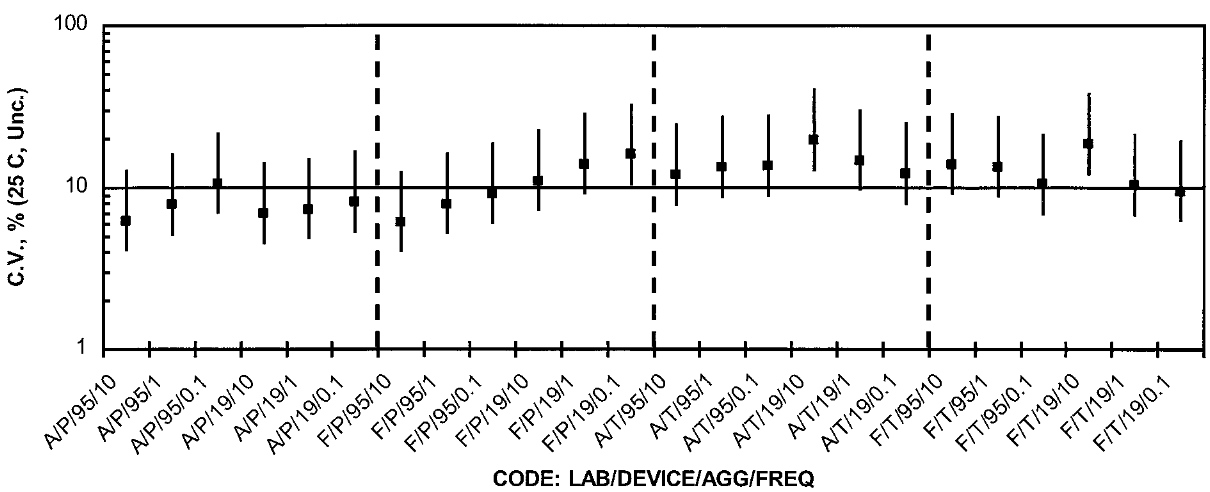


Coding
Laboratory: **A = AAT; F = FHWA**
Device: **P = Shedworks (IPC); T = Interlaken (ITC)**
Mix: **95 = 9.5 mm nominal maximum aggregate size (NMAS); 19 = 19.0 mm NMAS**
Frequency: **10 = 10 Hz; 1 = 1.0 Hz; .1 = 0.1 Hz**

Figure 16. 95% confidence limits for |E| standard deviation at 25 °C, unconfined.*

simple performance devices is reasonable, with coefficients of variation for various conditions ranging from 5 to 15 percent.

2.3.3.2.2 Detailed Analysis of Variability. Experiments of the type performed in this project are often analyzed using analysis of variance techniques. One of the assumptions in analysis of variance is that the variances for the different factors are the same (*14*). To evaluate this assumption and potential differences in variability between the two first-article devices, a detailed analysis of the equality of the variances in the cells of the experiment was performed. Two statistical tests were used to evaluate the equality of variances. In the



Coding
Laboratory: **A = AAT; F = FHWA**
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Mix: **95 = 9.5 mm nominal maximum aggregate size (NMAS); 19 = 19.0 mm NMAS**
Frequency: **10 = 10 Hz; 1 = 1.0 Hz; .1 = 0.1 Hz**

Figure 17. 95% confidence limits for |E| coefficient of variation at 25 °C, unconfined.*

cases where two variances were compared, such as comparing the variability of the Interlaken device to that of the Shedworks device, an F-test was used. The F-test was performed as follows (*14*):

H_0: $\sigma_1 \geq \sigma_2$

H_a: $\sigma_1 < \sigma_2$

If $F(\alpha;\, n_1 - 1,\, n_2 - 1) \leq s_1^2/s_2^2$, conclude H_0, otherwise conclude H_a

where F is the value of the F-test statistic for the specified value of α and degrees of freedom, n_i is the number of observations, s_i is the sample standard deviation, and α is the probability of incorrectly concluding that one standard deviation is larger than the other.

In other cases, an analysis of the equivalence of more than two variances was desired, an example being a check on the equality of variances for data collected in both laboratories with both devices for the 9.5 mm mixture. For these cases, all standard deviations can be compared simultaneously using the Hartley test (*14*):

H_0: $\sigma_1 = \sigma_2 = \sigma_3 = \sigma_4$

H_a: not all σ_i all equal

If $H(1 - \alpha;\, r,\, n - 1) \geq \max(s_i^2)/\min(s_i^2)$, conclude H_0, otherwise conclude H_a

where H is the Hartley test statistic, and r is the total number of sample standard deviations being compared.

To evaluate the variability in the data generated at the two laboratories thoroughly using the two devices, both the Hartley test for equality of standard deviations and F-tests for comparing standard deviations (between devices and between laboratories) were performed for combinations of major factors: temperature/confinement, frequency (10 Hz and 0.1 Hz), and mixture. The results for comparisons of the standard deviation of |E*| are summarized in Table 22. Values in boldface type are considered to show significant differences. These cases have a probability of incorrectly concluding that the standard deviation for one condition tested is greater than the others (α) less than or equal to 0.10. Out of the total of 12 cases, the Hartley test indicates that the standard deviations are not all equal in 3 cases. There does not appear to be any pattern to those situations exhibiting unequal standard deviations.

Using the F-test to compare standard deviations between devices, in 4 out of the 12 cases the Interlaken device exhibits a larger value than the Shedworks device. In three cases, the reverse is true. In comparing the standard deviations between the two laboratories, in only one case does one of the laboratories exhibit significantly greater variability than the other—for the 9.5-mm mixture at 45 °C (confined) and 0.1 Hz, data produced by the FHWA shows greater variability than that produced by AAT.

The corresponding summary of comparisons of standard deviations for phase angle is shown in Table 23. In this case, the Hartley test shows unequal standard deviations in 5 of the 12 cases. In comparing devices, the Interlaken device exhibits greater standard deviation values in 7 of 12 cases, while the

TABLE 22 Summary of statistical tests for comparison of modulus standard deviations

Hartley Test for Equality of All Standard Deviations					F-Test Comparing Standard Deviations for Devices			F-Test Comparing Standard Deviations for Laboratories		
Test Conditions	Freq. *Hz*	Mix	Ratio of Maximum / Minimum s^2 Values	Conclude Std. Devs. Not Equal?[1]	Ratio of IPC / ITC s^2 Values	Device with Greater Std. Dev.	Prob.[2]	Ratio of AAT / FHWA s^2 Values	Lab with Greater Std. Dev.	Prob.[3]
25 °C/Unc.	**10**	**9.5-mm**	6.20	NO	**0.19**	**ITC**	**0.002**	1.01	---	0.496
25 °C/Unc.	**10**	**19-mm**	**11.45**	**YES**	**0.19**	**ITC**	**0.002**	0.85	---	0.379
25 °C/Unc.	**0.1**	**9.5-mm**	3.25	NO	0.49	**ITC**	**0.096**	1.09	---	0.438
25 °C/Unc.	**0.1**	**19-mm**	4.47	NO	1.23	---	0.350	0.51	---	0.113
45 °C/Unc.	**10**	**9.5-mm**	5.30	NO	**2.28**	**IPC**	**0.067**	0.62	---	0.192
45 °C/Unc.	**10**	**19-mm**	2.89	NO	0.86	---	0.390	0.86	---	0.393
45 °C/Unc.	**0.1**	**9.5-mm**	1.81	NO	1.16	---	0.395	0.73	---	0.281
45 °C/Unc.	**0.1**	**19-mm**	**12.48**	**YES**	**0.24**	**ITC**	**0.005**	0.84	---	0.371
45 °C/Con.	**10**	**9.5-mm**	1.47	NO	1.13	---	0.411	0.85	---	0.381
45 °C/Con.	**10**	**19-mm**	2.31	NO	0.97	---	0.477	0.68	---	0.243
45 °C/Con.	**0.1**	**9.5-mm**	**8.62**	**YES**	**2.29**	**IPC**	**0.067**	**0.32**	**FHWA**	**0.022**
45 °C/Con.	**0.1**	**19-mm**	4.25	NO	**2.54**	**IPC**	**0.046**	1.65	---	0.178

[1]Hartley Test: if Max / Min s^2 value > 8.44, conclude all standard deviations not equal.
[2]Probability of incorrectly concluding that one device has a larger standard deviation than the other (α).
[3]Probability of incorrectly concluding that one laboratory has a larger standard deviation than the other (α).

TABLE 23 Summary of statistical tests for comparison of phase angle variance values

Hartley Test for Equality of All Standard Deviations					F-Test Comparing Standard Deviations for Devices			F-Test Comparing Standard Deviations for Laboratories		
Test Conditions	Freq. *Hz*	Mix	Ratio of Maximum / Minimum s^2 Values	Conclude Std. Devs. Not Equal?[1]	Ratio of IPC / ITC s^2 Values	Device with Greater Std. Dev.	Prob.[2]	Ratio of AAT / FHWA s^2 Values	Lab with Greater Std. Dev.	Prob.[3]
25 °C/Unc.	10	9.5-mm	**11.52**	**YES**	**0.19**	**ITC**	**0.002**	0.90	---	0.423
25 °C/Unc.	10	19-mm	**23.27**	**YES**	**0.18**	**ITC**	**0.001**	0.81	---	0.350
25 °C/Unc.	0.1	9.5-mm	5.25	NO	**0.33**	**ITC**	**0.022**	0.91	---	0.429
25 °C/Unc.	0.1	19-mm	6.87	NO	**0.22**	**ITC**	**0.004**	0.94	---	0.455
45 °C/Unc.	10	9.5-mm	3.02	NO	1.65	---	0.179	0.56	---	0.145
45 °C/Unc.	10	19-mm	**40.03**	**YES**	**0.10**	**ITC**	**0.000**	0.91	---	0.431
45 °C/Unc.	0.1	9.5-mm	2.57	NO	**0.45**	**ITC**	**0.072**	0.98	---	0.487
45 °C/Unc.	0.1	19-mm	**18.05**	**YES**	**0.14**	**ITC**	**0.000**	0.88	---	0.411
45 °C/Con.	10	9.5-mm	6.31	NO	1.38	---	0.277	1.25	---	0.340
45 °C/Con.	10	19-mm	4.59	NO	**2.75**	**IPC**	**0.034**	0.60	---	0.177
45 °C/Con.	0.1	9.5-mm	**17.66**	**YES**	**7.18**	**IPC**	**0.000**	**0.20**	**FHWA**	**0.002**
45 °C/Con.	0.1	19-mm	4.67	NO	**3.41**	**IPC**	**0.014**	0.63	---	0.197

[1]Hartley Test: if Max / Min s^2 values > 8.44, conclude all standard deviations not equal.
[2]Probability of incorrectly concluding that one device has a larger standard deviation than the other (α).
[3]Probability of incorrectly concluding that one laboratory has a larger standard deviation than the other (α).

Shedworks device exhibits greater standard deviation values in 3 of 12 cases—all at 45 °C, confined. As with modulus, in only one case does one of the laboratories exhibit a greater standard deviation than the other, and it is again FHWA.

The primary reason for including both a 9.5-mm aggregate gradation and a 19-mm aggregate gradation was that the variability for these mixtures was expected to be different. In general, most paving engineers and technicians believe that mixtures with larger nominal maximum aggregate sizes are more difficult to work with and will exhibit more variability in the results of mechanical property tests. Table 24 is a summary of comparisons between standard deviations for mixtures made with the two aggregate types. For modulus values, the 19-mm mixture appears to exhibit greater variability, with a larger standard deviation in 10 of 12 cases. However, the modulus values for the 19-mm mixture are somewhat

TABLE 24 Summary of statistical tests for comparison of modulus and phase angle variability between aggregate types

			F-Test Comparing Standard Deviations for Modulus			F-Test Comparing Coefficient of Variation for Modulus[1]			F-Test Comparing Standard Deviations for Phase Angle		
Test Conditions	Freq. *Hz*	Device	Ratio of 19-mm / 9.5-mm s^2 Values	Aggregate with Greater Std. Dev.	Prob.[2]	Ratio of 19-mm / 9.5-mm CV^2 Values	Aggregate with Greater C.V.	Prob.[3]	Ratio of 19-mm/ 9.5-mm s^2 Values	Aggregate with Greater Std. Dev.	Prob.[2]
25 °C/Unc.	10	IPC	**5.07**	**19 mm**	**0.002**	**2.20**	**19 mm**	**0.076**	1.33	---	0.300
25 °C/Unc.	10	ITC	**5.04**	**19 mm**	**0.002**	**2.16**	**19 mm**	**0.081**	1.44	---	0.252
25 °C/Unc.	0.1	IPC	**6.18**	**19 mm**	**0.001**	1.63	---	0.186	0.89	---	0.414
25 °C/Unc.	0.1	ITC	**2.45**	**19 mm**	**0.053**	0.81	---	0.350	1.32	---	0.307
45 °C/Unc.	10	IPC	**3.44**	**19 mm**	**0.014**	0.96	---	0.468	**0.42**	**9.5 mm**	**0.059**
45 °C/Unc.	10	ITC	**9.13**	**19 mm**	**0.000**	**2.70**	**19 mm**	**0.036**	**7.31**	**19 mm**	**0.000**
45 °C/Unc.	0.1	IPC	**3.44**	**19 mm**	**0.014**	0.72	---	0.272	1.12	---	0.420
45 °C/Unc.	0.1	ITC	**16.90**	**19 mm**	**0.000**	**6.43**	**19 mm**	**0.001**	**3.60**	**19 mm**	**0.011**
45 °C/Con.	10	IPC	**2.54**	**19 mm**	**0.046**	0.87	---	0.402	1.52	---	0.221
45 °C/Con.	10	ITC	**2.96**	**19 mm**	**0.026**	1.07	---	0.452	0.77	---	0.312
45 °C/Con.	0.1	IPC	0.80	---	0.340	**0.28**	**9.5 mm**	**0.011**	**0.45**	**9.5 mm**	**0.076**
45 °C/Con.	0.1	ITC	0.72	---	0.272	**0.42**	**9.5 mm**	**0.060**	0.96	---	0.469

[1]Approximate test treating coefficient of variation (C.V.) as a standard deviation.
[2]Probability of incorrectly concluding that one mixture has a larger standard deviation than the other (α).
[3]Probability of incorrectly concluding that one mixture has a larger coefficient of variation than the other (α).

higher than for the 9.5-mm mixture; and, for this type of measurement, variability tends to increase with higher values of modulus. Therefore, coefficient of variation (C.V.) is a better indicator of variability. Unfortunately, strict statistical tests cannot be constructed using C.V. However, an approximate test can be constructed using C.V. in place of standard deviation. The results of the approximate F-tests using C.V. is also included in Table 24. In this case, the 19-mm mixture exhibits greater variability in only 4 of 12 cases, and the 9.5-mm shows greater variability in 1 case. It appears that, once adjusted for differences in mean response, the variability in modulus values for the two mixtures is similar. The results for phase angle agree better with the results of the approximate C.V. F-tests. In 2 of 12 cases, the 19-mm mixture does exhibit greater variability, while in 2 of 12 cases, the 9.5-mm mixture exhibits greater variability. It appears that the two mixtures, in general, exhibited similar levels of variability. Care should be taken in generalizing these results, as this series of tests involved only two different aggregates. It is also possible that in other situations, with less careful control over conditions and specimen preparation, the 19-mm mixture would have shown greater variability than the 9.5-mm mixture.

The detailed analysis of variability resulted in several pertinent findings. These are summarized and discussed below:

1. There are significant differences in variance of the dynamic modulus and phase angle for the factor and treatment levels in the experiment; therefore, analysis of variance techniques cannot be used to analyze differences in mean response.
2. The variability in the dynamic modulus and phase angle data for the 9.5 mm and 19.0 mm mixtures is similar. This was an unexpected finding given that these mixtures were selected because they exhibited large differences in variability during previous shear modulus testing.
3. The variability in data generated in the two laboratories is similar. This finding is probably the result of the protocol used in the laboratory testing. First, all specimens were fabricated at AAT, then distributed to the two laboratories to have the same average and range of air voids. Second, the same temperature conditioning methods were used in both laboratories. Specimens to be tested on a particular day were conditioned with a dummy specimen in a separate environmental chamber. Once the specimens and the device reached the test temperature, the specimen to be tested was removed and quickly inserted into the test chamber. The test chamber was closed and allowed to return to equilibrium before testing proceeded.
4. The variability in data generated with the Interlaken device is higher than that generated with the Shedworks device for unconfined tests. However, the variability for data generated with the Shedworks device is higher for confined tests. This finding can be rationally explained considering the configuration of the deformation measuring systems. As discussed in a later section of this report dealing with functional characteristics, the Interlaken extensometer system requires further refinement. Often the system had to be re-seated several times to obtain acceptable contact with the specimen. Thus, the higher variability for the Interlaken device for unconfined tests is probably due to slip or uncontrolled movement of the extensometer contact. In confined tests, the rubber membrane apparently provides a better, more stable contact. For confined testing with the Shedworks device, the membrane is sandwiched between the LVDT bracket and the glued-on contact point. The bracket is held in place with a screw that is tightened before confining pressure is applied. When confining pressure is applied, the membrane gets thinner as it stretches over the contact point, allowing the LVDT bracket to loosen. Greater variability in the test data, compared with that collected for unconfined testing when the membrane is not between the bracket and the contact would be expected.

2.3.3.2.3 Detailed Analysis of Mean Response. Analysis of variance is often used to analyze the significance of differences in means in the type of experiment used here. However, as discussed previously, analysis of variance assumes equality of means in the various cells being analyzed, which is clearly not the case for the dynamic modulus data. An approximate test of equality between two means can be made, even with somewhat unequal standard deviations. Because the sample sizes in all cases are equal (n = 8), the common standard deviation for comparing means can be estimated using the following Equation 8 (*14*):

$$s_{DIFF} = \sqrt{\left(\frac{s_1^2 + s_2^2}{2}\right)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)} \tag{8}$$

where s_1 and s_2 represent the standard deviations for the two measurements, and n_1, n_2 is the sample size for each case. For this experiment, $n_1 = n_2 = 8$; therefore, there are 14 degrees of freedom associated with the comparison of two mean values. This is large enough to provide a very good estimate of the standard deviation, so that a normal distribution may be used in making the statistical test rather than the t-distribution used for small sample sizes. Then, the significance level, or chance of incorrectly concluding that the mean of one measurement is greater than the other, is given by Equation 9:

$$N(\alpha) = \left(\left|\bar{E}^*\right|_1 - \left|\bar{E}^*\right|_2\right) \Big/ s_{DIFF} \tag{9}$$

where $N(\alpha)$ represents the z-value at which there is only a chance, α, that it will be exceeded. This approximate test was conducted, comparing both mean values as determined using each device (averaged across laboratory) and as measured at each laboratory (averaged across device). The results for $|E^*|$ are shown graphically in Figure 18 for comparison between

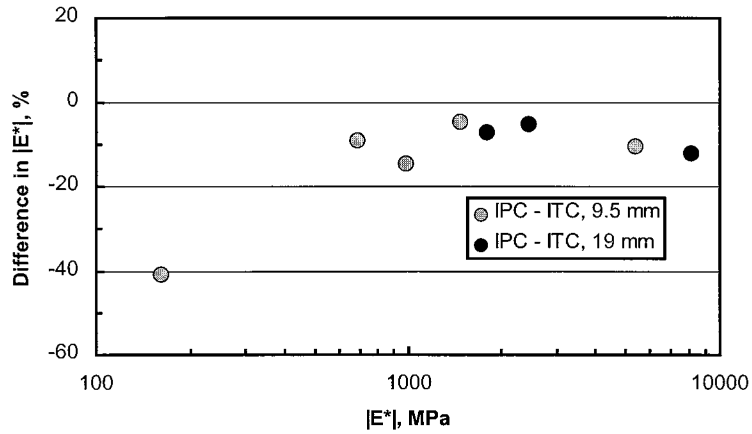


Figure 18. Statistically significant (p ≥ 0.10) differences in modulus measurement for comparisons between devices, as a percent of mean value.

laboratories and Figure 19 for comparisons between devices. In these figures, only differences which are statistically significant ($\alpha = 0.10$) are plotted.

In comparing devices, 8 out of 12 comparisons were significant ($\alpha = 0.10$); in comparing laboratories, 10 out of 12 comparisons were significant. Furthermore, it was found that the magnitude of the difference between laboratories appeared to depend on the mix type. For the 9.5-mm mixture, significantly higher modulus values were measured at the FHWA laboratory, while for the 19-mm mixture, higher values were measured at the AAT laboratory, though the difference in this case was not as great. The difference in |E*| as determined using the two devices, on the other hand, appears to be independent of aggregate type. In this case, the Interlaken device measures higher modulus values, the difference becoming larger at lower modulus values.

The corresponding plot for comparison of mean phase angle values is shown in Figures 20 and 21. In these cases, the patterns are not as pronounced. For the comparison of phase angles measured by the two devices, 10 of 12 cases exhibited significant differences, with the ITC device generally producing lower phase angle values, by as much as 6 degrees. For comparison of phase angles measured at the two laboratories, 8 of 12 showed significant differences; and, in each of these cases, the difference was less than 2 degrees.

A second approach to comparing data from the two devices involves the use of regression in combination of confidence intervals. This provides a general evaluation of equality, useful for evaluating bias in the data. The |E*| data were evaluated in this manner for three conditions: 25 °C unconfined, 45 °C unconfined, and 45 °C confined. In Figure 22, the log of |E*| at 25 °C as measured using the Interlaken

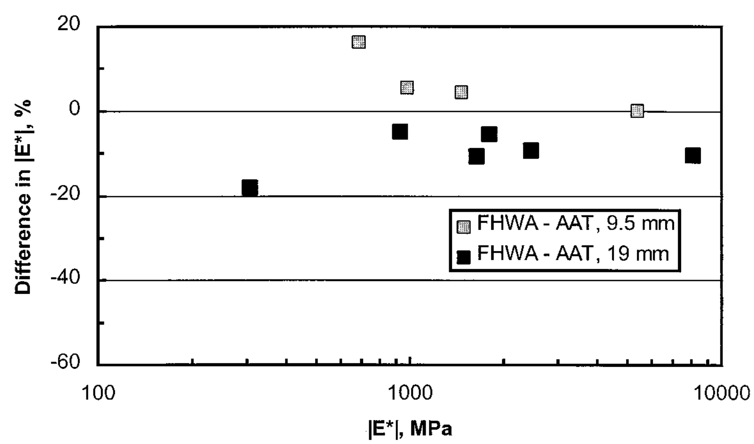


Figure 19. Statistically significant (p ≥ 0.10) differences in modulus measurement for comparisons between laboratories, as a percent of mean value.

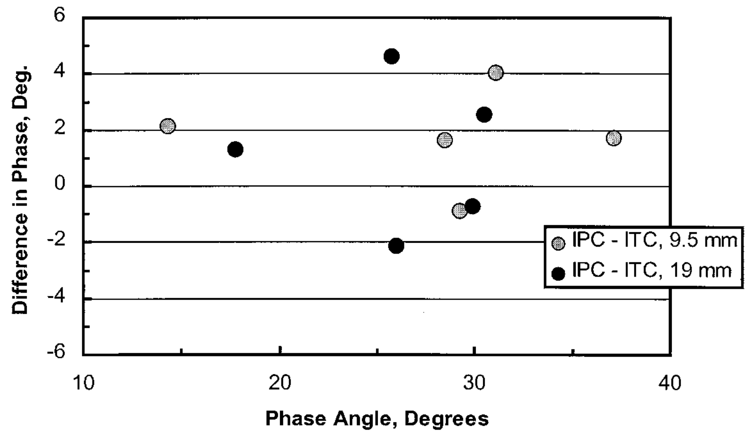


Figure 20. Statistically significant (p ≥ 0.10) differences in phase angle measurement for comparisons between devices.

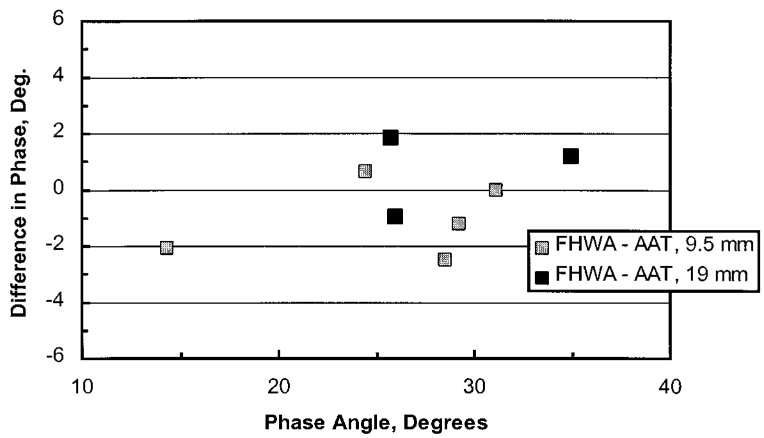


Figure 21. Statistically significant (p ≥ 0.10) differences in phase angle measurement for comparisons between laboratories.

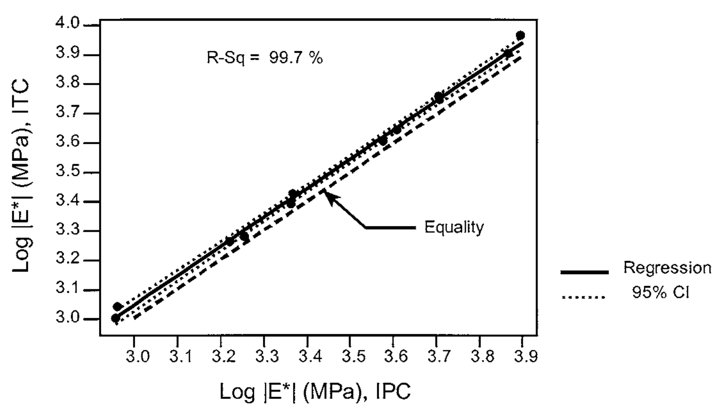


Figure 22. Regression of log |E|/ITC device as a function of log |E*|/IPC device, 25 °C data only, with 95% confidence interval for the regression and line of equality.*

device is shown as a function of log |E*| at 25 °C as measured using the Shedworks device. A log transformation was used to provide a better distribution of residuals. This plot includes the 95-percent confidence interval for the regression relationship and the line of equality. In this case, the regression line appears to run parallel and quite close to the line of equality, but the confidence interval for the regression line does not quite capture the line of equality. Therefore, it appears that at 25 °C, modulus values measured using the Interlaken device are slightly greater than those measured using the Shedworks device. This bias, though consistent, is not large.

Figure 23 shows the relationship between |E*| measured with the two devices for the 45 °C unconfined data only. In this case, the line of equality is not parallel to the regression line—instead, it falls below the regression line at low modulus levels and falls above it at high modulus values. As modulus values decrease, the values measured by the Interlaken device become larger relative to those measured using the Shedworks device.

Figure 24 shows the relationship between |E*| measured with the two devices at 45 °C, but for confined data. In this case, the 95-percent confidence interval appears to capture the line of equality over most of the data range. As with the unconfined data, there is much more scatter than in the 25 °C unconfined data, which is probably due to the overall low modulus values and relatively low applied stress levels. Despite the higher noise, it appears that, in this case, the trends in the data are similar to those observed in the 25 °C unconfined data.

To compare overall trends in modulus measurements for the two devices, Figure 25 was constructed, which shows the relationship between modulus values measured with both devices for all conditions, separately coded, and with individual regression lines (but no confidence intervals). It appears that the 25 °C unconfined and 45 °C confined data compare very well and follow a similar relationship, although the modulus values at 25 °C were slightly higher for the Interlaken device. The unconfined data at 45 °C clearly follow a different relationship than the other two cases, with the Interlaken device producing higher modulus values at low modulus levels and lower values at higher overall modulus levels.

The relationship between modulus values is made even clearer in Figure 26, which is a plot of the percent differ-

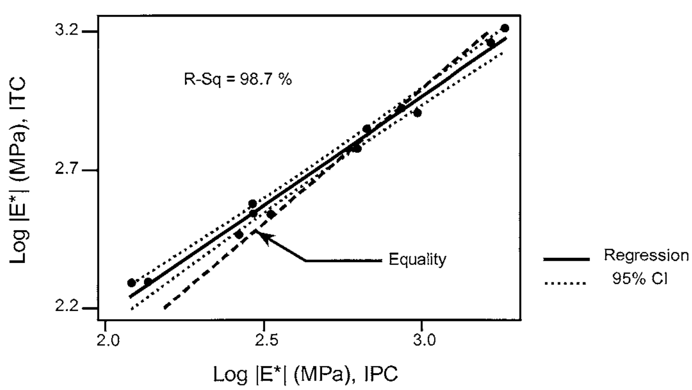


Figure 23. Relationship between modulus as measured using ITC and IPC devices, 45 °C, unconfined data only, with 95% confidence interval for the regression and line of equality.

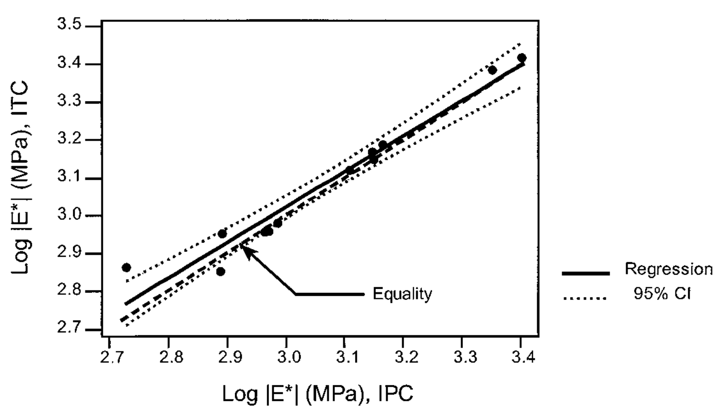


Figure 24. Relationship between modulus as measured using ITC and IPC devices, 45 °C, confined data only, with 95% confidence interval for the regression and line of equality.

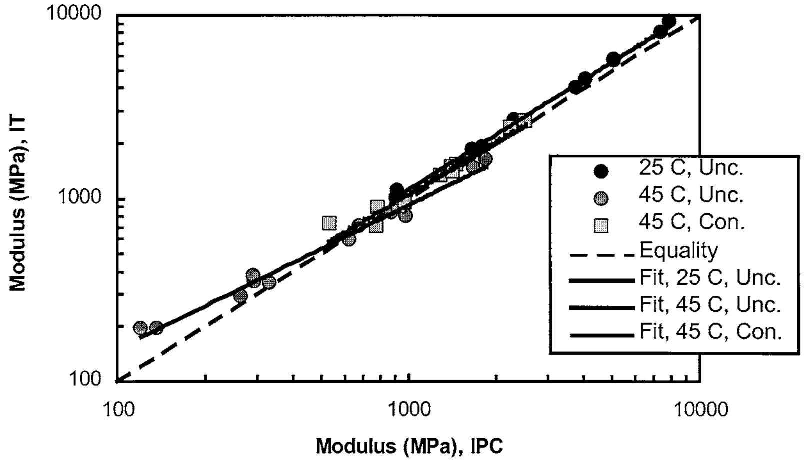


Figure 25. Relationship between modulus as measured using ITC and IPC devices, all conditions, showing separate regression lines.

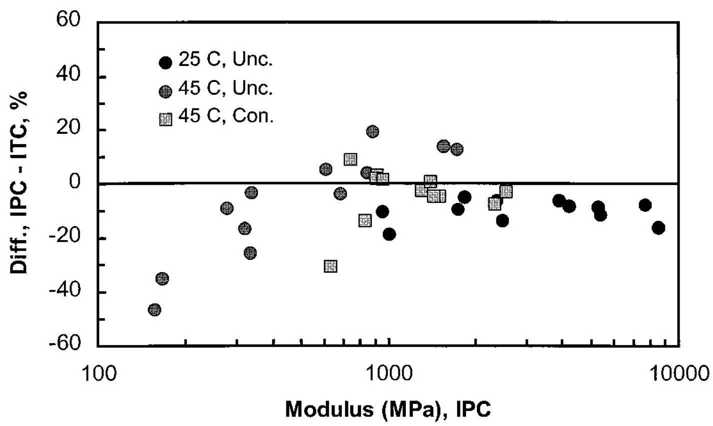


Figure 26. Percent difference between modulus as measured using ITC and IPC devices, all conditions.

ence between modulus values as measured using the Shedworks and Interlaken devices. At modulus values above about 1,000 MPa, there is relatively little scatter in the data, and the Interlaken device produces slightly higher modulus values compared with the Shedworks device. As the modulus decreases below 1,000 MPa, the scatter in the data becomes greater, and the difference between the two devices becomes greater. For the two data points below 200 MPa, the Interlaken device produced values about 40 percent higher than those generated using the Shedworks device.

The final regression plot in this series is shown in Figure 27, which is a plot comparing phase angle measurements made with the two devices at both temperatures. The variability in phase angle appears to be larger than the variability in |E*| measurements. At phase angles below about 28 degrees, the two devices appear to be in reasonable agreement. However, at higher phase angles, the Shedworks device produces slightly higher phase angle values.

The major finding from the detailed analysis of the mean response is that dynamic moduli measured with the Interlaken device are higher than those measured with the Shedworks device for unconfined conditions. For confined conditions, dynamic moduli measured with the two devices are similar. These findings are also rationally explained by errors in the two measuring systems. As discussed previously in the detailed analysis of the equality of variances, the Interlaken specimen-mounted deformation system probably has errors caused by movement at the point where the extensometer contacts the specimen. Such errors result in lower measured strains and higher moduli. For confined conditions, the membrane appears to reduce these errors for the Interlaken device. For the Shedworks device, the membrane is sandwiched between the glued contact point and the LVDT bracket, producing a measuring system that also has relative movement errors. Thus, the net result of confinement is to reduce errors in the Interlaken measurement and increase errors in the Shedworks measurement, making the dynamic moduli for confined conditions the same. The lower phase angles for the Interlaken data are also consistent with this type of measurement error.

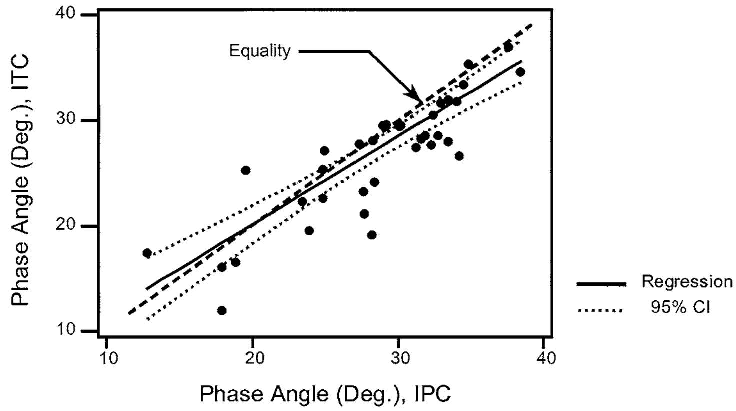


Figure 27. Regression of phase angle/ITC device as a function of phase angle/IPC device, with 95% confidence interval for the regression and line of equality (R^2 = 73.2%, adj. for d.f.).

2.3.3.2.4 Analysis of Test Variability. The final statistical analysis done was to assess the overall variability of the dynamic modulus measurements and the effect that the data quality indicators recommended in this project may have on reducing test variability. Table 25 summarizes pooled values for the coefficient of variation for dynamic modulus (|E*|) and for standard deviation for the phase angle. These values thus represent overall variability for the two devices, two laboratories, and two aggregates. The trends for modulus and phase angle are similar. The overall variability for the Shedworks device is slightly lower than for the Interlaken device, though the variability of the Interlaken device is better for the confined tests at 45 °C. The variability of data generated at the two laboratories appears to be similar. The overall variability for the two aggregates also appears similar. It appears that the variability in test data at 45 °C is greater for unconfined than for confined data. The last column in Table 25 shows overall values for coefficient of variation and standard deviation. The overall coefficient of variation for modulus is 13.0 percent and the standard deviation for phase angle is 1.73 degrees. These values are very similar to values reported from data collected in Project 9-19 as summarized in Table 26. Keep in mind that these values are for one replicate measurement only. Typically, three replicate measurements are made when measuring the modulus of asphalt concrete specimens. For n = 3 replicates, the coefficient of variation for average modulus would then be $13.0/\sqrt{3} = 7.5\%$. The standard deviation for average phase angle for n = 3 replicates would be 1.0 degrees. This amount of variability appears to be quite good for mechanical measurements on asphalt concrete.

TABLE 25 Pooled coefficient of variation for |E*| and standard deviation for phase angle at 10 Hz

Treatment	25 °C/ Unconfined	45 °C/ Unconfined	45 °C/ Confined	Overall
Pooled Coefficient of Variation for |E|, %*				
IPC	9.8	12.9	15.0	**12.8**
ITC	13.8	15.2	9.9	**13.2**
AAT	11.7	15.0	10.4	**12.5**
FHWA	12.2	13.2	14.6	**13.4**
9.5 mm	10.8	11.6	15.1	**12.6**
19 mm	13.0	16.3	9.7	**13.3**
Overall	**11.9**	**14.1**	**12.7**	**13.0**
Pooled Standard Deviation for Phase Angle, degrees				
IPC	0.89	1.08	2.49	**1.65**
ITC	1.76	2.23	1.34	**1.81**
AAT	1.38	1.79	1.50	**1.57**
FHWA	1.42	1.72	2.40	**1.89**
9.5 mm	1.31	1.24	2.18	**1.64**
19 mm	1.48	2.15	1.80	**1.83**
Overall	**1.40**	**1.75**	**2.00**	**1.73**

The final part of this analysis is an evaluation of the quality indices that are part of the output of the dynamic modulus test with the first-article devices. These indices provide information concerning the accuracy of loading and response waveforms, using statistical parameters such as standard errors. The following quality indicators are provided by the dynamic modulus software included in the first-article devices:

- **Load standard error**—this is the standard error of the load waveform compared with an ideal sine function of identical magnitude and phase lag.
- **Load drift**—this is the amount of gradual, permanent change in the applied load during a test, in addition to the desired sinusoidal load.
- **Deformation standard error**—the standard error between the actual deformation waveform and an ideal sine function of identical magnitude and phase lag.

TABLE 26 Pooled coefficient of variation for |E*| and standard deviation for phase angle from studies involving a large number of dynamic modulus tests

Study	Pooled Coefficient of Variation for |E*|, %	Pooled Standard Deviation for Phase Angle, degrees
This project	13.0	1.8
Pellinen, 2001 (*16*)	13.0	2.3
Witczak, 2000 (*15*)	15.2	2.3

- **Deformation drift**—the amount of gradual, permanent change in the deformation during a test, in addition to the sinusoidal component of deformation.
- **Deformation uniformity**—this is the average difference between (or among) the amplitude of the deformation signals expressed as a percentage of the mean deformation. If all signals are identical in amplitude, the deformation uniformity is zero.
- **Phase uniformity**—the average difference between (or among) the deformation phase lags, expressed in degrees; a value of zero indicates that the deformations are completely in phase.

The initial evaluation of the quality indices involved determining correlations between the various indices and the coefficient of variation of the modulus and standard deviation for the phase angle values. A high degree of correlation between a particular quality index and the modulus coefficient of variation and/or the phase angle standard deviation would indicate that that indicator was potentially important in determining the quality of the measurement. Low correlation, on the other hand, does not necessarily indicate that that quality index is not important. Low correlation suggests that it is either not important or, more likely, that the values for the index in this data set were low enough so that they did not have a substantial effect on the quality of the resulting data.

For this particular set of data, R^2 values between the quality indices and the modulus coefficient of variation and the phase angle standard deviation were very low, ranging from 1 to 8 percent. It is believed that these low values suggest that the quality indicators were in the range where they did not cause significant problems in most of the data. Table 27 is a summary of the quality indices for the two devices, for load and deformation. The values for the indices have been broken down by loading frequency, because the frequency had a significant effect on their magnitude. Shown in the table is the average value for each index at each of three frequencies, the standard deviation for the index, and the 95 percent confidence limit for each index. This confidence limit represents the value for the index which, in the long run, will only be exceeded one time in twenty, and so serves as a basis for establishing a limit for that index that can be used to identify questionable data. In general, the standard errors are lower for the Shedworks device compared with the Interlaken device. The values at 0.10 Hz for the Interlaken device are not reported here, because it was found that they had been incorrectly calculated by the Interlaken software because the device was applying a loading slightly slower than 0.10 Hz.

TABLE 27 Summary of quality indices for load and deformation

Device	Parameter	Load Standard Error (%), at Frequency (Hz):			Deformation Std. Error (%), at Frequency (Hz):		
		10.00	1.00	0.10	10.00	1.00	0.10
IPC	Avg.	4.18	1.39	3.30	6.46	4.01	4.35
	Std. Dev.	1.76	0.87	2.37	1.42	1.01	1.20
	95 % C.L.	7.07	2.82	7.19	8.80	5.68	6.32
ITC	Avg.	6.47	2.13	14.21	13.52	8.03	16.11
	Std. Dev.	2.19	1.34	12.57	3.19	2.09	11.90
	95 % C.L.	10.07	4.34	---	18.77	11.47	---

It was found that the standard errors for deformation are strongly dependent on the standard errors for load; the R^2 value between these two indices was 81 percent. Although this might seem to suggest that only one of these indices need be specified, it is believed that both should be specified to ensure that devices and software produced in the future maintain the needed quality in loading and measurement. Another trend in these quality indices is that the best quality data (lowest index values) are produced at 1 Hz, with poorer data at both 10 and 0.1 Hz. This might be the result of the devices having optimal performance characteristics at 1 Hz, or it might be the result of the manufacturers' tuning process.

As discussed previously, the Interlaken deformation measurement system, although innovative, easy to use, and quite promising, seems to exhibit some bias compared with the Shedworks system because of movement of the deformation transducers relative to the specimen. This should be expected to increase standard errors in deformation also. In examining Table 27, it is clear that the deformation standard errors for the Interlaken device are substantially larger than those for the Shedworks device. These values should, therefore, be interpreted with caution and should be disregarded in determining preliminary limits for quality indices. After eliminating these values from Table 27, it would appear that a reasonable general limit for load and deformation standard error would be 10 percent. Most test data would pass this limit. If the device tuning can be improved over the full range of frequencies, a lower limit of 7 percent can probably be applied.

Table 28 is a summary of drift and uniformity coefficients for load and deformation for the two first-article devices. The load drift values are quite low, suggesting a limit of 3 percent would be appropriate. Deformation drift values are larger and vary significantly with frequency. Based on these data, reasonable limits for deformation drift would be 400 percent at 10 Hz, 300 percent at 1 Hz, and 200 percent at 0.10 Hz. Limits at other frequencies should be interpolated from these values. Deformation uniformity should be limited to 20 percent, and phase uniformity to 3 percent.

Based on an analysis of quality indices, the following limits should be used by dynamic modulus test users to identify potentially poor test data:

- Load and deformation standard error: 10 percent
- Load drift (absolute value): 3 percent
- Deformation drift (absolute value): 400 percent at 10 Hz, 300 percent at 1 Hz, and percent % at 0.1 Hz
- Deformation uniformity: 20 percent
- Phase uniformity: 3 percent

These limits are intended to help operators identify suspect data, so that such data can be evaluated and repeated if necessary.

TABLE 28 Summary of drift and uniformity for load and deformation

Device	Parameter	Load Drift (%)	Deformation Drift (%), at Frequency (Hz): 10.0	1.00	0.10	Deformation Uniformity (%)	Phase Uniformity (Degrees)
IPC	Avg.	0.21	221	106	85	11.46	0.92
	Std. Dev.	0.26	85	109	61	2.79	0.35
	95 % C.L.	0.65	360	286	186	16.05	1.49
ITC	Avg.	0.54	230	132	68	12.48	1.34
	Std. Dev.	1.07	100	108	58	3.43	0.79
	95 % C.L.	2.31	395	310	162	18.12	2.64

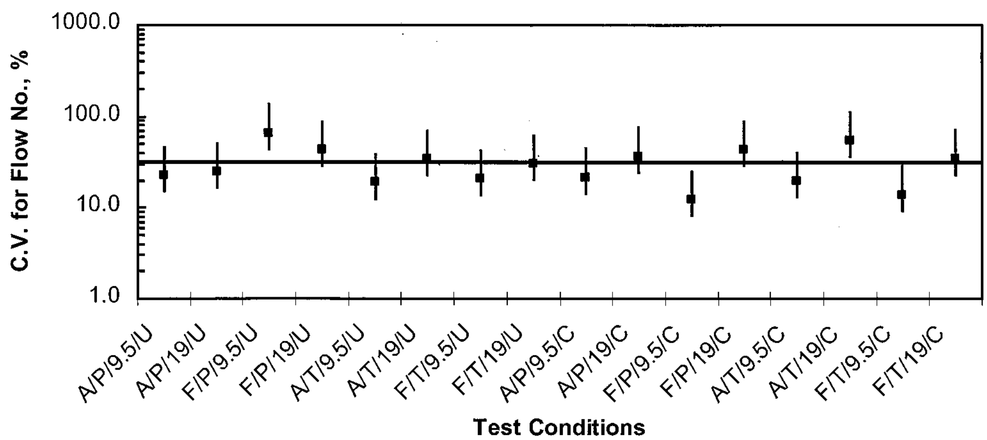
The limits should be set so that when tests are properly conducted by an experienced operator on a properly calibrated and maintained system, no more than about 5 percent of the test results should be identified as being suspect. It would not be efficient to identify a larger proportion of tests as being suspect, because this would result in unnecessary investigations into test results and procedure and unnecessary repeated tests.

2.3.3.3 Flow Number

The same approach described for the dynamic modulus was used to analyze the flow number data. Because there was only one test temperature and no differences in loading frequency, the flow number data were somewhat simpler.

2.3.3.3.1 General Trends. Figure 28 is a plot showing 95 percent confidence intervals for the coefficient of variation (C.V.) in flow number for the various combinations of conditions (laboratory, device, mixture, confinement). The C.V. values range from about 12 to 66 percent with an average of 31 percent. Most of the confidence intervals overlap, suggesting that there are not large differences in the standard deviations relative to the mean values for most cases. The only pattern apparent from a visual examination of this plot is that the C.V. values for the 19-mm mixture appear to be generally higher than those for the 9.5-mm mixture. Figure 29 is the corresponding figure for strain at flow, but in this case the confidence intervals are for standard deviation rather than coefficient of variation, because the range in this parameter was much smaller than for flow number and using C.V. did not significantly remove variability from the standard deviation values. Again, many of the confidence intervals overlap, suggesting that there are not many cases where large differences exist in the variability in this measurement. One trend that does appear is that the standard deviations determined using confinement seem to be slightly larger than those determined without confinement.

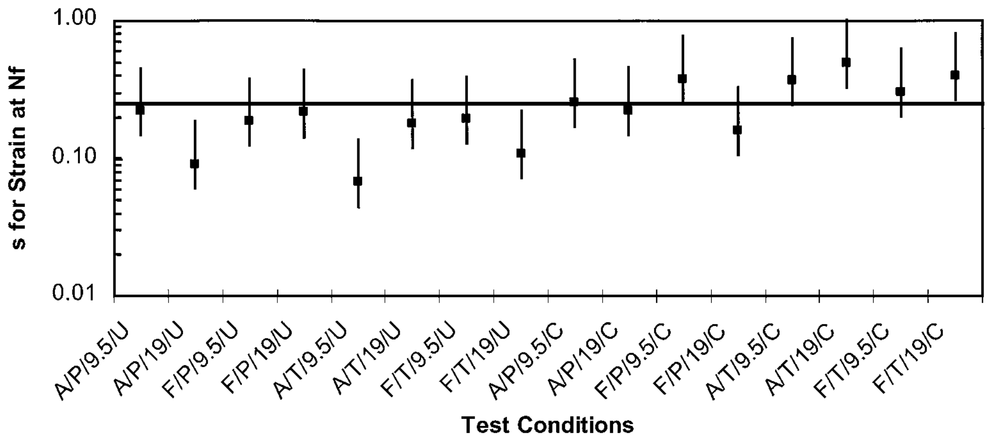
Scatter plots with regression lines and confidence intervals were constructed to evaluate general trends between data generated in the two laboratories and by the two devices, both for flow number and strain at flow. For three of the four cases, the line of equality was captured by the confidence interval, indicating that there was not a strong indication of inequality. However, in the case of strain at flow, values generated by the Interlaken device tended to be higher at large strain values compared with those generated using the



Coding

Laboratory:	**A = AAT; F = FHWA**
Device:	**P = Shedworks (IPC); T = Interlaken (ITC)**
Mix:	**95 = 9.5 mm nominal maximum aggregate size (NMAS); 19 = 19.0 mm NMAS**
Confinement:	**U = unconfined; C = confined (20 kPa confining stress)**

Figure 28. 95% confidence limits for flow number coefficient of variation at 45 °C.



Coding

Laboratory:	**A = AAT; F = FHWA**
Device:	**P = Shedworks (IPC); T = Interlaken (ITC)**
Mix:	**95 = 9.5 mm nominal maximum aggregate size (NMAS); 19 = 19.0 mm NMAS**
Confinement:	**U = unconfined; C = confined (20 kPa confining stress)**

Figure 29. 95% confidence limits for strain at flow standard deviation at 45 °C.

Shedworks device, as shown in Figure 30. The deviation from equality is caused by the two measurements having the highest values; in both cases, these represent confined data for the 9.5-mm mixture. Flow in this mixture under confinement was particularly difficult to detect. The rate of change of permanent strain had a very long trough, making it difficult to detect the minimum rate of strain using the specified algorithm. The differences are, therefore, probably the result of differences in resolution of the measuring system caused by differences in electrical noise on the signal from the LVDT.

2.3.3.3.2 Detailed Analysis of Variability. In Table 29, a formal statistical comparison of standard deviations or coefficient of variation (C.V.) is presented, based on an F-test on the ratio of s^2-values. In comparing variability for flow number, C.V. was used and treated as a normalized standard deviation, because otherwise the wide range in flow number values could give misleading conclusions concerning variability. For flow number, the variability in the data generated at FHWA was somewhat greater than that produced at AAT, while the variability for data generated using the Shedworks device was somewhat greater than that measured using the Interlaken device. The variability in the data for the 19-mm mix was greater than that produced for the 9.5-mm mix, which is not surprising, though this was not observed in the modulus data. For the strain-at-flow data, the variability generated at the two laboratories was not significantly different, but the variability for data produced using the Interlaken device was higher than that produced using the Shedworks device. For strain at flow, the confined data also showed more variability than the unconfined data, which is not surprising because

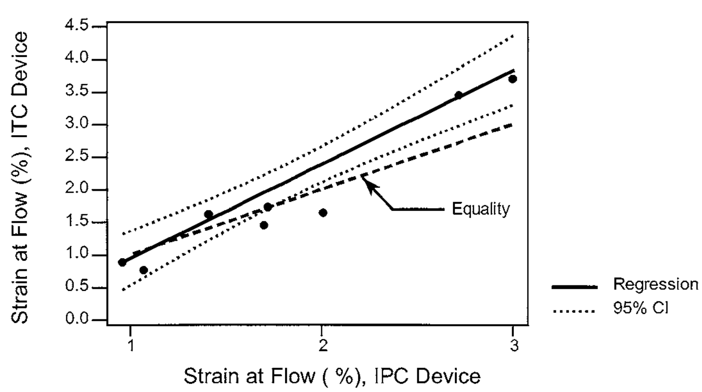


Figure 30. Comparison of strain at flow values generated using the ITC and IPC devices at 45 °C, including confined and unconfined data (R^2 = 91.9%, adj. for d.f.).

TABLE 29 Comparison of variability for flow number and strain at flow

Measurement	Comparison	Test on s or C.V.	Ratio of s^2 or C.V.^{2}	Case with Greater Variability	Prob.
Flow Number	AAT/FHWA	CV	0.71	FHWA	0.10
	IPC/ITC	CV	1.45	IPC	0.08
	9.5-mm/19-mm	CV	0.57	19-mm	0.00
	Unc./Confined	CV	1.19	---	0.26
Strain at Flow	AAT/FHWA	S	1.08	---	0.39
	IPC/ITC	S	0.59	ITC	0.02
	9.5-mm/19-mm	S	0.97	---	0.45
	Unc./Confined	S	0.25	Con.	0.00

using confinement provides additional complexity to the test and greater chance for error.

2.3.3.3.3 Detailed Analysis of Mean Response. Table 30 is a summary of statistical comparisons of mean responses for the different cases. For flow number, the mean responses for the two laboratories and two devices are not significantly different. The flow number for the 19-mm mixture tended to be significantly greater than that for the 9.5-mm mixture, and the flow number under confinement was larger than that measured with no confinement. Both of these differences should be expected. For strain at flow, there again is no difference in mean response for the two laboratories. However, the Interlaken device tended to show a somewhat larger value for strain at flow compared with the Shedworks device. The 9.5-mm mixture showed a larger value for strain at flow than the 19-mm mixture, while confinement tended to increase the strain at flow. The only discrepancy of concern is the slightly larger mean value for strain at flow measured using the Interlaken device compared with the Shedworks device. As observed for Figure 30 and the related discussion, this difference is due to a greater response in only two cases—the confined tests for the 9.5-mm mixture, and flow in this mixture was particularly difficult to detect.

2.3.3.3.4 Analysis of Test Variability. A summary of the coefficient of variation (C.V.) values is given in Table 31. This table lists coefficient of variation values for different cases (laboratories, devices, mixtures, confinement), and over-

TABLE 30 Comparison of mean response for flow number and strain at flow

Measurement	Comparison	Diff.	S(Diff.)	Case with Greater Value	Prob.
Flow Number	AAT – FHWA	-29	443	---	0.47
	IPC - ITC	-245	443	---	0.29
	9.5-mm - 19-mm	-1163	443	19-mm	0.00
	Unc. - Confined	-1715	443	Confined	0.00
Strain at Flow	AAT - FHWA	-0.10	0.144	---	0.23
	IPC - ITC	-0.31	0.144	ITC	0.02
	9.5-mm - 19-mm	1.26	0.144	9.5-mm	0.00
	Unc. - Confined	-1.03	0.144	Confined	0.00

TABLE 31 Coefficient of variation for flow number and strain at flow

Case	Flow Number			Strain at Flow		
	Unconfined	Confined	Overall	Unconfined	Confined	Overall
IPC	43.1	31.2	37.6	13.8	12.2	13.0
ITC	27.2	34.7	31.2	11.3	19.1	15.7
AAT	26.1	36.2	31.5	11.6	17.1	14.6
FHWA	43.8	29.5	37.3	13.5	14.8	14.2
9.5 mm	37.8	17.5	29.4	9.7	10.2	9.9
19 mm	34.2	43.3	39.0	15.0	20.2	17.8
Overall	36.0	33.0	34.6	12.6	16.0	14.4

all coefficient of variations, both for flow number and strain at flow. Considering all flow number data, the overall C.V. was 34.6 percent, which is quite high compared with the C.V. for modulus of 13.0 percent. The C.V. for strain at failure was lower, with an overall average of 14.4 percent. The C.V. for the flow number from this study is somewhat higher than those reported for the large number of specimens testing during the Project 9-19 research. In the Project 9-19 research, coefficients of variation for the flow number test were reported to be 23.3 percent for 12.5 mm mixtures and 28.1 percent for 37.5 mm mixtures (*17*). These coefficients of variation are for one replicate measurement only. If the flow number test in practice is to represent the average of three determinations, then the coefficient of variation of the mean would be about $34.6/\sqrt{3} = 20$ percent, which is still high. Based on these tests, additional effort is needed to improve the precision of the flow number procedure before it can be used as a specification test.

The statistical analysis of flow number test data resulted in several pertinent findings. These are summarized and discussed below:

1. The flow number and strain at flow data were in general agreement among the devices and laboratories.
2. The variability in flow number data was slightly higher at the FHWA laboratory compared with the AAT laboratory and was higher for the Shedworks device than for the Interlaken device.
3. The 19-mm mixture exhibited greater variability in flow number data than the 9.5-mm mixture.
4. The variability in strain at flow was greater for the Interlaken device compared with the Shedworks device and was also greater for confined conditions compared with unconfined conditions.
5. Most of the differences in mean response for both flow number and strain at flow were associated with different mixtures and/or different levels of confinement, which is to be expected. The one unexpected difference in mean response was for strain at flow for the two measurements on the 9.5-mm mixture in confined testing, where the Interlaken device produced significantly higher values compared with the Shedworks device.
6. The overall variability of the flow number test data was much higher than that for the dynamic modulus, and the

data from this study showed higher variability than that reported in the original Project 9-19 research. The primary difference in the flow number testing between this study and the Project 9-19 research was the algorithm used to calculate the flow number. In this study, the derivatives of the permanent strain curve were obtained using equally spaced sampling over the range of the data. In Project 9-19 logarithmic sampling was used in computing the derivatives, and these were further smoothed using a polynomial fit. This approach appears to further filter the data and provide less variable flow numbers but significantly reduces the range over which the flow number can be detected. Using the Project 9-19 algorithm and 10,000 load cycles, the flow cannot be detected beyond about 8,000 cycles.

2.3.4 Functionality

The primary objective of Project 9-29 was to stimulate the development of commercial equipment for performing the Project 9-19 simple performance tests in routine laboratory mixture design. For routine use, the functionality of the equipment is an extremely important consideration. The first-article specifications described minimum requirements for functionality, leaving ample opportunity for the manufacturers to design user-friendly systems. In fact, perceived user-friendliness was a significant factor considered in the selection of the first-article manufacturers. Areas where the manufacturers could exercise substantial design freedom are listed below:

1. **Aesthetics.** Equipment size and shape, finish, noise levels, location of operator controls.
2. **Safety Features.** Emergency stops, safety interlocks, protection for load, pressure, and temperature.
3. **Accessibility.** Location of maintenance items and calibration points.
4. **Operation.** Ease of operation, particularly specimen instrumentation, specimen insertion, and the helpful use of automation.
5. **Controls.** Logic and ease of use of the controls for temperature, load, and pressure.
6. **Software.** Function in addition to the minimum required by the specifications.

Both first-article devices were demonstrated by the research team to the project panel, several engineers and technicians from a limited number of state highway agencies, and consultants. During the project, the Shedworks equipment was also demonstrated at various events by the FHWA in their Mobile Asphalt Laboratory. This provided the opportunity for some feedback from a wider range of individuals, including engineers and technicians from state highway agencies, hot-mix contractors, consulting firms, and universities. Overall, both first-article devices received favorable reviews by the research team, project panel, and most technicians and engineers who participated in equipment demonstrations. However, representatives from several hot-mix contractors expressed concern over the complexity of the equipment and its estimated cost. The sections that follow address the major strengths and weaknesses of the functional characteristics of the two first-article devices.

2.3.4.1 Interlaken

Table 32 presents a summary of the assessment of the functional characteristics of the Interlaken Simple Performance Test Device. Although the equipment meets the minimum requirements of the specifications, there are several areas needing improvement in future production units.

The Interlaken first-article device looks very much like a prototype, primarily due to the configuration of the test chamber and the construction of the sight port. The finish of the metal work, particularly the horizontal surface around the test chamber and the chamber latch covers, also give the device a prototype appearance. Additionally, noise levels are high, and the overall size makes it difficult to use the equipment in a laboratory trailer.

The safety features on the first-article device require some improvement. The overall control of the chamber is quite good. The chamber lift is interlocked with the chamber pressure so that the chamber cannot be raised while it is pressurized. On power loss, the chamber slowly lowers onto the latches. On loss of air pressure, the chamber slowly lowers to its seated position. Although well controlled, the mass of the chamber intimidates most users. Also the emergency stop is located in a position were it can be inadvertently activated during normal operations.

Several critical operational areas require improvement. Perhaps the most important is the stability of the unique extensometer system. In addition to the apparent errors discussed in the statistical analysis section, the extensometer system exhibited an unacceptable amount of initial drift during test initiation and often had to be released and reapplied multiple times to obtain acceptable contact. This poor operational performance of the extensometer system negates the benefit afforded by an automated deformation measuring system. The extensometer system has the potential to simplify the dynamic modulus testing, but requires substantial improvement for use in production units. The configuration of the test chamber also presented operational difficulties. First, the specimen could not be seen through the sight port because there is no light inside the chamber. Although a lighted chamber would be an improvement, the engineers and technicians who performed the evaluation tests prefer a view of the specimen, instrumentation, and loading platens. The latches for the test chamber and the required position of the extensometer system result in a very confined space for inserting the specimen and platen assembly. This is particularly troublesome when confinement

TABLE 32 Rating of functional characteristics of the Interlaken simple performance test device

Criteria	Rating	Strengths	Weaknesses
Aesthetics	Needs Improvement		• Overall size • Noise level • Temperature/pressure chamber • Metal work and finish
Safety Features	Needs Improvement	• Temperature/pressure chamber control	• Chamber weight • Location of emergency stop
Accessibility	Acceptable	• Minor disassembly for calibration and maintenance	
Operational	Needs Improvement	• Rugged hydraulic system • Quick heating	• Stability of extensometer system • Specimen is not visible • Cramped specimen test area • Marginal cooling capacity • Leak detector system • Temperature/pressure chamber O-ring
Controls	Needs Improvement		• High standard errors for 45 °C, 0.1 Hz data • Lack of fine control for ram • Occasional "run-time error" during testing
Software	Good	• Easy to use and learn • Summary dynamic modulus page	• Awkward process for changing tests

is used and the hoses for the leak detection system need to be attached. Other more minor operational weaknesses in the device include the following:

- **Marginal cooling capacity**. Although the system has sufficient capacity to return to the specified test temperature within the time stated in the specifications, it takes a long time initially to equilibrate the test chamber to temperatures below room temperature.
- **Poor leak detection system.** The leak detection system was poorly assembled and required constant repair of joints and hoses.
- **Chamber O-ring seal.** The O-ring seal at the bottom of the chamber is easily damaged and often sticks to the chamber when lifted.

The equipment controls also require additional refinement and troubleshooting. Very high standard errors were observed for the unconfined 45 °C dynamic modulus data. Closer investigation revealed that for these soft conditions, the hydraulic control system actually applies loading at 0.097 Hz. This difference in loading rate results in very high standard errors. The actuator lacks a fine stroke control for initially seating the specimen prior to the start of testing. Occasionally a "run time error" is experienced during operation, which requires restarting the UniTest program.

Overall, the UniTest software, as configured for the simple performance tests, was found to be very logical and easy to use. Users found the summary dynamic modulus page, which shows test data and quality indicators for the entire frequency sweep extremely useful. The only weakness noted in the software is that it is somewhat awkward to change between the three types of simple performance tests.

2.3.4.2 Shedworks

Table 33 presents a summary of the assessment of the functional characteristics of the Shedworks Simple Performance Test Device. This equipment received high ratings for its appearance and many operational characteristics, but still requires some improvements for future production units.

The Shedworks device does not look like a first-article. Operators and observers were impressed with the quality of the metal work, the quality of the machine work, and the overall finish of the device. They also commented very positively on its compact size and relatively quiet operation. The ability to move the hydraulic power supply to a remote location is another strength of the Shedworks design.

The device received mixed reviews for its safety features. It includes a hands clear safety feature that requires the operator to hold two buttons to close the test chamber. Other safety features, however, require improvement. The chamber lift is not interlocked with pressure, allowing the operator to open the chamber while it is pressurized. On loss of power, the chamber closes too rapidly, and the emergency stop is located in a position where it can be inadvertently activated during testing.

The Shedworks device was found to be very user-friendly. The automated gauge point system is well designed and worked extremely well. This system combined with the clip-on LVDTs produced a very rugged, practical specimen deformation measuring system. The chamber provided a view of

TABLE 33 Rating of functional characteristics of the Shedworks simple performance test device

Criteria	Rating	Strengths	Weaknesses
Aesthetics	Good	• Compact size • Ability to separate hydraulic pump from test chamber • Noise level • Metal work and finish	
Safety Features	Needs Improvement	• Hands clear buttons	• Can open chamber when pressurized • Closure rate on power loss • Location of emergency stop
Accessibility	Acceptable	• Minor disassembly for calibration and maintenance	
Operational	Good	• Automated gauge point attachment • LVDT clip attachment system • Specimen visibility • Heating/cooling capacity	
Controls	Needs Improvement		• Occasional system lock-up upon completion of testing • Some instability of hydraulics when cold
Software	Needs Improvement		• Complicated by optional IPC analyses • Too many significant digits on screen readouts • Layering of windows

the specimen, instrumentation, and loading platens during testing, which operators and observers found to be essential. Finally, the temperature control system has sufficient excess capacity to allow for very rapid heating and cooling of the chamber.

The Shedworks first-article device requires improvements in machine control and some software refinements for production units. The most urgent improvement is to remedy the situation where the control software locks up during the flow number testing when the maximum number of load cycles is reached. When this situation occurs, the software must be restarted. Instability of the hydraulics was observed when the system was cold. This instability was characterized by a rapid, uncontrolled oscillation of the loading actuator and was only observed on start-up when the hydraulic oil was cold.

The software used in the Shedworks first-article device also requires further refinement. Although the software was found to be user-friendly and relatively easy to learn, the optional IPC data analyses must be removed from the software for production units to eliminate confusion caused by multiple data analysis methods. Also, the software displays too many significant digits, giving the impression that there is a large amount of noise in the transducer signals and making it difficult to assess the status of the transducers quickly. Finally, the layering of the windows in the software sometimes covers important control information. For example, the LVDT levels window is sometimes not visible during testing. Having this window as a bar that is constantly displayed would allow operators to quickly view the status of the transducers at any time.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

In Phase II of Project 9-29, a detailed purchase specification was developed for equipment to perform the three Project 9-19 simple performance tests: dynamic modulus, flow number, and flow time. The specification was used to procure two simple performance test systems from Interlaken Technology Corporation and Shedworks, Incorporated. These two systems were similar in several critical design areas. Both are relatively small bottom-loading servo-hydraulic devices with an automated test chamber that serves as both the confining pressure cell and the environmental chamber. The primary differences between the devices are the specific methods used to heat and cool the chamber and the specimen-mounted deformation measuring system used exclusively in the dynamic modulus test. The Interlaken device uses heating elements and an air-driven vortex cooler to control temperature in the chamber. The specimen deformation measuring system is a unique extensometer system that is held against the specimen with small pneumatic actuators. The Shedworks device circulates conditioned air through the test chamber. The specimen deformation measuring system is a refined version of the glued contact point system used in the original Project 9-19 research.

An extensive evaluation of these two devices was undertaken in Phase II of Project 9-29. This evaluation included specific testing to ensure that the devices were in compliance with the specifications and properly calibrated and an extensive mixture testing program to evaluate mechanical properties measured with the two devices and to assess the functionality of the devices. The overall findings from the evaluation are as follows:

1. Both devices meet the requirements of the first-article specifications and are reasonably user-friendly. Both have functional deficiencies that need to be addressed in future production units.
2. For the dynamic modulus test, the evaluation testing revealed significant differences in both the mean and the variability of dynamic modulus data collected with the two devices. These differences appear to be associated with differences in the specimen-mounted deformation measuring system.
3. The overall variability of the dynamic modulus test was found acceptable for specification testing, and the variability is expected to decrease as limits are placed on the quality indicators developed in this project for the dynamic modulus test.
4. For the flow number test, the evaluation testing showed no significant difference in flow numbers obtained with the two devices.
5. The overall variability of the flow number test was found to be too high for specification testing. One potential source of variability that could be improved is the algorithm used to select the flow point.

The remainder of this chapter discusses specific changes to the specification and the two first-article devices that are required based on the results of the evaluation testing. At the end of the chapter, revisions to the Project 9-19 test protocols to adapt them to the simple performance test system are discussed.

3.1 FIRST-ARTICLE SPECIFICATION MODIFICATIONS

Table 34 presents a summary of the modifications to the first-article specification required based on the findings of the evaluation testing. This table lists each of the major sections of the specification, issues revealed by the evaluation testing, and the modifications, if any, that are required to address these issues and improve the specification. The sections that follow discuss each of the modifications in detail. These modifications were incorporated in the final specification, which is included in Appendix D.

3.1.1 Section 1.0 Summary

The summary section of the first-article specification referred to three Project 9-19 Draft Test Protocols available at the beginning of Project 9-29. NCHRP later published updates of these test methods in *NCHRP Report 465*. The summary section of the specification was revised to refer to the test methods published in *NCHRP Report 465*. Specific test methods for use with the Simple Performance Test System based on these methods were included as appendices to the specification.

3.1.2 Section 7.0 Load Measuring System

Requirement 7.2 of this section places requirements on the maximum error of the load measuring system over a range of

TABLE 34 Summary of first-article specification modifications

Section	Topic	Issue	Modification
1.0	Summary	Project 9-19 Test Protocols not current	Modify based on NCHRP Report 465
2.0	Definitions	None	None
3.0	Test Specimens	None	None
4.0	Simple Performance Test System	None	None
5.0	Compression Loading Machine	None	None
6.0	Loading Platens	None	None
7.0	Load Measuring System	Error specified in 7.2 is ambiguous when machines exceeding capacity are provided	Modify 7.2 using capacities given in requirement 5.1.
8.0	Deflection Measuring System	None	None
9.0	Specimen Measuring System	Does not address potential for slip of measuring system	Specify glued gage point system as standard. Alternatives permitted if shown to have similar performance as standard.
10.0	Confining Pressure System	Does not require view of specimen and instrumentation	Add requirement that pressure cell must provide visibility of specimen, platens, and instrumentation.
11.0	Environmental Chamber	Does not require view of specimen and instrumentation	Add requirement that environmental chamber must provide visibility of specimen, platens, and instrumentation.
12.0	Computer Control and Data Acquisitio n	Does not require summary dynamic modulus output	Add requirement for a summary dynamic modulus output.
13.0	Computations	Project 9-29 flow algorithm produces more variable flow number data than Project 9-19.	No change at this time. Recommend study to further refine the flow number algorithm.
14.0	Calibration and Verification of Dynamic Performance	Stiffness of verification device not specified	Specify stiffness of verification device.
15.0	Verification of Normal Operation	None	None
16.0	Documentation	None	None
17.0	Warranty	None	None

2 to 100 percent of the capacity of the machine. Both first-article devices that were supplied had capacities exceeding those listed in the specification for the machine; therefore, it was unclear whether the specification requirement applied to the listed capacities or the machine capacity as supplied. As written, a manufacturer supplying a larger machine than needed would be held to a less stringent maximum error at low load levels. Because very low loads are used in the dynamic modulus test at higher temperatures, manufacturers should not be allowed to circumvent the maximum error requirement by supplying machines with excess capacity. The language of this section was revised to require the error tolerance over a range of 2 to 100 percent of the capacities listed in Requirement 5.2.

3.1.3 Section 9.0 Specimen Deformation Measuring System

The primary finding from the statistical analysis of the dynamic modulus test data was that there was a difference in dynamic modulus test data measured using the two first-article devices. The Interlaken device consistently produced higher dynamic modulus values than the Shedworks device. Errors caused by slip between the specimen and the deformation measuring system are the likely cause of this difference. The first-article specification does not address this potential problem. By design, the first-article specification allowed a wide range of deformation measuring systems to be considered by potential manufacturers. This was done to encourage innovation in the design of this critical subsystem to provide user-friendly systems. Both manufacturers provided user-friendly systems, but the Interlaken approach was clearly more innovative.

Two approaches were considered for strengthening the equipment specification in this critical area. The first involves the development of standard specimens that can be used to evaluate systematic errors of this type for a wide range of deformation measuring systems. The design of the standard specimens must be carefully considered such that they span the range of moduli and phase angles measured with asphalt concrete and have surface texture similar to the cored simple performance test specimens. Additionally, an organizational structure is needed to certify the standards and evaluate various manufacturer-developed systems. The second approach involves standardizing the specimen-mounted deformation system. In this approach, a generic version of the glued gage point system supplied by Shedworks would be selected as the standard and included in the specifications. To encourage manufacturers to still consider innovative designs, other designs that measure over the middle 70 mm (2.75 in) of the specimen would be acceptable, provided the manufacturer can verify that the system provides equivalent data. This type of verification would involve an experiment similar to that conducted in the project where specimens are instrumented with the standard system and the proposed system and tested.

After considerable discussion, the second approach was selected for two reasons. First, the data that the NCHRP Project 9-19 researchers used to establish the dynamic modulus criteria were collected with a glued gage point system. Thus, the standard glued gage point system would minimize any errors between data collected with the production equipment and the future specification criteria. Second, implementation of the standard measuring system approach will be much quicker than the development of standard specimens and an organizational structure to perform evaluations of various measuring systems.

In the final specification, Section 9 was modified to include a generic sketch of a glued gage point system similar to that used by Shedworks. Section 9 also specifies the following critical elements of the system:

1. Gauge point contact area,
2. Distance from specimen to transducer,
3. Mass of mounting system and transducer, and
4. Transducer spring force.

Language was also added to permit alternatives to this system provided data are submitted showing that the alternatives have accuracy comparable with the standard system when testing asphalt concrete specimens.

3.1.4 Section 10.0 Confining Pressure System and Section 11.0 Environmental Chamber

These sections of the first-article specification did not require the specimen and instrumentation to be visible to the operator. The evaluation testing and the various equipment demonstrations revealed that the ability to see the specimen and the instrumentation is a desirable feature for the system. The operator must have this visibility to confirm that the deformation measuring system is in proper contact with the specimen and that the appropriate platen arrangement is in place and to make sure that the specimen has not deformed to the point that equipment may be damaged. For the final specification, these sections were revised to include language that requires the specimen, the specimen-mounted deformation measuring system, and the end platens to be visible to the operator during testing.

3.1.5 Section 12.0 Computer Control and Data Acquisition

The first-article specification did not require a summary output of the frequency sweep data from the dynamic modulus test. Individual reports were specified for each frequency. During the evaluation, the summary report provided by the Interlaken software was found to be very useful. In the final specification, the output requirements for the dynamic modulus test were revised to include a summary report in addition to the detailed report required for each frequency.

3.1.6 Section 13.0 Computations

One of the findings of the evaluation testing was that flow number data collected with the two first-article devices had higher variability than data collected during Project 9-19. The likely cause of this variability is the algorithm developed in Project 9-29 to detect the flow number. The Project 9-29 algorithm samples the specimen permanent deformations on each cycle, computes the rate of permanent deformation using a central difference algorithm and a user-selected sampling interval, and then smoothes these rates using a moving average filter. This protocol was developed because the Project 9-19 test protocols did not provide a specific flow number algorithm and the proposed Project 9-19 algorithm for flow time used a minimum amount of data and two polynomial curve fits. Assuming that the Project 9-19 flow time algorithm was also applied to the flow number tests, it appears that the use of logarithmic spaced data combined with curve fitting reduces the effect of signal noise on the flow number data. However, this algorithm limits the range of data over which the flow number can be detected. For a test conducted to 10,000 load cycles, the Project 9-19 algorithm cannot detect flow if it occurs beyond 8,000 cycles. Additional study of various flow algorithms is needed; however, until it is completed, no change is recommended for the final specification. Data collected using the first-article algorithm can be manipulated outside the control program to perform the flow analysis described in the Project 9-19 test protocols.

3.1.7 Section 14.0 Calibration and Verification of Dynamic Performance

In addition to describing equipment calibration requirements, this section of the specification introduces a procedure to verify that the equipment measures accurately under dynamic loading conditions. This is accomplished by loading a proving ring or similar elastic device and comparing load versus deformation data measured statically and dynamically. The specifications require the manufacturer to provide the proving ring so that it can be tailored to the geometry of the simple performance test equipment. One issue uncovered during the specification compliance testing was that the two manufacturers supplied proving rings with significantly different stiffnesses. This resulted in the verifications being performed over different deformation ranges. Given that the simple performance test device is designed to operate at strain levels between 75 and 125 μstrain, the verification device should cover this deformation level. This can be done by specifying that the elastic device will have a deflection of 0.007 mm (0.0003 in.) at a load of 1.2 kN (0.25 kips). This requirement was added to the final specification.

3.2 ACCEPTABILITY OF FIRST-ARTICLE DEVICES

One of the objectives of the evaluation testing was to make recommendations concerning the acceptability of the first-article designs for use in future production units. Three categories were identified in the Project 9-29 Research Problem Statement: approved, conditionally approved, or disapproved. The recommendations for the two devices are discussed below.

3.2.1 Interlaken

Based on the results of the evaluation testing and the final specification, the Interlaken device was disapproved. The primary reason for this recommendation was the poor performance of the unique extensometer system used in the dynamic modulus test. The evaluation testing revealed a significant bias toward higher dynamic moduli for this system that appears to be related to slip at the contact points. In addition to the bias, the extensometer system exhibited an unacceptable amount of drift on test initialization and often had to be released and reapplied multiple times to obtain acceptable contact. This poor operational performance of the extensometer system negates the benefit afforded by an automated deformation measuring system. The extensometer system has the potential to simplify the dynamic modulus testing, but requires substantial improvement and re-testing before it can be considered acceptable for use in production units. Other items that need to be addressed by Interlaken in future production units to meet the final specification include the following:

1. **Configuration of the test chamber.** A test chamber that allows the operator to view the specimen, the deformation measuring system, and the end platens must be provided. The current chamber does not meet the revised requirements included in the final specification.
2. **Leak detection system.** The leak detection system requires constant maintenance to eliminate leaks at joints. A properly designed system is needed in future production units.
3. **Hydraulic control.** The poor performance of the loading system for 0.1 Hz loading of soft specimens must be improved. The system must be capable of performing tests at the user-selected loading rate. Additionally, a fine control for the ram is needed to allow operators to initially position the loading ram at the beginning of the test.
4. **Software errors.** The control software needs to be further refined to eliminate the run-time errors experienced during the evaluation testing.
5. **Software upgrades.** Interlaken must be prepared to issue software upgrades for production units based on changes that may occur to the data analysis algorithms. A change to the flow time and flow number algorithms is likely in the near future.
6. **Verification device.** A verification device meeting the stiffness requirements of the final specification must be designed and provided with future production units.

In addition to these required changes, Interlaken should seriously consider addressing the other functional weaknesses identified in Section 2.3.4.1. These were based on information provided by the engineers and technicians who operated the equipment and potential future users who inspected the equipment during demonstrations. Correcting these weaknesses represents an excellent opportunity for further improving the equipment.

3.2.2 Shedworks

Based on the results of the evaluation testing and the final specification, the Shedworks device was conditionally approved. This conditional approval requires the following items to be addressed:

1. **Safety features.** Safety features for the testing chamber must be improved for production units. The revised safety features must ensure that the chamber cannot be opened while pressurized and that its closure rate on power loss is slow enough to avoid injury to the operator.
2. **Control.** The programming error that results in system lock-up upon completion of the flow number and flow time tests must be identified and resolved.
3. **Software.** For future production units, the optional IPC analyses must be removed from the software and a dynamic modulus summary screen and report must be added.
4. **Software upgrades.** Shedworks must be prepared to issue software upgrades for production units based on changes that may occur to the data analysis algorithms. A change to the flow time and flow number algorithms is likely in the near future.

In addition to these required actions, Shedworks should seriously consider addressing the other functional weaknesses identified in Section 2.3.4.2. These were based on information provided by the engineers and technicians who operated the equipment and potential future users who inspected the equipment during demonstrations. Correcting these weaknesses represents an excellent opportunity for further improving the equipment.

3.3 DRAFT TEST METHODS FOR THE SIMPLE PERFORMANCE TEST SYSTEM

The final section of this chapter discusses draft test methods that were developed for use with the Simple Performance Test System. These test methods are included in Appendix D as annexes to the final equipment specification. These methods are adaptations of the following four Project 9-19 Test Protocols for specific use with the Simple Performance Test System specified in this project:

1. Test Method For Static Creep/Flow Time of Asphalt Concrete Mixtures in Compression,
2. Test Method for Repeated Load Testing of Asphalt Concrete Mixtures in Uniaxial Compression,
3. Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Permanent Deformation, and
4. Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Fatigue Cracking

The sections that follow summarize the modifications of the Project 9-19 Test Protocols that were made to tailor the test protocols to the Simple Performance Test System. First, recommendations for two new standard practice documents are discussed:

1. Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor and
2. Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System

These recommendations are followed by a summary of the modifications to the Project 9-19 Test Protocols. The draft test methods assume that the two standard practice documents listed above will be developed in the future.

3.3.1 Specimen Fabrication

Section 7 in all of the Project 9-19 Test Protocols addresses the fabrication of test specimens. A separate standard practice for the fabrication of performance test specimens using the Superpave gyratory compactor should be developed. This document should cover the equipment and procedures for preparing specimens, as well as the allowable air void gradient, dimensional tolerances, and air void tolerances for the finished specimens. Information developed in Project 9-19 on the preparation of field-sampled mixtures to a specific target air void content should also be included in this practice. Moving the specimen fabrication to a separate document would reduce redundancy in the test methods, ensure consistency of the specimen fabrication process between test methods, and make it easier to update the test methods and the specimen fabrication process in the future. Each test method should still include a section on test specimens, but the information included in this section should be limited to the following:

1. Reference to Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor for details on specimen preparation,
2. Required number of specimens for the test, and
3. Nominal size of the test specimen.

A draft of this standard practice should be prepared as part of the evaluation of the automated specimen fabrication equipment.

3.3.2 Permanent Deformation and Fatigue Evaluation

A standard practice for permanent deformation and fatigue evaluation of HMA using the Simple Performance Test System is also needed to complement the Simple Performance Test System and AASHTO MP2, "Specification for Superpave Volumetric Mix Design." This Standard Practice should address the following:

1. Computation of the effective pavement temperatures for a specific project site,
2. Target air void content for permanent deformation and fatigue analyses,
3. Type of laboratory aging required for permanent deformation and fatigue analyses,
4. Deviatoric and confining stress levels to be used in permanent deformation analyses,
5. Loading frequencies to be used in the dynamic modulus test and
6. Criteria for differentiating acceptable versus unacceptable performance.

This standard practice document would gather the engineering analysis associated with the use of the Simple Performance

Test System into a single document that is separate from the test methods. This would simplify the test methods and make it easier to update the test methods and engineering analysis.

3.3.3 Draft Simple Performance Test System Test Methods

Three draft test methods for use with the Simple Performance Test System were developed and included as annexes to the final specification in Appendix D. These draft test methods are adaptations of the Project 9-19 Test Methods to the specific capabilities of the Simple Performance Test System. Tables 35, 36, and 37 present a section-by-section summary of the modifications to the Project 9-19 Test Methods that were made to adapt these methods to the Simple Performance Test System. Because of the standardization of the testing equipment and the data acquisition and analysis software, the Simple Performance Test System Test Methods are shorter and less detailed than the corresponding Project 9-19 Test Method.

TABLE 35 Modifications to the Project 9-19 flow time test protocol to produce the simple performance test system flow time test method

Section	Topic	Modifications
1	Scope	Minor editorial revisions to reflect specific loading and measurement capabilities of the Simple Performance Test System.
2	Referenced Documents	Revised to refer only to the two new recommended Standard Practices and the Equipment Specification.
3	Definitions	1. Revised flow time definition to be consistent with definition in Equipment Specification. 2. Deleted definition of compliance. 3. Deleted definition of Effective Temperature.
4	Summary	Minor editorial revisions to simplify summary and make it consistent with terminology used in the Equipment Specification.
5	Significance and Use	Editorial revisions to describe use of flow time with criteria to judge mix acceptability or flow time to rank expected mixture performance.
6	Apparatus	1. Modified to reference Equipment Specification. 2. Added separate environmental chamber for conditioning specimens. 3. Modified to use thin Teflon sheet to reduce friction.
7	Test Specimens	1. Revised to reference new Standard Practice for specimen fabrication. 2. Requires average from three specimens. (Subject to change based on analysis of criteria and test variability).
8	Test Specimen Instrumentation	Deleted. Not needed with Simple Performance Test System.
9	Procedure	1. Changed to Section 8. 2. Modified for specific steps required with the Simple Performance Test System.
10	Calculations	1. Changed to Section 9. 2. Modified to reflect that flow time is computed by the Simple Performance Test Software. 3. Added computation of average and standard deviation of three tests.
11	Reporting	1. Changed to Section 10. 2. Modified to reflect standard report is generated by software.

TABLE 36 Modifications to the Project 9-19 flow number test protocol to produce the simple performance test system flow number test method

Section	Topic	Modifications
1	Scope	Minor editorial revisions to reflect specific loading and measurement capabilities of the Simple Performance Test System.
2	Referenced Documents	Revised to refer only to the two new recommended Standard Practices and the Equipment Specification.
3	Definitions	1. Revised permanent deformation definition. 2. Revised flow number definition to be consistent with definition in Equipment Specification. 3. Deleted definition of Effective Temperature.
4	Summary	Minor editorial revisions to simplify summary and make it consistent with terminology used in the Equipment Specification.
5	Significance and Use	Editorial revisions to describe use of flow number with criteria to judge mix acceptability or flow number to rank expected mixture performance.
6	Apparatus	1. Modified to reference Equipment Specification. 2. Added separate environmental chamber for conditioning specimens. 3. Modified to use thin Teflon sheet to reduce friction.
7	Test Specimens	1. Revised to reference new Standard Practice for specimen fabrication. 2. Requires average from three specimens. (Subject to change based on analysis of criteria and test variability.)
8	Test Specimen Instrumentation	Deleted. Not needed with Simple Performance Test System.
9	Procedure	1. Changed to Section 8. 2. Modified for specific steps required with the Simple Performance Test System.
10	Calculations	1. Changed to Section 9. 2. Modified to reflect that flow number is computed by the Simple Performance Test Software. 3. Added computation of average and standard deviation of three tests.
11	Reporting	1. Changed to Section 10. 2. Modified to reflect standard report is generated by software.

TABLE 37 Modifications to the Project 9-19 dynamic modulus test protocol to produce the simple performance test system dynamic modulus test method

Section	Topic	Modifications
1	Scope	Minor editorial revisions to reflect specific loading and measurement capabilities of the Simple Performance Test System.
2	Referenced Documents	Revised to refer only to the two new recommended Standard Practices and the Equipment Specification.
3	Definitions	1. Revised dynamic modulus definition to be consistent with definition in Equipment Specification. 2. Deleted definition of complex modulus. 3. Deleted definition of linear viscoelastic. 4. Deleted definition of effective temperature.
4	Summary	Minor editorial revisions to simplify summary and make it consistent with terminology used in the Equipment Specification.
5	Significance and Use	Editorial revisions to describe use of dynamic modulus with criteria to judge mix acceptability or dynamic modulus to rank expected mixture performance.
6	Apparatus	1. Modified to reference Equipment Specification. 2. Added separate environmental chamber for conditioning specimens. 3. Modified to use thin Teflon sheet to reduce friction.
7	Test Specimens	1. Revised to reference new Standard Practice for specimen fabrication. 2. Requires average from three specimens.
8	Test Specimen Instrumentation	1. Revised to address standard glued gage point system. 2. Gage length modified to 70 mm.
9	Procedure	Modified for specific steps required with the Simple Performance Test System.
10	Calculations	1. Re-titled Calculations and Data Quality Indicators. 2. Added guidelines for data quality indicators. 3. Modified to reflect that dynamic modulus and phase angle are computed by the Simple Performance Test Software. 4. Added computation of average and standard deviation of three tests.
11	Reporting	Modified to reflect standard report is generated by software.

CHAPTER **4**

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Phase II of Project 9-29 was extremely successful. A detailed purchase specification was developed for equipment to perform the three Project 9-19 simple performance tests: dynamic modulus, flow number, and flow time. Input from both potential users and manufacturers was included in the specification.

The specification generated a significant amount of interest from manufacturers. In response to a request for proposals issued under Project 9-29, four manufacturers proposed first-article equipment designs, and two were selected for evaluation. These systems, produced by Interlaken Technology Corporation and Shedworks, Incorporated, are similar in several critical design areas. Both are relatively small bottom-loading servo-hydraulic devices with an automated test chamber that serves as both the confining pressure cell and the environmental chamber. The primary differences with the devices are the specific methods used to heat and cool the chamber and the specimen-mounted deformation measuring system used exclusively in the dynamic modulus test. The Interlaken device uses heating elements and an air-driven vortex cooler to control temperature in the chamber. The specimen deformation measuring system is a unique extensometer system that is held against the specimen with small pneumatic actuators. The Shedworks device circulates conditioned air through the test chamber. The specimen deformation measuring system is a refined version of the glued contact point system used in the original Project 9-19 research.

An extensive evaluation of these two devices was also undertaken in Phase II of Project 9-29. This evaluation included specific testing to ensure that the devices were in compliance with the specifications and properly calibrated and an extensive mixture testing program to evaluate mechanical properties measured with the two devices and to assess the functionality of the devices. The overall findings from the evaluation are as follows:

1. Both devices meet the requirements of the first-article specifications and are reasonably user-friendly. Both have functional deficiencies that need to be addressed in future production units.
2. For the dynamic modulus test, the evaluation testing revealed significant differences in both the mean and the variability of dynamic modulus data collected with the two devices. These differences appear to be associated with differences in the specimen-mounted deformation measuring system.
3. The overall variability of the dynamic modulus test was found acceptable for specification testing, and the variability is expected to decrease as limits are placed on the quality indicators developed in this project for the dynamic modulus test.
4. For the flow number test, the evaluation testing showed no significant difference in flow numbers obtained with the two devices.
5. The overall variability of the flow number test was found to be too high for specification testing. One potential source of variability that could be improved is the algorithm used to select the flow point.

The equipment specification was revised based on these findings. The most significant revision addressed the specimen deformation measuring system for the dynamic modulus test. A generic glued gage point system was included in the specification as the standard system with the option to use other systems if they can be shown to produce the same measured specimen responses. Test methods for performing the flow time, flow number, and dynamic modulus tests with the Simple Performance Test System were developed. The test methods are adaptations of the Project 9-19 Test Methods to the specific capabilities of the Simple Performance Test System.

Based on the findings of the evaluation testing and the revised specification requirements, the Interlaken Simple Performance Test System was disapproved. The performance of the unique extensometer system was the primary deficiency with this system. The Shedworks Simple Performance Test System was conditionally approved. This device requires minor improvements in several functional areas.

4.2 RECOMMENDATIONS

When the criteria development and validation are completed in Project 9-19, procurement of production Simple Performance Test Systems can begin using the final specification developed in Project 9-29. The specification and test methods should be reviewed based on the final recommendations of Project 9-19. It is anticipated that only minor revisions to the specification and test methods will be required.

Manufacturers should be encouraged to continue development of innovative deformation sensors for the dynamic modulus test. Although the performance of the Interlaken prototype was found unacceptable, the results, considering the limited design and fabrication time allowed in Project 9-29, are encouraging. A rapid specimen fabrication system, and automated deformation sensors of this type, will be needed to use the dynamic modulus test in quality control operations.

Additional refinement of the flow number test is needed if it is to be used as a specification test. Coefficients of variation for this test from this study and Project 9-19 are too high for use in a specification. The algorithm used to compute the flow number is a likely source of a significant amount of the test variability. Various flow number algorithms should be investigated using the data already collected in this project and Project 9-19 to determine an optimum flow number algorithm.

Work should be initiated on the development of two standard practice documents to complement the simple performance test methods. The first of these, Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor, would address the fabrication of simple performance test specimens. This document should cover the equipment and procedures for preparing specimens, as well as the allowable air void gradient, dimensional tolerances, and air void tolerances for the finished specimens. Information developed in Project 9-19 on the preparation of field-sampled mixtures to a specific target air void content should also be included in this practice. A draft of this standard practice should be developed as part of the automated specimen fabrication evaluation to be completed in Project 9-29. The second, Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System, would address determination of testing condition for a specific site as well as the application of the criteria differentiating acceptable versus unacceptable performance. A draft of this standard practice should be developed when Project 9-19 is completed.

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APPENDIX A

FIRST-ARTICLE EQUIPMENT SPECIFICATIONS

NCHRP
Project 9-29

Simple Performance Tester for Superpave Mix Design

First-Article Equipment Specifications For The Simple Performance Test System

LIMITED USE DOCUMENT

The information contained in this Document is regarded as fully privileged. Dissemination of information included herein must be approved by the NCHRP.

November 19, 2001
Includes Amendment 1

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ADVANCED ASPHALT TECHNOLOGIES
ENGINEERING SERVICES FOR THE ASPHALT INDUSTRY

Table of Contents

1.0 Summary

1.1 This specification describes the requirements for a testing system to conduct the following National Cooperative Highway Research Program (NCHRP) Project 9-19 simple performance tests:

Protocol W1: Simple Performance Test for Permanent Deformation Based Upon Static Creep / Flow Time Strength of Asphalt Concrete Mixtures.

Protocol W2: Simple Performance Test for Permanent Deformation Based Upon Repeated Load Test of Asphalt Concrete Mixtures.

Protocol X1: Simple Performance Test for Permanent Deformation Based Upon Dynamic Modulus of Asphalt Concrete Mixtures.

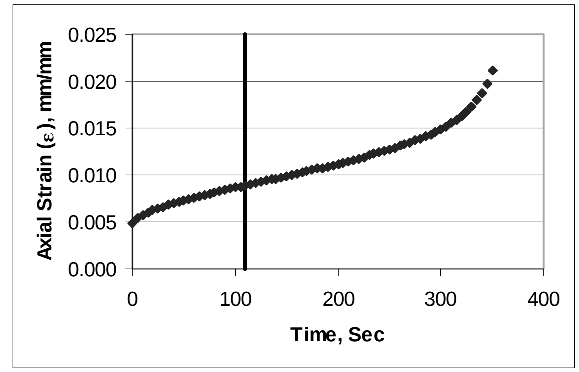
The Project 9-19 Draft Test Protocols are reproduced in Annex A, B and C of this equipment specification to provide manufacturers with a description of the proposed test procedure.

Note: This equipment specification represents a revision of the equipment requirements contained in the Project 9-19 Draft Test Protocols. The requirements of this specification supersede those contained in Project 9-19 Draft Test Protocols.

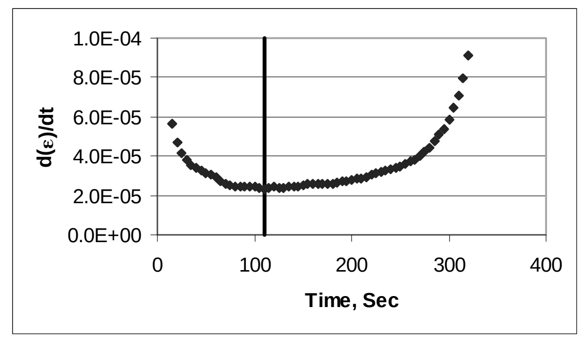
1.2 The testing system shall be capable of performing three compressive tests on nominal 100 mm (4 in) diameter, 150 mm (6 in) high cylindrical specimens. The tests are briefly described below.

1.3 **Flow Time Test.** In this test, the specimen is subjected to a constant axial compressive load at a specific test temperature. The test may be conducted with or without confining pressure. The resulting axial strain is measured as a function of time and numerically differentiated to calculate the flow time. The flow time is defined as the time corresponding to the minimum rate of change of axial strain. This is shown schematically in Figure 1.

1.4 **Flow Number Test.** In this test, the specimen, at a specific test temperature, is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function of time and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain. This is shown schematically in Figure 2.

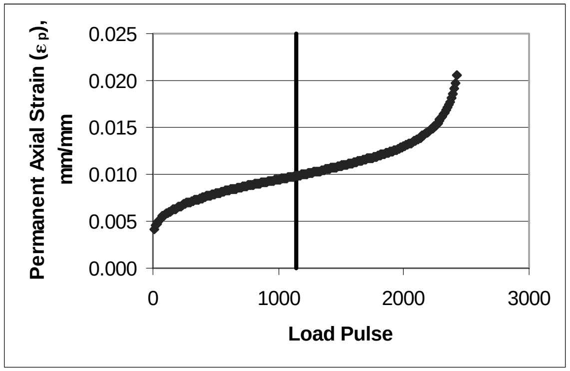


a. Axial Strain in Flow Time Test.

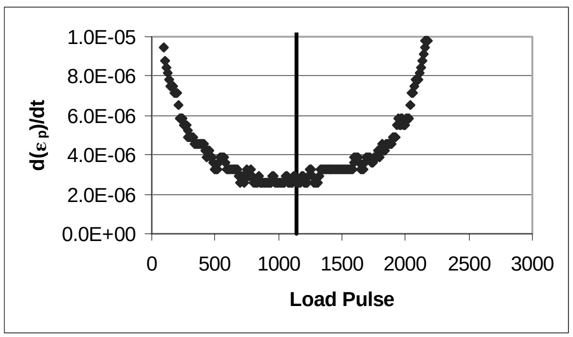


b. Rate of Change of Axial Strain.

Figure 1. Schematic of Flow Time Test Data.



a. Permanent Axial Strain in Flow Number Test.



b. Rate of Change of Permanent Axial Strain.

Figure 2. Schematic of Flow Number Test Data.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

1.5 **Dynamic Modulus Test.** In this test, the specimen, at a specific test temperature, is subjected to controlled sinusoidal (haversine) compressive stress of various frequencies. The applied stresses and resulting axial strains are measured as a function of time and used to calculate the dynamic modulus and phase angle. The dynamic modulus and phase angle are defined by Equations 1 and 2. Figure 3 presents a schematic of the data generated during a typical dynamic modulus test.

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \quad (1)$$

$$\Phi = \frac{T_i}{T_p}(360) \quad (2)$$

Where:

$|E^*|$ = dynamic modulus
Φ =phaseangle, degree
σ_o = stress amplitude
ε_o = strain amplitude
T_i = time lag between stress and strain
T_p = period of applied stress

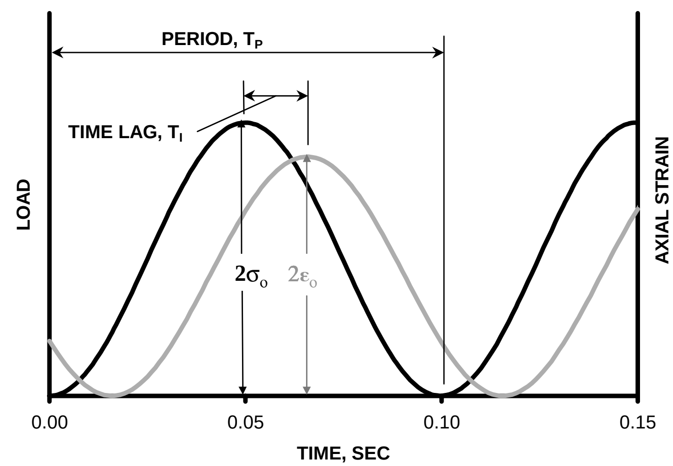


Figure 3. Schematic of Dynamic Modulus Test Data.

2.0 Definitions

2.1 *Flow Time.* Time corresponding to the minimum rate of change of axial strain during a creep test.

2.2 *Flow Number.* The number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test.

2.3 *Dynamic Modulus.* Ratio of the stress amplitude to the strain amplitude for asphalt concrete subjected to sinusoidal loading (Equation 1).

2.4 *Phase Angle*. Angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled stress test (Equation 2).

2.5 *Resolution.* The smallest change of a measurement that can be displayed or recorded by the measuring system. When noise produces a fluctuation in the display or measured value, the resolution shall be one-half of the range of the fluctuation.

2.6 *Accuracy.* The permissible variation from the correct or true value.

2.7 *Error.* The value obtained by subtracting the value indicated by a traceable calibration device from the value indicated by the measuring system.

2.8 *Confining Pressure.* Stress applied to all surfaces in a confined test.

2.9 *Deviator Stress.* Difference between the total axial stress and the confining pressure in a confined test.

2.10 *Dynamic Stress*. Sinusoidal deviator stress applied during the Dynamic Modulus Test.

2.11 *Dynamic Strain*. Sinusoidal axial strain measured during the Dynamic Modulus Test.

3.0 Test Specimens

3.1 Test specimens for the Simple Performance Test System will be cylindrical meeting the following requirements.

Item	Specification	Remarks
Average Diameter	100 mm to 104 mm	
Standard Deviation of Diameter	1.0 mm	See note 1
Height	147.5 mm to 152.5 mm	
End Flatness	0.3 mm	See note 2
End Parallelism	1 degree	See note 3

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

Notes:

1. Measure the diameter at the center and third points of the test specimen along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 1.0 mm. The average diameter, reported to the nearest 1 mm, shall be used in all material property calculations.
2. Check this requirement using a straight edge and feeler gauges.
3. Check this requirement using a machinists square and feeler gauges.

Note: Test specimens will be fabricated using separate equipment. This information is provided for design of the Simple Performance Test system.

4.0 Simple Performance Test System

4.1 The Simple Performance Test System shall be a complete, fully integrated testing system meeting the requirements of these specifications and having the capability to perform the Flow Time, Flow Number, and Dynamic Modulus simple performance tests described in Annex A, B, and C, respectively.

4.2 Annex D summarizes the methods that will be used to verify that the Simple Performance Test System complies with the requirements of this specification.

4.3 The Simple Performance Test System shall include the following components:
1. Compression loading machine.
2. Loading platens.
3. Load measuring system.
4. Deflection measuring system.
5. Specimen deformation measuring system.
6. Confining pressure system.
7. Environmental chamber.
8. Computer control and data acquisition system.

4.4 The load frame, environmental chamber, and computer control system for the Simple Performance Test System shall occupy a foot-print no greater than 1.5 m (5 ft) by 1.5 m (5 ft) with a maximum height of 1.8 m (6 ft). A suitable frame, bench or cart shall be provided so that the bottom of the test specimen, and the computer keyboard and display are approximately 90 cm (36 in) above the floor.

4.5 The load frame, environmental chamber and computer control system for the Simple Performance Test System shall operate on single phase 115 or 230 VAC 60 Hz electrical power.

4.6 If a hydraulic power supply is required, it shall be air-cooled occupying a foot-print no larger than 1 m (3 ft) by 1.5 m (5 ft). The noise level 2 m (6.5 ft) from the hydraulic power supply shall not exceed 70 dB. The hydraulic power supply shall operate on single phase 115 of 230 VAC 60 Hz electrical power.

4.7 When disassembled, the width of any single component shall not exceed 76 cm (30 in).

4.8 Air supply requirements shall not exceed 0.005 m^3/s (10.6 ft^3/min) at 850 kPa (125 psi).

4.9 The Simple Performance Test System shall include appropriate limit and overload protection.

4.10 An emergency stop shall be mounted at an easily accessible point on the system.

5.0 Compression Loading Machine

5.1 The machine shall have closed-loop load control with the capability of applying constant, ramp, sinusoidal, and pulse loads. The requirements for each of the simple performance tests are listed below.

Test	Type of Loading	Capacity	Rate
Flow Time	Ramp, constant	10 kN (2.25 kips)	0.5 sec ramp
Flow Number	Ramp, constant, pulse	8 kN (1.80 kips)	10 Hz pulse with 0.9 sec dwell
Dynamic Modulus	Ramp, constant, sinusoidal	6 kN (1.35 kips)	0.1 to 25 Hz

5.2 For ramp and constant loads, the load shall be maintained within +/- 2 percent of the desired load.

5.3 For sinusoidal loads, the standard error of the applied load shall be less than 5 percent. The standard error of the applied load is a measure of the difference between the measured load data, and the best fit sinusoid. The standard error of the load is defined in Equation 3.

$$se(P) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n-4}} \left[\frac{100\%}{\hat{x}_o}\right] \tag{3}$$

Where:

$se(P)$ = Standard error of the applied load
x_i = Measured load at point *i*
$\hat{x}_i$ = Predicted load at point *i* from the best fit sinusoid, See Equation 16
$\hat{x}_o$ = Amplitude of the best fit sinusoid
n = Total number of data points collected during test.

5.4 For pulse loads, the peak of the load pulse shall be within +/- 2 percent of the specified value and the standard error of the applied load during the sinusoidal pulse shall be less than 10 percent.

5.5 For the Flow Time and Flow Number Tests, the loading platens shall remain parallel during loading. For the Dynamic Modulus Test, the load shall be applied to the specimen through a ball or swivel joint.

6.0 Loading Platens

6.1 The loading platens shall be fabricated from aluminum and have a Brinell Hardness Number HBS 10/500 of 95 or greater.

6.2 The loading platens shall be at least 25 mm (1 in) thick. The diameter of the loading platens shall not be less than 105 mm (4.125 in) nor greater than 108 mm (4.25 in).

6.3 The loading platens shall not depart from a plane by more than 0.0125 mm (0.0005 in) across any diameter.

7.0 Load Measuring System

7.1 The Simple Performance Test System shall include an electronic load measuring system with full scale range equal to or greater than the stall force for the actuator of the compression loading machine.

7.2 The load measuring system shall have an error equal to or less than +/- 1 percent for loads ranging from 2 to 100 percent of the capacity of the machine when verified in accordance with ASTM E4.

7.3 The resolution of the load measuring system shall comply with the requirements of ASTM E4.

8.0 Deflection Measuring System

8.1 The Simple Performance Test System shall include a electronic deflection measuring system that measures the movement of the loading actuator for use in the Flow Time and Flow Number Tests

8.2 The deflection measuring system shall have a range of at least 12 mm (0.5 in).

8.3 The deflection measuring system shall have a resolution equal to or better than 0.0025 mm (0.0001 in).

8.4 The deflection measuring system shall have an error equal to or less than 0.03 mm (0.001 in) over the 12 mm range when verified in accordance with ASTM D 6027.

8.5 The deflection measuring system shall be designed to minimize errors due to compliance and/or bending of the loading mechanism. These errors shall be less than 0.25 mm (0.01 in) at 8 kN (1.8 kips) load.

9.0 Specimen Deformation Measuring System

9.1 The Simple Performance Test System shall include an electronic system for measuring deformations on the specimen over a gauge length of 70 mm (2.76 in) at the middle of the specimen. This system will be used in the Dynamic Modulus Test, and shall include at least two transducers spaced equally around the circumference of the specimen.

9.2 The transducers shall have a range of at least 1 mm (0.04 in).

9.3 The transducers shall have a resolution equal to or better than 0.0002 mm (7.8 micro inch).

9.4 The transducers shall have an error equal to or less than 0.0025 mm (0.0001 in) over the 1 mm range when verified in accordance with ASTM D 6027.

9.5 The axial deformation measuring system shall be designed for rapid specimen installation and subsequent testing. Specimen instrumentation, installation, application of confining pressure, and temperature equilibration shall take no longer than 3 minutes over the complete range of temperatures.

10.0 Confining Pressure System

10.1 The confining pressure system shall be capable of providing a constant confining pressure up to 210 kPa (30 psi) to the test specimen. The system shall include a pressure cell with appropriate pressure regulation and control, a flexible specimen membrane, a device or method for detecting leaks in the membrane, a pressure transducer, and a temperature sensing device that is mounted internal to the cell.

10.2 Confining pressure shall be controlled by the computer control and data acquisition system. The confining pressure control system shall have the capability to maintain a constant confining pressure throughout the test within +/- 2 percent of the desired pressure.

10.3 The specimen shall be enclosed in an impermeable flexible membrane sealed against the loading platens.

10.4 The pressure inside the specimen membrane shall be maintained at atmospheric pressure through vents in the loading platens. The system shall include a device or method for detecting membrane leaks.

10.5 The confining pressure system shall include a pressure transducer for recording confining pressure during the test. The pressure transducer shall have a range of at least 210 kPa, (30 psi) and a resolution of 0.5 kPa (0.07 psi). The pressure transducer shall have an error equal to or less than ±1 percent of the indicated value over the range of 35 kPa (5 psi) to 210 kPa (30 psi) when verified in accordance with ASTM D5720.

10.6 A suitable temperature sensor shall be mounted at the mid-height of the specimen in the pressure cell between the specimen and the cell wall. This temperature sensor shall have a range of 20 to 60 °C (68 to 140 °F), and be readable and accurate to the nearest 0.25 °C. (0.5 °F). For confined tests this sensor shall be used to control the temperature in the chamber, and provide a continuous reading of temperature that will be sampled by the data acquisition system during the test.

10.7 The confining pressure system shall be designed for rapid installation of the test specimen in the confining cell and subsequent equilibration of the chamber temperature to the target test temperature. Specimen instrumentation, installation, application of confining pressure, and temperature equilibration shall take no longer than 3 minutes over the complete range of temperatures.

11.0 Environmental Chamber

11.1 The environmental chamber shall be capable of controlling temperatures inside the chamber over the range from 20 to 60 °C (68 to 140 °F) within +/- 0.5 °C (1 °F), when room temperature is between 15 and 27 °C (60 and 80 °F).

11.2 The environmental chamber need only be large enough to accommodate the test specimen. It is envisioned that specimens will be preconditioned in a separate chamber that is large enough to hold the number of specimens needed for a particular project along with one or more dummy specimens with internally mounted temperature sensors.

11.3 The Flow Time Test system shall be designed for rapid installation of the test specimen and subsequent equilibration of the environmental chamber temperature to the target test temperature. Specimen instrumentation, installation, application of confining pressure, and temperature equilibration shall take no longer than 3 minutes over the complete range of temperatures.

11.4 A suitable temperature sensor shall be mounted in the environmental chamber within 25 mm (1 in) of the specimen at the mid-height of the specimen. This temperature sensor shall have a range of 20 to 60 °C (68 to 140 °F), and be readable and accurate to the nearest 0.25 °C (0.5 °F). This sensor shall be used to control the temperature in the chamber, and provide a continuous reading of temperature that will be sampled by the data acquisition system during the test.

12.0 Computer Control and Data Acquisition

12.1 The Simple Performance Test System shall be controlled from a Personal Computer operating software specifically designed to conduct the Flow Time, Flow Number, and Dynamic Modulus Tests described in Annex A, B, and C, and to analyze data in accordance with Section 13.

12.2 The Simple Performance Test System Software shall provide the option for user selection of SI or US Customary units.

12.3 Flow Time Test Control and Data Acquisition

12.3.1 The control system shall control the deviator stress, and the confining pressure within the tolerances specified in Sections 5 and 10.2

12.3.2 The control system shall ramp the deviator stress from the contact stress condition to the creep stress condition in 0.5 sec.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

12.3.3 Zero time for data acquisition and zero strain shall be defined as the start of the ramp from contact stress to creep stress. Using this time as a reference, the system shall provide a record of deviator stress, confining pressure, axial strain, and temperature at zero time and a user specified sampling interval, t, between (0.5 and 10 sec). The axial strains shall be based on the user provided specimen length and the difference in deflection at any time and the deflection at zero time.

12.3.4 The control system shall terminate the test and return the deviator stress and confining pressure to zero when the axial strain exceeds 5 percent or the maximum user specified test duration time is exceeded.

Note: in Project 9-19, flow time criteria will be developed for mixtures as a function of climate, and traffic level. These criteria will be used by the user to determine the maximum duration of the test.

12.3.5 Figure 4 presents a schematic of the specified loading and data acquisition.

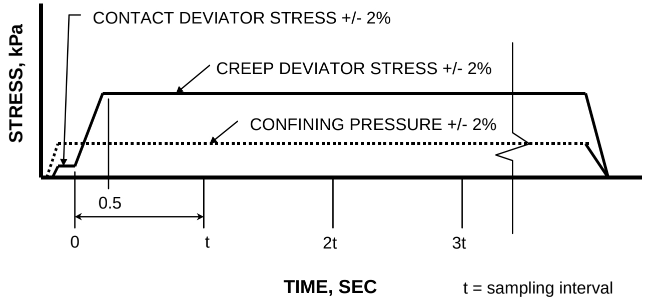


Figure 4. Schematic of Loading and Data Acquisition.

12.3.6 The Flow Time Test Software shall include a screen to input test and file information including:

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress
9. Target Contact Deviator Stress
10. Target Creep Deviator Stress
11. Specimen Conditioning Time
12. Sampling Interval
13. Test Duration
14. Remarks

12.3.7 The Flow Time Test Software shall prompt the operator through the Flow Time Test.

1. Test and file information screen.
2. Insert specimen.
3. Apply confining pressure and contact stress.
4. Wait for temperature equilibrium, check for confining system leaks.
5. Ramp to creep stress and collect and store data.
6. Post test remarks.
7. Remove tested specimen.

12.3.8 During the creep loading portion of the test, the Flow Time Test Software shall provide a real-time display of the time history of the deviator stress, the axial strain, and the rate of change of axial strain. The rate of change of axial strain shall be computed in accordance with the algorithm presented in Section 13.

12.3.9 If at any time during the creep loading portion of the test, the deviator stress, confining pressure, or temperature exceed the tolerances listed below, the Flow Time Test Software shall display a warning and indicate the parameter that exceeded the control tolerance. The test shall continue and the software shall include this warning in the data file and the hard copy output.

Response	Tolerance
Deviator stress	+/- 2 percent of target
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 $^{\circ}$C of target

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

12.3.10 Data files shall include the following information:

1. Test information supplied by the user in Section 12.3.6.
2. Date and time stamp.
3. Computed flow time.
4. Axial strain at the flow time.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Time and corresponding measured deviator stress, measured confining pressure, measured temperature, measured axial strain, and computed rate of change of strain.
8. Warnings
9. Post test remarks.

12.3.11 The Flow Time Test Software shall provide the capability of retrieving data files and exporting them to an ASCII comma delimited file for further analysis.

12.3.12 The Flow Time Test Software shall provide a one page hard copy output with the following:

1. Test information supplied by the user in Section 12.3.6.
2. Date and time stamp.
3. Computed flow time.
4. Axial strain at the flow time.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Warnings
8. Post test remarks
9. Plot of axial strain versus time.
10. Plot of rate of change of axial strain versus time with the flow time indicated.

12.4 Flow Number Test Control and Data Acquisition

12.4.1 The control system shall control the deviator stress, and the confining pressure within the tolerances specified in Sections 5 and 10.2

12.4.2 The control system shall be capable of applying an initial contact stress, then testing the specimen with the user specified cyclic deviator stress.

12.4.3 The data acquisition and control system shall provide the user the ability to select the sampling interval as a whole number of load cycles.

12.4.4 Zero deflection shall be defined as that at the start of the first load pulse. At the user specified sampling interval, the control system shall provide a record of peak deviator stress, standard error of the applied load (See Section 5.3), contact stress, confining pressure, permanent axial strain at the end of the load cycle, and temperature. The axial strains shall be based on the user provided specimen length and the difference in deflection the end of any load cycle and the zero deflection.

12.4.5 The control system shall terminate the test and return the deviator stress and confining pressure to zero when the axial strain exceeds 5 percent or the user specified test duration is reached.

Note: in Project 9-19, flow number criteria will be developed for mixtures as a function of climate, and traffic level. These criteria will be used by the user to determine the maximum duration of the test.

12.4.6 Figure 5 presents a schematic of the specified loading and data acquisition.

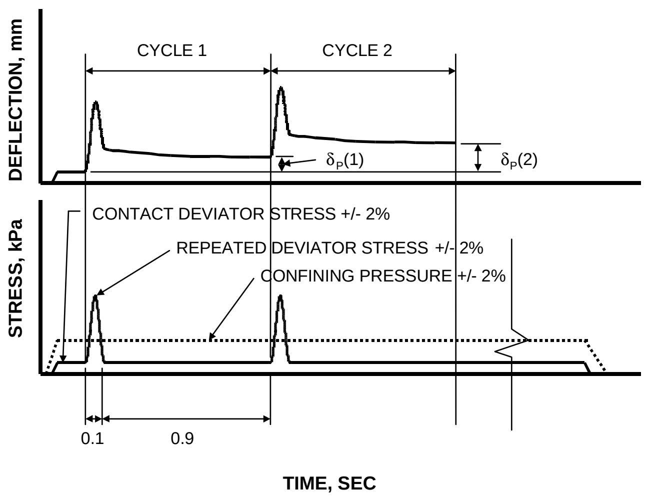


Figure 5. Schematic of Loading and Data Acquisition for Flow Time Test.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

12.4.7 The Flow Number Test Software shall include a screen to input test and file information including:

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress
9. Target Contact Deviator Stress
10. Target Repeated Deviator Stress
11. Specimen Conditioning Time
12. Sampling Interval
13. Maximum Number of Load Cycles
14. Remarks

12.4.8 The Flow Number Test Software shall prompt the operator through the Flow Number Test.

1. Test and file information screen.
2. Insert specimen.
3. Apply confining pressure and contact stress.
4. Wait for temperature equilibrium, check for confining system leaks.
5. Test specimen, collect and store data.
6. Post test remarks.
7. Remove tested specimen.

12.4.9 During the test, the Flow Number Test Software shall provide the user the ability to select the following displays and the ability to change between displays:

1. Digital oscilloscope showing stress and strain as a function of time.
2. A display of the history of the peak deviator stress, permanent axial strain, and the rate of change of permanent axial strain as a function of the number of load cycles. The rate of change of permanent axial strain shall be computed in accordance with the algorithm presented in Section 13.

12.4.10 If at any time during the test, the peak deviator stress, standard error of the applied load, confining pressure, or temperature exceed the tolerances listed below, the Flow Number Test Software shall display a warning and indicate the parameter that exceeded the control tolerance. The test shall continue and the software shall include this warning in the data file and the hard copy output.

Response	Tolerance
Peak deviator stress	+/- 2 percent of target
Load standard error	10 percent
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 °C of target

12.4.11 Data files shall include the following information:

1. Test information supplied by the user in Section 12.4.7.
2. Date and time stamp.
3. Computed flow number.
4. Axial strain at the flow number.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Average peak deviator stress.
8. Average contact stress.
9. Maximum standard error of the applied load.
10. Cycle and corresponding measured peak deviator stress, computed load standard error, measured contact stress, measured confining pressure, measured temperature, measured permanent axial strain, and computed rate of change of permanent strain.
11. Warnings
12. Post test remarks.

12.4.12 The Flow Number Test Software shall provide the capability of retrieving data files and exporting them to an ASCII comma delimited file for further analysis.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

12.4.13 The Flow Number Test Software shall provide a one page hard copy output with the following:

1. Test information supplied by the user in Section 12.4.7.
2. Date and time stamp.
3. Computed flow number.
4. Axial strain at the flow number.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Average peak deviator stress.
8. Average contact stress.
9. Maximum load standard error.
10. Warnings.
11. Post test remarks.
12. Plot of permanent axial strain versus load cycles.
13. Plot of rate of change of axial strain versus load cycles with the flow number indicated.

12.5 Dynamic Modulus Test Control and Data Acquisition

12.5.1 The control system shall control the axial stress and the confining pressure. The confining pressure shall be controlled within the tolerances specified in Section 10.2.

12.5.2 The control system shall be capable of applying confining stress, an initial contact deviator stress, then conditioning and testing the specimen with a haversine loading at a minimum of 5 user selected frequencies.

12.5.3 Conditioning and testing shall proceed from the highest to lowest loading frequency. Ten conditioning and ten testing cycles shall be applied for each frequency.

12.5.4 The control system shall have the capability to adjust the dynamic stress and contact stress during the test to keep the average dynamic strain within the range of 75 to 125 strain. Adjustment of the dynamic stress shall be performed during the ten conditioning cycles at each loading frequency.

12.5.5 A contact stress equal to 5 percent of the dynamic stress shall be maintained during conditioning and testing.

12.5.6 During the 10 testing cycles, record and store the load, specimen deformations from the individual transducers, confining pressure, and temperature as a function of time. The data acquisition rate shall be set to obtain 50 data points per loading cycle.

12.5.7 The Dynamic Modulus Test Software shall include a screen to input test and file information including:

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress
9. Loading Rates
10. Specimen Conditioning Time
11. Remarks

12.5.8 The Dynamic Modulus Test Software shall prompt the operator through the Dynamic Modulus Test.

1. Test and file information screen.
2. Insert specimen and attach strain instrumentation.
3. Apply confining pressure and contact stress.
4. Wait for temperature equilibrium, check for confining system leaks.
5. Condition and test specimen.
6. Review dynamic modulus, phase angle, temperature, confining pressure, and data quality statistics (See Section 13) for each frequency tested.
7. Post test remarks.
8. Remove tested specimen.

12.5.9 During the conditioning and testing, the Dynamic Modulus Test Software shall provide a real-time display of the axial stress, and the axial strain measured individually by the transducers.

12.5.10 If at any time during the conditioning and loading portion of the test, confining pressure, temperature, or average accumulated permanent strain exceed the tolerances listed below, the Dynamic Modulus Test Software shall display a warning and indicate the parameter that exceeded the control tolerance. The test shall continue and the software shall include this warning in the data file and the hard copy output.

Response	Tolerance
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 $^{\circ}$C of target
Permanent Axial Strain	0.0050 mm/mm

12.5.11 For each loading frequency, a separate data file shall be produced. This file shall include he test information supplied by the user in Section 12.5.7, a date and time stamp, and the following information for each frequency of loading included in the test.

1. Dynamic modulus.
2. Phase angle.
3. Average temperature during the test.
4. Average confining pressure.
5. Data quality measures (See Section 13)
   - The drift for the applied load, ΔY_P, %
   - The standard error for the applied load, $se(P)$, %
   - The average drift for the deformations, $\Delta \overline{Y}_D$, %
   - The average standard error for the deformations, $se(Y)$, %
   - The uniformity coefficient for the deformations, U_A %
   - The uniformity coefficient for the deformation phase angles, U_θ, degrees.
6. Time and corresponding measured axial stress, individual measured axial strains, measured confining pressure, and measured temperature,
7. Warnings
8. Post test remarks.

12.5.12 The Dynamic Modulus Test Software shall provide the capability of retrieving data files and exporting them to an ASCII comma delimited file for further analysis.

12.5.13 For each loading frequency, the Dynamic Modulus Test Software shall provide a one page hard copy output with the following. Figure 6 presents an example one page output.

1. Test information supplied by the user in Section 12.5.7.
2. Date and time stamp.
3. Dynamic modulus.
4. Phase angle.
5. Average temperature during the test.
6. Average confining pressure during the test.
7. Data quality measures (See Section 13)
   - The drift for the applied load, ΔY_P, %
   - The standard error for the applied load, $se(P)$, %
   - The average drift for the deformations, $\Delta \overline{Y}_D$, %
   - The average standard error for the deformations, $se(Y)$, %
   - The uniformity coefficient for the deformations, U_A %
   - The uniformity coefficient for the deformation phase angles, U_θ, degrees.
9. Warnings

10. Post test remarks
11. Plot showing centered stress and centered strains as a function of time
12. Plot showing normalized stress and strains as a function of phase angle. This plot shall include both the measured and fit data.
13. Plot showing normalized stress as a function of normalized strain. This plot shall include both the measured and fit data.

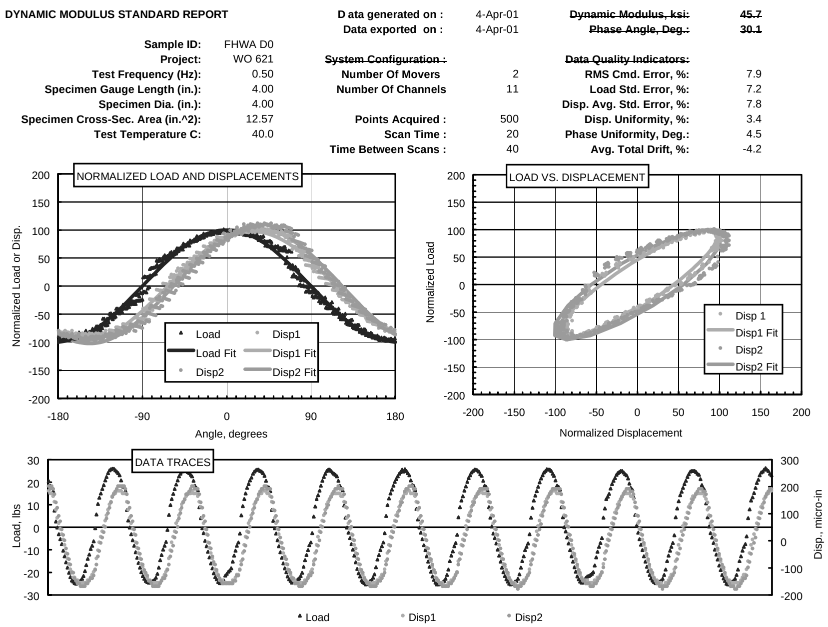


Figure 6. Example Dynamic Modulus Output.

13.0 Computations

13.1 Flow Time Test

13.1.1 The Flow Time is defined as the time corresponding to the minimum rate of change of axial strain during a creep test. To ensure that different laboratories

produce comparable results for this test method, the procedure described in this section shall be followed in determining the flow time. The procedure consists of three steps: (1) numerical calculation of the creep rate ; (2) smoothing of the creep rate data; and (3) identification of the point at which the minimum creep rate occurs as the flow time.

13.1.2 The first step in determining the flow time is to estimate the rate of change (derivative) of the axial strain ε with respect to time *t* using a finite-difference formula. The rate of change of the strain with respect to time is estimated using the following equation:

$$\frac{d\,\varepsilon_i}{dt} \cong \frac{\varepsilon_{i+\Delta t} - \varepsilon_{i-\Delta t}}{2\Delta t} \qquad (4)$$

Where:

$d\varepsilon_i/dt$ = rate of change of strain with respect to time or creep rate at i sec, 1/s
$\varepsilon_{i-\Delta t}$ = strain at i-Δt sec
$\varepsilon_{i+\Delta t}$ = strain at i+Δt sec
Δt = sampling interval

13.1.3 The derivatives calculated in Section 13.1.2 shall then be smoothed by calculating the running average at each point, by adding to the derivative at that point the two values before and two values after that point, and dividing the sum by five:

$$\frac{d\varepsilon_i'}{dt} = \frac{1}{5}\left[\frac{d\varepsilon_{i-2\Delta t}}{dt} + \frac{d\varepsilon i_{i-\Delta t}}{dt} + \frac{d\varepsilon_i}{dt} + \frac{d\varepsilon_{+\Delta t}}{dt} + \frac{d\varepsilon_{i+2\Delta t}}{dt}\right] \qquad (5)$$

Where:

$d\varepsilon'_i/dt$ = smoothed creep rate at i sec, /s
$d\varepsilon_{i-2\Delta t}/dt$ = creep rate at i-2Δt sec, 1/s
$d\varepsilon_{i-\Delta t}/dt$ = creep rate at i-Δt sec, 1/s
$d\varepsilon_i/dt$ = creep rate at i sec, 1/s
$d\varepsilon_{i+\Delta t}/dt$ = creep rate at i+Δt sec, 1/s
$d\varepsilon_{i+2\Delta t}/dt$ = creep rate at i+2Δt sec, 1/s

13.1.4 The flow time is reported as the time at which the minimum value of the smoothed creep rate occurs, and shall be reported to nearest Δt seconds. If there is no minimum, then the flow time is reported as being greater than or equal to the length of the test. If more than one point share the minimum creep rate, the first such minimum shall be reported as the flow time.

13.2 Flow Number Test

13.2.1 The Flow Number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test. To ensure that different laboratories produce comparable results for this test method, the procedure described in this section shall be followed in determining the Flow Number. The procedure consists of three steps: (1) numerical calculation of the creep rate; (2) smoothing of the creep rate data; and (3) identification of the point at which the minimum creep rate occurs as the Flow Number.

13.2.2 The first step in determining the Flow Number is to estimate the rate of change (derivative) of the permanent axial strain, ε_p, with respect to the number of load cycles, N, using a finite-difference formula. The rate of change of the permanent strain with respect to the number of cycles is estimated using the following equation:

$$\frac{d(\varepsilon_p)_i}{dN} \quad \frac{(\varepsilon_p)_{i+\Delta N} \quad (\varepsilon_p)_{i-\Delta N}}{2\Delta N} \tag{6}$$

Where:

$d(\varepsilon_p)_i/dN$ = rate of change of permanent axial strain with respect to cycles or creep rate at cycle i, 1/cycle
$(\varepsilon_p)_{i-\Delta N}$ = permanent strain at i-ΔN cycles
$(\varepsilon_p)_{i+\Delta N}$ = permanent strain at i+ΔN cycles
ΔN = sampling interval

13.2.3 The derivatives calculated in Section 12.2.3 shall then be smoothed by calculating the running average at each point, by adding to the derivative at that point the two values before and two values after that point, and dividing the sum by five:

$$\frac{d(\varepsilon_p)_i'}{dN} = \frac{1}{5}\left[\frac{d(\varepsilon_p)_{i-2\Delta N}}{dN} + \frac{d(\varepsilon_p)_{i-\Delta N}}{dN} + \frac{d(\varepsilon_p)_i}{dN} + \frac{d(\varepsilon_p)_{i+\Delta N}}{dN} + \frac{d(\varepsilon_p)_{i+2\Delta N}}{dN}\right] \tag{7}$$

Where:

$d(\varepsilon_p)'_i/dN$ = smoothed creep rate at i sec, 1/cycle
$d(\varepsilon_p)_{i-2\Delta N}/dN$ = creep rate at i-2ΔN cycles, 1/cycle
$d(\varepsilon_p)_{i-\Delta N}/dN$ = creep rate at i-ΔN cycles, 1/cycle
$d(\varepsilon_p)_i/dN$ = creep rate at i cycles, 1/cycle
$d(\varepsilon_p)_{i+\Delta N}/dN$ = creep rate at i+ΔN cycles, 1/cycle
$d(\varepsilon_p)_{i+2\Delta N}/dN$ = creep rate at i+2ΔN cycles, 1/cycle

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

13.2.4 The Flow Number is reported as the cycle at which the minimum value of the smoothed creep rate occurs. If there is no minimum, then the Flow Number is reported as being greater than or equal to the length of the test. If more than one point share the minimum creep rate, the first such minimum shall be reported as the Flow Number.

13.3 Dynamic Modulus Test

13.3.1 The data produced from the dynamic modulus test at frequency ω_0 will be in the form of several arrays, one for time [t_i], one for each of the j = 1, 2, 3,…m transducers used [y_j]. In the typical arrangement, there will be m = 3 transducers: the first transducer will be a load cell, and transducers 2 and 3 will be specimen deformation transducers. However, this approach is general and can be adapted to any number of specimen deformation transducers. The number of i = 1, 2, 3…n points in each array will be equal to 500 based on the number of cycles and acquisition rate specified in Section 12.5.6. It has been assumed in this procedure that the load will be given in Newtons (N), and the deformations in millimeters (mm). The analysis has been devised to provide complex modulus in units of Pascals (1 Pa = 1 N/m^2) and phase angle in units of degrees. The general approach used here is based upon the least squares fit of a sinusoid, as described by Chapra and Canale in *Numerical Methods for Engineers* (McGraw-Hill, 1985, pp. 404-407). However, the approach used here is more rigorous, and also includes provisions for estimating drift of the sinusoid over time by including another variable in the regression function. Regression is used, rather than the Fast Fourier transform (FFT), because it is a simpler and more direct approach, which should be easier for most engineers and technicians in the paving industry to understand and apply effectively. The regression approach also lends itself to calculating standard errors and other indicators of data quality. This approach should however produce results essentially identical to those produced using FFT analysis.

13.3.2 The calculation proceeds as follows. First, the data for each transducer are centered by subtracting from the measured data the average for that transducer:

$$Y_{ji}' = Y_{ji} - \overline{Y_j} \tag{8}$$

Where:

Y_{ji}' = Centered data for transducer j at point i in data array
Y_{ji} = Raw data for transducer j at point i in data array
$\overline{Y_j}$ = Average for transducer j

13.3.3 In the second step in the procedure, the [*X'X*] matrix is constructed as follows:

$$[X'X] = \begin{bmatrix} N & \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} \cos(\omega_0 t_i) & \sum_{i=1}^{n} \sin(\omega_0 t_i) \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 & \sum_{i=1}^{n} t_i \cos(\omega_0 t_i) & \sum_{i=1}^{n} t_i \sin(\omega_0 t_i) \\ \sum_{i=1}^{n} \cos(\omega_0 t_i) & \sum_{i=1}^{n} t_i \cos(\omega_0 t_i) & \sum_{i=1}^{n} \cos^2(\omega_0 t_i) & \sum_{i=1}^{n} \cos(\omega_0 t_i)\sin(\omega_0 t_i) \\ \sum_{i=1}^{n} \sin(\omega_0 t_i) & \sum_{i=1}^{n} t_i \sin(\omega_0 t_i) & \sum_{i=1}^{n} \cos(\omega_0 t_i)\sin(\omega_0 t_i) & \sum_{i=1}^{n} \sin^2(\omega_0 t_i) \end{bmatrix} \quad (9)$$

Where N is the total number of data points, ω_0 is the frequency of the data, t is the time from the start of the data array, and the summation is carried out over all points in the data array.

13.3.4 The inverse of this matrix, $[X'X]^{-1}$, is then calculated. Then, for each transducer, the $[X'Y_j]$ array is constructed:

$$[X'Y_j] = \begin{bmatrix} \sum_{i=1}^{n} Y_{ji}' \\ \sum_{i=1}^{n} Y_{ji}' t \\ \sum_{i=1}^{n} Y_{ji}' \cos(\omega_0 t) \\ \sum_{i=1}^{n} Y_{ji}' \sin(\omega_0 t) \end{bmatrix} \quad (10)$$

Where Y_j represents the output from one of the three transducers (j=1 for the load cell, j=2 and 3 for the two deformation transducers). Again, the summation is carried out for all points in the data arrays.

13.3.5 The array representing the regression coefficients for each transducer is then calculated by multiplying the $[X'X]^{-1}$ matrix by the $[X'Y_j]$ matrix:

$$\begin{bmatrix} A_{j0} \\ A_{j1} \\ A_{j2} \\ B_{j2} \end{bmatrix} = [X'X]^{-1}[X'Y_j] \quad (11)$$

Where the regression coefficients can be used to calculate predicted values for each of the j transducers using the regression function:

$$\hat{Y}_{ji} = A_{j0} + A_{j1} t_i + A_{j2} \cos(\omega_0 t_i) + B_{j2} \sin(\omega_0 t_i) + \varepsilon_{ji} \quad (12)$$

Where $\hat{Y}_{ji}$ is the predicted value for the i^{th} point of data for the j^{th} transducer, and ε_{ji} represents the error term in the regression function.

13.3.6 From the regression coefficients, several other functions are then calculated as follows:

$$\theta_j = \arctan\left(-\frac{B_{j2}}{A_{j2}}\right) \quad (13)$$

$$|Y_j^*| = \sqrt{A_{j2}^2 + B_{j2}^2} \quad (14)$$

$$\Delta Y_j = \frac{A_{j1} t_N}{|Y_j^*|} \quad 100\% \quad (15)$$

$$se(Y_j) = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_{ji}' - Y_{ji}'\right)^2}{n-4}}\left(\frac{100\%}{|Y_j^*|}\right) \quad (16)$$

Where:

θ_j	=	Phase angle for transducer j, degrees
$\lvert Y_j^*\rvert$	=	Amplitude for transducer j, N for load or mm for displacement
ΔY_j	=	Drift for transducer j, as percent of amplitude.
t_N	=	Total time covered by data
$\hat{Y}_{ji}'$	=	Predicted centered response for transducer j at point i, N or mm
$se(Y_j)$	=	Standard error for transducer j, %
n	=	number of data points = 500

The calculations represented by Equations 13 through 16 are carried out for each transducer—typically the load cell, and two deformation transducers. This produces values for the phase angle, and standard errors for each transducer output. The phase angles given by Equation 13 represent absolute phase angles, that is, θ_j is an arbitrary value indicating the angle at which data collection started.

13.3.7 The phase angle of the deformation (response) relative to the load (excitation) is the important mechanical property. To calculate this phase angle, the average phase angle for the deformations must first be calculated:

$$\overline{\theta}_D = \frac{\sum_{j=2}^{m} \theta_j}{m-1} \tag{17}$$

Where $\overline{\theta}_D$ is the average absolute phase angle for the deformation transducers, and θ_j is the phase angle for each of the j = 2, 3, …, m deformation transducers. For the typical case, there are one load cell and two deformation transducers, so m = 3, and Equation 17 simply involves summing the phase angle for the two deformation transducers and dividing by two.

13.3.8 The relative phase angle at frequency ω between the deformation and the load, $\theta(\omega)$, is then calculated as follows:

$$\theta(\omega) = \overline{\theta_D} - \theta_P \tag{18}$$

Where θ_P is the absolute phase angle calculated for the load.

13.3.9 A similar set of calculations is needed to calculate the overall modulus for the material. First, the average amplitude for the deformations must be calculated:

$$\left|\overline{Y}_D *\right| = \frac{\sum_{j=2}^{m} \left|Y_j *\right|}{m \quad 1} \tag{19}$$

Where $\left|\overline{Y}_D *\right|$ represents the average amplitude of the deformations (mm).

13.3.10 Then, the dynamic modulus $|E^*|$ at frequency ω is calculated using the following equation:

$$\left|E*(\omega)\right| = \frac{\left|Y_P *\right| L_g}{\left|\overline{Y}_D *\right| A} \tag{20}$$

Where $|E^*(\omega)|$ is in Pa, L_g is the average gage length for the deformation transducers (mm), and A is the loaded cross-sectional area for the specimen, m^2.

13.3.11 The final part of the analysis involves calculation of several factors indicative of data quality, including the average drift for the deformations, the average standard error for the deformations, and uniformity coefficients for deformation amplitude and phase:

$$\Delta\overline{Y}_D = \frac{\sum_{j=2}^{m} A_{j1} t_N}{\sum_{j=2}^{m} \left|Y_j *\right|} \times 100\% \tag{21}$$

$$se(Y_D) = \frac{\sum_{j=2}^{m} se(Y_j)}{m-1} \tag{22}$$

$$U_A = \sqrt{\frac{\sum_{j=2}^{m} \left(\left|Y_j *\right| - \left|\overline{Y}_D *\right|\right)^2}{m-1}} \, \frac{100\%}{\left|\overline{Y}_D *\right|} \tag{23}$$

$$U_\theta = \sqrt{\frac{\sum_{j=2}^{m} \left(\theta_j - \overline{\theta}_D\right)^2}{m-1}} \tag{24}$$

Where:

$\Delta\overline{Y}_D$	=	Average deformation drift, as percent of average deformation amplitude
$se(Y_D)$	=	Average standard error for all deformation transducers, %
U_A	=	Uniformity coefficient for deformation amplitude, %
U_θ	=	Uniformity coefficient for deformation phase, degrees

14.0 Calibration and Verification of Dynamic Performance

14.1 Prior to shipment, the complete Simple Performance Test System shall be assembled at the manufacturer's facility and calibrated. This calibration shall include calibration of the computer control and data acquisition electronics/software, static calibration of the load, deflection, specimen deformation, confining pressure and temperature measuring systems; and verification of the dynamic performance of the load and specimen deformation measuring systems.

14.2 The results of these calibrations shall be documented, certified by the manufacturer, and provided with the system documentation.

14.3 Static calibration of the load, deflection, specimen deformation, and confining pressure systems shall be performed in accordance with the following standards:

System	ASTM Standard
Load	ASTM E4
Deflection	ASTM D 6027
Specimen Deformation	ASTM D 6027
Confining Pressure	ASTM D 5720

14.4 The calibration of the temperature measuring system shall be verified over the range that the testing system will be used. A NIST traceable reference thermal detector with resolution equal to or better than the temperature sensor shall be used.

14.5 Verification of the dynamic performance of the force and specimen deformation measuring systems shall be performed by loading a proving ring or similar verification device with the specimen deformation measuring system attached. The manufacturer shall be responsible for fabricating the verification device and shall supply it with the Simple Performance Test System. The verification shall include loads of 0.6, 1.2, 3.0, and 4.8 kN (0.13, 0.27, 0.67, and 1.08 kips) at frequencies of 0.1, 1, and 25 Hz. The verification shall include measurement of load, and displacement of the verification device using the specimen deformation measuring system. All of the resulting load versus deformation data shall be within 2 percent of that determined by static loading of the verification device. The phase difference between load and displacement measurements shall be less than 1 degree.

14.6 The Simple Performance System shall include a calibration mode for subsequent annual calibration in accordance with the standards listed in Section 14.3 and the method described in 14.4. It shall also include a dynamic verification mode to perform the verification test described in Section 14.5. Access points for calibration work shall be clearly shown in the system reference manual.

15.0 Verification of Normal Operation

15.1 The manufacturer shall develop and document procedures for verification of normal operation for each of the systems listed in Section 14.3, and the dynamic performance verification discussed in Section 14.5. It is anticipated that these verification procedures will be performed by the operating technician on a frequent basis. Equipment used in the verification process shall be provided as part of the Simple Performance Test System.

16.0 Documentation

16.1 The Simple Performance Test System shall include an on-line help and documentation.

16.2 A reference manual completely documenting the Simple Performance Test System shall be provided. This manual shall include the following Chapters:

1. System Introduction.
2. Installation.
3. Loading System.
4. Confining Pressure System.
5. Environmental Chamber.
6. Control and Data Acquisition System.
7. Flow Time Test.
8. Flow Number Test.
9. Dynamic Modulus Test.
10. Calibration.
11. Verification of Dynamic Performance.
12. Verification of Normal Operation.
13. Preventative Maintenance.
14. Spare Parts List
15. Drawings.

17.0 Warranty

17.1 The Simple Performance Test System shall carry a one year on-site warranty.

Annex A
NCHRP Project 9-19 Draft Test Protocol W1:
Simple Performance Test for Permanent Deformation Based Upon Static Creep / Flow Time Strength of Asphalt Concrete Mixtures
Arizona State University, September, 2000

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

1. Scope

1.1 This test method covers procedures for the preparation, testing and measurement of the resistance to tertiary flow of cylindrical asphalt concrete specimens in a triaxial state of compressive loading.

1.2 In this test, a cylindrical sample of bituminous paving mixture is subjected to a static axial load. Permanent axial and/or radial strains are recorded through out the test.

1.3 The test is conducted at a single effective temperature T_{eff} and design stress levels.

1.4 This standard is applicable to laboratory prepared specimens 100 mm in diameter and 150 mm in height for mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in).

1.4 *This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 AASHTO Standards

TP4 Method for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the SHRP Gyratory Compactor

PP2 Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)

T67 Standard Practices for Load Verification of Testing Machines (cross-listed with ASTM E4)

T269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

3. Definitions

3.1 *Flow Time* – is defined as the postulated time when shear deformation, under constant volume, starts.

3.2 *Compliance* – is the reciprocal of the modulus and represents the ratio of strain to stress for a viscoela

3.3 *Effective Temperature* T_{eff} – is a single test temperature at which an amount of permanent deformation would occur equivalent to that measured by considering each season separately throughout the year

4. Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a static axial load. The test can be performed either without confinement, or a confining pressure is applied to better simulate in situ stress conditions. The flow time is defined as the postulated time when shear deformation, under constant volume, starts. The applied stress and the resulting permanent and/or axial strain response of the specimen is measured and used to calculate the flow time.

5. Significance and Use

5.1 Current Superpave volumetric mix design procedure lacks a fundamental design criterion to evaluate fundamental engineering properties of the asphalt mixture that directly affect performance. In this test, the selection of the design binder content and aggregate structure is fundamentally enhanced by the evaluation of the mix resistance to shear flow (Flow Time).

5.2 This fundamental engineering property can be used as a performance criteria indicator for permanent deformation resistance of the asphalt concrete mixture, or can be simply used to compare the shear resistance properties of various bituminous paving mixtures.

6. Apparatus

6.1 Load Test System – A load test system consisting of a testing machine, environmental chamber, measuring system, and specimen end fixtures.

6.1.1 *Testing Machine* – The testing machine should be capable of applying static loads up to 25 kN (5,600 1bs). An electro-hydraulic machine is recommended but not necessarily required. The loading device should be calibrated as outlined in the "Equipment Calibration" Section of the testing manual.

6.1.2 *Confining Pressure Device*: a system capable of maintaining a constant confining pressure, up to 207 kPa (30 psi), such as an air pressure intensifier or a hydraulic pump. The device shall be equipped with a pressure relief valve, and a system to pressurize and depressurize the cell with gas or fluid. The device should also have a high temperature control subsystem for testing up to 60 °C (140 °F) within an accuracy of ± 0.5 °C (1 °F) at constant pressure.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

Note 1 – It has been found that feedback control of a servovalve to control the pressure is the preferred method of control. However, manual valves or proportional valves may be adequate for some applications. The axisymmetric triaxial cells of AASHTO T292 or T294 may be used for this purpose. Other types of triaxial cells may be permitted. In all cases, see-through cells are not recommended for use with gas confining media. Sight glass ports or reduced area windows are recommended with gas media for safety reasons. It is not required that the specimen be visible through the cell wall if specimen centering and proper instrumentation operation can be verified without a see-through pressure vessel. Certain simulations of pavement loads and extended material characterization desired for local conditions may suggest using confining pressures greater than 207 kPa. For pressures higher than 690 kPa (100 psi), fluid cells are recommended.

6.1.3 *Environmental Chamber* – A chamber for controlling the test specimen at the desired temperature is required. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 25 to 60 °C (77 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate the test specimen and a dummy specimen with temperature sensor mounted at the center for temperature verification.

Note 2 – If the chamber does not have sufficient room for a dummy specimen, it is permissible to have a second chamber controlling the temperature of the dummy. The separate dummy chamber must be operated similar to the operation of the main test specimen chamber so that the dummy will accurately register the time required to obtain temperature equilibrium on the test specimen.

6.1.4 *Measurement System* - The system shall include a data acquisition system comprising analog to digital conversion and/or digital input for storage and analysis on a computer. The system shall be capable of measuring and recording the time history of the applied load, axial and radial deformations for the time duration required by this test method. The system shall be capable of measuring the load and resulting deformations with a resolution of 0.5 percent.

6.1.4.1 *Load* - The load shall be measured with an electronic load cell having adequate capacity for the anticipated load requirements. The load cell shall be calibrated in accordance with AASHTO T67. The load measuring transducer shall have accuracy equal to or better than 0.25 percent of full scale.

Note 3 – A 25 kN (5600 lbf) load cell has been found to be the approximate maximum capacity limit for this test method because of range versus resolution factors. It is recommended that if the selected load cell capacity is 25 kN or greater, the system should be equipped with either manual or automatic amplification selection capability so that it can be used to enhance control of the system at lower anticipated loads.

6.1.4.2 *Axial and Radial Deformations* – Axial and/or radial deformations shall be measured with displacement transducers referenced to gauge points contacting the specimen as shown in Figure 1. The axial deformations shall be measured at a minimum of two locations 180° apart (in plan view); radial deformations shall be measured at a minimum of four locations aligned, in planform, on diametral, perpendicular lines which intersect at the center of the specimen.

Note 4 – Analog transducers such as linear variable differential transformers (LVDTs) having a range of ± 0.5 mm (0.02 in) and inherent nonlinearity equal to or better than ±0.025 percent of full scale have been found adequate for this purpose. Software or firmware linearization techniques may be used to improve the inherent nonlinearity. Amplification and signal conditioning techniques may be used with the ± 0.5 mm range LVDTs to obtain resolutions down to 0.001mm (0.00004 in) or better for small strain tests conditions. These techniques may be manual or automatic. In general, increasing the resolution by manual signal amplification will result in reduction of the overall range of the instrument by the same factor.

6.1.5 *Loading Platens* – Platens, with a diameter equal to or greater than that of the test specimen are required above and below the specimen to transfer the load from the testing machine to the specimen. Generally, these platens should be made of hardened or plated steel, or anodized high strength aluminum. Softer materials will require more frequent replacement. Materials that have linear elastic modulus properties and hardness properties lower than that of 6061-T6 aluminum shall not be used.

6.1.6 *Flexible Membrane*: for the confined tests, the specimen should be enclosed in an impermeable flexible membrane. The membrane should be sufficiently long to extend well onto the platens and when slightly stretched be of the same diameter as the specimen. Typical membrane wall thickness range between 0.012 and 0.0625 inches (0.305 – 1.588 mm).

6.1.7 *End Treatment* – Friction reducing end treatments shall be placed between the specimen ends and the loading platens.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

Note 5 - End treatments consisting of two 0.5 mm (0.02 in) thick latex sheets separated with silicone grease have been found to be suitable friction reducing end treatments.

6.2 *Gyratory Compactor* – A gyrator compactor and associated equipment for preparing laboratory specimens in accordance with AASHTO TP4 shall be used. Field cores shall meet the requirements of paragraphs 7.4 through 7.6 of this test method and any reports on cores so tested will contain a detailed description of the location of any lift boundaries within the height of the specimen (e.g. lift order, thickness and material homogeneity).

6.3 *Saw* – A machine for sawing test specimens ends to the appropriate length is required. The saw machine shall be capable of cutting specimens to the prescribed dimensions without excessive heating or shock.

Note 6 – A diamond masonry saw greatly facilitates the preparation of test specimens with smooth, parallel ends. Both single or double-bladed diamond saws should have feed mechanisms and speed controls of sufficient precision to ensure compliance with paragraphs 7.5 and 7.6 of this method. Adequate blade stiffness is also important to control flexing of the blade during thin cuts.

6.4 *Core Drill* - A coring machine with cooling system and a diamond bit for cutting nominal 100 mm (4 in) diameter test specimens.

Note 7 – A coring machine with adjustable vertical feed and rotational speed is recommended. The variable feeds and speeds may be controlled by various methods. A vertical feed rate of approximately 0.05 mm/rev (0.002 in/rev) and a rotational speed of approximately 455 RPM has been found to be satisfactory for several of the Superpave mixtures.

7. Test Specimens

7.1 *Size – T*esting shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens cored from gyratory compacted mixtures.

7.2 *Aging* – Mixtures shall be aged in accordance with the short-term oven aging procedure in AASHTO PP2.

7.3 *Gyratory Specimens* – Prepare 165 mm (6.5 in) high specimens to the required air void content in accordance with AASHTO TP-4.

7.4 *Coring* - Core the nominal 100 mm (4 in) diameter test specimens from the center of the gyratory specimens. Both the core drill and the gyratory specimen should be adequately supported to ensure that the resulting test specimen is cylindrical with sides that are smooth, parallel, and free from steps, ridges, and grooves.

7.5 *Diameter* – Measure the diameter of the test specimen at the mid height and third points along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm (0.05 in). Calculate the average and the standard deviation of the six measurements. If the standard deviation is greater than 2.5 mm (0.01 in) discard the specimen. For acceptable specimens, the average diameter, reported to the nearest 1 mm, shall be used in the stress calculations.

7.6 *End Preparation*- The ends of all test specimens shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the specimen by sawing with a single or double bladed saw. To ensure that the sawed samples have parallel ends, the prepared specimen ends shall meet the tolerances described below. Reject test specimens not meeting these tolerances.

7.6.1 The specimen ends shall have a cut surface waviness height within a tolerance of ± 0.05 mm across any diameter. This requirement shall be checked in a minimum of three positions at approximately 120° intervals using a straight edge and feeler gauges approximately 8-12.5 mm (0.315-0.5 in) wide or an optical comparator.

7.6.2 The specimen end shall not depart from perpendicular to the axis of the specimen by more than 0.5 degrees (i.e. 0.87 mm or 0.03 in across the diameter of a 100 mm diameter specimen). This requirement shall be checked on each specimen using a machinists square and feeler gauges.

7.7 *Air Void Content* – Determine the air void content of the final test specimen in accordance with AASHTO T269. Reject specimens with air voids that differ by more than 0.5 percent from the target air voids.

7.8 *Replicates* – The number of test specimens required depends on the number of axial and/or radial strain measurements made per specimen and the desired accuracy of the average flow time values. Table 1 summarizes the LVDTs and replicate number of specimens needed to obtain a desired accuracy limit.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

Table 1. Recommended Number of Specimens.

LVDTs per Specimen (Total for either vertical or horizontal, not combined total)	Number of Specimens	Estimated Standard Error of the Mean, % Per Mixture's Nominal Aggregate Size		
		12.5mm	19mm	37.5mm
2	2	7.6	9.5	18.8
2	3	6.2	7.7	15.3
3	2	6.7	8.9	17.4
3	3	5.5	7.3	14.2
4	2	6.2	8.6	16.6
4	3	5.0	7.0	13.6

7.9 *Sample Storage* – Wrap completed specimens in polyethylene and store in an environmentally protected storage area at temperatures between 5 and 25 °C (40 and 75 °F).

Note 8 – To eliminate effects of aging on test results, it is recommended that specimens be stored no more than two weeks prior to testing.

8. Test Specimen Instrumentation

8.1 Attach mounting studs for the axial LVDTs to the sides of the specimen with epoxy cement. Figure 2 presents details of the mounting studs and LVDT mounting hardware.

Note 9 – Quick setting epoxy such as Duro Master Mend Extra Strength Quick Set QM-50 has been found satisfactory for attaching studs. Under certain conditions when using the triaxial cell with confining pressure, the mounting studs may not require gluing to the specimen. While the surface contact area of the mounting studs is normally minimized consistent with transducer support requirements, it is generally recommended that the area of the studs be sufficiently large to bridge any open void structure features evident on the cut face of the specimen. The minimum diameter mounting stud consistent with support requirements is normally set at 8 mm (0.315 in), maximum diameters have not been established. A circular stud contact surface shape is not required, rectangular or other shapes are acceptable.

8.2 The gauge length for measuring axial deformations shall be 100 mm ±1 mm. Suitable alignment and spacing fixture shall be used to facilitate mounting of the axial deformation measuring hardware. The gauge length is normally measured between the stud centers.

9. Procedure

9.1 The recommended test protocol for the Simple Performance Test for use in the Superpave volumetric mix design consists of testing the asphalt mix at one effective pavement temperature T_{eff} and one design stress level selected by the design engineer. The effective pavement temperature T_{eff} covers approximately the temperature range of 25 to 60 °C (77 to 140 °F). The design stress levels covers the range between 69 and 207 kPa (10 –30 psi) for the unconfined tests, and 483 to 966 kPa for the confined tests. Typical confinement levels range between 35 and 207 kPa (5 – 30 psi).

9.2 Place the test specimen in the environmental chamber and allow it to equilibrate to the specified testing temperature. For the confined tests, in a standard geotechnical cell, glue the gauge points to the specimen surface as necessary, fit the flexible membrane over the specimen and mount the axial hardware fixtures to the gauge points through the membranes. Place the test specimen with the flexible membrane on in the environmental chamber. A dummy specimen with a temperature sensor mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, Table 2 provides a summary of the minimum required temperature equilibrium times for samples starting from room temperature (i.e. 25 °C).

Table 2. Recommended Equilibrium Times.

Specimen Test Temperature, °C (°F)	Time, hrs
25 (77)	0.5
30 (86)	1.0
37.8 (100)	1.5
>54.4 (130)	2.0

Unconfined Tests

9.3 After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, and mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

9.4 Place the upper friction reducing end treatment and platen on top of the specimen. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.5 Apply a contact load equal to 5 percent of the static load that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., check for proper direction sensing for all LVDTs).

9.6 Place the radial LVDTs in contact with the specimen, adjust the LVDTs to near the end of their linear range to allow the full range to be available for the accumulation of radial permanent deformation. Adjust and balance the electronic measuring system as necessary.

9.7 Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber.

9.8 After the time required for the sample to reach the testing temperature, apply a rapid (50 μsec) axial static load at 50 mm/sec which yields the desired stress on the specimen.

9.9 Hold the load constant until tertiary flow occurs or the total axial strain reaches approximately 2%. The test time will depend on the temperature and the stress levels applied.

9.10 During the load application, record the load applied, the axial and radial deflection measured from all LVDTs through the data acquisition system.

Confined Tests

9.11 After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, place the top platen and extend the flexible membrane over the top and bottom platens. Attach the O-rings to seal the specimen on top and bottom platens from the confining air/fluid. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.12 Mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

9.13 Connect the appropriate hose through the upper or lower platen (or take other appropriate steps) to keep the specimen's internal void structure under atmospheric pressure while pressure greater than atmospheric is applied to the outside of the membrane during testing.

9.14 Assemble the triaxial cell over the specimen, ensure proper seal with the base and connect the fluid (or gas) pressure lines.

9.15 Apply a contact load equal to 5 percent of the static load that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., both decrease accordingly). Place the radial LVDTs in contact with the specimen, adjust the LVDTs to near the end of their linear range to allow the full range to be available for the accumulation of radial permanent deformation.

9.16 Record the initial LVDT readings and slowly increase the lateral pressure to the desired test level (e.g. 2 psi /sec). Adjust and balance the electronic measuring system as necessary. Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber

9.17 After the time required for the sample to reach the testing temperature, apply a rapid (50 μsec) axial static load, which yields the desired deviatoric stress on the specimen. Hold the load constant until the tertiary flow occurs or the total axial strain reaches 4 - 5%. The test time will depend on the temperature and the stress levels applied.

9.18 During the load application, record the load, confining pressure, the axial and radial deflection measured from all LVDTs through the data acquisition system.

10. Calculations

10.1 Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to total axial strain (ε_{Ta}), in/in, by dividing by the gauge length, L (100mm (4-inches). Typical total axial strain versus time is shown in Figure 3.

10.2 Compute the total axial compliance D(t) = ε_T/σ_d , where σ_d is the deviator stress applied during testing in psi. (σ_d = applied constant load (1b) divided by the cross sectional area of the specimen (in^2).

10.3 Plot the total axial compliance versus time in log space.

10.4 Using the data generated between the total axial compliance and time, determine the axial creep compliance parameters (D_o, D_1, M_1) from the linear portion of the creep compliance data between a time of ten seconds until the end of the linear curve (see Figure 4). The creep compliance parameters are estimated as follows:

D_o : is the instantaneous compliance, and can be assumed to be the value of the total compliance at a time equal to 100μsec (if the load is applied rapidly at 50μsec).
D_1 : is the intercept of the creep compliance – time relationship, which is the estimated value of the total compliance at a time of one second.

M_1 : is the slope of the creep compliance-time relationship.

10.5 The flow point is viewed as the lowest point in the curve of rate of change in axial compliance vs. loading time (see Figure 5). The rate of change of creep compliance D'(t) versus loading time should be plotted and the flow time (F_t) is estimated using the following mathematical procedure:

Ten data points are taken from every log scale unit of time at approximately equal intervals. Then, at a specific time t_1, a polynomial equation is fitted by five points (two points forward and two points backward above the time t_1). The form of this equation is:

$$D(t)_I = a + bt + ct^2$$

Where

$D(t)_1$	=	compliance at time t for t_1 point evaluated
t =	time of loading	
a,b,c	=	regression coefficients

By taking the derivative of the above equation, one obtains the following:

$$\frac{d(D(t)_i)}{dt} = b + 2ct$$

Therefore, the rate of change in compliance at time t_i is equal to $b+2ct_i$. For each data point selected one can obtain the rate of change in compliance by repeating the above procedure. Once all the rates of change in compliance are calculated, one can find the zero value of rate of change in compliance, i.e., the flow point. This is accomplished by another polynomial curve fitting, using equal data points on both sides of the minimum value. Theoretically the "flow point" is the time corresponding to a rate of compliance change equal to zero.

11. Report

11.1 Report all specimen information including mix identification, storage conditions, dates of manufacturing and testing, specimen diameter and length, volumetric properties, stress levels used, confining pressure, creep compliance parameters (Do, D1, M1) and flow time.

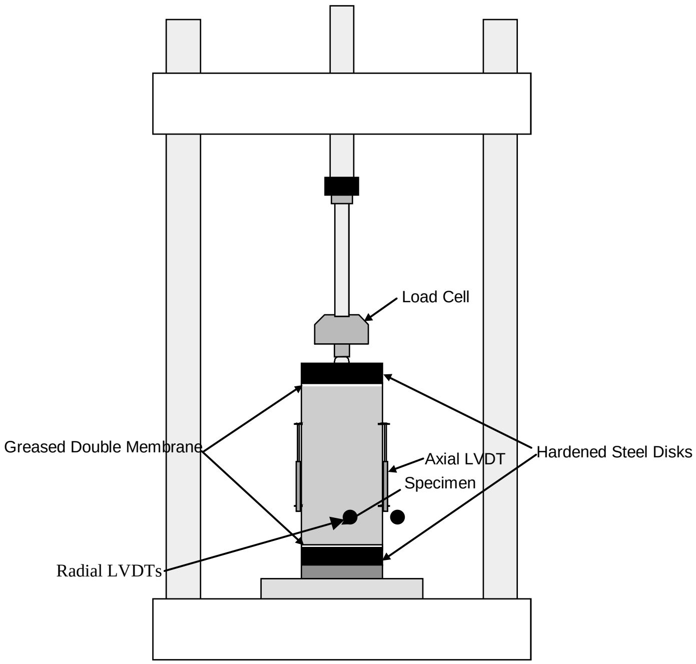


Figure 1. Schematic of Static Creep / Flow Time Test.

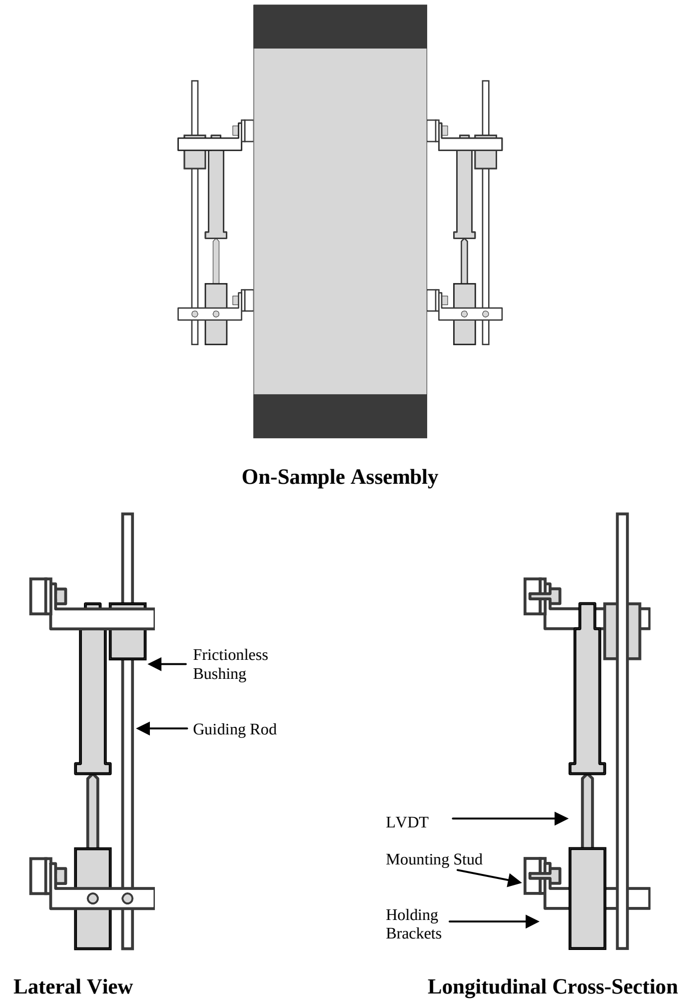


Figure 2. Axial LVDTs Instrumentation.

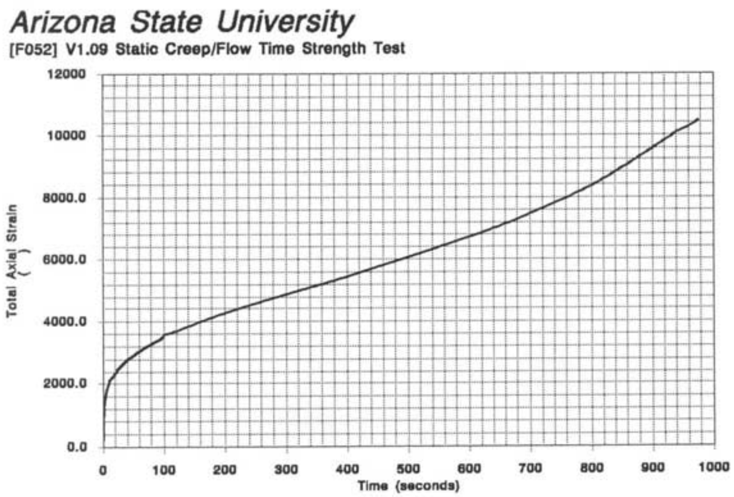
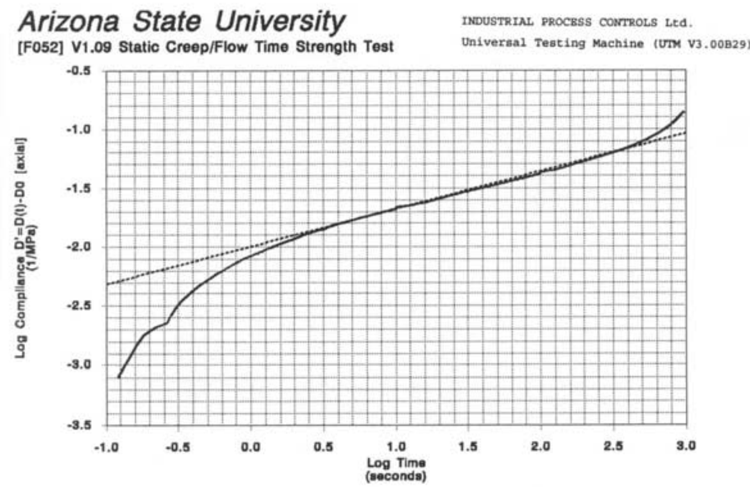


Figure 3. Total Axial Strain Vs. Time From a Static Creep / Flow Time Test.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1




```
        test date and time: Thursday February 3, 2000  9:56 PM

    specimen identification: A0943

Data analysis results:
----------------------
 minimum regression time (s)      1.0  average deviator stress (kPa) 69.2
 maximum regression time (s)    300.0  average confining stress (kPa) 1.4
             time at D0 (s)       0.1
[averaged]       axial based D0 0.008744
                 axial based D1 0.009997
                 axial based m1 0.321279
   axial based flow time (s) 303.3023
```

Figure 4. Regression Constants "D_1" and "M_1" from Log Compliance – Log Time Plot.

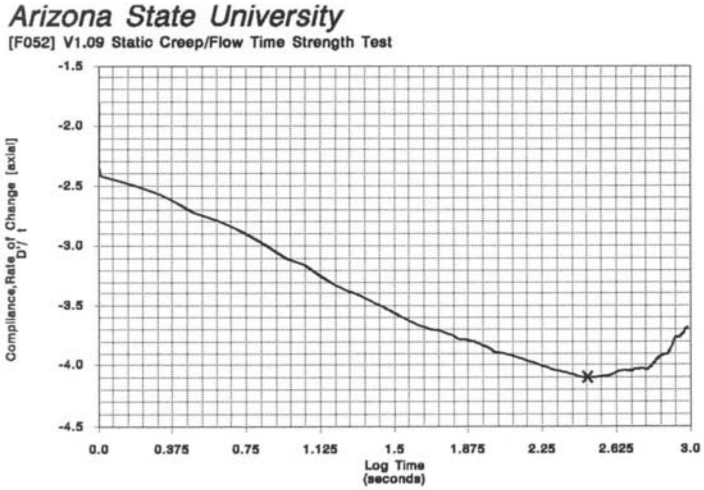


Figure 5. Typical Plot of the Rate of Change in Compliance Vs. Loading Time on a Log-Log Scale.

Annex B
NCHRP Project 9-19 Draft Test Protocol W2:
Simple Performance Test for Permanent Deformation Based Upon Repeated Load Test of Asphalt Concrete Mixtures
Arizona State University, September, 2000

1. Scope

1.5 This test method covers procedures for the preparation, testing and measurement of permanent deformation of cylindrical asphalt concrete specimens in a triaxial state of compressive loading.

1.6 The procedure uses a loading cycle of 1.0 second in duration, and consisting of applying 0.1-second haversine load followed by 0.9-second rest period. Permanent axial and/or radial strains are recorded through out the test.

1.7 The test is conducted at a single effective temperature T_{eff} and design stress levels.

1.8 This standard is applicable to laboratory prepared specimens 100 mm in diameter and 150 mm in height for mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in).

1.9 This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

TP4 Method for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the SHRP Gyratory Compactor

PP2 Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)

T67 Standard Practices for Load Verification of Testing Machines (cross-listed with ASTM E4)

T269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

3. Definitions

3.1 *Permanent Deformation* – is a manifestation of two different mechanisms and is a combination of densification (volume change) and repetitive shear deformation (plastic flow with no volume change).

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

3.2 *Flow Number* - is defined as the number of load repetitions at which shear deformation, under constant volume, starts.

3.3 *Effective Temperature* T_{eff} – Is a single test temperature at which an amount of permanent deformation would occur equivalent to that measured by considering each season separately throughout the year

4. Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a haversine axial load. The load is applied for duration of 0.1-second with a rest period of 0.9-second. The rest period has a load equivalent to the seating load. The test can be performed either without confinement, or a confining pressure is applied to better simulate in situ stress conditions. Cumulative permanent axial and radial strains are recorded through out the test. In addition, the number of repetitions at which shear deformation, under constant volume, starts is defined as the Flow Number.

5. Significance and Use

5.1 Current Superpave volumetric mix design procedure lacks a fundamental design criterion to evaluate fundamental engineering properties of the asphalt mixture that directly affect performance. In this test, the selection of the design binder content and aggregate structure is fundamentally enhanced by the evaluation of the mix resistance to shear flow (Flow Number of Repetitions).

5.2 This fundamental engineering property can be used as a performance criteria indicator for permanent deformation resistance of the asphalt concrete mixture, or can be simply used to compare the shear resistance properties of various bituminous paving mixtures.

6. Apparatus

6.1 Load Test System – A load test system consisting of a testing machine, environmental chamber, measuring system, and specimen end fixtures.

6.1.1 *Testing Machine* – The testing machine should be capable of applying haversine loads up to 25 kN (5,600 1bs). An electro-hydraulic machine is recommended but not necessarily required. The loading device should be calibrated as outlined in the "Equipment Calibration" Section of the testing manual.

6.1.2 *Confining Pressure Device*: a system capable of maintaining a constant confining pressure, up to 207 kPa (30 psi), such as an air pressure intensifier or a hydraulic pump. The device shall be equipped with a pressure relief valve and a system to pressurize and depressurize the cell with gas or fluid. The device should also have a high temperature control subsystem for testing up to 60 °C (140 °F) within an accuracy of ± 0.5 °C (1 °F) at constant pressure.

Note 1 – It has been found that feedback control of a servovalve to control the pressure is the preferred method of control. However, manual valves or proportional valves may be adequate for some applications. The axisymmetric triaxial cells of AASHTO T292 or T294 may be used for this purpose. Other types of triaxial cells may be permitted. In all cases, see-through cells are not recommended for use with gas confining media. Sight glass ports or reduced area windows are recommended with gas media for safety reasons. It is not required that the specimen be visible through the cell wall if specimen centering and proper instrumentation operation can be verified without a see-through pressure vessel. Certain simulations of pavement loads and extended material characterization desired for local conditions may suggest using confining pressures greater than 207 kPa. For pressures higher than 690 kPa (100 psi), fluid cells are recommended.

6.1.3 *Environmental Chamber* – A chamber for controlling the test specimen at the desired temperature is required. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 25 to 60 °C (77 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate the test specimen and a dummy specimen with temperature sensor mounted at the center for temperature verification.

Note 2 – If the chamber does not have sufficient room for a dummy specimen, it is permissible to have a second chamber controlling the temperature of the dummy. The separate dummy chamber must be operated similar to the operation of the main test specimen chamber so that the dummy will accurately register the time required to obtain temperature equilibrium on the test specimen.

6.1.4 *Measurement System* - The system shall include a data acquisition system comprising analog to digital conversion and/or digital input for storage and analysis on a computer. The system shall be capable of measuring and recording the time history of the applied load, axial and radial deformations for the time duration required by this test method. The system shall be capable of measuring the load and resulting deformations with a resolution of 0.5 percent.

6.1.4.1 *Load* - The load shall be measured with an electronic load cell having adequate capacity for the anticipated load requirements. The load cell shall be calibrated in accordance with AASHTO T67. The load measuring transducer shall have accuracy equal to or better than 0.25 percent of full scale.

Note 3 – A 25 kN (5600 lbf) load cell has been found to be the approximate maximum capacity limit for this test method because of range versus resolution factors. It is recommended that if the selected load cell capacity is 25 kN or greater, the system should be equipped with either manual or automatic amplification selection capability so that it can be used to enhance control of the system at lower anticipated loads.

6.1.4.2 *Axial and Radial Deformations* – Axial and/or radial deformations shall be measured with displacement transducers referenced to gauge points contacting the specimen as shown in Figure 1. The axial deformations shall be measured at a minimum of two locations 180° apart (in plan view); radial deformations shall be measured at a minimum of four locations aligned, in planform, on diametral, perpendicular lines which intersect at the center of the specimen.

Note 4 – Analog transducers such as linear variable differential transformers (LVDTs) having a range of ± 0.5 mm (0.02 in) and inherent nonlinearity equal to or better than ±0.025 percent of full scale have been found adequate for this purpose. Software or firmware linearization techniques may be used to improve the inherent nonlinearity. Amplification and signal conditioning techniques may be used with the ± 0.5 mm range LVDTs to obtain resolutions down to 0.001mm (0.00004 in) or better for small strain tests conditions. These techniques may be manual or automatic. In general, increasing the resolution by manual signal amplification will result in reduction of the overall range of the instrument by the same factor.

6.1.5 *Loading Platens* – Platens, with a diameter equal to or greater than that of the test specimen are required above and below the specimen to transfer the load from the testing machine to the specimen. Generally, these platens should be made of hardened or plated steel, or anodized high strength aluminum. Softer materials will require more frequent replacement. Materials that have linear elastic modulus properties and hardness properties lower than that of 6061-T6 aluminum shall not be used.

6.1.6 *Flexible Membrane*: for the confined tests, the specimen should be enclosed in an impermeable flexible membrane. The membrane should be sufficiently long to extend well onto the platens and when slightly stretched be of the same diameter as the specimen. Typical membrane wall thickness range between 0.012 and 0.0625 inches (0.305 – 1.588 mm).

6.1.7 *End Treatment* – Friction reducing end treatments shall be placed between the specimen ends and the loading platens.

Note 5 - End treatments consisting of two 0.5 mm (0.02 in) thick latex sheets separated with silicone grease have been found to be suitable friction reducing end treatments.

6.2 *Gyratory Compactor* – A gyrator compactor and associated equipment for preparing laboratory specimens in accordance with AASHTO TP4 shall be used. Field cores shall meet the requirements of paragraphs 7.4 through 7.6 of this test method and any reports on cores so tested will contain a detailed description of the location of any lift boundaries within the height of the specimen (e.g. lift order, thickness and material homogeneity).

6.3 *Saw* – A machine for sawing test specimens ends to the appropriate length is required. The saw machine shall be capable of cutting specimens to the prescribed dimensions without excessive heating or shock.

Note 6 – A diamond masonry saw greatly facilitates the preparation of test specimens with smooth, parallel ends. Both single or double-bladed diamond saws should have feed mechanisms and speed controls of sufficient precision to ensure compliance with paragraphs 7.5 and 7.6 of this method. Adequate blade stiffness is also important to control flexing of the blade during thin cuts.

6.4 *Core Drill* - A coring machine with cooling system and a diamond bit for cutting nominal 100 mm (4 in) diameter test specimens.

Note 7 – A coring machine with adjustable vertical feed and rotational speed is recommended. The variable feeds and speeds may be controlled by various methods. A vertical feed rate of approximately 0.05 mm/rev (0.002 in/rev) and a rotational speed of approximately 455 RPM has been found to be satisfactory for several of the Superpave mixtures.

7. Test Specimens

7.1 *Size* – *T*esting shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens cored from gyratory compacted mixtures.

7.2 *Aging* – Mixtures shall be aged in accordance with the short-term oven aging procedure in AASHTO PP2.

7.3 *Gyratory Specimens* – Prepare 165 mm (6.5 in) high specimens to the required air void content in accordance with AASHTO TP-4.

7.4 *Coring* - Core the nominal 100 mm (4 in) diameter test specimens from the center of the gyratory specimens. Both the core drill and the gyratory specimen should be adequately supported to ensure that the resulting test specimen is cylindrical with sides that are smooth, parallel, and free from steps, ridges, and grooves.

7.5 *Diameter* – Measure the diameter of the test specimen at the mid height and third points along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm (0.05 in). Calculate the average and the standard deviation of the six measurements. If the standard deviation is greater than 2.5 mm (0.01 in) discard the specimen. For acceptable specimens, the average diameter, reported to the nearest 1 mm, shall be used in the stress calculations.

7.6 *End Preparation*- The ends of all test specimens shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the specimen by sawing with a single or double bladed saw. To ensure that the sawed samples have parallel ends, the prepared specimen ends shall meet the tolerances described below. Reject test specimens not meeting these tolerances.

7.6.1 The specimen ends shall have a cut surface waviness height within a tolerance of ± 0.05 mm across any diameter. This requirement shall be checked in a minimum of three positions at approximately 120° intervals using a straight edge and feeler gauges approximately 8-12.5 mm (0.315-0.5 in) wide or an optical comparator.

7.6.2 The specimen end shall not depart from perpendicular to the axis of the specimen by more than 0.5 degrees (i.e. 0.87 mm or 0.03 in across the diameter of a 100 mm diameter specimen). This requirement shall be checked on each specimen using a machinists square and feeler gauges.

7.7 *Air Void Content* – Determine the air void content of the final test specimen in accordance with AASHTO T269. Reject specimens with air voids that differ by more than 0.5 percent from the target air voids.

7.8 *Replicates* – The number of test specimens required depends on the number of axial and/or radial strain measurements made per specimen and the desired accuracy of the average flow time values. Table 1 summarizes the LVDTs and replicate number of specimens needed to obtain a desired accuracy limit.

Table 1. Recommended Number of Specimens

LVDTs per Specimen (Total for either vertical or horizontal, not combined total)	Number of Specimens	Estimated Standard Error of the Mean, % Per Mixture's Nominal Aggregate Size		
		12.5mm	19mm	37.5mm
2	2	7.6	9.5	18.8
2	3	6.2	7.7	15.3
3	2	6.7	8.9	17.4
3	3	5.5	7.3	14.2
4	2	6.2	8.6	16.6
4	3	5.0	7.0	13.6

7.9 *Sample Storage* – Wrap completed specimens in polyethylene and store in an environmentally protected storage area at temperatures between 5 and 25 °C (40 and 75 °F).

Note 8 – To eliminate effects of aging on test results, it is recommended that specimens be stored no more than two weeks prior to testing.

8. Test Specimen Instrumentation

8.1 Attach mounting studs for the axial LVDTs to the sides of the specimen with epoxy cement. Figure 2 presents details of the mounting studs and LVDT mounting hardware.

Note 9 – Quick setting epoxy such as Duro Master Mend Extra Strength Quick Set QM-50 has been found satisfactory for attaching studs. Under certain conditions when using the triaxial cell with confining pressure, the mounting studs may not require gluing to the specimen. While the surface contact area of the mounting studs is normally minimized consistent with transducer support requirements, it is generally recommended that the area of the studs be sufficiently large to bridge any open void structure features evident on the cut face of the specimen. The minimum diameter mounting stud consistent with support requirements is normally set at 8 mm (0.315 in), maximum diameters have not been established. A circular stud contact surface shape is not required, rectangular or other shapes are acceptable.

8.2 The gauge length for measuring axial deformations shall be 100 mm ±1 mm. Suitable alignment and spacing fixture shall be used to facilitate mounting of the axial deformation measuring hardware. The gauge length is normally measured between the stud centers.

9. Procedure

9.1 The recommended test protocol for the Simple Performance Test for use in the Superpave volumetric mix design consists of testing the asphalt mix at one effective pavement temperature T_{eff} and one design stress level selected by the design engineer. The effective pavement temperature T_{eff} covers approximately the temperature range of 25 to 60 °C (77 to 140 °F). The design stress levels covers the range between 69 and 207 kPa (10 –30 psi) for the unconfined tests, and 483 to 966 kPa for the confined tests. Typical confinement levels range between 35 and 207 kPa (5 – 30 psi).

9.2 Place the test specimen in the environmental chamber and allow it to equilibrate to the specified testing temperature. For the confined tests in a standard geotechnical cell, glue the gauge points to the specimen surface as necessary, fit the flexible membrane over the specimen and mount the axial hardware fixtures to the gauge points through the membrane. Place the test specimen with the flexible membrane on in the environmental chamber. A dummy specimen with a temperature sensor mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, Table 2 provides a summary of the minimum required temperature equilibrium times for samples starting from room temperature (i.e. 25 °C).

Table 2. Recommended Equilibrium Times.

Specimen Test Temperature, °C (°F)	Time, hrs
25 (77)	0.5
30 (86)	1.0
37.8 (100)	1.5
>54.4 (130)	2.0

<u>**Unconfined Tests**</u>

9.3 After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, and mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

9.4 Place the upper friction reducing end treatment and platen on top of the specimen. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.5 Apply a contact load equal to 5 percent of the total load that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., check for proper direction sensing for all LVDTs).

9.6 Place the radial LVDTs in contact with the specimen, adjust the LVDTs to near the end of their linear range to allow the full range to be available for the accumulation of radial permanent deformation. Adjust and balance the electronic measuring system as necessary.

9.7 Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber.

9.8 After the time required for the sample to reach the testing temperature, apply the haversine load which yields the desired stress on the specimen. The maximum applied load (Pmax) is the maximum total load applied to the sample, including the contact and cyclic load: Pmax = Pcontact + Pcyclic

9.9 The contact load (Pcontact) is the vertical load placed on the specimen to maintain a positive contact between loading strip and the specimen: Pcontact = 0.05 x Pmax

9.10 The cyclic load (Pcyclic) is the load applied to the test specimen which is used to calculate the permanent deformation parameters: Pcyclic = Pmax - Pcontact

9.11 Apply the haversine loading (Pcyclic) and continue until 10,000 cycles (2.8 hours) or until the specimen fails and results in excessive tertiary deformation to the specimen, whichever comes first. The total number of cycles or the testing time will depend on the temperature and the stress levels applied.

9.12 During the load applications, record the load applied, the axial and radial deflection measured from all LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, it is recommended to use the data acquisition of the cycles shown in Table 3.

Table 3. Suggested Data Collection for the Repeated Load Permanent Deformation Test

Data collected During Cycles	Data collected During Cycles	Data collected During Cycles
1 through 100	700	4,500
130	750	5,000
170	800	5,500
200	850	6,000
230	900	6,500
270	950	7,000
300	1,000	7,500
350	1,300	8,000
400	1,700	8,500
450	2,000	9,000
500	2,300	9,500
550	2,700	10,000
600	3,000	
650	4,000	

Confined Tests

9.13 After temperature equilibrium is reached, place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, place the top platen and extend the flexible membrane over the top and bottom platens. Attach the O-rings to seal the specimen on top and bottom platens from the confining air/fluid. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.14 Mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

9.15 Connect the appropriate hose through the upper or lower platen (or take other appropriate steps) to keep the specimen's internal void structure under atmospheric pressure while pressure greater than atmospheric is applied to the outside of the membrane during testing.

9.16 Assemble the triaxial cell over the specimen, ensure proper seal with the base and connect the fluid (or gas) pressure lines.

9.17 Apply a contact load equal to 5 percent of the load that will be applied to the specimen, while ensuring the proper response of the LVDTs (i.e., both decrease accordingly). Place the radial LVDTs in contact with the specimen, adjust the LVDTs to near the end of their linear range to allow the full range to be available for the accumulation of radial permanent deformation.

9.18 Record the initial LVDT readings and slowly increase the lateral pressure to the desired test level (e.g. 2 psi /sec). Adjust and balance the electronic measuring system as necessary. Close the environmental chamber and allow sufficient time (normally 10 to 15 minutes) for the temperature to stabilize within the specimen and the chamber

9.19 After the time required for the sample to reach the testing temperature, apply the haversine load which yields the desired stress on the specimen. Continue until 10,000 cycles (2.8 hours) or until the specimen fails and results in excessive tertiary deformation to the specimen, whichever comes first. The total number of cycles or the testing time will depend on the temperature and the stress levels applied.

9.20 During the load applications, record the load applied, confining pressure, the axial and radial deflection measured from all LVDTs through the data acquisition system. Signal-to-noise ratio should be at least 10. All data should be collected in real time and collected/processed so as to minimize phase errors due to sequential channel sampling. In order to save storage space during data acquisition for 10,000 cycles, it is recommended to use the data acquisition of the cycles shown in Table 3.

10. Calculations

10.1 Calculate the average axial deformation for each specimen by averaging the readings from the two axial LVDTs. Convert the average deformation values to total axial strain (ε_{Ta}), in/in, by dividing by the gauge length, L (100mm (4-inches). Typical total axial strain versus time is shown in Figure 3.

10.2 Compute the cumulative axial permanent strain.

10.3 Plot the cumulative axial permanent strain versus number of loading cycles in log space. Determine the permanent deformation parameters, intercept (a) and slope (b), from the linear portion of the permanent strain curve (see Figure 4).

10.4 The flow number of repetitions is viewed as the lowest point in the curve of rate of change in axial strain vs. number of loading cycles (see Figure 5). The rate of change of axial strain versus number of loading cycles should be plotted and the flow number (F_N) is estimated where a minimum or zero slope is observed.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

11. Report

11.1 Report all specimen information including mix identification, storage conditions, dates of manufacturing and testing, specimen diameter and length, volumetric properties, stress levels used, confining pressure, axial permanent deformation parameters: a, b and flow number of repetitions.

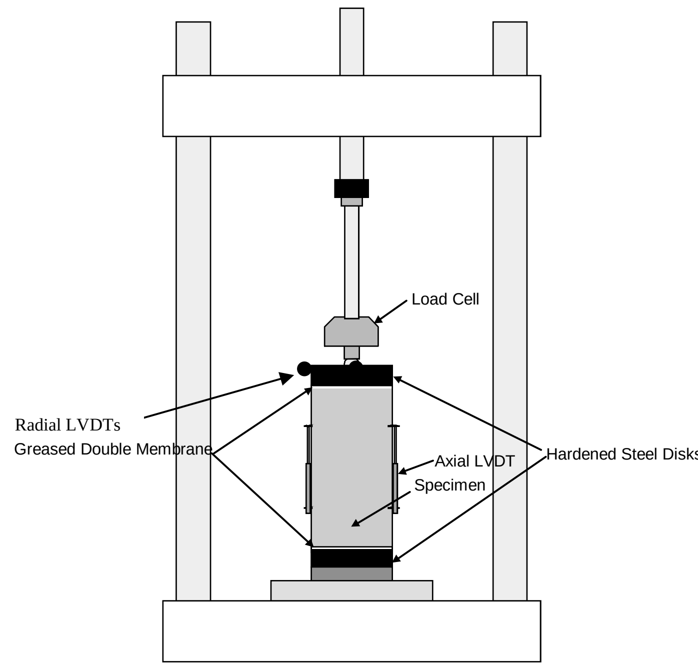
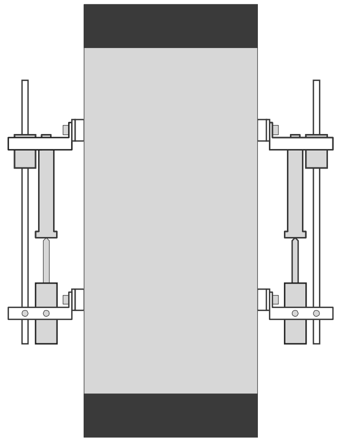
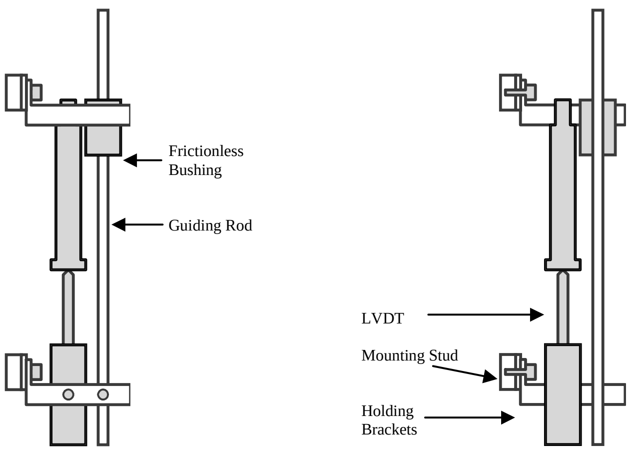


Figure 1. Schematic of Repeated Load Permanent Deformation Test.



On-Sample Assembly



Lateral View **Longitudinal Cross-Section**

Figure 2. Axial LVDTs Instrumentation.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

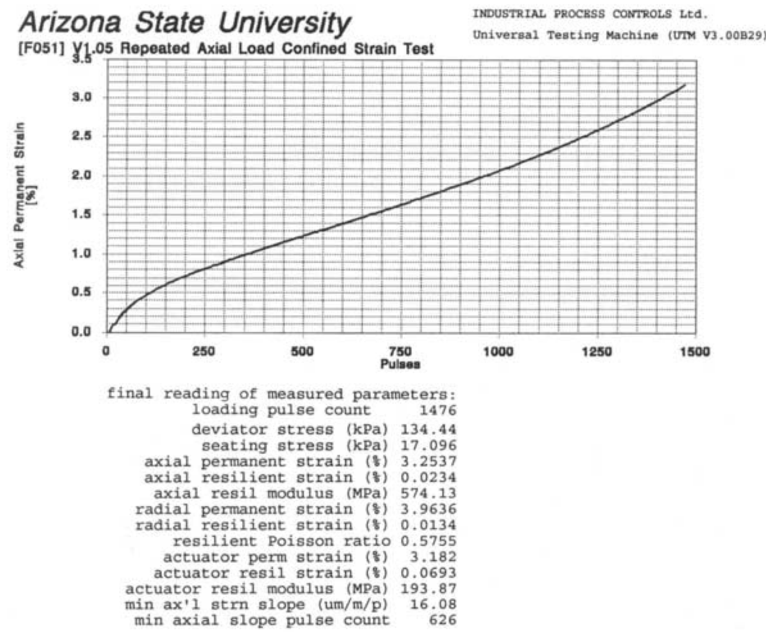


Figure 3. Cumulative Permanent Strain Vs. Loading Cycles From a Repeated Load Permanent Deformation Test.

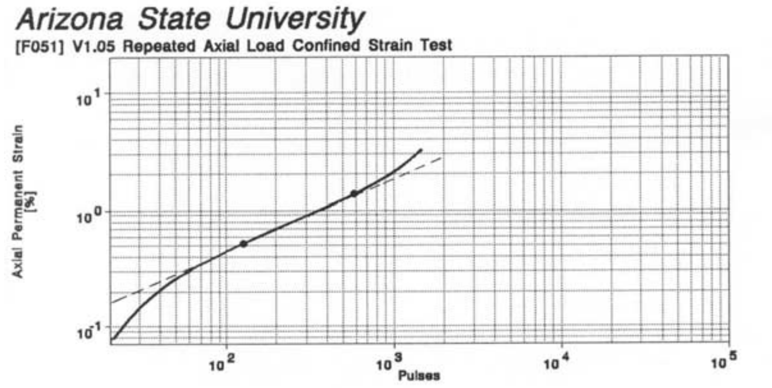


Figure 4. Regression Constants "a" and "b" from Log Permanent Strain – Log Number of Loading Cycles Plot.

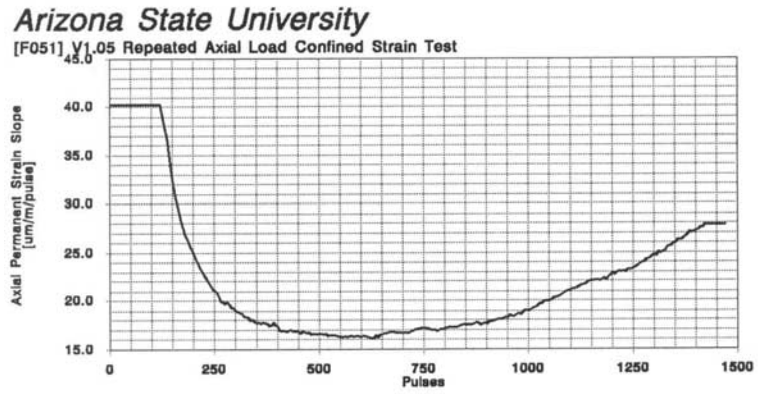


Figure 5. Typical Plot of the Rate of Change in Permanent Strain Vs. Loading Cycles.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

Annex C
NCHRP Project 9-19 Draft Test Protocol X1:
Simple Performance Test for Permanent Deformation Based Upon Dynamic Modulus of Asphalt Concrete Mixtures
Arizona State University, September, 2000

1. Scope

1.1 This test method covers procedures for preparing and testing asphalt concrete mixtures to determine the dynamic modulus and phase angle at a single effective temperature T_{eff} and design loading frequency.

1.2 This test method is a part of test protocols that include determination of the dynamic modulus of the asphalt mix for paving purposes. The other test methods are Standard Test Method for Simple Performance Test for Fatigue Cracking based Upon Dynamic Modulus of Asphalt Concrete Mixture and Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures, which is for constructing a master curve for characterizing asphalt concrete for pavement thickness design and performance analysis

1.3 This standard is applicable to laboratory prepared specimens of mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in).

1.4 This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

TP4 Method for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the SHRP Gyratory Compactor

PP2 Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)

T67 Standard Practices for Load Verification of Testing Machines (cross-listed with ASTM E4)

T269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

3. Definitions

3.1 *Dynamic Modulus* – $|E^*|$, the norm value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

3.2 *Complex Modulus* – E^*, a complex number that defines the relationship between stress and strain for a linear viscoelastic material.

3.3 *Phase angle* – δ, the angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled-stress test.

3.4 *Linear viscoelastic* – within the context of this test, refers to behavior in which the dynamic modulus is independent of stress or strain amplitude.

3.5 *Effective Temperature* T_{eff} – Is a single test temperature at which an amount of permanent deformation would occur equivalent to that measured by considering each season separately throughout the year

4. Summary of Method

4.1 A sinusoidal (haversine) axial compressive stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The applied stress and the resulting recoverable axial strain response of the specimen is measured and used to calculate the dynamic modulus and phase angle.

4.2 Figure 1 presents a schematic of the dynamic modulus test device.

5. Significance and Use

5.1 Dynamic modulus values, measured at one effective temperature T_{eff} and one design frequency selected by the design engineer, are used as performance criteria for permanent deformation resistance of the asphalt concrete mixture to be used in conjunction of the Superpave Volumetric Mix Design Method.

Note 1 – The effective temperature T_{eff} covers approximately the temperature range of 25 to 60 °C (77 to 140 °F).

Note 2 – 10 Hz frequency can be used for highway speed and 0.1 Hz for creep – intersection traffic.

5.2 Dynamic modulus values measured over a range of temperatures and frequencies of loading can be shifted into a master curve for characterizing asphalt concrete for pavement thickness design and performance analysis.

5.3 This test method covers the determination of the dynamic modulus values measured unconfined within the linear viscoelastic range of the asphalt mixture.

Note 3 - Future research may indicate the need for confined stress states and nonlinear material characterization. Confinement may be applied with various types of axisymmetric triaxial cells to address these needs.

6. Apparatus

6.1 Dynamic Modulus Test System – A dynamic modulus test system consisting of a testing machine, environmental chamber, measuring system, and specimen end fixtures.

6.1.1 *Testing Machine* – A materials testing machine capable of producing a controlled haversine compressive loading of paragraphs 9.7 and 9.8 is required.

Note 4 - The testing machine shall have a capability of applying load over a range of frequencies from 0.1 to 30 Hz. Stress levels up to 2800 kPa (400 psi) may be required at certain temperatures and frequencies. However, for virtually all effective temperatures in the US, stress levels between 10 kPa and 690 kPa (1.5-100 psi) have been found to be sufficient. This latter range of stress levels converts to an approximate range of 0.08-5.5 kN 18-1218 lbf) on a 100 mm diameter specimen. If the machine is to be dedicated only to this test procedure with no requirement for additional strength testing or low temperature testing, it is recommended that the lowest capacity machine capable of applying the required waveforms be used. Alternatively, larger capacity machines may be used with low capacity load cells or signal amplifiers. It has been found that feedback controlled testing machines equipped with appropriate servovalves can be used for this test. As a general rule of thumb, the dynamic load capacity of a testing machine between 10 and 30 Hz will be approximately 65-75 percent of the monotonic ("static") capacity, but this rule varies by manufacturer. A 25-50 kN capacity servohydraulic testing machine has been found to be adequate for virtually all of the tests in the suite of simple performance tests.

6.1.2 *Environmental Chamber* – A chamber for controlling the test specimen at the desired temperature is required. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 25 to 60 °C (77 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate the test specimen and a dummy specimen with temperature sensor mounted at the center for temperature verification.

Note 5 – A chamber that will control temperatures down to –10 °C (14 °F) may be required for other tests mentioned in paragraph 1.2 of this method.

Note 6 – If the chamber does not have sufficient room for a dummy specimen, it is permissible to have a second chamber controlling the

temperature of the dummy. The separate dummy chamber must be operated similar to the operation of the main test specimen chamber so that the dummy will accurately register the time required to obtain temperature equilibrium on the test specimen.

6.1.3 *Measurement System* - The system shall include a data acquisition system comprising analog to digital conversion and/or digital input for storage and analysis on a computer. The system shall be capable of measuring and recording the time history of the applied load and the axial deformations for the cycles required by this test method. The system shall be capable of measuring the period of the applied sinusoidal load and resulting deformations with a resolution of 0.5 percent.

6.1.3.1 *Load* - The load shall be measured with an electronic load cell having adequate capacity for the anticipated load requirements. The load cell shall be calibrated in accordance with AASHTO T67. The load measuring transducer shall have an accuracy equal to or better than 0.25 percent of full scale.

Note 7 – A 25 kN (5600 lbf) load cell has been found to be the approximate maximum capacity limit for this test method because of range versus resolution factors. It is recommended that if the selected load cell capacity is 25 kN or greater, the system should be equipped with either manual or automatic amplification selection capability so that it can be used to enhance control of the system at the minimum anticipated loads given in paragraph 9.7.

6.1.3.2 *Axial Deformations* – Axial deformations shall be measured with displacement transducers referenced to gauge points contacting the specimen as shown in Figure 2. The deformations shall be measured at a minimum of two locations 180° apart (in planview); however, three locations located 120° apart is recommended to minimize the number of replicate specimens required for testing.

Note 8 – Analog transducers such as linear variable differential transformers (LVDTs) having a range of ± 0.5 mm (0.02 in) and inherent nonlinearity equal to or better than ±0.025 percent of full scale have been found adequate for this purpose. Software or firmware linearization techniques may be used to improve the inherent nonlinearity. Amplification and signal conditioning techniques may be used with the ± 0.5 mm range LVDTs to obtain resolutions down to 0.001mm (0.00004 in) or better for small strain tests conditions. These techniques may be manual or automatic. In general, increasing the resolution by manual signal amplification will result in reduction of the overall range of the instrument by the same factor.

6.1.4 *Loading Platens* – Platens, with a diameter equal to or greater than that of the test specimen are required above and below the specimen to transfer the load from the testing machine to the specimen. Generally, these platens should be made anodized high strength aluminum. Softer materials will require more frequent replacement. Materials that have linear elastic modulus properties and hardness properties lower than that of 6061-T6 aluminum shall not be used. Steel platens may cause too much seating load to the specimen at high temperature and are not recommended.

6.1.5 *End Treatment* – Friction reducing end treatments shall be placed between the specimen ends and the loading platens.

Note 9 - End treatments consisting of two 0.5 mm (0.02 in) thick latex sheets separated with silicone grease have been found to be suitable friction reducing end treatments.

6.2 *Gyratory Compactor* – A gyrator compactor and associated equipment for preparing laboratory specimens in accordance with AASHTO TP4 shall be used. Field cores shall meet the requirements of paragraphs 7.4 through 7.6 of this test method and any reports on cores so tested will contain a detailed description of the location of any lift boundaries within the height of the specimen (e.g. lift order, thickness and material homogeneity).

6.3 *Saw* – A machine for cutting test specimens to the appropriate length is required. The saw or grinding machine shall be capable of cutting specimens to the prescribed dimensions without excessive heating or shock.

Note 10 – A double bladed diamond masonry saw greatly facilitates the preparation of test specimens with smooth, parallel ends. Both single- and double-bladed diamond saws should have feed mechanisms and speed controls of sufficient precision to ensure compliance with paragraphs 7.5 and 7.6 of this method. Adequate blade stiffness is also important to control flexing of the blade during thin cuts.

6.4 *Core Drill* - A coring machine with cooling system and a diamond bit for cutting nominal 100 mm (4 in) diameter test specimens.

Note 11 – A coring machine with adjustable vertical feed and rotational speed is recommended. The variable feeds and speeds may be controlled by various methods. A vertical feed rate of approximately 0.05 mm/rev (0.002 in/rev) and a rotational speed of approximately 455 RPM has been found to be satisfactory for several of the Superpave mixtures.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

7. Test Specimens

7.1 *Size* – Dynamic modulus testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens cored from gyratory compacted mixtures.

7.2 *Aging* – Mixtures shall be aged in accordance with the short-term oven aging procedure in AASHTO PP2.

7.3 *Gyratory Specimens* – Prepare 165 mm (6.5 in) high specimens to the required air void content in accordance with AASHTO TP-4.

Note 12 – Testing should be performed on test specimens meeting specific air void tolerances. The gyratory specimen air void content required to obtain a specified test specimen air void content must be determined by trial and error. Generally, the test specimen air void content is 1.5 to 2.5 percent lower than the air void content of the gyratory specimen when the test specimen is removed from the middle as specified in this test method.

7.4 *Coring* - Core the nominal 100 mm (4 in) diameter test specimens from the center of the gyratory specimens. Both the core drill and the gyratory specimen should be adequately supported to ensure that the resulting test specimen is cylindrical with sides that are smooth, parallel, and free from steps, ridges, and grooves.

7.5 *Diameter* – Measure the diameter of the test specimen at the mid height and third points along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm (0.05 in). Calculate the average and the standard deviation of the six measurements. If the standard deviation is greater than 2.5 mm (0.01 in) discard the specimen. For acceptable specimens, the average diameter, reported to the nearest 1 mm, shall be used in the stress calculations.

7.6 *End Preparation*- The ends of all test specimens shall be smooth and perpendicular to the axis of the specimen. Prepare the ends of the specimen by sawing with a single or double bladed saw. The prepared specimen ends shall meet the tolerances described below. Reject test specimens not meeting these tolerances.

7.6.1 The specimen ends shall have a cut surface waviness height within a tolerance of ± 0.05 mm across any diameter. This requirement shall be checked in a minimum of three positions at approximately 120° intervals using a straight edge and feeler gauges approximately 8-12.5 mm (0.315-0.5 in) wide or an optical comparator.

7.6.2 The specimen end shall not depart from perpendicular to the axis of the specimen by more than 0.5 degrees (i.e. 0.87 mm or 0.03 in across the diameter of a 100 mm diameter specimen). This requirement shall be checked on each specimen using a machinists square and feeler gauges.

7.7 *Air Void Content* – Determine the air void content of the final test specimen in accordance with AASHTO T269. Reject specimens with air voids that differ by more than 0.5 percent from the target air voids.

7.8 *Number* – The number of test specimens required depends on the number of axial strain measurements made per specimen and the desired accuracy of the average dynamic modulus. Table 1 summarizes the replicate number of specimens that should be tested to obtain an accuracy limit of less than ±15 percent.

Table 1. Recommended Number of Specimens

LVDTs per Specimen	Number of Specimens	Estimated Limit of Accuracy
2	4	13.4
3	2	13.1

7.9 *Sample Storage* – Wrap completed specimens in polyethylene and store in an environmentally protected storage area at temperatures between 5 and 25°C (40 and 75 °F).

Note 13 – To eliminate effects of aging on test results, it is recommended that specimens be stored no more than two weeks prior to testing.

8. Test Specimen Instrumentation

8.1 Attach mounting studs for the axial LVDTs to the sides of the specimen with epoxy cement. Figure 3 presents details of the mounting studs and LVDT mounting hardware.

Note 14 – Quick setting epoxy such as Duro Master Mend Extra Strength Quick Set QM-50 has been found satisfactory for attaching studs. Under certain conditions when using the triaxial cell mentioned in Note 3, the mounting studs may not require gluing to the specimen. While the surface contact area of the mounting studs is normally minimized consistent with transducer support requirements, it is generally recommended that the area of the studs be sufficiently large to bridge any open void structure features evident on the cut face of the specimen. The minimum diameter mounting stud consistent with support requirements is normally set at 8 mm (0.315 in), maximum diameters

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

have not been established. A circular stud contact surface shape is not required, rectangular or other shapes are acceptable.

8.2 The gauge length for measuring axial deformations shall be 100 mm ±1 mm. An alignment and spacing fixture similar to that shown in Figure 3 can be used to facilitate mounting of the axial deformation measuring hardware. The gauge length is normally measured between the stud centers.

9. Procedure

9.1 The recommended test protocol for the Simple Performance Test for use in the Superpave volumetric mix design consists of testing the asphalt mix at one effective pavement temperature T_{eff} and one design frequency selected by the design engineer. The effective pavement temperature T_{eff} covers approximately the temperature range of 25 to 60 °C (77 to 140°F). The design frequency covers the range between 0.1 to 10 Hz

9.2 Place the test specimen in the environmental chamber and allow it to equilibrate to the specified testing temperature. A dummy specimen with a temperature sensor mounted at the center can be monitored to determine when the specimen reaches the specified test temperature. In the absence of the dummy specimen, Table 2 summarizes minimum recommended temperature equilibrium times from room temperature (i.e. 25 °C).

Table 2. Recommended Equilibrium Times.

Specimen Test Temperature, °C (°F)	Time, hrs
30 (86)	TBD*
40 (104)	
50 (122)	
60 (140)	

* To be determined

9.3 Place one of the friction reducing end treatments on top of the platen at the bottom of the loading frame. Place the specimen on top of the lower end treatment, and mount the axial LVDTs to the hardware previously attached to the specimen. Adjust the LVDT to near the end of its linear range to allow the full range to be available for the accumulation of compressive permanent deformation.

9.4 Place the upper friction reducing end treatment and platen on top of the specimen. Center the specimen with the load actuator visually in order to avoid eccentric loading.

9.5 Apply a contact load (P_{min}) equal to 5 percent of the dynamic load that will be applied to the specimen.

9.6 Adjust and balance the electronic measuring system as necessary.

9.7 Apply haversine loading ($P_{dynamic}$) to the specimen without impact in a cyclic manner. The dynamic load should be adjusted to obtain axial strains between 50 and 150 microstrain.

Note 15 – The dynamic load depends upon the specimen stiffness and generally ranges between 10 and 690 kPa (1.5 and 100 psi). Higher load is needed at colder temperatures. Table 3 presents target dynamic load levels based on temperature.

Table 3. Target Dynamic Loads

Temperature, °C (°F)	Range, kPa	Range, psi
25 (77)	70 – 690	10 –100
38 (100)	40-200	6 –29
54 (130)	10 - 70	1.5 – 10

9.8 Test the specimens at selected temperature by first precondition the specimen with 200 cycles at 25 Hz using the target dynamic loads in Table 3 (interpolate if necessary). Then load the specimen using the selected frequency and number of cycles as specified in Table 4.

Table 4. Cycles for Test Sequence.

Frequency	Number of Cycles
10	100
5	50
1	25
0.5	6
0.1	6

9.9 If excessive permanent deformation (greater than 1000 micro units of strain) occurs, reduce the maximum loading stress level to half. Discard the specimen and use a new specimen for testing under reduced load conditions.

10. Calculations

10.1 Capture and store the last 6 loading cycles of full waveform data for each transducer. Determine the average amplitude of the sinusoidal load and deformation from each axial displacement transducer over the first 5 cycles of the last 6 loading cycle group

(since the displacement will lag behind the load, the computations may use data from the 6th cycle, but might not have enough of the waveform to fully determine the properties in the 6th cycle).

10.2 Average the signals from the displacement transducers. Determine the average time lag between the peak load and the peak deformation over the 5 loading cycles.

Note 16 – Different approaches are available to determine these. The approach is highly dependent upon the number of data points collected per cycle. Approaches that have been used include peak search algorithms, various curve fitting techniques, and Fourier Transform. Curve fitting techniques and other numerical techniques have also been used to determine the phase angle from the more stable center portion of the waveform instead of the peaks. If any displacement transducer is out of range or otherwise obviously reading incorrectly during a cycle, discard the data for that cycle.

Note 17 – For testing that will be used for statistical within-specimen variability and for establishing local precision and bias statements, paragraphs 10.3 through 10.7 must include computations from each individual displacement transducer in addition to the results from the averaged displacements. Therefore, it is a strict requirement that the data storage requirements of paragraph 10.1 be met.

10.3 Calculate the loading stress, σ_o, as follows (see Figure 4):

$$\sigma_o = \frac{\overline{P}}{A}$$

Where:

$\overline{P}$ = average load amplitude
A = area of specimen
σ_o = stress.

10.4 Calculate the recoverable axial strain for each frequency, ε_o, as follows:

$$\varepsilon_o = \frac{\overline{\Delta}}{GL}$$

Where:

$\overline{\Delta}$ = average deformation amplitude.
GL = gage length
σ_o = strain

10.5 Calculate dynamic modulus, |E*| for each frequency as follows:

$$Dynamic\ Modulus, |E^*| = \frac{\sigma_o}{\varepsilon_o}$$

10.6 Calculate the phase angle for each frequency:

$$\phi = \frac{t_i}{t_p} x(360)$$

Where
t_i = average time lag between a cycle of stress and strain (sec)
t_p = average time for a stress cycle (sec.)

10.7 Calculate the dynamic modulus divided by sine of phase angle for each frequency:

$$\frac{|E^*|}{\sin\phi}$$

11. Report

11.1 Report the average stress and strain for each temperature-frequency combination tested.

11.2 Report the dynamic modulus and phase angle for each temperature-frequency combination tested.

11.3 Report the average dynamic modulus divided by sin of phase angle for the test specimen for each temperature-frequency tested.

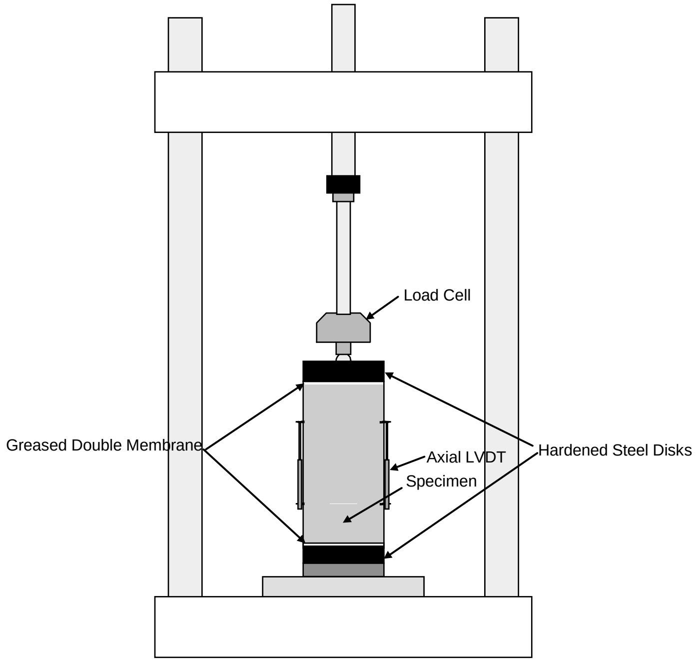
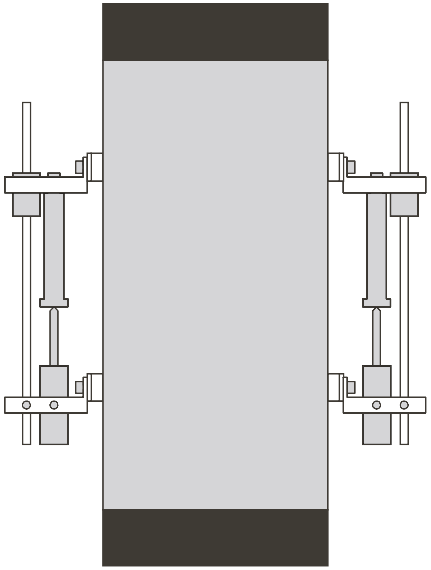
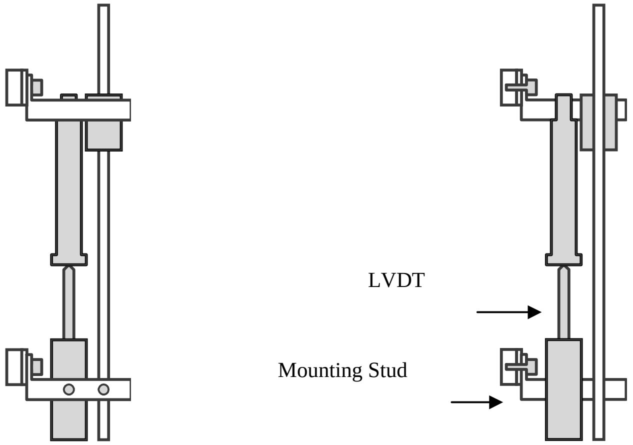


Figure 1. Schematic of Dynamic Modulus Test Device.



On-Sample Assembly

Figure 2. Schematic of Gauge Points.



Lateral View **Longitudinal Cross-Section**

Figure 3. Mounting Hardware Details.

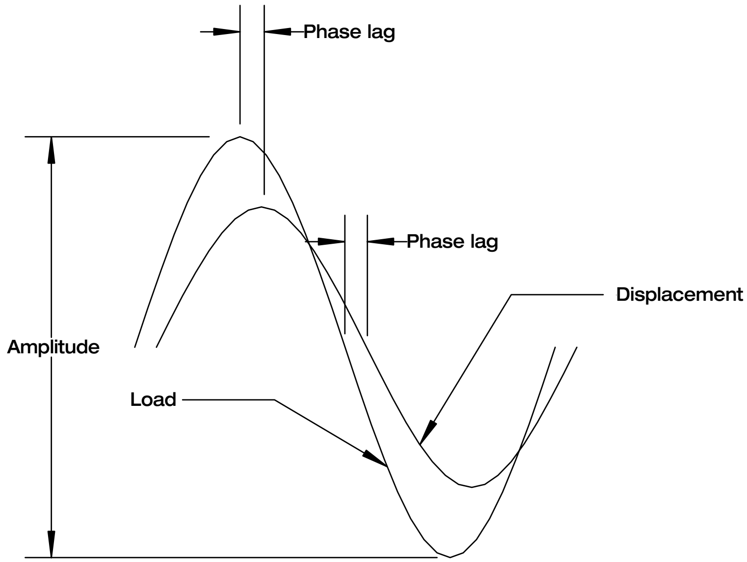


Figure 4. Ideal Waveform Schematic.

NCHRP 9-29 First-Article Equipment Specifications for Simple Performance Test System
Version 1.1
November 19, 2001
Includes Amendment 1

Annex D
Specification Compliance Test Methods for the Simple Performance Test System

Table D1. Summary of Specification Compliance Tests.

Item	Section	Method
Assembled Size	4.4 and 4.6	Measure
Specimen and Display Height	4.4	Measure
Component Size	4.7	Measure
Electrical Requirements	4.5 and 4.6	Documentation and trial
Air Supply Requirements	4.8	Documentation and trial
Limit Protection	4.9	Documentation and trial
Emergency Stop	4.10	Documentation, visual inspection, trial
Loading Machine Capacity	5.1	Independent force verification (See verification procedures below)
Load Control Capability	5.2 through 5.4	Trial tests on asphalt specimens and manufacturer provided dynamic verification device.
Platen Configuration	5.5	Visual
Platen Hardness	6.1	Test ASTM E10
Platen Dimensions	6.2	Measure
Platen Smoothness	6.3	Measure
Load Cell Range	7.1	Load cell data plate
Load Accuracy	7.2	Independent force verification (See verification procedures below)
Load Resolution	7.3	Independent force verification (See verification procedures below)
Configuration of Deflection Measuring System	8.1	Visual
Transducer Range	8.2	Independent deflection verification (See verification procedures below)
Transducer Resolution	8.3	Independent deflection verification (See verification procedures below)
Transducer Accuracy	8.4	Independent deflection verification (See verification procedures below)
Load Mechanism Compliance and Bending	8.5	Measure on steel specimens with various degrees of lack of parallelism
Configuration of Specimen Deformation Measuring System	9.1	Visual
Gauge Length of Specimen Deformation Measuring System	9.1	Measure
Transducer Range	9.2	Independent deflection verification (See verification procedures below)

Table D1. Summary of Specification Compliance Tests (Continued).

Item	Section	Method
Transducer Resolution	9.3	Independent deflection verification (See verification procedures below)
Transducer Accuracy	9.4	Independent deflection verification (See verification procedures below)
Specimen Deformation System Complexity	9.5	Trial
Confining Pressure Range	10.1 and 10.5	Independent pressure verification (See verification procedures below)
Confining Pressure Control	10.2	Trial tests on asphalt specimens
Confining Pressure System Configuration	10.3 and 10.4	Visual
Confining Pressure Resolution and Accuracy	10.5	Independent pressure verification (See verification procedures below)
Temperature Sensor	10.6 and 11.4	Independent temperature verification (See verification procedures below)
Specimen Installation and Equilibration Time	9.5, 10.7 and 11.3	Trial
Environmental Chamber Range and Control	11.1	Independent temperature verification (See verification procedures below)
Control System and Software	12	Trial
Data Analysis	13	Independent computations on trial test
Initial Calibration and Dynamic Performance Verification	14	Certification and independent verification
Calibration Mode	14.6	Trial
Verification of Normal Operation Procedures and Equipment	15	Review
On-line Documentation	16.1	Trial
Reference Manual	16.2	Review

INDEPENDENT VERIFICATION PROCEDURES FOR SIMPLE PERFORMANCE TESTING MACHINE

1.0 General

1.1 The testing machine shall be verified as a system with the load, deflection, specimen deformation, confining pressure, and temperature measuring systems in place and operating as in actual use.

1.2 System verification is invalid if the devices are removed and checked independently of the testing machine.

2.0 Load Measuring System Static Verification

2.1 Perform load measuring system verification in accordance with ASTM E-4.

2.2 All calibration load cells used for the load calibration shall be certified to ASTM E-74 and shall not be used below their Class A loading limits.

2.3 When performing the load verification, apply at least two verification runs of at least 5 loads throughout the range selected.

2.4 If the initial verification loads are within +/- 1% of reading, these can be applied as the "As found" values and the second set of verification forces can be used as the final values. Record return to zero values for each set of verification loads.

2.5 If the initial verification loads are found out of tolerance, calibration adjustments shall be made according to manufacturers specifications until the values are established within the ASTM E-4 recommendations. Two applications of verification loads shall then be applied to determine the acceptance criteria for repeatability according to ASTM E-4.

2.6 At no time will correction factors be utilized to corrected values that do not meet the accuracy requirements of ASTM E-4.

3.0 Deflection and Specimen Deformation Measuring System Static Verification

3.1 Perform verification of the deflection and specimen deformation measuring systems in accordance with ASTM D 6027 Test Method B.

3.2 The micrometer used shall conform to the requirements of ASTM E-83.

3.3 When performing verification of the deflection and strain measuring system, each transducer and associated electronics must be verified individually throughout it's intended range of use.

3.4 Mount the appropriate transducer in the micrometer stand and align it to prevent errors caused by angular application of measurements.

3.5 Apply at least 5 verification measurements to the transducer throughout it's range. Re-zero and repeat the verification measurements to determine repeatability.

3.6 If the readings of the first verification do not meet the specified error tolerance, perform calibration adjustments according to manufacturers specifications and repeat the applications of measurement to satisfy the error tolerances.

4.0 Confining Pressure Measuring System Verification

4.1 Perform verification of the confining pressure measuring system in accordance with ASTM D-5720.

4.2 All calibrated pressure standards shall meet the requirements of ASTM D-5720.

4.3 Attach the pressure transducer to the pressure standardizing device.

4.4 Apply at least 5 verification pressures to the device throughout it's range recording each value. Determine if the verification readings fall within +/- 1 % of the value applied.

4.5 If the readings are within tolerance, apply a second set of readings to determine repeatability. Record the return to zero values for each set of verification pressures.

4.6 If readings are beyond tolerance, adjust the device according to manufacturers specifications and repeat the dual applications of pressure as described above to complete verification.

5.0 Temperature Measuring System Verification

5.1 Verification of the temperature measuring system will be performed using a using a NIST traceable reference thermal detector that is readable and accurate to 0.1 °C.

5.2 A rubber band or O-ring will be used to fasten the reference thermal detector to the system temperature sensor.

5.3 Comparisons of the temperature from the reference thermal detector and the system temperature will be made at 6 temperatures over the operating range of the environmental chamber.

5.4 Once equilibrium is obtained at each temperature setting, record the temperature of the reference thermal detector and the system temperature sensor.

5.5 Also check stability of the environmental chamber by noting the maximum and minimum temperatures during cycling at the set temperature.

6.0 Dynamic Performance Verification

6.1 The verification of the dynamic performance of the equipment will be performed after static verification of the system.

6.2 The dynamic performance verification will be performed using the verification device provided with the system by the manufacturer.

6.3 First, the verification device will be loaded statically to obtain the static relationship between force and displacement. This relationship will be compared to that provided by the manufacturer in the system documentation.

6.4 The verification device will then be used to simulate dynamic modulus test conditions. Load and displacement data will be collected on the verification device using loads of 0.6, 1.2, 3.0, and 4.8 kN at frequencies of 0.1, 1, and 25 Hz. The peak load and displacements will be determined and plotted along with the static data. The data shall plot within +/- 2 percent of the static force displacement relationship.

6.5 The verification device will also be used to check the phase difference between the load and specimen deformation measuring system. The phase difference shall be less than 1 degree.

APPENDIX B

MATERIALS AND LABORATORY METHODS

1. INTRODUCTION

This Appendix documents the laboratory methods used in the preparation and testing of specimens for the mixture testing component of the first-article evaluation. Although the first-article simple performance devices are capable of performing three tests: dynamic modulus, flow number, and flow time, only two of these tests were included in the mixture testing component of the evaluation due to budget constraints. The dynamic modulus and flow number were the tests selected for evaluation because these were the two tests for which criteria differentiating between good and poor performance were being developed in Project 9-19. Research in Project 9-19 found a good correlation between flow number and flow time, allowing flow time to be used as a surrogate test for flow number, but the criteria differentiating between good and poor performance will be based in the flow number test and the performance of in-service sections.

Tables 1 and 2 present the experimental design for the dynamic modulus and flow number tests. Data for the two simple performance test devices in were collected in two laboratories (AAT and FHWA) on two mixtures (9.5 mm and 19.0 mm). Eight independent tests were included in each cell to provide sufficient replication to evaluate differences in means and differences in variances between devices, laboratories, and testing conditions. The dynamic modulus tests were conduced for three conditions selected to exercise the range of the equipment capabilities:

- Unconfined dynamic modulus at 25 °C, a representative condition for evaluating mixtures for fatigue cracking potential.
- Unconfined dynamic modulus at 45 °C, a representative condition for evaluating mixtures for rutting potential.
- Confined dynamic modulus at 45 °C, a representative condition for possibly evaluating open or gap graded mixtures for rutting potential.

The flow number was evaluated only at 45 °C for unconfined and confined conditions. The levels of confinement and deviatoric stress were selected to provide a relatively short test, less than 1000 cycles, and a relatively long test, greater than 5000 cycles.

Table 1. Experimental Design for Dynamic Modulus Testing.

			Dynamic Modulus and Phase Angle		
Device	Lab	Mix	Unconfined, 25 C	Unconfined, 45 C	Confined, 45 C
Interlaken	AAT	9.5 mm	8	8	8
		19.0 mm	8	8	8
	FHWA	9.5 mm	8	8	8
		19.0 mm	8	8	8
Shedworks	AAT	9.5 mm	8	8	8
		19.0 mm	8	8	8
	FHWA	9.5 mm	8	8	8
		19.0 mm	8	8	8

Table 2. Experimental Design for Flow Number Testing.

			Flow Number	
Device	Lab	Mix	Unconfined, 45 C	Confined, 45 C
Interlaken	AAT	9.5 mm	8	8
		19.0 mm	8	8
	FHWA	9.5 mm	8	8
		19.0 mm	8	8
Shedworks	AAT	9.5 mm	8	8
		19.0 mm	8	8
	FHWA	9.5 mm	8	8
		19.0 mm	8	8

2. MIXTURES

Two mixtures that exhibited different levels of variability in mechanical properties when tested in NCHRP Project 9-18 “Field Shear Test for Hot-Mix Asphalt,” were used in the evaluation testing. The first was a 9.5 mm mixture with low variability, having a shear modulus coefficient of variation of approximately 5 percent when tested in NCHRP Project 9-18. The second was a 19.0 mm mixture that had a shear modulus coefficient of variation of approximately 17 percent. Volumetric properties for the mixtures are provided in Table 3. As shown in Figures 1 and 2, both are coarse graded mixtures Superpave mixtures. The 9.5 mm mixture was made with limestone coarse and fine aggregates. Granite aggregates were used in the 19.0 mm mixtures. Both mixtures were made with the same PG 64-22 binder. AASHTO M320 properties for the binder are summarized in Table 4.

Table 3. Volumetric Properties of Evaluation Mixtures.

Property	9.5 mm	19.0 mm
N_{design}	65	96
Coarse Aggregate Angularity. One Face/ Two Face	100/100	100/100
Fine Aggregate Angularity	45.0	52.1
Flat & Elongated, % (Ratio 5 : 1)	1.6	1.9
Sand Equivalent, %	83	80
Binder Content, %	6.2%	4.4%
Gyratory Compaction, % Gmm		
N_{ini}	85.2%	85.9%
N_{des}	96.0%	95.8%
N_{max}	97.8%	97.2%
Voids in Mineral Aggregate (VMA), %	17.2	14.5
Voids in Total Mixture (VTM), %	4.0	4.2
Voids Filled with Asphalt (VFA), %	76.7	71.0
Fines to Effective Binder Ratio (F/A)	1.2	1.1
Gradation, % passing Sieve Size, mm		
37.5	100	100
25	100	100
19	100	94
12.5	100	73
9.5	97	52
4.75	62	33
2.36	42	24
1.18	27	17
0.6	18	14
0.3	11	10
0.15	8	6
0.075	6.8	3.6

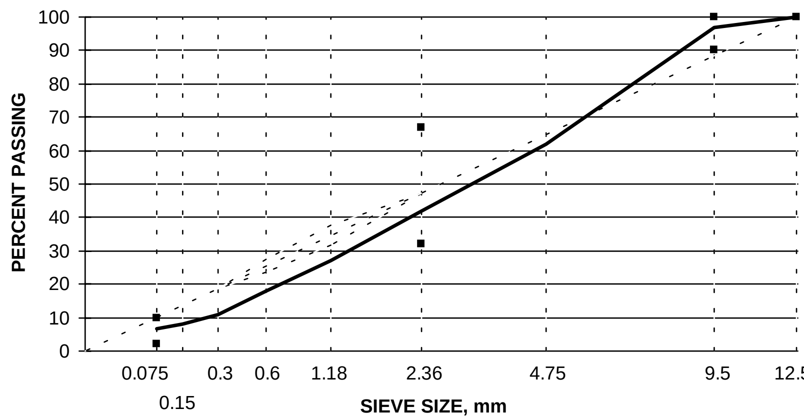


Figure 1. Gradation of 9.5 mm Mixture.

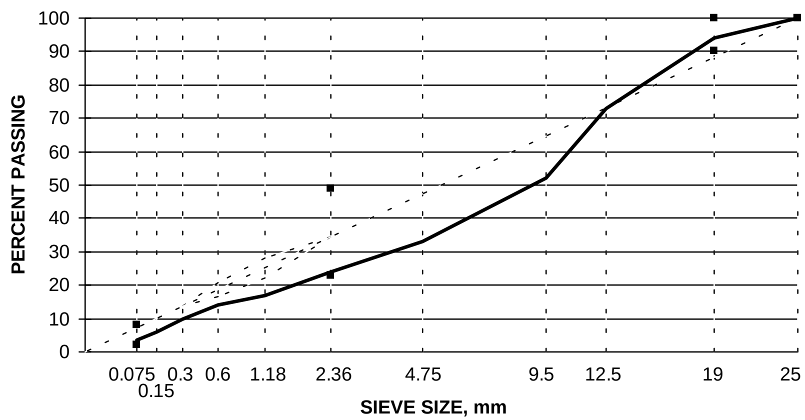


Figure 2. Gradation of 19.0 mm Mixture.

Table 4. Binder Properties for Evaluation Mixtures.

Condition	Test	Method	Result
Unaged Asphalt	Specific Gravity at 25 °C	AASHTO T228	1.032
	Viscosity at 135 °C	ASTM D4402	0.38 Pa·s
	G*/sinδ at 10 rad/sec, 64 °C	AASHTO T515	1.58 kPa
RTFO Aged Residue	Mass Change, %	AASHTO T240	-0.32
	G*/sinδ, at 10 rad/sec, 64 °C	AASHTO T315	5.27 kPa
PAV Aged Residue	G*sinδ, at 10 rad/sec, 25 °C	AASHTO T315	2800 kPa
	Creep Stiffness, at 60 sec, -12 °C	AASHTO T313	138 MPa
	m-value at 60 sec, -12 °C	AASHTO T313	0.331

3. SPECIMEN PREPARATION

The simple performance test specimens were prepared to a target air void content of 4.0 percent. First 150 mm diameter by 165 mm high gyratory specimens were prepared to an air void contents 5.5 percent. From these, 100 mm diameter by 150 mm high specimens were cored and sawed using a portable core drilling machine and double bladed saw. The sections that follow discuss procedures used in the specimen fabrication process for:

- Binder and aggregate handling
- Laboratory mixing, aging and compaction
- Simple performance test specimens fabrication, and
- Test specimen handling

3.1 Binder Handling

The binder used in the first-article evaluation was an unmodified PG 64-22 obtained from the Paulsboro, New Jersey refinery of the Citgo Asphalt Refining Company (Citgo). This binder was being used by AAT on several NCHRP projects including: Project 9-29, Phase III of Project 9-29, Project 9-25, Project 9-31, and Project 9-34. For these projects, 37, five-gallon samples of PG 64-22 binder were obtained by Citgo representatives on November 9, 2001. The sample containers were sealed, marked, and forwarded to AAT. Each five-gallon sample was treated as a representative sample of the binder with no mixing of the binder from individual containers. Upon receipt at AAT, one five-gallon sample was divided into quart containers by heating the five-gallon container in an oven set at 135 °C, stirring with a mechanical stirrer, and pouring the

binder into the individual quart containers. A representative sample was obtained from one of the quart containers and viscosities were determined at 135, 150, and 165 °C in accordance with ASTM D4402 to determine appropriate mixing and compaction temperatures. The quart containers were then used in the preparation of laboratory mixture batches. Quart containers were only heated once. Excess binder in the quart containers was discarded. As additional binder was required by the testing program, additional five-gallon samples were divided into quart containers using the procedure outlined above.

3.2 Aggregate Handling

Representative samples of the aggregates used in the evaluation mixtures were obtained by AAT technicians in sample bags of varying sizes. The procedures described in the Appendix of Asphalt Institute Publication MS-2 were used to prepare the aggregate samples for laboratory batching. Coarse aggregate samples were separated into individual sizes, while individual samples of fine aggregate were mixed together to produce a homogeneous supply for subsequent batching. For the two mixtures, Table 5 summarizes the sizes that the aggregates were separated into for preparation of laboratory specimens. For the 19.0 mm mixture, stockpile samples of the #57 and #78 stone were combined prior to separating into the fractions shown.

Table 5. Summary of Aggregate Sizes Used in Phase 1 Specimen Preparation.

9.5 mm Mixture			19.0 mm Mixture		
Material	%	Sizes, mm	Material	%	Sizes, mm
8P	31	Retained 9.5	Combined #57 and #78	72	Retained 19.0
		Retained 4.75			Retained 12.5
1/4 in	63	As-received			Retained 9.5
Manufactured Sand	5	As-received			Retained 4.75
Lime	1	As-received			Retained 2.36
			#10	14	As-received
			#34	14	As-received

3.3 Mixing, Aging, and Compaction

Gyratory specimens for the simple performance tests before sawing and coring were 150 mm diameter by 165 mm high. These specimens were prepared to a target air void content in accordance with AASHTO T314. An Interlaken compactor meeting the requirements of AASHTO T314 and AASHTO PP35 was used to prepare the gyratory specimens.

Mixing and compaction temperatures were determined from viscosities measured at 135, 150, and 165 °C in accordance with ASTM D4402. These were converted to kinematic viscosities using the binder specific gravity measured at 25 °C and the specific gravity temperature correction factors given in Annex A1 of AASHTO T201. This resulted in a mixing temperature of 158 °C and a compaction temperature of 145 °C. Prior to compaction, materials for all specimens were short-term oven aged in accordance with AASHTO PP2 for two hours at the compaction temperature.

3.4 Sawing and Coring of Simple Performance Test Specimens

The simple performance test specimens were manufactured by coring and sawing 100 mm diameter by 150 mm high test specimens from the middle of 150 mm by 165 mm high gyratory compacted specimens. The procedure is described in the test protocols submitted to the NCHRP in Project 9-19, *Superpave Support and Performance Models Management*. There are three reasons for using smaller test specimens obtained from larger gyratory specimens in the simple performance tests. The first is to obtain an appropriate aspect ratio for the test specimens. Research performed during Project 9-19, found that a minimum specimen diameter of 100 mm was needed in the flow number and flow time tests, and that a minimum height to diameter ratio of 1.5 was needed in all three simple performance tests: dynamic modulus, flow number, and flow time. The second reason is to eliminate areas of high air voids in the gyratory specimens. Gyratory compacted specimens typically have high air voids near the ends and the circumference the specimen. The third reason is to obtain relatively smooth, parallel ends for testing.

In Phase I of this project, measurements on a large number of specimens prepared in accordance with the Project 9-19 draft test protocols showed that some of the specimen dimensional tolerances could not be achieved with standard laboratory saws and drills. The tolerances in the Project 9-19 test protocols were based on those presented in AASHTO T231 for capping concrete cylinders. The revised tolerances listed in Table 6 were recommended and incorporated in the first-article specifications.

Table 6. Project 9-29 Specimen Dimension Tolerances.

Item	Specification	Remarks
Average Diameter	100 mm to 104 mm	
Standard Deviation of Diameter	1.0 mm	See note 1
Height	147.5 mm to 152.5 mm	
End Flatness	0.3 mm	See note 2
End Parallelism	1 degree	See note 3

Notes:

1. Measure the diameter at the center and third points of the test specimen along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 1.0 mm. The average diameter, reported to the nearest 1 mm, shall be used in all material property calculations.

2. Check this requirement using a straight edge and feeler gauges.

3. Check this requirement using a machinists square and feeler gauges.

Several laboratories have adapted equipment for preparing the simple performance test specimens that range from elaborate feed control drills combined with sophisticated holders and double bladed saws to standard drills and single bladed saws with simple clamping arrangements. For this project, specimens meeting the tolerances listed in Table 6 were prepared using a portable core drilling machine, and a double bladed saw. As shown in Figure 3, the portable core drilling machine was mounted to a heavy stand on the laboratory floor to facilitate vertical drilling of the specimen. The 150 mm diameter by 165 mm high gyratory compacted specimen was held in place under the drill by blocks of wood cut to provide a tight fit between the gyratory specimen and the stand. A sophisticated clamp for holding the gyratory specimen is not needed to obtain the tolerances on the specimen diameter listed in Table 6. Figure 4 shows the 100 mm diameter core and the waste portion of the gyratory specimen.

Figure 3. Portable Core Drilling Machine and Stand.

Figure 4. 100 mm Diameter Core and Waste Ring.

Reasonably smooth, parallel ends for the test specimen were then provided by trimming the 100 mm diameter core using the double bladed saw shown in Figure 5. This step is more critical than the coring step and requires the 100 mm diameter core to fit tightly in the saw clamp, and sufficient waste material on each end to keep the saw blades from bending.

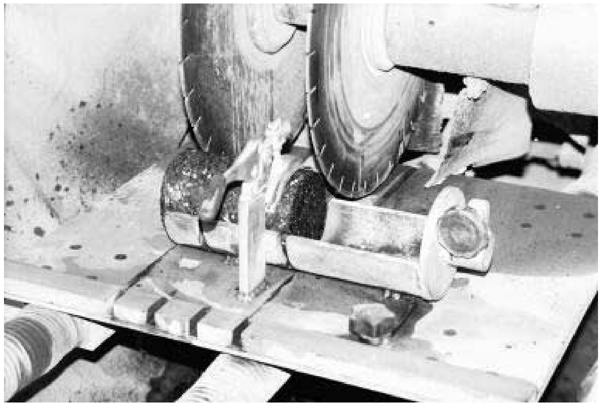


Figure 5. Double Bladed Saw With 100 mm Core.

All coring and sawing was done using water to cool the cutting tools. After all cutting was complete, the bulk specific gravity of the finished specimen was determined in accordance with AASHTO T166 by first measuring the immersed mass, then the saturated surface dry mass, and finally the dry mass. The cores were measured for compliance with the NCHRP Project 9-29 specimen tolerances, which are summarized the Table 6. Figure 6 shows a completed test specimen.

Figure 6. Final Simple Performance Test Specimen.

4. SPECIMEN HANDLING

The evaluation testing program required fabrication and testing of 192 specimens. Sample fabrication and testing was split into two phases as shown in Table 7. In the first phase the Interlaken equipment was operated in the FHWA laboratory and the Shedworks equipment was operated in AAT's laboratory. In the second phase, the location of the equipment was switched. Each phase was divided into two blocks, and all of the testing for a given block in both laboratories was completed before the next block began. To allow reasonable productivity during specimen fabrication, the over-height gyratory specimens were fabricated on a regular schedule of four specimens per day. To minimize aging of the test specimens, the simple

performance test specimens were sawed and cored from the over-height gyratory specimens when needed. All of the simple performance test specimens for a specific mixture for a block were cored, sawed, and measured at the same time. They were then distributed to the two laboratories based on their air void contents to obtain approximately the same average and range of air void contents.

5. TESTING

The dynamic modulus and flow number tests were performed with the simple performance test devices in accordance with the Project 9-19 test protocols. Test specimens were conditioned in a separate environmental chamber prior to testing. Dummy specimens with thermocouples were used to ensure that the test specimens were with the specified 0.5 °C tolerance of the target test temperature. The test chamber of the simple performance test device was also equilibrated to the target testing temperature. Once the specimens and the test chamber reached the target temperature, the specimens were removed from the separate environmental chamber, placed in the test chamber, and instrumented if required. The test chamber was then closed and allowed to equilibrate to the test temperature before the testing began.

The three dynamic modulus tests, 25 °C unconfined, 45 °C confined, and 45 °C unconfined, were performed on the same test specimen. For each condition dynamic moduli and phase angles were measured at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. Stress levels were varied automatically by the simple performance testers to achieve a target strain level of 100 μstrain. A confining pressure of 138 kPa was used in the confined testing.

Separate test specimens were used for each of the flow time tests. Table 8 summarizes the confining and deviatoric stresses used in the flow number testing for the two mixtures. These stress levels were selected to obtain a short test, less than 1000 load repetitions and a long test, greater than 1000 load repetitions.

Table 7. Evaluation Testing Program.

Phase	Block	Device	Lab	Mix	Dynamic Modulus 25 °C Unconfined	Dynamic Modulus 45 °C Confined	Dynamic Modulus 45 °C Unconfined	Flow Number 45 °C Unconfined	Flow Number 45 °C Confined
1	1	Interlaken	AAT	9.5 mm	4			4	4
				19.0 mm	4			4	4
		Shedworks	FHWA	9.5 mm	4			4	4
				19.0 mm	4			4	4
	2	Interlaken	AAT	9.5 mm	4			4	4
				19.0 mm	4			4	4
		Shedworks	FHWA	9.5 mm	4			4	4
				19.0 mm	4			4	4
2	1	Shedworks	AAT	9.5 mm	4			4	4
				19.0 mm	4			4	4
		Interlaken	FHWA	9.5 mm	4			4	4
				19.0 mm	4			4	4
	2	Shedworks	AAT	9.5 mm	4			4	4
				19.0 mm	4			4	4
		Interlaken	FHWA	9.5 mm	4			4	4
				19.0 mm	4			4	4
Total					64			128	

Table 8. Flow Number Test Conditions.

Mixture	Condition	Deviatoric Stress, kPa	Confining Pressure, kPa
9.5 mm	Unconfined	400	0
9.5 mm	Confined	600	20
19.0 mm	Unconfined	600	0
19.0 mm	Confined	900	20

APPENDIX C
EVALUATION TEST DATA

TABLE C-1 Modulus and phase angle data and values for associated quality indices

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	AAT	95MM	25.0	0.0	10.00	5001	28.9	0.0	2.8	-343.1	6.9	4.8	0.5
IPC	AAT	95MM	25.0	0.0	1.00	2258	33.5	0.1	0.8	-245.2	3.6	5.4	0.8
IPC	AAT	95MM	25.0	0.0	0.10	881	32.7	0.0	2.2	-82.4	3.1	4.3	0.7
IPC	AAT	95MM	25.0	0.0	10.00	5301	27.7	0.0	2.6	-278.6	6.3	18.8	0.7
IPC	AAT	95MM	25.0	0.0	1.00	2451	31.7	0.0	0.6	-173.5	3.2	18.7	1.2
IPC	AAT	95MM	25.0	0.0	0.10	986	31.2	-0.1	2.0	-44.7	3.3	18.2	1.4
IPC	AAT	95MM	25.0	0.0	10.00	4663	29.5	0.1	3.5	-354.4	6.9	2.3	0.1
IPC	AAT	95MM	25.0	0.0	1.00	2091	34.0	0.1	0.7	-272.8	4.1	2.9	0.4
IPC	AAT	95MM	25.0	0.0	0.10	805	33.2	-0.4	2.3	-104.9	3.5	6.1	0.7
IPC	AAT	95MM	25.0	0.0	10.00	5289	28.7	0.0	2.7	-331.2	6.7	3.6	0.4
IPC	AAT	95MM	25.0	0.0	1.00	2411	33.3	-0.1	0.7	-245.8	3.7	3.4	0.7
IPC	AAT	95MM	25.0	0.0	0.10	972	32.7	0.1	1.9	-98.9	3.2	4.3	0.3
IPC	AAT	95MM	25.0	0.0	10.00	4578	28.2	0.1	2.9	-268.2	6.6	11.6	0.5
IPC	AAT	95MM	25.0	0.0	1.00	2048	32.7	0.3	0.8	-163.2	3.0	12.7	0.1
IPC	AAT	95MM	25.0	0.0	0.10	769	33.3	0.2	2.3	-18.0	3.1	12.6	0.8
IPC	AAT	95MM	25.0	0.0	10.00	5377	27.4	-0.1	2.7	-316.6	6.5	3.4	0.5
IPC	AAT	95MM	25.0	0.0	1.00	2552	32.5	0.1	0.7	-277.5	3.9	1.7	0.8
IPC	AAT	95MM	25.0	0.0	0.10	1049	32.5	0.2	1.7	-140.9	2.9	0.3	1.0
IPC	AAT	95MM	25.0	0.0	10.00	5101	27.9	0.1	2.9	-271.9	6.5	2.5	0.2
IPC	AAT	95MM	25.0	0.0	1.00	2303	32.7	0.4	0.8	-172.7	3.2	2.4	0.2
IPC	AAT	95MM	25.0	0.0	0.10	882	32.9	-0.1	2.1	-60.1	2.9	1.8	0.1
IPC	AAT	95MM	25.0	0.0	10.00	5397	28.3	0.0	2.6	-343.4	6.7	5.5	0.2
IPC	AAT	95MM	25.0	0.0	1.00	2475	33.5	0.3	0.7	-296.7	4.1	2.4	0.3
IPC	AAT	95MM	25.0	0.0	0.10	981	33.6	0.4	1.8	-134.9	3.0	1.5	0.1
IPC	AAT	95MM	45.0	0.0	10.00	888	37.4	-0.6	5.2	-271.3	8.2	3.0	1.2
IPC	AAT	95MM	45.0	0.0	1.00	282	33.4	1.1	2.6	14.5	4.8	2.6	1.3
IPC	AAT	95MM	45.0	0.0	0.10	131	26.1	0.9	9.7	95.1	5.0	5.6	0.9
IPC	AAT	95MM	45.0	0.0	10.00	965	36.6	-0.4	5.4	-193.7	7.1	16.8	2.1
IPC	AAT	95MM	45.0	0.0	1.00	341	32.5	0.0	3.2	17.9	5.9	16.7	2.9
IPC	AAT	95MM	45.0	0.0	0.10	149	26.5	1.6	7.8	248.6	5.9	21.2	3.0
IPC	AAT	95MM	45.0	0.0	10.00	843	39.8	-0.3	5.7	-361.4	9.1	8.6	0.1
IPC	AAT	95MM	45.0	0.0	1.00	274	35.0	-2.1	3.8	10.1	6.3	6.5	0.9

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	AAT	95MM	45.0	0.0	0.10	109	29.2	1.7	11.0	244.0	8.4	6.6	1.4

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	AAT	95MM	45.0	0.0	10.00	952	36.7	0.0	5.1	-245.2	7.3	3.2	0.5
IPC	AAT	95MM	45.0	0.0	1.00	334	32.7	-0.1	2.7	-19.6	6.3	1.1	1.1
IPC	AAT	95MM	45.0	0.0	0.10	129	27.8	0.3	8.9	71.0	5.2	3.7	0.9
IPC	AAT	95MM	45.0	0.0	10.00	685	38.3	-0.8	7.8	-213.1	8.3	14.6	1.4
IPC	AAT	95MM	45.0	0.0	1.00	225	34.1	0.7	3.8	26.0	5.5	12.3	1.8
IPC	AAT	95MM	45.0	0.0	0.10	89	28.4	-4.6	9.0	338.4	7.0	13.0	0.9
IPC	AAT	95MM	45.0	0.0	10.00	891	37.1	0.1	7.2	-258.5	8.7	7.9	0.7
IPC	AAT	95MM	45.0	0.0	1.00	314	32.5	1.3	3.4	-14.2	6.0	10.4	0.9
IPC	AAT	95MM	45.0	0.0	0.10	125	27.3	4.2	7.3	123.8	5.8	11.4	0.7
IPC	AAT	95MM	45.0	0.0	10.00	874	37.8	-0.5	6.1	-231.9	7.4	8.2	0.7
IPC	AAT	95MM	45.0	0.0	1.00	292	34.5	0.6	3.1	-8.1	4.9	10.0	1.0
IPC	AAT	95MM	45.0	0.0	0.10	117	28.1	-1.8	9.9	126.2	5.2	11.5	1.0
IPC	AAT	95MM	45.0	0.0	10.00	852	37.5	-0.3	6.9	-232.6	7.7	12.3	0.8
IPC	AAT	95MM	45.0	0.0	1.00	297	32.9	-2.2	3.5	-0.9	6.0	11.6	1.0
IPC	AAT	95MM	45.0	0.0	0.10	118	27.8	2.8	9.0	217.0	6.2	10.7	1.1
IPC	AAT	95MM	45.0	138.0	10.00	1369	27.6	0.3	4.3	-83.4	4.5	6.0	0.8
IPC	AAT	95MM	45.0	138.0	1.00	877	19.3	0.1	1.1	-38.1	2.5	5.1	0.7
IPC	AAT	95MM	45.0	138.0	0.10	782	12.5	0.2	2.1	-58.1	2.8	5.1	1.1
IPC	AAT	95MM	45.0	138.0	10.00	1586	30.2	0.2	3.5	-91.9	4.6	13.6	2.4
IPC	AAT	95MM	45.0	138.0	1.00	1025	22.7	-0.1	1.1	-25.4	3.8	15.0	2.4
IPC	AAT	95MM	45.0	138.0	0.10	825	16.3	-0.7	2.8	-14.3	4.7	14.0	0.6
IPC	AAT	95MM	45.0	138.0	10.00	1544	25.6	-0.1	3.6	-55.8	3.9	12.7	0.1
IPC	AAT	95MM	45.0	138.0	1.00	996	17.7	-0.2	1.2	-24.4	2.3	11.5	0.3
IPC	AAT	95MM	45.0	138.0	0.10	817	10.8	0.3	2.2	-28.6	2.5	10.6	0.4
IPC	AAT	95MM	45.0	138.0	10.00	1450	27.4	0.2	4.0	-77.5	4.4	5.4	0.3
IPC	AAT	95MM	45.0	138.0	1.00	892	20.0	-0.7	1.3	-16.1	2.6	5.9	0.3
IPC	AAT	95MM	45.0	138.0	0.10	705	13.0	0.4	2.1	-28.9	4.7	12.5	0.5
IPC	AAT	95MM	45.0	138.0	10.00	1315	27.0	0.1	3.3	-100.6	3.9	9.9	0.7
IPC	AAT	95MM	45.0	138.0	1.00	843	19.2	0.4	1.4	-42.1	2.8	11.2	0.6
IPC	AAT	95MM	45.0	138.0	0.10	780	12.9	-1.6	3.5	-92.9	4.6	3.1	1.1
IPC	AAT	95MM	45.0	138.0	10.00	1693	25.0	0.0	3.2	-72.5	3.5	4.4	0.7
IPC	AAT	95MM	45.0	138.0	1.00	1091	17.8	-0.3	1.1	-13.7	2.3	5.5	0.7
IPC	AAT	95MM	45.0	138.0	0.10	861	11.0	-0.1	2.6	-16.3	2.8	5.7	0.5
IPC	AAT	95MM	45.0	138.0	10.00	1377	28.1	0.2	3.3	-95.0	4.2	16.8	1.4
IPC	AAT	95MM	45.0	138.0	1.00	879	19.8	-0.1	1.1	-30.7	2.2	17.3	0.9
IPC	AAT	95MM	45.0	138.0	0.10	765	12.6	-0.1	3.1	-59.8	4.1	15.7	0.2

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	AAT	95MM	45.0	138.0	10.00	1412	28.0	0.3	4.0	-89.0	4.5	8.3	1.0
IPC	AAT	95MM	45.0	138.0	1.00	888	20.0	-0.3	1.3	-29.2	2.5	8.2	0.1
IPC	AAT	95MM	45.0	138.0	0.10	665	13.3	0.3	3.3	2.4	3.5	6.4	0.4
IPC	AAT	19MM	25.0	0.0	10.00	7307	25.2	-0.1	2.1	-273.3	5.6	22.6	0.4
IPC	AAT	19MM	25.0	0.0	1.00	3766	30.4	0.1	0.6	-266.7	3.8	21.4	0.8
IPC	AAT	19MM	25.0	0.0	0.10	1693	32.0	-0.4	1.4	-180.0	3.2	19.5	1.2
IPC	AAT	19MM	25.0	0.0	10.00	7728	24.3	0.0	2.2	-195.7	5.6	14.0	0.8
IPC	AAT	19MM	25.0	0.0	1.00	3891	29.1	0.2	0.5	-115.1	2.9	15.8	0.8
IPC	AAT	19MM	25.0	0.0	0.10	1648	30.6	-0.1	1.2	-47.5	3.4	17.9	0.7
IPC	AAT	19MM	25.0	0.0	10.00	6951	24.6	-0.1	2.1	-261.9	5.5	24.0	0.6
IPC	AAT	19MM	25.0	0.0	1.00	3616	29.9	0.2	0.6	-250.5	4.0	24.1	0.1
IPC	AAT	19MM	25.0	0.0	0.10	1611	31.6	-0.3	0.9	-145.0	3.4	22.8	0.6
IPC	AAT	19MM	25.0	0.0	10.00	7252	25.5	0.0	2.2	-276.8	5.8	15.9	0.3
IPC	AAT	19MM	25.0	0.0	1.00	3670	30.6	0.1	0.5	-235.5	4.0	13.3	0.3
IPC	AAT	19MM	25.0	0.0	0.10	1582	32.1	0.4	0.6	-103.3	2.8	14.5	0.9
IPC	AAT	19MM	25.0	0.0	10.00	7801	24.6	0.0	2.2	-272.8	5.6	5.3	0.4
IPC	AAT	19MM	25.0	0.0	1.00	4025	30.5	0.1	0.6	-279.6	4.0	5.2	0.4
IPC	AAT	19MM	25.0	0.0	0.10	1771	32.3	-0.4	1.1	-186.5	2.9	5.7	0.4
IPC	AAT	19MM	25.0	0.0	10.00	8294	24.3	0.1	2.1	-266.4	5.5	4.1	0.5
IPC	AAT	19MM	25.0	0.0	1.00	4303	30.1	0.1	0.6	-265.8	3.7	3.1	0.7
IPC	AAT	19MM	25.0	0.0	0.10	1919	32.4	0.1	1.2	-177.5	2.9	2.4	1.0
IPC	AAT	19MM	25.0	0.0	10.00	6999	24.8	0.1	2.9	-254.9	5.5	9.7	0.1
IPC	AAT	19MM	25.0	0.0	1.00	3605	29.9	0.1	0.6	-252.4	3.7	9.1	0.0
IPC	AAT	19MM	25.0	0.0	0.10	1605	31.6	0.2	1.3	-171.8	2.8	9.5	0.3
IPC	AAT	19MM	25.0	0.0	10.00	6802	25.7	0.1	2.3	-285.4	6.0	13.2	0.5
IPC	AAT	19MM	25.0	0.0	1.00	3422	31.2	-0.1	0.6	-282.4	3.9	12.3	0.7
IPC	AAT	19MM	25.0	0.0	0.10	1466	32.8	0.0	1.4	-198.9	3.3	14.6	0.8
IPC	AAT	19MM	45.0	0.0	10.00	1694	34.7	0.5	5.0	-250.7	7.0	6.0	0.8
IPC	AAT	19MM	45.0	0.0	1.00	656	31.9	0.1	1.5	-57.5	4.8	5.4	0.9
IPC	AAT	19MM	45.0	0.0	0.10	285	27.4	-0.2	5.3	-58.8	7.2	7.0	0.5
IPC	AAT	19MM	45.0	0.0	10.00	1912	33.9	0.1	5.3	-199.8	7.2	12.5	0.3
IPC	AAT	19MM	45.0	0.0	1.00	711	31.6	-0.5	1.5	-36.2	5.2	12.9	0.9
IPC	AAT	19MM	45.0	0.0	0.10	281	29.1	-0.3	5.3	1.5	5.2	20.8	2.4
IPC	AAT	19MM	45.0	0.0	10.00	1643	35.0	0.0	4.6	-246.7	8.1	26.0	1.3
IPC	AAT	19MM	45.0	0.0	1.00	632	32.7	-0.5	1.5	-32.6	4.8	23.6	2.4
IPC	AAT	19MM	45.0	0.0	0.10	285	28.1	-2.0	5.7	95.0	5.2	26.5	2.2

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	AAT	19MM	45.0	0.0	10.00	1583	35.2	0.1	5.0	-203.8	6.9	13.6	0.1
IPC	AAT	19MM	45.0	0.0	1.00	578	32.6	-1.1	1.6	-22.1	4.8	16.6	0.6
IPC	AAT	19MM	45.0	0.0	0.10	248	28.0	0.5	6.1	52.3	4.9	22.5	0.7
IPC	AAT	19MM	45.0	0.0	10.00	1735	35.2	-0.2	5.5	-259.3	8.5	11.4	0.6
IPC	AAT	19MM	45.0	0.0	1.00	642	32.9	1.3	1.9	-54.1	5.1	13.5	1.0
IPC	AAT	19MM	45.0	0.0	0.10	267	29.1	4.9	4.7	5.7	5.1	13.3	0.9
IPC	AAT	19MM	45.0	0.0	10.00	1825	35.2	0.1	5.3	-274.6	8.2	8.2	1.5
IPC	AAT	19MM	45.0	0.0	1.00	694	32.8	1.1	1.9	-61.5	5.0	9.5	1.3
IPC	AAT	19MM	45.0	0.0	0.10	286	29.4	1.1	4.1	22.0	5.2	8.8	1.8
IPC	AAT	19MM	45.0	0.0	10.00	1621	34.5	0.1	5.3	-254.4	8.0	14.8	0.8
IPC	AAT	19MM	45.0	0.0	1.00	617	32.2	0.1	1.7	-56.9	5.0	16.5	1.4
IPC	AAT	19MM	45.0	0.0	0.10	261	28.5	0.4	4.7	10.6	4.9	22.1	0.9
IPC	AAT	19MM	45.0	0.0	10.00	1351	35.6	-0.4	5.8	-244.3	8.2	17.2	0.9
IPC	AAT	19MM	45.0	0.0	1.00	502	32.8	0.2	2.6	-44.0	5.1	18.6	1.4
IPC	AAT	19MM	45.0	0.0	0.10	214	27.7	-0.7	6.8	31.2	5.3	25.5	1.8
IPC	AAT	19MM	45.0	138.0	10.00	2312	29.4	0.1	3.7	-156.1	5.5	12.8	1.7
IPC	AAT	19MM	45.0	138.0	1.00	1336	23.8	0.1	0.9	-53.9	3.1	11.8	1.9
IPC	AAT	19MM	45.0	138.0	0.10	956	18.6	-0.1	2.1	-51.6	3.6	14.7	1.7
IPC	AAT	19MM	45.0	138.0	10.00	2444	28.7	-0.1	3.1	-113.0	4.8	10.3	0.2
IPC	AAT	19MM	45.0	138.0	1.00	1394	23.1	0.3	1.3	-44.8	3.1	10.9	0.4
IPC	AAT	19MM	45.0	138.0	0.10	1002	17.3	0.1	1.7	-40.6	3.2	10.7	0.3
IPC	AAT	19MM	45.0	138.0	10.00	2415	27.1	0.2	3.3	-135.7	5.1	25.5	0.8
IPC	AAT	19MM	45.0	138.0	1.00	1461	21.7	0.0	0.8	-53.8	2.8	21.8	1.1
IPC	AAT	19MM	45.0	138.0	0.10	1094	16.4	-0.1	1.7	-46.3	3.1	17.3	0.8
IPC	AAT	19MM	45.0	138.0	10.00	2310	27.8	-0.2	3.8	-103.5	4.8	8.4	0.3
IPC	AAT	19MM	45.0	138.0	1.00	1376	22.0	-0.3	0.8	-49.1	2.8	9.8	0.5
IPC	AAT	19MM	45.0	138.0	0.10	1029	16.5	0.7	1.9	-47.5	3.1	10.1	0.5
IPC	AAT	19MM	45.0	138.0	10.00	2092	32.2	0.1	3.7	-170.0	6.0	2.0	0.5
IPC	AAT	19MM	45.0	138.0	1.00	1038	27.7	0.8	1.3	-42.2	3.5	5.6	0.6
IPC	AAT	19MM	45.0	138.0	0.10	636	22.5	-2.0	3.4	-14.0	4.0	10.1	0.6
IPC	AAT	19MM	45.0	138.0	10.00	2388	29.2	0.0	2.9	-119.2	4.4	5.9	1.4
IPC	AAT	19MM	45.0	138.0	1.00	1364	23.5	-0.2	1.0	-36.6	2.9	7.2	1.1
IPC	AAT	19MM	45.0	138.0	0.10	971	17.5	0.6	2.6	-26.1	3.1	7.1	0.7
IPC	AAT	19MM	45.0	138.0	10.00	2094	29.1	-0.1	3.2	-138.6	4.9	4.8	1.1
IPC	AAT	19MM	45.0	138.0	1.00	1169	23.9	0.8	1.3	-48.3	3.2	10.8	1.7
IPC	AAT	19MM	45.0	138.0	0.10	828	18.5	1.0	2.8	-72.3	5.0	12.8	1.4

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	AAT	19MM	45.0	138.0	10.00	1984	28.6	-0.1	2.9	-101.7	4.0	11.5	0.9
IPC	AAT	19MM	45.0	138.0	1.00	1157	22.1	1.7	1.5	-36.1	2.8	11.4	1.1
IPC	AAT	19MM	45.0	138.0	0.10	857	16.3	0.0	2.7	-37.6	2.9	10.0	0.9
IPC	FHWA	95MM	25.0	0.0	10.00	5183	29.3	-0.1	3.0	-383.1	7.5	7.8	0.5
IPC	FHWA	95MM	25.0	0.0	1.00	2337	34.4	-0.5	0.8	-290.9	4.3	6.6	1.0
IPC	FHWA	95MM	25.0	0.0	0.10	915	33.6	-0.4	1.9	-127.0	3.0	8.9	1.1
IPC	FHWA	95MM	25.0	0.0	10.00	5424	28.0	0.0	2.8	-280.7	6.7	10.1	0.3
IPC	FHWA	95MM	25.0	0.0	1.00	2467	32.4	0.2	0.7	-164.7	3.1	10.0	0.6
IPC	FHWA	95MM	25.0	0.0	0.10	949	32.5	-0.2	1.6	-47.3	3.0	10.1	0.6
IPC	FHWA	95MM	25.0	0.0	10.00	5230	29.6	0.0	2.8	-395.3	7.4	8.5	0.5
IPC	FHWA	95MM	25.0	0.0	1.00	2378	34.4	0.0	0.7	-341.6	4.6	9.7	0.1
IPC	FHWA	95MM	25.0	0.0	0.10	964	33.3	0.0	1.5	-168.0	3.3	10.9	0.4
IPC	FHWA	95MM	25.0	0.0	10.00	5491	27.6	0.1	2.8	-271.2	6.6	18.0	0.4
IPC	FHWA	95MM	25.0	0.0	1.00	2528	32.0	0.2	0.7	-168.4	3.3	19.2	0.5
IPC	FHWA	95MM	25.0	0.0	0.10	988	32.6	0.1	1.6	-53.8	3.2	19.3	0.9
IPC	FHWA	95MM	25.0	0.0	10.00	4835	30.1	0.0	3.1	-381.5	7.6	13.3	0.5
IPC	FHWA	95MM	25.0	0.0	1.00	2130	34.6	0.1	0.8	-272.9	4.1	14.2	0.9
IPC	FHWA	95MM	25.0	0.0	0.10	819	34.0	-0.1	2.2	-89.3	3.3	12.8	0.9
IPC	FHWA	95MM	25.0	0.0	10.00	5224	28.9	0.1	3.0	-366.4	6.9	12.9	0.4
IPC	FHWA	95MM	25.0	0.0	1.00	2422	33.9	0.0	0.7	-314.9	4.3	10.8	0.5
IPC	FHWA	95MM	25.0	0.0	0.10	999	33.2	0.1	1.6	-172.3	3.5	7.9	0.5
IPC	FHWA	95MM	25.0	0.0	10.00	4535	30.1	0.1	3.1	-410.0	7.3	24.9	0.5
IPC	FHWA	95MM	25.0	0.0	1.00	2002	34.9	-0.2	0.8	-371.8	4.6	25.3	0.4
IPC	FHWA	95MM	25.0	0.0	0.10	795	33.9	0.6	1.7	-183.0	4.1	23.0	0.6
IPC	FHWA	95MM	25.0	0.0	10.00	5021	30.5	-0.2	3.0	-414.7	7.6	8.8	0.3
IPC	FHWA	95MM	25.0	0.0	1.00	2179	35.7	-0.2	1.2	-317.6	4.8	7.6	0.3
IPC	FHWA	95MM	25.0	0.0	0.10	818	35.0	1.0	2.9	-97.7	2.9	5.9	0.0
IPC	FHWA	95MM	45.0	0.0	10.00	1014	39.0	-0.1	7.0	-282.2	8.6	4.0	0.7
IPC	FHWA	95MM	45.0	0.0	1.00	353	34.2	1.7	3.6	-27.4	5.7	8.2	0.9
IPC	FHWA	95MM	45.0	0.0	0.10	142	27.9	0.5	8.8	143.4	5.8	10.9	0.8
IPC	FHWA	95MM	45.0	0.0	10.00	1041	37.6	-0.2	8.9	-249.6	9.1	7.4	0.7
IPC	FHWA	95MM	45.0	0.0	1.00	365	33.0	1.0	2.5	-24.1	5.5	5.8	0.6
IPC	FHWA	95MM	45.0	0.0	0.10	153	27.1	2.2	4.6	68.4	5.1	4.7	0.9
IPC	FHWA	95MM	45.0	0.0	10.00	1035	37.3	-0.2	7.3	-150.4	7.8	19.5	1.9
IPC	FHWA	95MM	45.0	0.0	1.00	341	34.7	0.6	2.4	0.4	4.8	16.9	2.2
IPC	FHWA	95MM	45.0	0.0	0.10	140	28.6	1.4	4.1	120.1	5.4	15.2	1.9

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. ºC	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	FHWA	95MM	45.0	0.0	10.00	1045	37.0	-0.7	7.8	-230.9	8.4	11.4	0.2
IPC	FHWA	95MM	45.0	0.0	1.00	371	33.1	2.9	2.4	-23.8	4.8	9.7	0.2
IPC	FHWA	95MM	45.0	0.0	0.10	158	27.7	-1.6	5.2	74.4	5.2	7.7	0.1
IPC	FHWA	95MM	45.0	0.0	10.00	728	40.1	-1.4	8.6	-281.0	9.6	7.8	1.0
IPC	FHWA	95MM	45.0	0.0	1.00	235	35.2	1.7	2.9	-7.2	5.4	7.2	0.9
IPC	FHWA	95MM	45.0	0.0	95.80	96	29.0	0.6	5.0	148.7	7.4	9.6	0.3
IPC	FHWA	95MM	45.0	0.0	10.00	1023	36.9	-0.5	8.1	-147.3	7.9	3.2	0.2
IPC	FHWA	95MM	45.0	0.0	1.00	364	32.7	0.2	2.5	-14.9	5.1	7.9	0.6
IPC	FHWA	95MM	45.0	0.0	95.80	159	26.8	-0.3	5.5	57.2	5.6	11.3	1.1
IPC	FHWA	95MM	45.0	0.0	10.00	1053	38.1	-0.3	9.2	-289.6	9.5	6.8	0.9
IPC	FHWA	95MM	45.0	0.0	1.00	366	34.0	1.5	2.9	-25.8	5.8	7.2	2.0
IPC	FHWA	95MM	45.0	0.0	95.80	141	29.4	-0.8	5.9	131.0	5.7	9.4	2.4
IPC	FHWA	95MM	45.0	0.0	10.00	873	41.5	-0.3	9.3	-265.2	9.5	9.6	0.8
IPC	FHWA	95MM	45.0	0.0	1.00	274	36.9	1.6	4.0	23.4	6.5	13.9	0.9
IPC	FHWA	95MM	45.0	0.0	95.80	107	29.5	0.9	6.7	353.3	4.8	17.1	0.2
IPC	FHWA	95MM	45.0	138.0	10.00	1340	30.9	-0.2	4.3	-75.5	4.8	7.5	0.3
IPC	FHWA	95MM	45.0	138.0	1.00	804	21.6	0.0	1.1	-22.0	2.3	8.4	0.1
IPC	FHWA	95MM	45.0	138.0	0.10	595	14.3	-0.5	2.4	-10.7	3.1	9.0	0.1
IPC	FHWA	95MM	45.0	138.0	10.00	1519	28.9	-0.2	4.1	-92.7	4.6	5.7	0.6
IPC	FHWA	95MM	45.0	138.0	1.00	946	20.5	-1.1	1.1	-31.4	2.5	2.6	0.8
IPC	FHWA	95MM	45.0	138.0	0.10	739	13.8	0.3	1.9	-33.3	3.3	2.7	0.3
IPC	FHWA	95MM	45.0	138.0	10.00	1312	32.1	-0.2	5.0	-124.1	5.9	15.1	1.0
IPC	FHWA	95MM	45.0	138.0	1.00	626	26.9	-0.8	1.6	-21.3	3.4	21.9	0.9
IPC	FHWA	95MM	45.0	138.0	0.10	308	22.5	-0.8	3.4	-16.1	4.7	22.7	1.5
IPC	FHWA	95MM	45.0	138.0	10.00	1717	30.3	0.1	3.9	-145.7	5.4	15.3	1.4
IPC	FHWA	95MM	45.0	138.0	1.00	1025	22.1	-0.2	1.0	-45.6	2.6	18.7	1.2
IPC	FHWA	95MM	45.0	138.0	0.10	756	15.1	0.9	1.7	-21.7	2.9	18.4	0.7
IPC	FHWA	95MM	45.0	138.0	10.00	1267	30.4	0.0	4.2	-159.7	6.4	8.1	0.6
IPC	FHWA	95MM	45.0	138.0	1.00	808	21.0	1.2	1.2	-59.8	2.6	7.8	0.9
IPC	FHWA	95MM	45.0	138.0	0.10	641	13.6	1.1	2.1	-41.3	3.3	6.0	0.6
IPC	FHWA	95MM	45.0	138.0	10.00	1346	33.5	-0.3	4.2	-132.2	5.9	5.4	0.5
IPC	FHWA	95MM	45.0	138.0	1.00	571	29.6	0.4	1.4	-10.3	3.4	5.0	0.5
IPC	FHWA	95MM	45.0	138.0	0.10	295	24.4	0.4	3.7	1.9	4.7	4.3	0.6
IPC	FHWA	95MM	45.0	138.0	10.00	1453	32.0	-0.3	4.2	-146.1	5.8	3.4	2.0
IPC	FHWA	95MM	45.0	138.0	1.00	686	27.2	1.1	1.5	-10.5	3.7	1.8	2.0
IPC	FHWA	95MM	45.0	138.0	0.10	360	24.0	0.6	4.2	-139.8	22.3	5.2	1.9

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	FHWA	95MM	45.0	138.0	10.00	1296	31.9	0.2	5.3	-159.9	6.0	10.3	1.6
IPC	FHWA	95MM	45.0	138.0	1.00	778	22.7	0.2	1.3	-64.1	2.9	13.4	1.5
IPC	FHWA	95MM	45.0	138.0	0.10	590	15.7	0.4	1.9	-61.8	3.7	25.6	0.9
IPC	FHWA	19MM	25.0	0.0	10.00	7976	24.5	0.1	2.2	-257.6	5.6	9.9	0.3
IPC	FHWA	19MM	25.0	0.0	1.00	4178	29.4	0.0	0.6	-243.0	4.3	10.0	0.5
IPC	FHWA	19MM	25.0	0.0	0.10	1902	30.7	0.1	1.1	-139.9	3.2	10.8	0.8
IPC	FHWA	19MM	25.0	0.0	10.00	8639	24.8	0.0	2.2	-274.5	5.7	8.4	1.0
IPC	FHWA	19MM	25.0	0.0	1.00	4494	29.9	0.0	0.5	-257.8	4.0	5.8	1.4
IPC	FHWA	19MM	25.0	0.0	0.10	1989	31.1	-0.4	0.9	-150.0	2.9	6.6	1.5
IPC	FHWA	19MM	25.0	0.0	10.00	7637	25.5	0.1	2.2	-298.8	5.9	11.8	0.3
IPC	FHWA	19MM	25.0	0.0	1.00	3880	31.1	0.4	0.6	-301.0	3.9	12.0	0.8
IPC	FHWA	19MM	25.0	0.0	0.10	1668	32.8	-0.1	1.0	-200.6	3.5	11.6	1.5
IPC	FHWA	19MM	25.0	0.0	10.00	7945	25.2	0.0	2.0	-294.8	5.8	22.1	1.0
IPC	FHWA	19MM	25.0	0.0	1.00	4083	30.2	0.4	0.6	-275.5	4.1	19.7	1.5
IPC	FHWA	19MM	25.0	0.0	0.10	1785	31.1	0.2	0.8	-188.4	6.2	17.4	1.8
IPC	FHWA	19MM	25.0	0.0	10.00	8427	23.4	-0.1	2.3	-261.6	5.5	6.2	0.8
IPC	FHWA	19MM	25.0	0.0	1.00	4539	29.1	0.1	0.6	-280.6	3.9	6.2	1.1
IPC	FHWA	19MM	25.0	0.0	0.10	2104	31.2	-0.3	1.1	-209.6	3.7	4.5	1.2
IPC	FHWA	19MM	25.0	0.0	10.00	8629	23.7	0.0	2.9	-220.6	5.5	6.4	0.2
IPC	FHWA	19MM	25.0	0.0	1.00	4551	28.8	0.2	0.5	-184.8	3.2	6.0	0.3
IPC	FHWA	19MM	25.0	0.0	0.10	1992	31.3	-0.1	1.0	-110.5	2.9	5.1	0.9
IPC	FHWA	19MM	25.0	0.0	10.00	7857	24.9	-0.1	2.3	-264.4	5.6	19.2	0.4
IPC	FHWA	19MM	25.0	0.0	1.00	4054	30.4	0.2	0.6	-273.8	4.0	17.6	0.6
IPC	FHWA	19MM	25.0	0.0	0.10	1803	32.2	0.1	1.1	-186.9	3.1	14.5	1.2
IPC	FHWA	19MM	25.0	0.0	10.00	5934	27.8	0.0	2.8	-286.1	6.6	14.6	0.3
IPC	FHWA	19MM	25.0	0.0	1.00	2804	32.3	0.3	0.6	-203.0	3.3	13.9	0.2
IPC	FHWA	19MM	25.0	0.0	0.10	1178	32.6	0.3	1.3	-86.8	3.3	10.7	0.3
IPC	FHWA	19MM	45.0	0.0	10.00	2010	33.5	0.1	4.8	-216.8	7.5	10.8	0.5
IPC	FHWA	19MM	45.0	0.0	1.00	769	31.8	1.7	1.7	-32.7	4.6	10.5	0.7
IPC	FHWA	19MM	45.0	0.0	0.10	339	27.4	-0.6	4.4	39.3	4.9	9.4	1.2
IPC	FHWA	19MM	45.0	0.0	10.00	1978	32.8	2.8	4.1	-271.4	7.6	5.3	0.8
IPC	FHWA	19MM	45.0	0.0	1.00	650	32.4	-0.8	1.6	-21.5	4.2	12.7	0.8
IPC	FHWA	19MM	45.0	0.0	0.10	313	26.5	1.1	3.5	1.3	4.7	18.6	0.7
IPC	FHWA	19MM	45.0	0.0	10.00	1548	36.1	-0.1	5.7	-260.9	8.0	6.8	1.0
IPC	FHWA	19MM	45.0	0.0	1.00	542	33.7	0.7	1.7	-45.4	5.0	6.5	0.0
IPC	FHWA	19MM	45.0	0.0	0.10	223	29.0	0.1	4.7	25.2	5.2	11.1	1.7

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. ºC	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	FHWA	19MM	45.0	0.0	10.00	1821	33.7	0.1	4.8	-183.3	6.8	22.8	0.9
IPC	FHWA	19MM	45.0	0.0	1.00	677	30.8	0.9	1.4	-32.5	4.8	24.2	0.2
IPC	FHWA	19MM	45.0	0.0	0.10	288	26.1	-0.3	3.8	6.5	5.4	25.5	1.0
IPC	FHWA	19MM	45.0	0.0	10.00	2050	34.3	-0.3	5.1	-255.5	7.9	9.1	0.7
IPC	FHWA	19MM	45.0	0.0	1.00	797	31.3	0.1	1.4	-53.4	5.0	9.2	1.1
IPC	FHWA	19MM	45.0	0.0	0.10	366	26.3	0.2	3.5	-13.4	5.8	8.9	1.1
IPC	FHWA	19MM	45.0	0.0	10.00	2054	35.0	-0.1	5.1	-255.1	8.1	17.0	1.3
IPC	FHWA	19MM	45.0	0.0	1.00	740	33.5	0.6	1.2	-54.9	4.6	16.9	1.6
IPC	FHWA	19MM	45.0	0.0	0.10	300	29.8	0.5	4.3	-24.3	5.9	15.9	1.5
IPC	FHWA	19MM	45.0	0.0	10.00	1719	35.1	0.5	5.1	-254.5	7.6	9.9	1.4
IPC	FHWA	19MM	45.0	0.0	1.00	645	32.3	0.0	1.5	-47.4	5.1	8.6	2.2
IPC	FHWA	19MM	45.0	0.0	0.10	265	28.3	0.2	3.6	25.0	5.1	14.3	2.0
IPC	FHWA	19MM	45.0	0.0	10.00	1590	35.8	-0.2	5.2	-259.1	8.2	16.8	0.5
IPC	FHWA	19MM	45.0	0.0	1.00	582	32.9	0.2	1.5	-53.7	4.9	19.0	0.9
IPC	FHWA	19MM	45.0	0.0	0.10	241	28.4	2.0	4.1	5.9	4.9	25.3	0.8
IPC	FHWA	19MM	45.0	138.0	10.00	2854	29.2	0.0	3.3	-157.5	5.3	9.1	1.2
IPC	FHWA	19MM	45.0	138.0	1.00	1591	24.6	-0.5	0.8	-56.3	2.8	7.3	1.2
IPC	FHWA	19MM	45.0	138.0	0.10	1084	19.0	0.0	1.3	-45.5	3.0	3.3	0.9
IPC	FHWA	19MM	45.0	138.0	10.00	2657	35.0	-0.1	4.0	-138.0	6.8	12.9	7.0
IPC	FHWA	19MM	45.0	138.0	1.00	1509	30.9	0.6	0.9	-46.5	4.8	21.2	8.9
IPC	FHWA	19MM	45.0	138.0	0.10	1024	23.9	-0.1	1.4	-33.6	4.1	23.5	7.4
IPC	FHWA	19MM	45.0	138.0	10.00	2371	29.0	0.0	3.5	-94.6	4.4	26.9	1.0
IPC	FHWA	19MM	45.0	138.0	1.00	1354	23.1	-0.5	0.8	-31.8	2.4	28.1	1.0
IPC	FHWA	19MM	45.0	138.0	0.10	995	16.7	0.6	1.2	-41.2	2.9	26.3	0.6
IPC	FHWA	19MM	45.0	138.0	10.00	2448	28.2	0.0	3.5	-109.6	4.9	12.4	0.5
IPC	FHWA	19MM	45.0	138.0	1.00	1400	22.6	-0.3	0.8	-50.1	2.8	17.4	0.3
IPC	FHWA	19MM	45.0	138.0	0.10	993	17.0	0.9	1.4	-45.1	3.8	19.6	0.4
IPC	FHWA	19MM	45.0	138.0	10.00	2702	29.5	0.0	3.8	-124.1	5.0	6.6	0.5
IPC	FHWA	19MM	45.0	138.0	1.00	1385	25.9	-0.3	1.2	-40.6	5.5	12.5	0.2
IPC	FHWA	19MM	45.0	138.0	0.10	765	22.1	0.1	2.0	-27.6	3.9	26.8	0.7
IPC	FHWA	19MM	45.0	138.0	10.00	2828	29.7	-0.2	3.3	-155.8	5.3	4.4	1.0
IPC	FHWA	19MM	45.0	138.0	1.00	1551	24.5	0.0	1.3	-61.0	3.0	7.3	1.4
IPC	FHWA	19MM	45.0	138.0	0.10	1064	17.8	0.2	1.9	-55.5	4.0	10.3	1.6
IPC	FHWA	19MM	45.0	138.0	10.00	2165	29.0	0.4	4.6	-110.5	5.4	9.4	0.4
IPC	FHWA	19MM	45.0	138.0	1.00	1271	22.3	-0.7	1.1	-41.5	2.8	10.5	0.4
IPC	FHWA	19MM	45.0	138.0	0.10	932	15.9	-0.2	1.9	-34.9	3.3	12.4	0.5

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
IPC	FHWA	19MM	45.0	138.0	10.00	2243	31.3	-0.2	3.6	-154.3	5.6	11.7	0.7
IPC	FHWA	19MM	45.0	138.0	1.00	1262	25.1	0.6	0.9	-69.2	2.8	11.6	1.0
IPC	FHWA	19MM	45.0	138.0	0.10	897	18.7	0.4	2.1	-60.7	3.3	13.5	0.8
ITC	AAT	95MM	25.0	0.0	10.00	6579	31.1	0.7	4.0	407.2	16.3	4.2	0.6
ITC	AAT	95MM	25.0	0.0	1.00	2937	34.0	0.1	1.1	308.8	10.6	5.0	0.3
ITC	AAT	95MM	25.0	0.0	0.10	1234	29.9	-1.0	-.-	134.7	-.-	1.9	0.9
ITC	AAT	95MM	25.0	0.0	10.00	4656	29.3	0.6	4.5	335.0	14.7	9.3	0.6
ITC	AAT	95MM	25.0	0.0	1.00	1974	31.0	0.0	1.4	168.6	9.4	10.9	0.5
ITC	AAT	95MM	25.0	0.0	0.10	810	27.3	-0.8	-.-	85.2	-.-	11.0	0.8
ITC	AAT	95MM	25.0	0.0	10.00	6153	30.5	0.9	3.9	422.2	15.4	17.1	0.4
ITC	AAT	95MM	25.0	0.0	1.00	2817	33.5	0.1	1.1	357.1	10.9	19.7	0.8
ITC	AAT	95MM	25.0	0.0	0.10	1193	29.7	-0.2	-.-	176.7	-.-	19.3	1.6
ITC	AAT	95MM	25.0	0.0	10.00	5337	31.8	0.6	3.9	431.4	15.5	14.1	0.4
ITC	AAT	95MM	25.0	0.0	1.00	2349	33.8	0.1	1.3	292.5	10.5	14.3	0.4
ITC	AAT	95MM	25.0	0.0	0.10	975	29.3	-0.5	-.-	130.8	-.-	14.3	0.6
ITC	AAT	95MM	25.0	0.0	10.00	5082	25.0	0.0	7.3	216.5	14.4	23.0	1.1
ITC	AAT	95MM	25.0	0.0	1.00	2810	32.3	0.0	0.7	392.5	10.3	21.8	1.2
ITC	AAT	95MM	25.0	0.0	0.10	1124	30.4	-0.8	-.-	150.1	-.-	18.0	2.5
ITC	AAT	95MM	25.0	0.0	10.00	6340	27.0	0.6	3.9	338.9	13.8	25.4	0.5
ITC	AAT	95MM	25.0	0.0	1.00	3050	31.0	0.0	0.8	309.1	10.0	23.8	0.8
ITC	AAT	95MM	25.0	0.0	0.10	1260	29.6	-0.1	-.-	161.8	-.-	18.5	1.7
ITC	AAT	95MM	25.0	0.0	10.00	6219	29.4	0.8	4.0	363.9	14.9	4.5	1.2
ITC	AAT	95MM	25.0	0.0	1.00	2876	32.9	0.1	1.4	304.0	9.5	4.2	1.0
ITC	AAT	95MM	25.0	0.0	0.10	1166	30.0	-0.7	-.-	119.6	-.-	5.0	1.4
ITC	AAT	95MM	25.0	0.0	10.00	5515	27.6	0.5	4.2	345.5	13.6	4.0	2.3
ITC	AAT	95MM	25.0	0.0	1.00	2568	31.3	0.2	1.6	289.2	10.0	8.1	1.7
ITC	AAT	95MM	25.0	0.0	0.10	1080	28.8	-0.5	-.-	152.0	-.-	9.2	1.0
ITC	AAT	95MM	45.0	0.0	10.00	923	35.5	-0.7	9.2	230.9	15.9	1.4	0.8
ITC	AAT	95MM	45.0	0.0	1.00	402	28.5	0.2	4.0	79.2	7.5	9.7	1.8
ITC	AAT	95MM	45.0	0.0	0.10	237	20.2	-1.6	-.-	15.1	-.-	14.8	1.4
ITC	AAT	95MM	45.0	0.0	10.00	756	36.8	-1.0	9.1	241.0	17.1	2.7	0.2
ITC	AAT	95MM	45.0	0.0	1.00	319	29.1	0.0	4.8	66.0	8.2	0.4	0.7
ITC	AAT	95MM	45.0	0.0	0.10	181	19.9	12.5	-.-	99.0	-.-	8.3	1.2
ITC	AAT	95MM	45.0	0.0	10.00	836	37.6	-1.9	9.2	246.4	17.6	5.6	0.2
ITC	AAT	95MM	45.0	0.0	1.00	343	30.7	0.3	5.6	72.6	9.0	6.3	0.4
ITC	AAT	95MM	45.0	0.0	0.10	186	22.2	11.0	-.-	69.7	-.-	9.1	0.1

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	AAT	95MM	45.0	0.0	10.00	797	37.6	-0.4	9.3	220.0	16.1	9.4	1.4
ITC	AAT	95MM	45.0	0.0	1.00	334	29.6	0.6	5.2	63.1	8.1	16.1	1.4
ITC	AAT	95MM	45.0	0.0	0.10	203	20.7	5.8	-.-	0.2	-.-	18.3	1.6
ITC	AAT	95MM	45.0	0.0	10.00	810	36.3	0.7	8.5	228.6	18.2	12.3	1.4
ITC	AAT	95MM	45.0	0.0	1.00	343	29.0	0.0	2.6	82.4	8.5	10.5	0.3
ITC	AAT	95MM	45.0	0.0	0.10	195	21.7	1.8	-.-	81.6	-.-	10.2	0.0
ITC	AAT	95MM	45.0	0.0	10.00	850	38.1	-0.3	8.8	229.7	16.2	7.1	0.5
ITC	AAT	95MM	45.0	0.0	1.00	337	30.4	0.3	5.3	76.8	8.4	9.7	0.5
ITC	AAT	95MM	45.0	0.0	0.10	180	23.0	6.4	-.-	68.0	-.-	10.8	0.6
ITC	AAT	95MM	45.0	0.0	10.00	872	38.4	-0.4	8.5	265.5	16.4	1.6	1.5
ITC	AAT	95MM	45.0	0.0	1.00	355	31.3	0.3	7.0	76.7	8.4	1.0	1.8
ITC	AAT	95MM	45.0	0.0	0.10	183	23.9	2.2	-.-	18.1	-.-	1.6	1.7
ITC	AAT	95MM	45.0	0.0	10.00	838	37.3	-1.0	8.4	213.4	16.1	1.6	0.1
ITC	AAT	95MM	45.0	0.0	1.00	356	29.9	0.3	4.4	56.5	7.4	4.5	0.1
ITC	AAT	95MM	45.0	0.0	0.10	190	23.0	4.3	-.-	37.0	-.-	8.9	0.7
ITC	AAT	95MM	45.0	138.0	10.00	1267	26.7	0.2	9.5	84.0	11.0	11.9	3.7
ITC	AAT	95MM	45.0	138.0	1.00	780	19.8	0.1	1.5	26.8	6.7	16.3	1.9
ITC	AAT	95MM	45.0	138.0	0.10	610	13.7	0.7	-.-	5.7	-.-	16.3	1.5
ITC	AAT	95MM	45.0	138.0	10.00	1670	27.5	0.3	6.9	58.7	6.9	3.2	0.8
ITC	AAT	95MM	45.0	138.0	1.00	1021	19.6	-0.1	1.7	22.3	4.2	4.9	1.6
ITC	AAT	95MM	45.0	138.0	0.10	805	12.5	-0.3	-.-	8.7	-.-	7.1	1.0
ITC	AAT	95MM	45.0	138.0	10.00	1545	27.6	0.3	6.7	99.7	8.5	8.2	2.1
ITC	AAT	95MM	45.0	138.0	1.00	906	20.3	0.1	2.2	31.4	4.3	4.8	0.8
ITC	AAT	95MM	45.0	138.0	0.10	702	13.8	0.4	-.-	10.8	-.-	3.0	0.1
ITC	AAT	95MM	45.0	138.0	10.00	1431	28.4	0.3	6.6	115.0	7.8	11.0	0.9
ITC	AAT	95MM	45.0	138.0	1.00	861	21.3	0.1	2.1	36.4	4.7	8.9	0.9
ITC	AAT	95MM	45.0	138.0	0.10	654	15.2	-0.6	-.-	0.5	-.-	7.2	0.9
ITC	AAT	95MM	45.0	138.0	10.00	1696	26.4	0.2	6.9	95.6	9.8	27.5	0.4
ITC	AAT	95MM	45.0	138.0	1.00	1045	19.4	0.2	1.2	40.0	5.0	26.9	0.4
ITC	AAT	95MM	45.0	138.0	0.10	825	12.1	0.7	-.-	25.8	-.-	26.7	0.6
ITC	AAT	95MM	45.0	138.0	10.00	1619	26.6	0.2	6.5	94.5	9.0	26.9	2.7
ITC	AAT	95MM	45.0	138.0	1.00	992	19.6	-0.1	2.1	36.1	5.2	15.2	1.5
ITC	AAT	95MM	45.0	138.0	0.10	794	12.3	0.3	-.-	17.2	-.-	10.3	0.9
ITC	AAT	95MM	45.0	138.0	10.00	1553	27.3	0.0	11.4	42.4	12.0	18.6	0.6
ITC	AAT	95MM	45.0	138.0	1.00	773	23.3	-0.1	2.7	28.4	4.8	16.3	0.4
ITC	AAT	95MM	45.0	138.0	0.10	532	16.5	1.1	-.-	5.8	-.-	18.9	1.4

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	AAT	95MM	45.0	138.0	10.00	1535	26.8	0.4	6.9	128.0	8.3	30.0	2.4
ITC	AAT	95MM	45.0	138.0	1.00	888	22.0	0.0	1.7	62.6	5.7	15.3	0.2
ITC	AAT	95MM	45.0	138.0	0.10	757	13.9	0.8	-.-	33.7	-.-	14.0	0.0
ITC	AAT	19MM	25.0	0.0	10.00	10820	31.3	0.9	3.3	402.8	16.7	30.8	5.4
ITC	AAT	19MM	25.0	0.0	1.00	4983	33.8	0.0	0.7	332.4	12.0	33.3	2.2
ITC	AAT	19MM	25.0	0.0	0.10	2105	31.4	-0.1	-.-	189.3	-.-	33.2	1.3
ITC	AAT	19MM	25.0	0.0	10.00	8212	24.8	0.7	3.3	249.3	15.1	42.6	0.6
ITC	AAT	19MM	25.0	0.0	1.00	3962	29.5	0.1	0.8	162.2	10.3	34.1	0.5
ITC	AAT	19MM	25.0	0.0	0.10	1757	28.0	0.4	-.-	78.0	-.-	27.0	0.5
ITC	AAT	19MM	25.0	0.0	10.00	9543	27.2	0.6	3.1	245.4	15.1	1.3	0.2
ITC	AAT	19MM	25.0	0.0	1.00	4587	31.4	0.1	0.6	136.5	9.4	1.0	1.4
ITC	AAT	19MM	25.0	0.0	0.10	2013	28.6	0.2	-.-	63.1	-.-	1.3	1.6
ITC	AAT	19MM	25.0	0.0	10.00	6210	27.2	0.8	3.8	344.4	12.9	6.4	3.0
ITC	AAT	19MM	25.0	0.0	1.00	3097	31.2	-0.1	1.0	331.4	11.2	10.0	1.6
ITC	AAT	19MM	25.0	0.0	0.10	1433	31.7	-0.9	-.-	211.1	-.-	13.3	0.4
ITC	AAT	19MM	25.0	0.0	10.00	7797	26.0	0.6	3.5	298.9	12.3	12.4	3.1
ITC	AAT	19MM	25.0	0.0	1.00	4098	30.1	0.0	0.9	321.5	10.5	3.4	0.6
ITC	AAT	19MM	25.0	0.0	0.10	1946	30.1	0.1	-.-	249.0	-.-	2.0	1.5
ITC	AAT	19MM	25.0	0.0	10.00	7989	23.7	0.6	3.5	290.5	12.2	18.8	1.0
ITC	AAT	19MM	25.0	0.0	1.00	3963	28.0	0.0	0.8	217.7	10.3	20.8	2.1
ITC	AAT	19MM	25.0	0.0	0.10	1970	26.9	-0.2	-.-	167.0	-.-	16.8	1.5
ITC	AAT	19MM	25.0	0.0	10.00	6156	23.8	0.6	3.8	292.6	12.0	4.6	3.0
ITC	AAT	19MM	25.0	0.0	1.00	3433	28.6	-0.2	0.9	295.7	9.8	1.6	1.8
ITC	AAT	19MM	25.0	0.0	0.10	1624	28.6	0.2	-.-	195.9	-.-	0.3	0.4
ITC	AAT	19MM	25.0	0.0	10.00	7471	25.2	0.6	3.6	306.7	13.5	11.3	1.6
ITC	AAT	19MM	25.0	0.0	1.00	4132	30.7	0.0	0.8	319.6	11.1	16.7	1.0
ITC	AAT	19MM	25.0	0.0	0.10	1824	30.2	0.9	-.-	177.8	-.-	20.0	0.2
ITC	AAT	19MM	45.0	0.0	10.00	1471	38.9	0.3	11.3	261.4	19.8	4.0	2.1
ITC	AAT	19MM	45.0	0.0	1.00	584	33.0	0.2	3.1	85.2	9.5	5.1	4.7
ITC	AAT	19MM	45.0	0.0	0.10	277	26.0	4.7	-.-	14.5	-.-	2.5	2.4
ITC	AAT	19MM	45.0	0.0	10.00	1221	36.8	-0.8	11.2	311.9	20.3	21.6	0.2
ITC	AAT	19MM	45.0	0.0	1.00	479	33.1	0.4	4.2	125.7	11.2	22.1	1.9
ITC	AAT	19MM	45.0	0.0	0.10	211	28.4	0.3	-.-	48.8	-.-	25.5	2.4
ITC	AAT	19MM	45.0	0.0	10.00	1085	41.0	-0.4	10.7	346.3	23.8	8.6	3.4
ITC	AAT	19MM	45.0	0.0	1.00	402	35.7	0.2	6.3	85.9	9.5	0.1	2.0
ITC	AAT	19MM	45.0	0.0	0.10	184	27.2	5.7	-.-	7.3	-.-	11.2	1.0

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	AAT	19MM	45.0	0.0	10.00	1364	34.0	-0.2	10.8	252.6	17.9	14.4	0.7
ITC	AAT	19MM	45.0	0.0	1.00	596	31.9	-0.3	4.7	76.4	9.5	15.0	1.1
ITC	AAT	19MM	45.0	0.0	0.10	278	26.6	-0.9	-.-	1.1	-.-	18.8	0.9
ITC	AAT	19MM	45.0	0.0	10.00	1367	38.6	-0.1	8.1	279.3	17.4	18.5	1.8
ITC	AAT	19MM	45.0	0.0	1.00	524	32.6	-0.1	3.8	98.3	8.9	18.8	0.1
ITC	AAT	19MM	45.0	0.0	0.10	251	24.6	6.6	-.-	58.5	-.-	23.7	0.6
ITC	AAT	19MM	45.0	0.0	10.00	1746	32.7	0.1	7.1	241.1	13.8	9.5	0.9
ITC	AAT	19MM	45.0	0.0	1.00	791	26.2	0.0	2.5	118.1	8.3	10.4	0.0
ITC	AAT	19MM	45.0	0.0	0.10	452	18.6	0.3	-.-	83.2	-.-	13.8	0.1
ITC	AAT	19MM	45.0	0.0	10.00	1816	31.7	0.5	7.4	206.2	14.6	19.6	0.6
ITC	AAT	19MM	45.0	0.0	1.00	798	26.9	0.0	3.2	75.6	8.7	25.2	0.6
ITC	AAT	19MM	45.0	0.0	0.10	389	22.7	1.8	-.-	36.8	-.-	35.4	1.1
ITC	AAT	19MM	45.0	0.0	10.00	1555	35.7	-0.2	8.5	309.4	19.1	3.7	0.2
ITC	AAT	19MM	45.0	0.0	1.00	611	31.1	0.7	3.7	113.6	9.2	8.4	1.5
ITC	AAT	19MM	45.0	0.0	0.10	293	25.8	-1.5	-.-	23.6	-.-	13.4	1.1
ITC	AAT	19MM	45.0	138.0	10.00	2738	29.6	0.4	5.8	124.2	9.6	2.4	1.8
ITC	AAT	19MM	45.0	138.0	1.00	1456	23.5	0.0	1.5	49.2	6.2	4.3	0.2
ITC	AAT	19MM	45.0	138.0	0.10	956	17.8	0.2	-.-	16.4	-.-	5.8	0.1
ITC	AAT	19MM	45.0	138.0	10.00	2247	28.4	0.4	5.1	112.3	7.4	13.5	0.8
ITC	AAT	19MM	45.0	138.0	1.00	1280	20.8	0.1	1.2	50.7	5.1	17.0	0.8
ITC	AAT	19MM	45.0	138.0	0.10	916	14.6	0.2	-.-	16.7	-.-	20.6	0.5
ITC	AAT	19MM	45.0	138.0	10.00	2217	31.8	0.4	5.8	106.3	11.2	41.8	0.3
ITC	AAT	19MM	45.0	138.0	1.00	1287	22.3	0.2	1.4	41.6	4.9	26.0	1.1
ITC	AAT	19MM	45.0	138.0	0.10	953	15.3	0.3	-.-	27.2	-.-	20.7	0.4
ITC	AAT	19MM	45.0	138.0	10.00	2498	29.4	0.3	5.0	129.6	9.3	36.7	2.2
ITC	AAT	19MM	45.0	138.0	1.00	1321	23.4	-0.1	1.4	60.0	5.7	39.5	1.4
ITC	AAT	19MM	45.0	138.0	0.10	869	18.0	0.5	-.-	33.3	-.-	36.3	0.2
ITC	AAT	19MM	45.0	138.0	10.00	2242	30.8	0.3	6.4	124.4	9.6	4.7	2.7
ITC	AAT	19MM	45.0	138.0	1.00	1212	24.2	0.0	1.5	56.5	5.7	2.4	1.7
ITC	AAT	19MM	45.0	138.0	0.10	799	18.4	-0.3	-.-	25.7	-.-	5.0	0.4
ITC	AAT	19MM	45.0	138.0	10.00	2823	32.1	0.7	6.2	161.6	11.1	28.0	3.6
ITC	AAT	19MM	45.0	138.0	1.00	1486	24.4	0.2	1.3	56.0	6.0	20.7	2.9
ITC	AAT	19MM	45.0	138.0	0.10	1016	17.5	-0.2	-.-	27.4	-.-	14.9	2.0
ITC	AAT	19MM	45.0	138.0	10.00	2386	30.6	0.3	6.5	131.0	8.7	2.2	1.7
ITC	AAT	19MM	45.0	138.0	1.00	1311	23.1	0.1	1.3	67.2	5.7	3.9	2.5
ITC	AAT	19MM	45.0	138.0	0.10	895	16.6	0.6	-.-	33.8	-.-	7.6	2.4

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	AAT	19MM	45.0	138.0	10.00	2303	30.2	0.2	6.4	124.4	10.0	5.3	0.4
ITC	AAT	19MM	45.0	138.0	1.00	1239	23.4	0.2	1.4	56.4	5.6	0.4	0.6
ITC	AAT	19MM	45.0	138.0	0.10	838	17.1	-0.5	-.-	29.7	-.-	0.6	0.2
ITC	FHWA	95MM	25.0	0.0	10.00	6836	30.9	0.9	3.7	389.6	15.4	2.2	1.2
ITC	FHWA	95MM	25.0	0.0	1.00	3080	33.5	0.2	1.2	303.7	10.4	0.3	0.4
ITC	FHWA	95MM	25.0	0.0	0.10	1202	29.7	0.6	-.-	121.0	-.-	0.2	0.7
ITC	FHWA	95MM	25.0	0.0	10.00	5948	30.5	0.7	3.9	428.7	15.4	5.9	0.3
ITC	FHWA	95MM	25.0	0.0	1.00	2594	33.0	0.1	1.5	349.3	8.9	4.6	0.0
ITC	FHWA	95MM	25.0	0.0	0.10	1048	29.0	-0.1	-.-	140.7	-.-	4.3	0.0
ITC	FHWA	95MM	25.0	0.0	10.00	5612	30.6	0.6	3.8	410.0	15.7	14.4	2.3
ITC	FHWA	95MM	25.0	0.0	1.00	2377	32.9	0.1	1.0	289.5	10.6	4.5	1.9
ITC	FHWA	95MM	25.0	0.0	0.10	936	28.7	-0.1	-.-	159.7	-.-	0.7	0.7
ITC	FHWA	95MM	25.0	0.0	10.00	6473	32.0	0.8	3.7	395.9	17.2	25.3	2.0
ITC	FHWA	95MM	25.0	0.0	1.00	2761	34.1	0.0	1.4	272.0	9.3	21.6	1.9
ITC	FHWA	95MM	25.0	0.0	0.10	1104	31.4	-0.5	-.-	127.3	-.-	22.9	1.4
ITC	FHWA	95MM	25.0	0.0	10.00	4926	27.8	0.5	4.1	340.2	13.9	1.5	3.8
ITC	FHWA	95MM	25.0	0.0	1.00	2274	30.7	-0.1	0.9	265.5	9.6	4.9	1.5
ITC	FHWA	95MM	25.0	0.0	0.10	974	28.8	-0.1	-.-	161.2	-.-	0.0	0.2
ITC	FHWA	95MM	25.0	0.0	10.00	5378	31.6	0.4	3.7	419.8	16.2	3.2	1.9
ITC	FHWA	95MM	25.0	0.0	1.00	2369	33.3	0.1	0.9	295.1	9.5	1.6	0.9
ITC	FHWA	95MM	25.0	0.0	0.10	1000	28.6	-0.2	-.-	145.5	-.-	1.2	1.1
ITC	FHWA	95MM	25.0	0.0	10.00	5117	32.2	0.6	3.8	422.0	16.0	0.8	2.4
ITC	FHWA	95MM	25.0	0.0	1.00	2167	33.8	-0.1	1.4	288.3	10.5	4.2	0.3
ITC	FHWA	95MM	25.0	0.0	0.10	886	29.4	0.7	-.-	151.8	-.-	8.3	1.1
ITC	FHWA	95MM	25.0	0.0	10.00	4536	28.0	0.5	4.0	227.1	13.6	8.7	2.2
ITC	FHWA	95MM	25.0	0.0	1.00	2078	29.6	0.2	1.3	95.2	7.9	9.4	1.3
ITC	FHWA	95MM	25.0	0.0	0.10	915	25.4	1.2	-.-	31.9	-.-	10.4	0.4
ITC	FHWA	95MM	45.0	0.0	10.00	782	34.2	-0.6	9.2	195.7	13.8	11.8	0.6
ITC	FHWA	95MM	45.0	0.0	1.00	353	26.4	0.3	3.2	75.7	7.9	9.5	0.6
ITC	FHWA	95MM	45.0	0.0	0.10	213	18.0	5.3	-.-	115.0	-.-	8.5	1.2
ITC	FHWA	95MM	45.0	0.0	10.00	720	34.9	-0.8	7.8	157.6	12.8	14.5	0.4
ITC	FHWA	95MM	45.0	0.0	1.00	329	25.9	0.0	2.9	64.1	7.9	23.0	0.3
ITC	FHWA	95MM	45.0	0.0	0.10	198	19.0	3.1	-.-	8.6	-.-	27.4	0.4
ITC	FHWA	95MM	45.0	0.0	10.00	773	37.2	-0.5	7.9	189.2	14.8	11.5	1.0
ITC	FHWA	95MM	45.0	0.0	1.00	331	28.9	0.1	2.0	71.2	7.8	15.2	0.4
ITC	FHWA	95MM	45.0	0.0	0.10	187	21.3	0.8	-.-	40.9	-.-	13.6	0.4

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	FHWA	95MM	45.0	0.0	10.00	735	35.7	-0.1	7.7	133.0	13.5	1.6	0.8
ITC	FHWA	95MM	45.0	0.0	1.00	330	27.2	0.0	5.3	47.2	8.2	0.2	0.7
ITC	FHWA	95MM	45.0	0.0	0.10	195	18.3	9.8	-.-	66.5	-.-	2.3	0.2
ITC	FHWA	95MM	45.0	0.0	10.00	879	36.4	-0.4	8.6	224.9	16.2	10.5	0.5
ITC	FHWA	95MM	45.0	0.0	1.00	373	29.5	0.3	3.1	85.1	8.7	9.8	0.7
ITC	FHWA	95MM	45.0	0.0	0.10	202	21.5	5.9	-.-	82.7	-.-	9.5	1.2
ITC	FHWA	95MM	45.0	0.0	10.00	920	35.9	-1.0	9.4	486.0	9.2	6.0	1.3
ITC	FHWA	95MM	45.0	0.0	1.00	408	26.4	0.2	4.6	54.9	8.8	4.4	0.6
ITC	FHWA	95MM	45.0	0.0	0.10			0.0	-.-	0.0	-.-	0.0	0.0
ITC	FHWA	95MM	45.0	0.0	10.00	730	35.8	0.7	9.5	219.2	23.6	8.5	0.6
ITC	FHWA	95MM	45.0	0.0	1.00	294	28.8	0.5	3.9	28.0	7.5	9.8	0.4
ITC	FHWA	95MM	45.0	0.0	0.10	158	21.9	2.0	-.-	2.8	-.-	5.5	0.6
ITC	FHWA	95MM	45.0	0.0	10.00	896	33.5	0.4	8.7	282.9	15.5	11.3	0.1
ITC	FHWA	95MM	45.0	0.0	1.00	348	26.9	0.1	3.2	66.1	7.8	10.8	0.4
ITC	FHWA	95MM	45.0	0.0	0.10	217	19.5	4.1	-.-	56.1	-.-	11.4	0.4
ITC	FHWA	95MM	45.0	138.0	10.00	1664	28.9	0.4	8.2	90.6	8.8	9.0	1.7
ITC	FHWA	95MM	45.0	138.0	1.00	997	20.7	0.0	1.9	38.8	5.1	12.6	1.7
ITC	FHWA	95MM	45.0	138.0	0.10	767	13.3	0.2	-.-	10.9	-.-	14.2	1.6
ITC	FHWA	95MM	45.0	138.0	10.00	1500	26.7	0.5	6.8	93.0	7.7	4.3	2.3
ITC	FHWA	95MM	45.0	138.0	1.00	932	19.1	0.1	1.3	43.3	4.9	6.8	1.9
ITC	FHWA	95MM	45.0	138.0	0.10	715	12.4	0.7	-.-	15.8	-.-	8.5	1.3
ITC	FHWA	95MM	45.0	138.0	10.00	1352	30.2	0.7	5.5	123.4	9.1	19.8	1.9
ITC	FHWA	95MM	45.0	138.0	1.00	656	24.6	0.1	1.0	44.9	5.0	21.0	0.0
ITC	FHWA	95MM	45.0	138.0	0.10	587	14.7	-0.4	-.-	24.6	-.-	25.4	0.6
ITC	FHWA	95MM	45.0	138.0	10.00	1580	26.5	0.6	7.1	101.8	9.8	14.2	0.4
ITC	FHWA	95MM	45.0	138.0	1.00	969	18.7	0.1	1.7	40.8	4.3	13.0	0.6
ITC	FHWA	95MM	45.0	138.0	0.10	766	11.9	-0.3	-.-	29.9	-.-	12.4	0.3
ITC	FHWA	95MM	45.0	138.0	10.00	1414	26.5	0.3	8.6	55.4	7.6	12.7	0.3
ITC	FHWA	95MM	45.0	138.0	1.00	918	18.7	0.1	2.1	25.2	5.1	12.0	0.4
ITC	FHWA	95MM	45.0	138.0	0.10	755	11.2	0.1	-.-	8.7	-.-	11.6	0.9
ITC	FHWA	95MM	45.0	138.0	10.00	1486	29.1	0.5	6.6	127.5	8.4	4.8	0.2
ITC	FHWA	95MM	45.0	138.0	1.00	886	20.7	0.0	2.1	39.9	4.8	8.4	0.4
ITC	FHWA	95MM	45.0	138.0	0.10	655	13.9	0.0	-.-	9.6	-.-	13.8	0.0
ITC	FHWA	95MM	45.0	138.0	10.00	1275	30.6	-0.1	7.2	66.3	8.1	10.7	1.4
ITC	FHWA	95MM	45.0	138.0	1.00	843	20.4	0.0	2.1	20.9	4.3	7.9	0.3
ITC	FHWA	95MM	45.0	138.0	0.10	731	12.6	0.1	-.-	14.0	-.-	7.1	0.1

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	FHWA	95MM	45.0	138.0	10.00	1528	27.7	0.2	6.2	96.5	8.4	0.5	1.4
ITC	FHWA	95MM	45.0	138.0	1.00	960	19.7	0.0	2.0	36.9	5.0	5.1	1.8
ITC	FHWA	95MM	45.0	138.0	0.10	852	12.1	0.1	-.-	22.4	-.-	1.8	0.2
ITC	FHWA	19MM	25.0	0.0	10.00	11131	29.2	0.4	3.2	358.2	17.1	18.4	0.9
ITC	FHWA	19MM	25.0	0.0	1.00	5446	32.3	0.1	0.4	314.4	11.1	13.8	0.9
ITC	FHWA	19MM	25.0	0.0	0.10	2298	30.7	-0.2	-.-	185.7	-.-	18.5	1.4
ITC	FHWA	19MM	25.0	0.0	10.00	12580	32.2	0.6	3.3	421.8	20.8	27.9	7.3
ITC	FHWA	19MM	25.0	0.0	1.00	4684	30.5	0.0	0.7	317.1	10.6	30.4	7.0
ITC	FHWA	19MM	25.0	0.0	0.10	1925	27.7	0.3	-.-	183.2	-.-	28.6	4.2
ITC	FHWA	19MM	25.0	0.0	10.00	8442	27.4	0.7	3.4	255.2	13.9	20.5	6.6
ITC	FHWA	19MM	25.0	0.0	1.00	4284	29.2	0.0	0.8	182.9	10.8	2.3	3.6
ITC	FHWA	19MM	25.0	0.0	0.10	1733	27.8	0.6	-.-	61.9	-.-	5.8	1.7
ITC	FHWA	19MM	25.0	0.0	10.00	9156	26.8	0.7	3.4	238.8	14.6	9.1	5.9
ITC	FHWA	19MM	25.0	0.0	1.00	4431	29.2	0.0	0.8	167.3	8.3	3.9	3.1
ITC	FHWA	19MM	25.0	0.0	0.10	1812	27.2	0.1	-.-	106.9	-.-	7.2	1.3
ITC	FHWA	19MM	25.0	0.0	10.00	9136	30.0	0.7	3.5	319.9	15.2	30.5	6.2
ITC	FHWA	19MM	25.0	0.0	1.00	4340	32.1	0.1	0.9	240.7	8.9	20.8	3.3
ITC	FHWA	19MM	25.0	0.0	0.10	1792	30.6	-0.1	-.-	45.8	-.-	14.3	1.2
ITC	FHWA	19MM	25.0	0.0	10.00	7832	24.9	0.5	3.5	280.1	12.1	9.6	2.3
ITC	FHWA	19MM	25.0	0.0	1.00	4114	29.2	0.2	0.8	318.3	9.7	10.2	0.9
ITC	FHWA	19MM	25.0	0.0	0.10	1980	29.3	-0.2	-.-	242.4	-.-	7.0	1.0
ITC	FHWA	19MM	25.0	0.0	10.00	7936	26.5	0.6	3.3	296.8	11.4	21.8	4.0
ITC	FHWA	19MM	25.0	0.0	1.00	4087	29.8	0.1	0.8	296.4	10.1	18.5	2.7
ITC	FHWA	19MM	25.0	0.0	0.10	1867	30.1	-0.5	-.-	149.3	-.-	13.4	1.5
ITC	FHWA	19MM	25.0	0.0	10.00	7918	26.7	0.9	3.8	306.4	15.0	12.4	2.9
ITC	FHWA	19MM	25.0	0.0	1.00	4073	29.9	0.0	0.8	303.0	12.9	10.9	0.0
ITC	FHWA	19MM	25.0	0.0	0.10	1780	29.5	0.5	-.-	129.3	-.-	18.9	2.1
ITC	FHWA	19MM	45.0	0.0	10.00	1637	36.4	0.9	8.5	306.1	20.4	18.1	1.7
ITC	FHWA	19MM	45.0	0.0	1.00	638	32.7	0.3	3.6	102.4	10.0	24.4	1.5
ITC	FHWA	19MM	45.0	0.0	0.10	314	26.2	5.8	-.-	49.3	-.-	16.8	0.7
ITC	FHWA	19MM	45.0	0.0	10.00	1729	33.1	0.0	7.7	202.2	12.6	4.6	1.3
ITC	FHWA	19MM	45.0	0.0	1.00	798	26.4	0.1	2.6	105.6	8.6	5.0	0.5
ITC	FHWA	19MM	45.0	0.0	0.10	462	18.9	-1.3	-.-	75.9	-.-	2.3	0.8
ITC	FHWA	19MM	45.0	0.0	10.00	1418	33.6	-0.7	9.8	215.7	16.8	8.1	2.1
ITC	FHWA	19MM	45.0	0.0	1.00	615	28.7	0.0	4.2	67.4	9.1	6.4	1.3
ITC	FHWA	19MM	45.0	0.0	0.10	330	22.0	-1.9	-.-	18.6	-.-	1.9	1.2

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	FHWA	19MM	45.0	0.0	10.00	1683	33.8	0.3	5.2	91.2	10.0	5.9	1.3
ITC	FHWA	19MM	45.0	0.0	1.00	756	25.3	0.2	2.6	23.6	5.9	4.1	0.1
ITC	FHWA	19MM	45.0	0.0	0.10	490	17.3	-0.3	-.-	-20.9	-.-	1.7	0.2
ITC	FHWA	19MM	45.0	0.0	10.00	1683	31.8	1.2	9.1	299.2	13.7	14.5	2.9
ITC	FHWA	19MM	45.0	0.0	1.00	740	26.9	0.2	1.6	48.6	6.8	6.2	0.4
ITC	FHWA	19MM	45.0	0.0	0.10	377	22.0	0.5	-.-	8.8	-.-	26.9	0.9
ITC	FHWA	19MM	45.0	0.0	10.00	1727	30.8	-0.1	8.6	202.0	13.5	19.6	0.7
ITC	FHWA	19MM	45.0	0.0	1.00	759	28.5	0.0	3.1	92.0	8.4	23.8	1.3
ITC	FHWA	19MM	45.0	0.0	0.10	358	23.5	1.8	-.-	54.2	-.-	26.6	0.3
ITC	FHWA	19MM	45.0	0.0	10.00	1387	37.9	-0.3	8.2	175.2	17.4	3.7	3.3
ITC	FHWA	19MM	45.0	0.0	1.00	566	30.7	0.1	2.5	38.2	7.9	2.3	0.2
ITC	FHWA	19MM	45.0	0.0	0.10	303	23.3	-1.7	-.-	-1.9	-.-	2.0	0.3
ITC	FHWA	19MM	45.0	0.0	10.00	1775	36.5	0.2	7.9	231.8	16.4	11.0	2.2
ITC	FHWA	19MM	45.0	0.0	1.00	754	28.9	0.1	2.2	104.3	9.3	19.4	1.1
ITC	FHWA	19MM	45.0	0.0	0.10	384	22.6	-0.9	-.-	47.8	-.-	24.5	0.1
ITC	FHWA	19MM	45.0	138.0	10.00	2612	29.7	0.6	4.6	134.3	9.4	23.2	1.0
ITC	FHWA	19MM	45.0	138.0	1.00	1417	23.4	0.0	1.1	52.8	5.9	21.5	2.1
ITC	FHWA	19MM	45.0	138.0	0.10	985	17.4	0.0	-.-	11.0	-.-	19.3	2.2
ITC	FHWA	19MM	45.0	138.0	10.00	3025	31.1	0.9	7.5	160.0	12.9	21.4	0.2
ITC	FHWA	19MM	45.0	138.0	1.00	1555	25.1	0.1	1.5	66.1	6.5	27.6	2.3
ITC	FHWA	19MM	45.0	138.0	0.10	953	19.6	-0.1	-.-	22.6	-.-	28.3	2.6
ITC	FHWA	19MM	45.0	138.0	10.00	2549	30.6	0.8	7.1	166.2	12.6	3.1	1.6
ITC	FHWA	19MM	45.0	138.0	1.00	1303	23.6	0.1	1.7	67.2	7.8	4.4	1.7
ITC	FHWA	19MM	45.0	138.0	0.10	815	17.3	-0.7	-.-	27.2	-.-	6.9	1.9
ITC	FHWA	19MM	45.0	138.0	10.00	2391	29.1	0.1	6.4	90.1	10.9	13.1	3.8
ITC	FHWA	19MM	45.0	138.0	1.00	1399	20.8	0.0	1.5	37.8	4.9	21.8	2.5
ITC	FHWA	19MM	45.0	138.0	0.10	1038	14.9	0.0	-.-	12.5	-.-	26.7	1.4
ITC	FHWA	19MM	45.0	138.0	10.00	2602	28.9	0.5	5.6	135.6	9.3	3.2	1.4
ITC	FHWA	19MM	45.0	138.0	1.00	1435	22.8	0.1	1.1	51.7	6.6	2.2	2.1
ITC	FHWA	19MM	45.0	138.0	0.10	982	17.0	0.5	-.-	11.7	-.-	7.3	1.7
ITC	FHWA	19MM	45.0	138.0	10.00	2693	30.0	0.2	6.8	117.7	10.1	26.6	1.8
ITC	FHWA	19MM	45.0	138.0	1.00	1501	24.0	0.1	1.4	59.0	6.1	28.6	3.3
ITC	FHWA	19MM	45.0	138.0	0.10	1076	17.4	-0.6	-.-	28.2	-.-	26.3	2.9
ITC	FHWA	19MM	45.0	138.0	10.00	2741	31.6	0.4	7.9	129.8	11.6	5.7	3.4
ITC	FHWA	19MM	45.0	138.0	1.00	1333	24.5	0.3	1.7	49.4	7.3	8.7	3.8
ITC	FHWA	19MM	45.0	138.0	0.10	862	17.9	0.0	-.-	17.1	-.-	9.9	2.3

TABLE C-1 Modulus and phase angle data and values for associated quality indices (continued)

Device	Lab	Mix Type	Nominal Temp. °C	Nominal Confining Pressure KPa	Freq. Hz	Modulus MPa	Phase Angle Deg.	Load Drift %	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity Deg.
ITC	FHWA	19MM	45.0	138.0	10.00	2317	31.2	0.2	8.0	123.8	10.5	6.0	0.1
ITC	FHWA	19MM	45.0	138.0	1.00	1303	23.5	-0.1	1.8	59.8	5.6	13.7	2.1
ITC	FHWA	19MM	45.0	138.0	0.10	922	17.5	-0.3	-.-	43.9	-.-	18.0	1.9

TABLE C-2 Flow number and strain at flow data

Device	Lab	Mix Type	Flow Number, Unconfined	Strain at Flow, Unconfined %	Flow Number, Confined	Strain at Flow, Confined %
IPC	AAT	9.5MM	511	1.92	1331	2.59
IPC	AAT	9.5MM	451	1.78	991	2.80
IPC	AAT	9.5MM	451	1.33	1171	3.08
IPC	AAT	9.5MM	451	1.70	1251	2.56
IPC	AAT	9.5MM	390	1.61	1111	2.47
IPC	AAT	9.5MM	431	1.68	1671	3.04
IPC	AAT	9.5MM	471	1.67	1151	2.80
IPC	AAT	9.5MM	751	2.09	1811	2.38
IPC	AAT	19MM	2111	0.99	4571	1.23
IPC	AAT	19MM	1491	1.02	3751	1.54
IPC	AAT	19MM	1311	0.80	2591	1.46
IPC	AAT	19MM	931	0.98	4911	1.89
IPC	AAT	19MM	1511	1.04	2831	1.26
IPC	AAT	19MM	1131	0.94	6531	1.23
IPC	AAT	19MM	1811	0.86	2711	1.38
IPC	AAT	19MM	1571	1.07	2751	1.30
IPC	FHWA	9.5MM	897	1.81	1811	3.46
IPC	FHWA	9.5MM	631	1.96	1411	2.53
IPC	FHWA	9.5MM	711	2.14	1471	3.31
IPC	FHWA	9.5MM	951	2.08	1271	2.87
IPC	FHWA	9.5MM	691	2.16	1551	3.00
IPC	FHWA	9.5MM	631	1.70	1431	3.36
IPC	FHWA	9.5MM	791	1.97	1791	3.08
IPC	FHWA	9.5MM	---.	2.26	1431	2.42
IPC	FHWA	19MM	2751	0.75	2191	2.01
IPC	FHWA	19MM	1071	1.33	3051	1.55
IPC	FHWA	19MM	1051	1.11	4971	1.79
IPC	FHWA	19MM	2111	0.80	1931	1.58
IPC	FHWA	19MM	1191	1.36	1431	1.75
IPC	FHWA	19MM	1451	1.05	2471	1.60
IPC	FHWA	19MM	951	1.07	1691	1.54
IPC	FHWA	19MM	1151	1.10	3451	1.77
ITC	AAT	9.5MM	677	1.95	2300	3.70
ITC	AAT	9.5MM	876	1.95	1613	2.88
ITC	AAT	9.5MM	522	1.90	1700	3.60
ITC	AAT	9.5MM	611	1.96	2604	3.48

TABLE C-2 Flow number and strain at flow data (continued)

Device	Lab	Mix Type	Flow Number, Unconfined	Strain at Flow, Unconfined %	Flow Number, Confined	Strain at Flow, Confined %
ITC	AAT	9.5MM	634	2.04	1733	3.80
ITC	AAT	9.5MM	533	1.88	2627	3.80
ITC	AAT	9.5MM	564	2.03	2440	4.00
ITC	AAT	9.5MM	773	2.07	2490	4.06
ITC	AAT	19MM	934	1.05	1629	1.18
ITC	AAT	19MM	1662	0.76	3434	2.23
ITC	AAT	19MM	1103	1.00	4352	2.02
ITC	AAT	19MM	596	1.10	2087	2.28
ITC	AAT	19MM	1022	1.25	5743	1.90
ITC	AAT	19MM	819	1.11	6448	1.70
ITC	AAT	19MM	1390	1.30	856	1.10
ITC	AAT	19MM	693	1.30	4427	2.45
ITC	FHWA	9.5MM	629	2.05	2821	4.40
ITC	FHWA	9.5MM	372	1.82	2148	3.40
ITC	FHWA	9.5MM	452	1.58	2836	3.96
ITC	FHWA	9.5MM	701	2.14	2210	4.22
ITC	FHWA	9.5MM	479	1.62	2469	4.00
ITC	FHWA	9.5MM	458	1.94	1837	3.71
ITC	FHWA	9.5MM	621	1.92	2474	3.91
ITC	FHWA	9.5MM	505	1.94	2364	3.81
ITC	FHWA	19MM	1557	0.87	4730	1.42
ITC	FHWA	19MM	1446	0.96	2204	1.34
ITC	FHWA	19MM	943	0.98	4672	1.89
ITC	FHWA	19MM	1587	0.99	>10000	0.00
ITC	FHWA	19MM	1722	1.24	3066	1.79
ITC	FHWA	19MM	847	0.99	2591	1.48
ITC	FHWA	19MM	831	0.94	5360	1.38
ITC	FHWA	19MM	912	0.93	5778	2.45

APPENDIX D

FINAL EQUIPMENT SPECIFICATION

NCHRP
Project 9-29

Simple Performance Tester for Superpave Mix Design

Equipment Specification For The Simple Performance Test System

LIMITED USE DOCUMENT

The information contained in this Document is regarded as fully privileged. Dissemination of information included herein must be approved by the NCHRP.

May 15, 2003

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ADVANCED ASPHALT TECHNOLOGIES
ENGINEERING SERVICES FOR THE ASPHALT INDUSTRY

Table of Contents

1.0 Summary

1.1 This specification describes the requirements for a testing system to conduct the following National Cooperative Highway Research Program (NCHRP) Project 9-19 simple performance tests:

Test Method For Static Creep/Flow Time of Asphalt Concrete Mixtures in Compression

Test Method for Repeated Load Testing of Asphalt Concrete Mixtures in Uniaxial Compression

Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Permanent Deformation

Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Fatigue Cracking

Test Methods for each of these tests using the equipment described in this specification are presented in Appendix A, B, and C of this equipment specification.

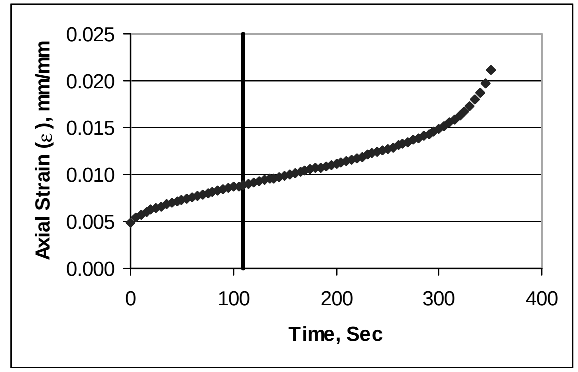
Note: This equipment specification represents a revision of the equipment requirements contained in the Project 9-19 Test Protocols. The requirements of this specification supersede those contained in Project 9-19 Test Protocols.

1.2 The testing system shall be capable of performing three compressive tests on nominal 100 mm (4 in) diameter, 150 mm (6 in) high cylindrical specimens. The tests are briefly described below.

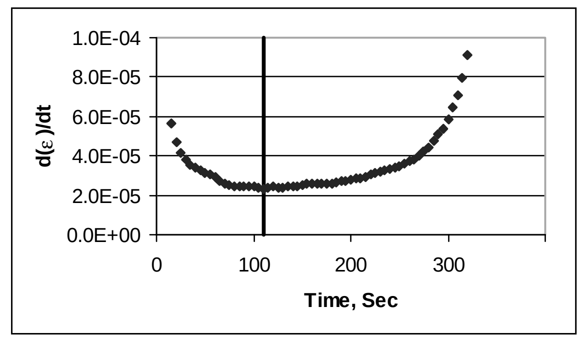
1.3 **Flow Time Test.** In this test, the specimen is subjected to a constant axial compressive load at a specific test temperature. The test may be conducted with or without confining pressure. The resulting axial strain is measured as a function of time and numerically differentiated to calculate the flow time. The flow time is defined as the time corresponding to the minimum rate of change of axial strain. This is shown schematically in Figure 1.

1.4 **Flow Number Test.** In this test, the specimen, at a specific test temperature, is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function of time and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain. This is shown schematically in Figure 2.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

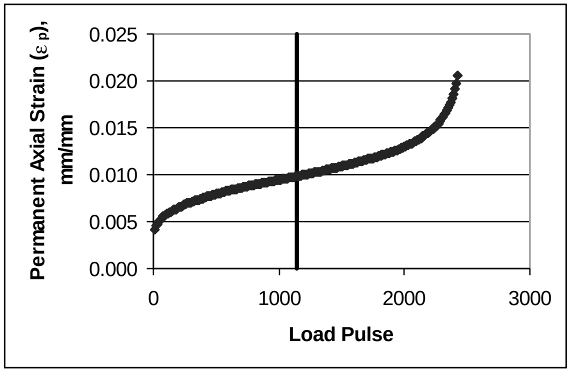


a. Axial Strain in Flow Time Test.

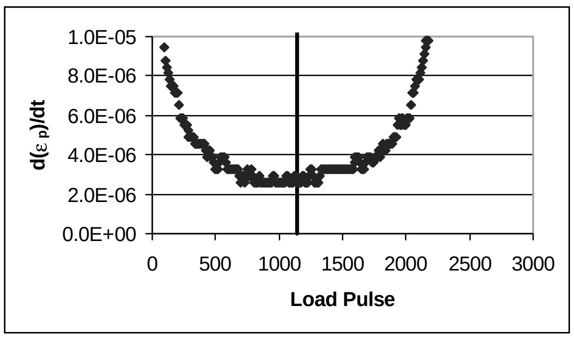


b. Rate of Change of Axial Strain.

Figure 1. Schematic of Flow Time Test Data.



a. Permanent Axial Strain in Flow Number Test.



b. Rate of Change of Permanent Axial Strain.

Figure 2. Schematic of Flow Number Test Data.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

1.5 **Dynamic Modulus Test.** In this test, the specimen, at a specific test temperature, is subjected to controlled sinusoidal (haversine) compressive stress of various frequencies. The applied stresses and resulting axial strains are measured as a function of time and used to calculate the dynamic modulus and phase angle. The dynamic modulus and phase angle are defined by Equations 1 and 2. Figure 3 presents a schematic of the data generated during a typical dynamic modulus test.

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \tag{1}$$

$$\phi = \frac{T_i}{T_p}(360) \tag{2}$$

Where:

$|E^*|$ = dynamic modulus
ϕ = phase angle, degree
σ_o = stress amplitude
ε_o = strain amplitude
T_i = time lag between stress and strain
T_p = period of applied stress

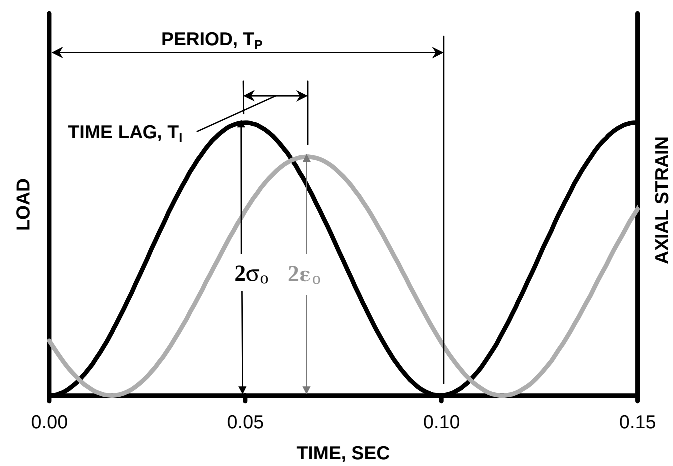


Figure 3. Schematic of Dynamic Modulus Test Data.

2.0 Definitions

2.1 *Flow Time.* Time corresponding to the minimum rate of change of axial strain during a creep test.

2.2 *Flow Number.* The number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test.

2.3 *Dynamic Modulus.* Ratio of the stress amplitude to the strain amplitude for asphalt concrete subjected to sinusoidal loading (Equation 1).

2.4 *Phase Angle*. Angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled stress test (Equation 2).

2.5 *Resolution.* The smallest change of a measurement that can be displayed or recorded by the measuring system. When noise produces a fluctuation in the display or measured value, the resolution shall be one-half of the range of the fluctuation.

2.6 *Accuracy.* The permissible variation from the correct or true value.

2.7 *Error.* The value obtained by subtracting the value indicated by a traceable calibration device from the value indicated by the measuring system.

2.8 *Confining Pressure.* Stress applied to all surfaces in a confined test.

2.9 *Deviator Stress.* Difference between the total axial stress and the confining pressure in a confined test.

2.10 *Dynamic Stress*. Sinusoidal deviator stress applied during the Dynamic Modulus Test.

2.11 *Dynamic Strain*. Sinusoidal axial strain measured during the Dynamic Modulus Test.

3.0 Test Specimens

3.1 Test specimens for the Simple Performance Test System will be cylindrical meeting the following requirements.

Item	Specification	Remarks
Average Diameter	100 mm to 104 mm	
Standard Deviation of Diameter	1.0 mm	See note 1
Height	147.5 mm to 152.5 mm	
End Flatness	0.3 mm	See note 2
End Parallelism	1 degree	See note 3

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

Notes:

1. Measure the diameter at the center and third points of the test specimen along axes that are 90 degrees apart. Record each of the six measurements to the nearest 1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 1.0 mm. The average diameter, reported to the nearest 1 mm, shall be used in all material property calculations.
2. Check this requirement using a straight edge and feeler gauges.
3. Check this requirement using a machinists square and feeler gauges.

Note: Test specimens will be fabricated using separate equipment. This information is provided for design of the Simple Performance Test system.

4.0 Simple Performance Test System

4.1 The Simple Performance Test System shall be a complete, fully integrated testing system meeting the requirements of these specifications and having the capability to perform the Flow Time, Flow Number, and Dynamic Modulus simple performance tests described in Appendix A, B, and C, respectively.

4.2 Appendix D summarizes the methods that will be used to verify that the Simple Performance Test System complies with the requirements of this specification.

4.3 The Simple Performance Test System shall include the following components:

1. Compression loading machine.
2. Loading platens.
3. Load measuring system.
4. Deflection measuring system.
5. Specimen deformation measuring system.
6. Confining pressure system.
7. Environmental chamber.
8. Computer control and data acquisition system.

4.4 The load frame, environmental chamber, and computer control system for the Simple Performance Test System shall occupy a foot-print no greater than 1.5 m (5 ft) by 1.5 m (5 ft) with a maximum height of 1.8 m (6 ft). A suitable frame, bench or cart shall be provided so that the bottom of the test specimen, and the computer keyboard and display are approximately 90 cm (36 in) above the floor.

4.5 The load frame, environmental chamber and computer control system for the Simple Performance Test System shall operate on single phase 115 or 230 VAC 60 Hz electrical power.

4.6 If a hydraulic power supply is required, it shall be air-cooled occupying a foot-print no larger than 1 m (3 ft) by 1.5 m (5 ft). The noise level 2 m (6.5 ft) from the hydraulic power supply shall not exceed 70 dB. The hydraulic power supply shall operate on single phase 115 of 230 VAC 60 Hz electrical power.

4.7 When disassembled, the width of any single component shall not exceed 76 cm (30 in).

4.8 Air supply requirements shall not exceed 0.005 m^3/s (10.6 ft^3/min) at 850 kPa (125 psi).

4.9 The Simple Performance Test System shall include appropriate limit and overload protection.

4.10 An emergency stop shall be mounted at an easily accessible point on the system.

5.0 Compression Loading Machine

5.1 The machine shall have closed-loop load control with the capability of applying constant, ramp, sinusoidal, and pulse loads. The requirements for each of the simple performance tests are listed below.

Test	Type of Loading	Capacity	Rate
Flow Time	Ramp, constant	10 kN (2.25 kips)	0.5 sec ramp
Flow Number	Ramp, constant, pulse	8 kN (1.80 kips)	10 Hz pulse with 0.9 sec dwell
Dynamic Modulus	Ramp, constant, sinusoidal	6 kN (1.35 kips)	0.1 to 25 Hz

5.2 For ramp and constant loads, the load shall be maintained within +/- 2 percent of the desired load.

5.3 For sinusoidal loads, the standard error of the applied load shall be less than 5 percent. The standard error of the applied load is a measure of the difference between the measured load data, and the best fit sinusoid. The standard error of the load is defined in Equation 3.

$$se(P) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n-4}}\left(\frac{100\%}{\hat{x}_o}\right) \quad (3)$$

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

Where:

$se(P)$ = Standard error of the applied load
x_i = Measured load at point *i*
$\hat{x}_i$ = Predicted load at point *i* from the best fit sinusoid, See Equation 16
$\hat{x}_o$ = Amplitude of the best fit sinusoid
n = Total number of data points collected during test.

5.4 For pulse loads, the peak of the load pulse shall be within +/- 2 percent of the specified value and the standard error of the applied load during the sinusoidal pulse shall be less than 10 percent.

5.5 For the Flow Time and Flow Number Tests, the loading platens shall remain parallel during loading. For the Dynamic Modulus Test, the load shall be applied to the specimen through a ball or swivel joint.

6.0 Loading Platens

6.1 The loading platens shall be fabricated from aluminum and have a Brinell Hardness Number HBS 10/500 of 95 or greater.

6.2 The loading platens shall be at least 25 mm (1 in) thick. The diameter of the loading platens shall not be less than 105 mm (4.125 in) nor greater than 108 mm (4.25 in).

6.3 The loading platens shall not depart from a plane by more than 0.0125 mm (0.0005 in) across any diameter.

7.0 Load Measuring System

7.1 The Simple Performance Test System shall include an electronic load measuring system with full scale range equal to or greater than the stall force for the actuator of the compression loading machine.

7.2 The load measuring system shall have an error equal to or less than +/- 1 percent for loads ranging from 0.12 kN (25 lb) to 10 kN (2.25 kips) when verified in accordance with ASTM E4.

7.3 The resolution of the load measuring system shall comply with the requirements of ASTM E4.

8.0 Deflection Measuring System

8.1 The Simple Performance Test System shall include a electronic deflection measuring system that measures the movement of the loading actuator for use in the Flow Time and Flow Number Tests

8.2 The deflection measuring system shall have a range of at least 12 mm (0.5 in).

8.3 The deflection measuring system shall have a resolution equal to or better than 0.0025 mm (0.0001 in).

8.4 The deflection measuring system shall have an error equal to or less than 0.03 mm (0.001 in) over the 12 mm range when verified in accordance with ASTM D 6027.

8.5 The deflection measuring system shall be designed to minimize errors due to compliance and/or bending of the loading mechanism. These errors shall be less than 0.25 mm (0.01 in) at 8 kN (1.8 kips) load.

9.0 Specimen Deformation Measuring System

9.1 The Simple Performance Test System shall include a glued gauge point system for measuring deformations on the specimen over a gauge length of 70 mm (2.76 in) ± 1 mm (0.04 in) at the middle of the specimen. This system will be used in the Dynamic Modulus Test, and shall include at least two transducers spaced equally around the circumference of the specimen.

9.2 Figure 4 shows a schematic of the standard specimen deformation measuring system with critical dimensions. Other properties of the deformation measuring system are listed below.

Property	Value
Gauge point contact area	80 mm ± 10 mm
Mass of mounting system and transducer	80 g max
Transducer spring force	1 N max

9.3 The transducers shall have a range of at least 1 mm (0.04 in).

9.4 The transducers shall have a resolution equal to or better than 0.0002 mm (7.8 micro inch).

9.5 The transducers shall have an error equal to or less than 0.0025 mm (0.0001 in) over the 1 mm range when verified in accordance with ASTM D 6027.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

9.6 The axial deformation measuring system shall be designed for rapid specimen installation and subsequent testing. Specimen instrumentation, installation, application of confining pressure, and temperature equilibration shall take no longer than 3 minutes over the complete range of temperatures.

9.7 Alternatives to the standard system described in this section will be considered provided the components meet the range, accuracy, and resolution requirements. Submit data showing the alternative system produces the same modulus and phase angles as the standard system on asphalt concrete specimens tested over the stiffness range of 150 to 10,000 MPa (20,000 to 1,500,000 psi). Annex E describes the minimum testing and analysis required for a non-standard system.

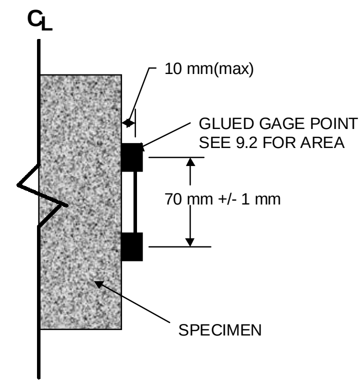


Figure 4. Schematic of Standard Specimen Mounted Deformation Measuring System.

10.0 Confining Pressure System

10.1 The confining pressure system shall be capable of providing a constant confining pressure up to 210 kPa (30 psi) to the test specimen. The system shall include a pressure cell with appropriate pressure regulation and control, a flexible specimen membrane, a device or method for detecting leaks in the membrane, a pressure transducer, and a temperature sensing device that is mounted internal to the cell.

10.2 The confining pressure cell shall be designed to allow the operator to view the specimen, the specimen mounted deformation measuring system, and the specimen end platens during testing.

10.3 Confining pressure shall be controlled by the computer control and data acquisition system. The confining pressure control system shall have the capability to maintain a constant confining pressure throughout the test within +/- 2 percent of the desired pressure.

10.4 The specimen shall be enclosed in an impermeable flexible membrane sealed against the loading platens.

10.5 The pressure inside the specimen membrane shall be maintained at atmospheric pressure through vents in the loading platens. The system shall include a device or method for detecting membrane leaks.

10.6 The confining pressure system shall include a pressure transducer for recording confining pressure during the test. The pressure transducer shall have a range of at least 210 kPa, (30 psi) and a resolution of 0.5 kPa (0.07 psi). The pressure transducer shall have an error equal to or less than ±1 percent of the indicated value over the range of 35 kPa (5 psi) to 210 kPa (30 psi) when verified in accordance with ASTM D5720.

10.7 A suitable temperature sensor shall be mounted at the mid-height of the specimen in the pressure cell between the specimen and the cell wall. This temperature sensor shall have a range of 20 to 60 °C (68 to 140 °F), and be readable and accurate to the nearest 0.25 °C. (0.5 °F). For confined tests this sensor shall be used to control the temperature in the chamber, and provide a continuous reading of temperature that will be sampled by the data acquisition system during the test.

10.8 The confining pressure system shall be designed for rapid installation of the test specimen in the confining cell and subsequent equilibration of the chamber temperature to the target test temperature. Specimen instrumentation, installation, application of confining pressure, and temperature equilibration shall take no longer than 3 minutes over the complete range of temperatures.

11.0 Environmental Chamber

11.1 The environmental chamber shall be capable of controlling temperatures inside the chamber over the range from 20 to 60 °C (68 to 140 °F) within +/- 0.5 °C (1 °F), when room temperature is between 15 and 27 °C (60 and 80 °F).

11.2 The environmental chamber need only be large enough to accommodate the test specimen. It is envisioned that specimens will be preconditioned in a separate

chamber that is large enough to hold the number of specimens needed for a particular project along with one or more dummy specimens with internally mounted temperature sensors.

11.3 The environmental chamber shall be designed to allow the operator to view the specimen, the specimen mounted deformation measuring system, and the specimen end platens during testing.

11.4 The environmental chamber shall be designed for rapid installation of the test specimen and subsequent equilibration of the environmental chamber temperature to the target test temperature. Specimen instrumentation, installation, application of confining pressure, and temperature equilibration shall take no longer than 3 minutes over the complete range of temperatures.

11.5 A suitable temperature sensor shall be mounted in the environmental chamber within 25 mm (1 in) of the specimen at the mid-height of the specimen. This temperature sensor shall have a range of 20 to 60 °C (68 to 140 °F), and be readable and accurate to the nearest 0.25 °C (0.5 °F). This sensor shall be used to control the temperature in the chamber, and provide a continuous reading of temperature that will be sampled by the data acquisition system during the test.

12.0 Computer Control and Data Acquisition

12.1 The Simple Performance Test System shall be controlled from a Personal Computer operating software specifically designed to conduct the Flow Time, Flow Number, and Dynamic Modulus Tests described in Appendix A, B, and C, and to analyze data in accordance with Section 13.

12.2 The Simple Performance Test System Software shall provide the option for user selection of SI or US Customary units.

12.3 Flow Time Test Control and Data Acquisition

12.3.1 The control system shall control the deviator stress, and the confining pressure within the tolerances specified in Sections 5 and 10.2

12.3.2 The control system shall ramp the deviator stress from the contact stress condition to the creep stress condition in 0.5 sec.

12.3.3 Zero time for data acquisition and zero strain shall be defined as the start of the ramp from contact stress to creep stress. Using this time as a reference, the system shall provide a record of deviator stress, confining pressure, axial strain, and temperature at zero time and a user specified sampling interval, t, between (0.5 and 10 sec). The axial strains shall be based on the user provided specimen length and the difference in deflection at any time and the deflection at zero time.

12.3.4 The control system shall terminate the test and return the deviator stress and confining pressure to zero when the axial strain exceeds 5 percent or the maximum user specified test duration time is exceeded.

Note: in Project 9-19, flow time criteria will be developed for mixtures as a function of climate, and traffic level. These criteria will be used by the user to determine the maximum duration of the test.

12.3.5 Figure 5 presents a schematic of the specified loading and data acquisition.

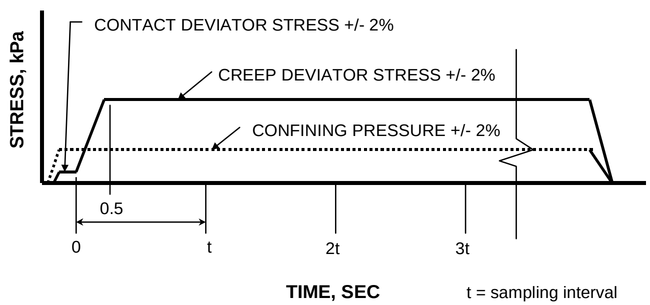


Figure 5. Schematic of Loading and Data Acquisition.

12.3.6 The Flow Time Test Software shall include a screen to input test and file information including:

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress
9. Target Contact Deviator Stress
10. Target Creep Deviator Stress

11. Specimen Conditioning Time
12. Sampling Interval
13. Test Duration
14. Remarks

12.3.7 The Flow Time Test Software shall prompt the operator through the Flow Time Test.

1. Test and file information screen.
2. Insert specimen.
3. Apply confining pressure and contact stress.
4. Wait for temperature equilibrium, check for confining system leaks.
5. Ramp to creep stress and collect and store data.
6. Post test remarks.
7. Remove tested specimen.

12.3.8 During the creep loading portion of the test, the Flow Time Test Software shall provide a real-time display of the time history of the deviator stress, the axial strain, and the rate of change of axial strain. The rate of change of axial strain shall be computed in accordance with the algorithm presented in Section 13.

12.3.9 If at any time during the creep loading portion of the test, the deviator stress, confining pressure, or temperature exceed the tolerances listed below, the Flow Time Test Software shall display a warning and indicate the parameter that exceeded the control tolerance. The test shall continue and the software shall include this warning in the data file and the hard copy output.

Response	Tolerance
Deviator stress	+/- 2 percent of target
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 °C of target

12.3.10 Data files shall include the following information:

1. Test information supplied by the user in Section 12.3.6.
2. Date and time stamp.
3. Computed flow time.
4. Axial strain at the flow time.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Time and corresponding measured deviator stress, measured confining pressure, measured temperature, measured axial strain, and computed rate of change of strain.
8. Warnings
9. Post test remarks.

12.3.11 The Flow Time Test Software shall provide the capability of retrieving data files and exporting them to an ASCII comma delimited file for further analysis.

12.3.12 The Flow Time Test Software shall provide a one page hard copy output with the following:

1. Test information supplied by the user in Section 12.3.6.
2. Date and time stamp.
3. Computed flow time.
4. Axial strain at the flow time.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Warnings
8. Post test remarks
9. Plot of axial strain versus time.
10. Plot of rate of change of axial strain versus time with the flow time indicated.

12.4 Flow Number Test Control and Data Acquisition

12.4.1 The control system shall control the deviator stress, and the confining pressure within the tolerances specified in Sections 5 and 10.2

12.4.2 The control system shall be capable of applying an initial contact stress, then testing the specimen with the user specified cyclic deviator stress.

12.4.3 The data acquisition and control system shall provide the user the ability to select the sampling interval as a whole number of load cycles.

12.4.4 Zero deflection shall be defined as that at the start of the first load pulse. At the user specified sampling interval, the control system shall provide a record of peak deviator stress, standard error of the applied load (See Section 5.3), contact stress, confining pressure, permanent axial strain at the end of the load cycle, and temperature. The axial strains shall be based on the user provided specimen length and the difference in deflection the end of any load cycle and the zero deflection.

12.4.5 The control system shall terminate the test and return the deviator stress and confining pressure to zero when the axial strain exceeds 5 percent or the user specified test duration is reached.

Note: in Project 9-19, flow number criteria will be developed for mixtures as a function of climate, and traffic level. These criteria will be used by the user to determine the maximum duration of the test.

12.4.6 Figure 6 presents a schematic of the specified loading and data acquisition.

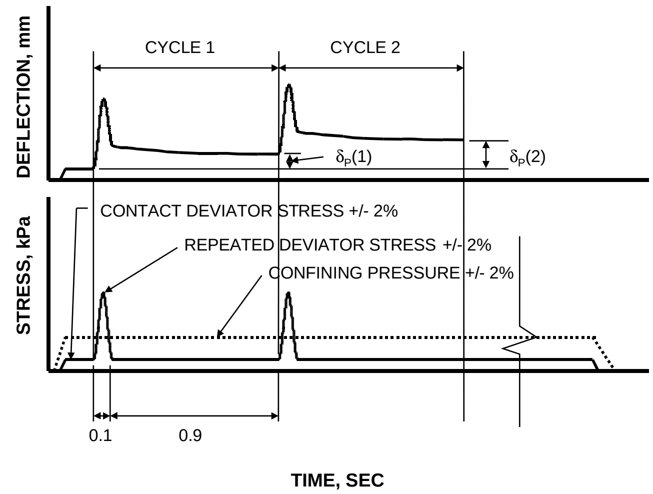


Figure 6. Schematic of Loading and Data Acquisition for Flow Time Test.

12.4.7 The Flow Number Test Software shall include a screen to input test and file information including:

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress
9. Target Contact Deviator Stress
10. Target Repeated Deviator Stress
11. Specimen Conditioning Time
12. Sampling Interval
13. Maximum Number of Load Cycles
14. Remarks

12.4.8 The Flow Number Test Software shall prompt the operator through the Flow Number Test.

1. Test and file information screen.
2. Insert specimen.
3. Apply confining pressure and contact stress.
4. Wait for temperature equilibrium, check for confining system leaks.
5. Test specimen, collect and store data.
6. Post test remarks.
7. Remove tested specimen.

12.4.9 During the test, the Flow Number Test Software shall provide the user the ability to select the following displays and the ability to change between displays:

1. Digital oscilloscope showing stress and strain as a function of time.
2. A display of the history of the peak deviator stress, permanent axial strain, and the rate of change of permanent axial strain as a function of the number of load cycles. The rate of change of permanent axial strain shall be computed in accordance with the algorithm presented in Section 13.

12.4.10 If at any time during the test, the peak deviator stress, standard error of the applied load, confining pressure, or temperature exceed the tolerances listed below, the Flow Number Test Software shall display a warning and indicate the parameter that exceeded the control tolerance. The test shall continue and the software shall include this warning in the data file and the hard copy output.

Response	Tolerance
Peak deviator stress	+/- 2 percent of target
Load standard error	10 percent
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 °C of target

12.4.11 Data files shall include the following information:

1. Test information supplied by the user in Section 12.4.7.
2. Date and time stamp.
3. Computed flow number.
4. Axial strain at the flow number.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Average peak deviator stress.
8. Average contact stress.

9. Maximum standard error of the applied load.
10. Cycle and corresponding measured peak deviator stress, computed load standard error, measured contact stress, measured confining pressure, measured temperature, measured permanent axial strain, and computed rate of change of permanent strain.
11. Warnings
12. Post test remarks.

12.4.12 The Flow Number Test Software shall provide the capability of retrieving data files and exporting them to an ASCII comma delimited file for further analysis.

12.4.13 The Flow Number Test Software shall provide a one page hard copy output with the following:

1. Test information supplied by the user in Section 12.4.7.
2. Date and time stamp.
3. Computed flow number.
4. Axial strain at the flow number.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Average peak deviator stress.
8. Average contact stress.
9. Maximum load standard error.
10. Warnings.
11. Post test remarks.
12. Plot of permanent axial strain versus load cycles.
13. Plot of rate of change of axial strain versus load cycles with the flow number indicated.

12.5 Dynamic Modulus Test Control and Data Acquisition

12.5.1 The control system shall control the axial stress and the confining pressure. The confining pressure shall be controlled within the tolerances specified in Section 10.2.

12.5.2 The control system shall be capable of applying confining stress, an initial contact deviator stress, then conditioning and testing the specimen with a haversine loading at a minimum of 5 user selected frequencies.

12.5.3 Conditioning and testing shall proceed from the highest to lowest loading frequency. Ten conditioning and ten testing cycles shall be applied for each frequency.

12.5.4 The control system shall have the capability to adjust the dynamic stress and contact stress during the test to keep the average dynamic strain within the range of 75 to 125 μstrain. Adjustment of the dynamic stress shall be performed during the ten conditioning cycles at each loading frequency.

12.5.5 A contact stress equal to 5 percent of the dynamic stress shall be maintained during conditioning and testing.

12.5.6 During the 10 testing cycles, record and store the load, specimen deformations from the individual transducers, confining pressure, and temperature as a function of time. The data acquisition rate shall be set to obtain 50 data points per loading cycle.

12.5.7 The Dynamic Modulus Test Software shall include a screen to input test and file information including:

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress
9. Loading Rates
10. Specimen Conditioning Time
11. Remarks

12.5.8 The Dynamic Modulus Test Software shall prompt the operator through the Dynamic Modulus Test.

1. Test and file information screen.
2. Insert specimen and attach strain instrumentation.
3. Apply confining pressure and contact stress.
4. Wait for temperature equilibrium, check for confining system leaks.
5. Condition and test specimen.
6. Review dynamic modulus, phase angle, temperature, confining pressure, and data quality statistics (See Section 13) for each frequency tested.
7. Post test remarks.
8. Remove tested specimen.

12.5.9 During the conditioning and testing, the Dynamic Modulus Test Software shall provide a real-time display of the axial stress, and the axial strain measured individually by the transducers.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

12.5.10 If at any time during the conditioning and loading portion of the test, confining pressure, temperature, or average accumulated permanent strain exceed the tolerances listed below, the Dynamic Modulus Test Software shall display a warning and indicate the parameter that exceeded the control tolerance. The test shall continue and the software shall include this warning in the data file and the hard copy output.

Response	Tolerance
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 °C of target
Permanent Axial Strain	0.0050 mm/mm

12.5.11 At the end of the user selected sweep of frequencies, the Dynamic Modulus Test software shall display a summary listing the following data for each frequency tested:

1. Dynamic modulus.
2. Phase angle.
3. Average temperature during the test.
4. Average confining pressure.
5. Data quality measures (See Section 13)
   - The drift for the applied load, ΔY_P, %
   - The standard error for the applied load, $se(P)$, %
   - The average drift for the deformations, $\Delta \overline{Y}_D$, %
   - The average standard error for the deformations, $se(Y)$, %
   - The uniformity coefficient for the deformations, U_A %
   - The uniformity coefficient for the deformation phase angles, U_θ, degrees.

The user should be provided options to save write this data to data file and/or produce a hard copy output.

12.5.12 For each loading frequency, a separate data file shall be produced. This file shall include he test information supplied by the user in Section 12.5.7, a date and time stamp, and the following information:

1. Dynamic modulus.
2. Phase angle.
3. Average temperature during the test.
4. Average confining pressure.
5. Data quality measures (See Section 13)
   - The drift for the applied load, ΔY_P, %
   - The standard error for the applied load, $se(P)$, %
   - The average drift for the deformations, $\Delta \overline{Y}_D$, %
   - The average standard error for the deformations, $se(Y)$, %

- The uniformity coefficient for the deformations, U_A %
- The uniformity coefficient for the deformation phase angles, U_θ, degrees.

6. Time and corresponding measured axial stress, individual measured axial strains, measured confining pressure, and measured temperature,
7. Warnings
8. Post test remarks.

12.5.13 The Dynamic Modulus Test Software shall provide the capability of retrieving data files and exporting them to an ASCII comma delimited file for further analysis.

12.5.14 For each loading frequency, the Dynamic Modulus Test Software shall provide a one page hard copy output with the following. Figure 7 presents an example one page output.

1. Test information supplied by the user in Section 12.5.7.
2. Date and time stamp.
3. Dynamic modulus.
4. Phase angle.
5. Average temperature during the test.
6. Average confining pressure during the test.
7. Data quality measures (See Section 13)
   - The drift for the applied load, ΔY_P, %
   - The standard error for the applied load, $se(P)$, %
   - The average drift for the deformations, $\Delta \overline{Y}_D$, %
   - The average standard error for the deformations, $se(Y)$, %
   - The uniformity coefficient for the deformations, U_A %
   - The uniformity coefficient for the deformation phase angles, U_θ, degrees.
8. Warnings
9. Post test remarks
10. Plot showing centered stress and centered strains as a function of time
11. Plot showing normalized stress and strains as a function of phase angle. This plot shall include both the measured and fit data.
12. Plot showing normalized stress as a function of normalized strain. This plot shall include both the measured and fit data.

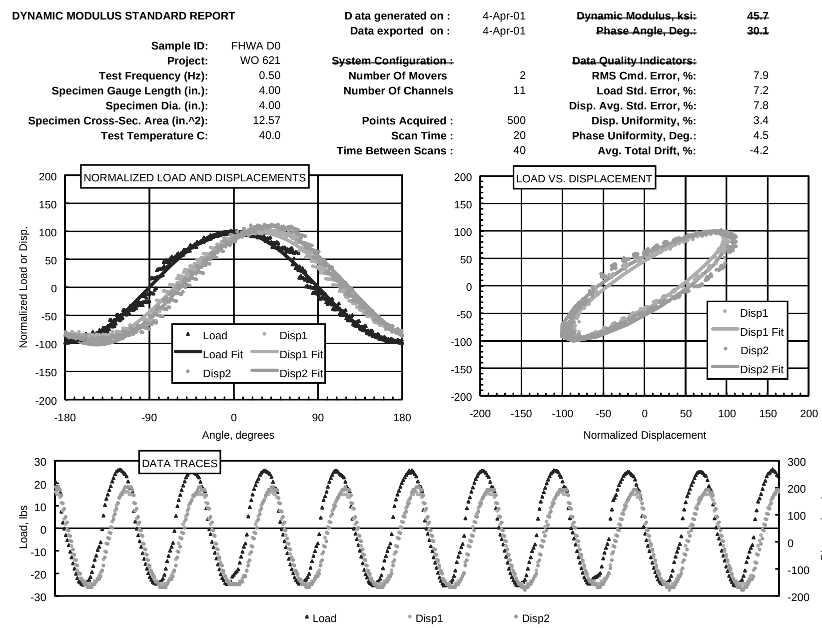


Figure 7. Example Dynamic Modulus Output.

13.0 Computations

13.1 Flow Time Test

13.1.1 The Flow Time is defined as the time corresponding to the minimum rate of change of axial strain during a creep test. To ensure that different laboratories produce comparable results for this test method, the procedure described in this section shall be followed in determining the flow time. The procedure consists of three steps: (1) numerical calculation of the creep rate ; (2) smoothing of the creep rate data; and (3) identification of the point at which the minimum creep rate occurs as the flow time.

13.1.2 The first step in determining the flow time is to estimate the rate of change (derivative) of the axial strain ε with respect to time *t* using a finite-difference formula. The rate of change of the strain with respect to time is estimated using the following equation:

$$\frac{d\varepsilon_i}{dt} \cong \frac{\varepsilon_{i+\Delta t} - \varepsilon_{i-\Delta t}}{2\Delta t} \quad (4)$$

Where:

$d\varepsilon_i/dt$ = rate of change of strain with respect to time or creep rate at i sec, 1/s
$\varepsilon_{i-\Delta t}$ = strain at i-Δt sec
$\varepsilon_{i+\Delta t}$ = strain at i+Δt sec
Δt = sampling interval

13.1.3 The derivatives calculated in Section 13.1.2 shall then be smoothed by calculating the running average at each point, by adding to the derivative at that point the two values before and two values after that point, and dividing the sum by five:

$$\frac{d\varepsilon_i'}{dt} = \frac{1}{5}\left(\frac{d\varepsilon_{i-2\Delta t}}{dt} + \frac{d\varepsilon i_{i-\Delta t}}{dt} + \frac{d\varepsilon_i}{dt} + \frac{d\varepsilon_{+\Delta t}}{dt} + \frac{d\varepsilon_{i+2\Delta t}}{dt}\right) \quad (5)$$

Where:

$d\varepsilon'_i/dt$ = smoothed creep rate at i sec, /s
$d\varepsilon_{i-2\Delta t}/dt$ = creep rate at i-2Δt sec, 1/s
$d\varepsilon_{i-\Delta t}/dt$ = creep rate at i-Δt sec, 1/s
$d\varepsilon_i/dt$ = creep rate at i sec, 1/s
$d\varepsilon_{i+\Delta t}/dt$ = creep rate at i+Δt sec, 1/s
$d\varepsilon_{i+2\Delta t}/dt$ = creep rate at i+2Δt sec, 1/s

13.1.4 The flow time is reported as the time at which the minimum value of the smoothed creep rate occurs, and shall be reported to nearest Δt seconds. If there is no minimum, then the flow time is reported as being greater than or equal to the length of the test. If more than one point share the minimum creep rate, the first such minimum shall be reported as the flow time.

13.2 Flow Number Test

13.2.1 The Flow Number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test. To ensure that different laboratories produce comparable results for this test method, the procedure described in this section shall be followed in determining the Flow Number. The procedure consists of three steps: (1) numerical calculation of the creep rate; (2) smoothing of the creep rate data; and (3) identification of the point at which the minimum creep rate occurs as the Flow Number.

13.2.2 The first step in determining the Flow Number is to estimate the rate of change (derivative) of the permanent axial strain, ε_p, with respect to the number of load cycles, N, using a finite-difference formula. The rate of change of the permanent strain with respect to the number of cycles is estimated using the following equation:

$$\frac{d(\varepsilon_p)_i}{dN} \cong \frac{(\varepsilon_p)_{i+\Delta N} - (\varepsilon_p)_{i-\Delta N}}{2\Delta N} \quad (6)$$

Where:

$d(\varepsilon_p)_i/dN$ = rate of change of permanent axial strain with respect to cycles or creep rate at cycle i, 1/cycle
$(\varepsilon_p)_{i-\Delta N}$ = permanent strain at i-ΔN cycles
$(\varepsilon_p)_{i+\Delta N}$ = permanent strain at i+ΔN cycles
ΔN = sampling interval

13.2.3 The derivatives calculated in Section 12.2.3 shall then be smoothed by calculating the running average at each point, by adding to the derivative at that point the two values before and two values after that point, and dividing the sum by five:

$$\frac{d(\varepsilon_p)_i'}{dN} = \frac{1}{5}\left(\frac{d(\varepsilon_p)_{i-2\Delta N}}{dN} + \frac{d(\varepsilon_p)_{i-\Delta N}}{dN} + \frac{d(\varepsilon_p)_i}{dN} + \frac{d(\varepsilon_p)_{i+\Delta N}}{dN} + \frac{d(\varepsilon_p)_{i+2\Delta N}}{dN}\right) \quad (7)$$

Where:

$d(\varepsilon_p)'_i/dN$ = smoothed creep rate at i sec, 1/cycle
$d(\varepsilon_p)_{i-2\Delta N}/dN$ = creep rate at i-2ΔN cycles, 1/cycle
$d(\varepsilon_p)_{i-\Delta N}/dN$ = creep rate at i-ΔN cycles, 1/cycle
$d(\varepsilon_p)_i/dN$ = creep rate at i cycles, 1/cycle
$d(\varepsilon_p)_{i+\Delta N}/dN$ = creep rate at i+ΔN cycles, 1/cycle
$d(\varepsilon_p)_{i+2\Delta N}/dN$ = creep rate at *i*+2ΔN cycles, 1/cycle

13.2.4 The Flow Number is reported as the cycle at which the minimum value of the smoothed creep rate occurs. If there is no minimum, then the Flow Number is reported as being greater than or equal to the length of the test. If more than one point share the minimum creep rate, the first such minimum shall be reported as the Flow Number.

13.3 Dynamic Modulus Test

13.3.1 The data produced from the dynamic modulus test at frequency ω_0 will be in the form of several arrays, one for time [t_i], one for each of the j = 1, 2, 3,…m transducers used [y_j]. In the typical arrangement, there will be m = 3 transducers: the first transducer will be a load cell, and transducers 2 and 3 will be specimen deformation transducers. However, this approach is general and can be adapted to any number of specimen deformation transducers. The number of i = 1, 2, 3…n points in each array will be equal to 500 based on the number of cycles and acquisition rate specified in Section 12.5.6. It has been assumed in this procedure that the load will be given in Newtons (N), and the deformations in millimeters (mm). The analysis has been devised to provide complex modulus in units of Pascals (1 Pa = 1 N/m^2) and phase angle in units of degrees. The general approach used here is based upon the least squares fit of a sinusoid, as described by Chapra and Canale in *Numerical Methods for Engineers* (McGraw-Hill, 1985, pp. 404-407). However, the approach used here is more rigorous, and also includes provisions for estimating drift of the sinusoid over time by including another variable in the regression function. Regression is used, rather than the Fast Fourier transform (FFT), because it is a simpler and more direct approach, which should be easier for most engineers and technicians in the paving industry to understand and apply effectively. The regression approach also lends itself to calculating standard errors and other indicators of data quality. This approach should however produce results essentially identical to those produced using FFT analysis.

13.3.2 The calculation proceeds as follows. First, the data for each transducer are centered by subtracting from the measured data the average for that transducer:

$$Y_{ji}' = Y_{ji} - \overline{Y_j} \qquad (8)$$

Where:
Y_{ji}' = Centered data for transducer j at point i in data array
Y_{ji} = Raw data for transducer j at point i in data array
$\overline{Y_j}$ = Average for transducer j

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

13.3.3 In the second step in the procedure, the [$X'X$] matrix is constructed as follows:

$$[X'X] = \begin{bmatrix} N & \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} \cos(\omega_0 t_i) & \sum_{i=1}^{n} \sin(\omega_0 t_i) \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 & \sum_{i=1}^{n} t_i \cos(\omega_0 t_i) & \sum_{i=1}^{n} t_i \sin(\omega_0 t_i) \\ \sum_{i=1}^{n} \cos(\omega_0 t_i) & \sum_{i=1}^{n} t_i \cos(\omega_0 t_i) & \sum_{i=1}^{n} \cos^2(\omega_0 t_i) & \sum_{i=1}^{n} \cos(\omega_0 t_i)\sin(\omega_0 t_i) \\ \sum_{i=1}^{n} \sin(\omega_0 t_i) & \sum_{i=1}^{n} t_i \sin(\omega_0 t_i) & \sum_{i=1}^{n} \cos(\;_0 t_i)\sin(\omega_0 t_i) & \sum_{i=1}^{n} \sin^2(\omega_0 t_i) \end{bmatrix} \qquad (9)$$

Where N is the total number of data points, ω_0 is the frequency of the data, t is the time from the start of the data array, and the summation is carried out over all points in the data array.

13.3.4 The inverse of this matrix, [$X'X$]$^{-1}$, is then calculated. Then, for each transducer, the [$X'Y_j$] array is constructed:

$$[X'Y_j] = \begin{bmatrix} \sum_{i=1}^{n} Y_{ji}' \\ \sum_{i=1}^{n} Y_{ji}' t \\ \sum_{i=1}^{n} Y_{ji}' \cos(\omega_0 t) \\ \sum_{i=1}^{n} Y_{ji}' \sin(\omega_0 t) \end{bmatrix} \qquad (10)$$

Where Y_j represents the output from one of the three transducers (j=1 for the load cell, j=2 and 3 for the two deformation transducers). Again, the summation is carried out for all points in the data arrays.

13.3.5 The array representing the regression coefficients for each transducer is then calculated by multiplying the [$X'X$]$^{-1}$ matrix by the [$X'Y_j$] matrix:

$$\begin{bmatrix} A_{j0} \\ A_{j1} \\ A_{j2} \\ B_{j2} \end{bmatrix} = [X'X]^{-1}[X'Y_j] \qquad (11)$$

Where the regression coefficients can be used to calculate predicted values for each of the *j* transducers using the regression function:

$$\hat{Y}_{ji} = A_{j0} + A_{j1}t_i + A_{j2}\cos(\omega_0 t_i) + B_{j2}\sin(\omega_0 t_i) + \varepsilon_{ji} \tag{12}$$

Where $\hat{Y}_{ji}$ is the predicted value for the i^{th} point of data for the j^{th} transducer, and ε_{ji} represents the error term in the regression function.

13.3.6 From the regression coefficients, several other functions are then calculated as follows:

$$\theta_j = \arctan\left(-\frac{B_{j2}}{A_{j2}}\right) \tag{13}$$

$$|Y_j *| = \sqrt{A_{j2}^2 + B_{j2}^2} \tag{14}$$

$$\Delta Y_j = \frac{A_{j1}t_N}{|Y_j *|} \times 100\% \tag{15}$$

$$se(Y_j) = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_{ji}' - Y_{ji}'\right)^2}{n-4}}\left(\frac{100\%}{|Y_j *|}\right) \tag{16}$$

Where:

θ_j	=	Phase angle for transducer *j*, degrees
$\lvert Y_j*\rvert$	=	Amplitude for transducer *j*, N for load or mm for displacement
ΔY_j	=	Drift for transducer *j*, as percent of amplitude.
t_N	=	Total time covered by data
$\hat{Y}_{ji}'$	=	Predicted centered response for transducer *j* at point *i*, N or mm
$se(Y_j)$	=	Standard error for transducer *j*, %
n	=	number of data points = 500

The calculations represented by Equations 13 through 16 are carried out for each transducer—typically the load cell, and two deformation transducers. This produces values for the phase angle, and standard errors for each transducer output. The phase angles given by Equation 13 represent absolute phase angles, that is, θ_j is an arbitrary value indicating the angle at which data collection started.

13.3.7 The phase angle of the deformation (response) relative to the load (excitation) is the important mechanical property. To calculate this phase angle, the average phase angle for the deformations must first be calculated:

$$\overline{\theta}_D = \frac{\sum_{j=2}^{m}\theta_j}{m-1} \tag{17}$$

Where $\overline{\theta}_D$ is the average absolute phase angle for the deformation transducers, and θ_j is the phase angle for each of the *j* = 2, 3, …, *m* deformation transducers. For the typical case, there are one load cell and two deformation transducers, so m = 3, and Equation 17 simply involves summing the phase angle for the two deformation transducers and dividing by two.

13.3.8 The relative phase angle at frequency ω between the deformation and the load, $\theta(\omega)$, is then calculated as follows:

$$\theta(\omega) = \overline{\theta_D} - \theta_P \tag{18}$$

Where θ_P is the absolute phase angle calculated for the load.

13.3.9 A similar set of calculations is needed to calculate the overall modulus for the material. First, the average amplitude for the deformations must be calculated:

$$|\overline{Y}_D *| = \frac{\sum_{j=2}^{m}|Y_j *|}{m-1} \tag{19}$$

Where $|\overline{Y}_D *|$ represents the average amplitude of the deformations (mm).

13.3.10 Then, the dynamic modulus $|E^*|$ at frequency ω is calculated using the following equation:

$$|E^*(\omega)| = \frac{|Y_P *| L_g}{|\overline{Y}_D *| A} \tag{20}$$

Where $|E^*(\omega)|$ is in Pa, L_g is the average gage length for the deformation transducers (mm), and *A* is the loaded cross-sectional area for the specimen, m^2.

13.3.11 The final part of the analysis involves calculation of several factors indicative of data quality, including the average drift for the deformations, the average standard error for the deformations, and uniformity coefficients for deformation amplitude and phase:

$$\Delta \overline{Y}_D = \frac{\sum_{j=2}^{m} A_{j1} t_N}{\sum_{j=2}^{m} \left| Y_j * \right|} \times 100\% \tag{21}$$

$$se(Y_D) = \frac{\sum_{j=2}^{m} se(Y_j)}{m-1} \tag{22}$$

$$U_A = \sqrt{\frac{\sum_{j=2}^{m} \left(\left| Y_j * \right| - \left| \overline{Y}_D * \right| \right)^2}{m-1}} \frac{100\%}{\left| \overline{Y}_D * \right|} \tag{23}$$

$$U_\theta = \sqrt{\frac{\sum_{j=2}^{m} \left(\theta_j - \overline{\theta}_D \right)^2}{m-1}} \tag{24}$$

Where:

$\Delta \overline{Y}_D$ = Average deformation drift, as percent of average deformation amplitude
$se(Y_D)$ = Average standard error for all deformation transducers, %
U_A = Uniformity coefficient for deformation amplitude, %
U_θ = Uniformity coefficient for deformation phase, degrees

14.0 Calibration and Verification of Dynamic Performance

14.1 Prior to shipment, the complete Simple Performance Test System shall be assembled at the manufacturer's facility and calibrated. This calibration shall include calibration of the computer control and data acquisition electronics/software, static calibration of the load, deflection, specimen deformation, confining pressure and temperature measuring systems; and verification of the dynamic performance of the load and specimen deformation measuring systems.

14.2 The results of these calibrations shall be documented, certified by the manufacturer, and provided with the system documentation.

14.3 Static calibration of the load, deflection, specimen deformation, and confining pressure systems shall be performed in accordance with the following standards:

System	ASTM Standard
Load	ASTM E4
Deflection	ASTM D 6027
Specimen Deformation	ASTM D 6027
Confining Pressure	ASTM D 5720

14.4 The calibration of the temperature measuring system shall be verified over the range that the testing system will be used. A NIST traceable reference thermal detector with resolution equal to or better than the temperature sensor shall be used.

14.5 Verification of the dynamic performance of the force and specimen deformation measuring systems shall be performed by loading a proving ring or similar verification device with the specimen deformation measuring system attached. The manufacturer shall be responsible for fabricating the verification device and shall supply it with the Simple Performance Test System.

14.6 The verification device shall have a static deflection of 0.007 mm ± 0.0005 mm (0.00028 in ± 0.00002 in) at a load of 1.2 kN (0.27 kips).

14.7 The verification shall include loads of 0.6, 1.2, 3.0, and 4.8 kN (0.13, 0.27, 0.67, and 1.08 kips) at frequencies of 0.1, 1, and 25 Hz. The verification shall include measurement of load, and displacement of the verification device using the specimen deformation measuring system. All of the resulting load versus deformation data shall be within 2 percent of that determined by static loading of the verification device. The phase difference between load and displacement measurements shall be less than 1 degree.

14.8 The Simple Performance System shall include a calibration mode for subsequent annual calibration in accordance with the standards listed in Section 14.3 and the method described in 14.4. It shall also include a dynamic verification mode to perform the verification test described in Section 14.5. Access points for calibration work shall be clearly shown in the system reference manual.

15.0 Verification of Normal Operation

15.1 The manufacturer shall develop and document procedures for verification of normal operation for each of the systems listed in Section 14.3, and the dynamic performance verification discussed in Section 14.5. It is anticipated that these verification procedures will be performed by the operating technician on a frequent basis. Equipment used in the verification process shall be provided as part of the Simple Performance Test System.

16.0 Documentation

16.1 The Simple Performance Test System shall include an on-line help and documentation.

16.2 A reference manual completely documenting the Simple Performance Test System shall be provided. This manual shall include the following Chapters:

1. System Introduction.
2. Installation.
3. Loading System.
4. Confining Pressure System.
5. Environmental Chamber.
6. Control and Data Acquisition System.
7. Flow Time Test.
8. Flow Number Test.
9. Dynamic Modulus Test.
10. Calibration.
11. Verification of Dynamic Performance.
12. Verification of Normal Operation.
13. Preventative Maintenance.
14. Spare Parts List
15. Drawings.

17.0 Warranty

17.1 The Simple Performance Test System shall carry a one year on-site warranty.

Annex A
Simple Performance Test System Flow Time Test

Adapted From
Test Method for Static Creep/Flow Time of Asphalt Concrete Mixtures in Compression

NCHRP Report 465, 2002

1 Scope

1.1 This test method covers testing and measurement of the resistance to tertiary flow of cylindrical asphalt concrete specimens in a triaxial state of compressive loading using the Simple Performance Test System.

1.2 In this test, a cylindrical sample of bituminous paving mixture is subjected to a static axial load. Axial strains are recorded throughout the test.

1.3 The test is conducted at a single temperature using specific deviatoric and confining stresses.

1.4 This standard is applicable to laboratory prepared specimens 100 mm in diameter and 150 mm in height for mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in) tested in the Simple Performance Test System.

1.5 *This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2 Referenced Documents

2.1 AASHTO Standards

PPXX Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System (To be developed).

PPYY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor (To be developed).

2.2 Other

NCHRP 9-29 Equipment Specification for the Simple Performance Test System

3 Definitions

3.1 *Flow Time* – Time corresponding to the minimum rate of change of axial strain during a creep test.

4 Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a static axial load. The test can be performed with or without confinement. The applied stress and the resulting axial deformation of the specimen is measured with the Simple Performance

Test System and used to calculate the flow time. The flow time is the time corresponding to the minimum rate of change of axial strain during a creep test.

5 Significance and Use

5.1 The flow time can be used with the criteria in AASHTO PPXX to judge the acceptability of a mixture to resist permanent deformation.

5.2 The flow time can also be used to compare or rank the permanent deformation resistance of various bituminous paving mixtures.

6 Apparatus

6.1 An approved Simple Performance Test System meeting the requirements of NCHRP 9-29 Equipment Specification for the Simple Performance Test System

6.2 An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 30 to 60 °C (85 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate three test specimens and a dummy specimen with temperature sensor mounted at the center for temperature verification.

6.3 Teflon sheeting, 0.25 mm thick to reduce friction between the specimen and the loading platens.

7 Test Specimens

7.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP YY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor.

7.2 Flow time shall be the average result obtained from three test specimens.

8 Procedure

8.1 Unconfined Tests

8.1.1 Assemble each specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom Teflon friction reducer, specimen, top Teflon friction, and top loading platen.

8.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

8.1.5 Close the testing chamber and allow the chamber temperature to return to testing temperature.

8.1.6 Steps 8.1.4 and 8.1.5 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.1.7 Enter the required identification and control information into the Flow Time Software.

8.1.8 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.

8.1.9 Upon completion of the test, open the test chamber, and remove the tested specimen.

8.1.10 Repeat steps 8.1.4 through 8.1.9 for the remaining test specimens.

8.2 Confined Tests

8.1.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

8.1.2 Encase the dummy specimen in a membrane.

8.1.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.1.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.1.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

8.1.6 Close the testing chamber and allow the chamber temperature to return to testing temperature.

8.1.7 Steps 8.2.5 and 8.2.6 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.1.8 Enter the required identification and control information into the Flow Time Software.

8.1.9 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.

8.1.10 Upon completion of the test, open the test chamber, and remove the tested specimen.

8.1.11 Repeat steps 8.1.5 through 8.1.10 for the remaining test specimens.

9 Calculations

9.1 The calculation of the flow time for individual specimens is performed automatically by the Simple Performance Test System software.

9.2 Compute the average and standard deviation of the flow times for the three specimens tested.

10 Report

10.1 Test temperature.

10.2 Deviatoric and confining stress levels.

10.3 Average and standard deviation of flow time for three specimens.

10.4 Attach Simple Performance Test System standard reports for individual specimens.

Annex B
Simple Performance Test System Flow Number Test

Adapted From
Test Method for Repeated Load Testing of Asphalt Concrete Mixtures in Uniaxial Compression

NCHRP Report 465, 2002

1. Scope

1.1 This test method covers testing and measurement of the resistance to tertiary flow of cylindrical asphalt concrete specimens in a triaxial state of compressive loading using the Simple Performance Test System.

1.2 This test uses a loading cycle of 1.0 second in duration, consisting of applying 0.1-second haversine load followed by 0.9-second rest period. Permanent axial deformations are recorded throughout the test.

1.3 The test is conducted at a single using specific deviatoric and confining stresses.

1.4 This standard is applicable to laboratory prepared specimens 100 mm in diameter and 150 mm in height for mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in).

1.5 This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

PPXX Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System (To be developed).

PPYY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor (To be developed).

2.2 Other

NCHRP 9-29 Equipment Specification for the Simple Performance Test System

3. Definitions

3.1 *Permanent Deformation* – Non-recovered deformation in a repeated load test.

3.2 *Flow Number* - The number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test.

4. Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a haversine axial load. The load is applied for duration of 0.1-second with a rest period of 0.9-second. The rest period has a load equivalent to the seating load. The test can be performed either with or without confinement. Cumulative permanent axial deformations are measured with the Simple Performance Test System and used to calculate the flow number. The flow number is the number of repetitions corresponding to the minimum rate of change of permanent deformation under repeated loading conditions.

5. Significance and Use

5.1 The flow number can be used with the criteria in AASHTO PPXX to judge the acceptability of a mixture to resist permanent deformation.

5.2 The flow number can also be used to compare or rank the permanent deformation resistance of various bituminous paving mixtures.

6. Apparatus

6.1 An approved Simple Performance Test System meeting the requirements of NCHRP 9-29 Equipment Specification for the Simple Performance Test System

6.2 An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 30 to 60 °C (85 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate three test specimens and a dummy specimen with temperature sensor mounted at the center for temperature verification.

6.3 Teflon sheeting, 0.25 mm thick to reduce friction between the specimen and the loading platens.

7. Test Specimens

7.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP YY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor.

7.2 The flow number shall be the average result obtained from three test specimens.

8. Procedure

8.1 Unconfined Tests

8.1.1 Assemble each specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom Teflon friction reducer, specimen, top Teflon friction, and top loading platen.

8.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

8.1.5 Close the testing chamber and allow the chamber temperature to return to testing temperature.

8.1.6 Steps 8.1.4 and 8.1.5 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.1.7 Enter the required identification and control information into the Flow Number Software.

8.1.8 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.

8.1.9 Upon completion of the test, open the test chamber, and remove the tested specimen.

8.1.10 Repeat steps 8.1.4 through 8.1.9 for the remaining test specimens.

9.1 Confined Tests

8.2.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

8.2.2 Encase the dummy specimen in a membrane.

8.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

8.2.6 Close the testing chamber and allow the chamber temperature to return to testing temperature.

8.2.7 Steps 8.2.5 and 8.2.6 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.2.8 Enter the required identification and control information into the Flow Time Software.

8.2.9 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.

8.2.10 Upon completion of the test, open the test chamber, and remove the tested specimen.

8.2.11 Repeat steps 8.1.5 through 8.1.10 for the remaining test specimens.

9. Calculations

9.1 The calculation of the flow number for individual specimens is performed automatically by the Simple Performance Test System software.

9.2 Compute the average and standard deviation of the flow numbers for the three specimens tested.

10. Report

10.1 Test temperature.

10.2 Deviatoric and confining stress levels.

10.3 Average and standard deviation of flow number for three specimens.

10.4 Attach Simple Performance Test System standard reports for individual specimens.

Annex C
Simple Performance Test System Dynamic Modulus Test

Adapted From
Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Permanent Deformation

and

Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Fatigue Cracking

NCHRP Report 465, 2002

1. Scope

1.1 This test method covers testing of asphalt concrete mixtures to determine the dynamic modulus and phase angle.

1.2 In the test dynamic modulus and phase angle data are collected at a specified test temperature using various frequencies of loading.

1.3 This standard is applicable to laboratory prepared specimen 100 mm in diameter and 150 mm in height for mixtures with nominal maximum size aggregate less than or equal to 37.5 mm (1.5 in).

1.4 This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

PPXX Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System (To be developed).

PPYY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor (To be developed).

2.2 Other

NCHRP 9-29 Equipment Specification for the Simple Performance Test System

3. Definitions

3.1 *Dynamic Modulus* – $|E^*|$, the absolute value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

3.2 *Phase angle* – δ, the angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled-stress test.

4. Summary of Method

4.1 A sinusoidal (haversine) axial compressive stress is applied to a cylindrical specimen of asphalt concrete at a given temperature using a sweep of frequencies. The applied stress and the resulting axial strain response of the specimen at each frequency is measured and used to calculate the dynamic modulus and phase angle for each frequency. The test can be performed either with or without confinement.

5. Significance and Use

5.1 The dynamic modulus can be used with the criteria in AASHTO PPXX to judge the acceptability of a mixture to resist permanent deformation and fatigue cracking.

5.2 The dynamic modulus can also be used to compare or rank the permanent deformation and fatigue resistance of various bituminous paving mixes.

6. Apparatus

6.1 An approved Simple Performance Test System meeting the requirements of NCHRP 9-29 Equipment Specification for the Simple Performance Test System

6.2 An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 20 to 60 °C (68 to 140 °F) to an accuracy of ±0.5 °C (1 °F). The chamber shall be large enough to accommodate three test specimens and a dummy specimen with temperature sensor mounted at the center for temperature verification.

6.3 Teflon sheeting, 0.25 mm thick to reduce friction between the specimen and the loading platens.

7. Test Specimens

7.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP YY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor.

7.2 The dynamic modulus shall be the average result obtained from three test specimens.

8. Test Specimen Instrumentation (Standard Glued Gage Point System)

8.1 If the Simple Performance Test System uses the standard glued gage point system, attach the gage points to the specimen in accordance with the manufacturers instructions.

8.2 Confirm that the gage length is 70 mm ±1 mm measured center to center of the gage points.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

9. Procedure

9.1 Unconfined Tests

9.1.1 Assemble each specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom Teflon friction reducer, specimen, top Teflon friction, and top loading platen.

9.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

9.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

9.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

9.1.5 Close the testing chamber and allow the chamber temperature to return to testing temperature.

9.1.6 Steps 9.1.4 and 9.1.5 including return of the test chamber to the target temperature shall be completed in 3 minutes.

9.1.7 Enter the required identification and control information into the Dynamic Modulus Software.

9.1.8 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete and display test data and data quality indicators.

9.1.9 Review the data quality indicators as discussed in Section 10 of this test method. Retest specimens with data quality indicators above the values specified in Section 10.

9.1.10 Once acceptable data have been collected, open the test chamber, and remove the tested specimen.

9.1.11 Repeat steps 9.1.4 through 9.1.10 for the remaining test specimens.

9.2 Confined Tests

9.2.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

9.2.2 Encase the dummy specimen in a membrane.

9.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

9.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

9.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

9.2.6 Close the testing chamber and allow the chamber temperature to return to testing temperature.

9.2.7 Steps 9.2.5 and 9.2.6 including return of the test chamber to the target temperature shall be completed in 3 minutes.

9.2.8 Enter the required identification and control information into the Dynamic Modulus Software.

9.2.9 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete and display test data and data quality indicators.

9.2.10 Review the data quality indicators as discussed in Section 10 of this test method. Retest specimens with data quality indicators above the values specified in Section 10.

9.2.11 Once acceptable data have been collected, open the test chamber, and remove the tested specimen.

9.2.12 Repeat steps 9.2.5 through 9.2.11 for the remaining test specimens.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

10. Data Quality Indicators and Calculations

10.1 The calculation of dynamic modulus, phase angle, and the data quality indicators is performed automatically by the Simple Performance Test System software.

10.2 Review the data quality indicators for each test frequency and compare them to the recommended maximum values listed below.

Data Quality Indicator	**Allowable Maximum Value**
Load Standard Error	10 percent
Deformation Standard Error	10 percent
Load Drift	3 percent
Deformation Drift	400 percent
Deformation Uniformity	20 percent
Phase Uniformity	3 degrees

10.3 Review the detailed modulus test report for those frequencies where the data quality indicators exceed the maximum allowable values. Repeat testing of specimens with data quality indicators exceeding the values listed in 10.2.

10.4 Compute the average and standard deviation of the modulus and flow numbers for the three specimens tested.

11. Report

11.1 Test temperature.

11.2 Confining stress level.

11.3 Average and standard deviation of dynamic modulus and phase angle for three specimens.

11.4 Attach Simple Performance Test System standard dynamic modulus summary report.

Annex D
Specification Compliance Test Methods for the Simple Performance Test System

Table D1. Summary of Specification Compliance Tests.

Item	Section	Method
Assembled Size	4.4 and 4.6	Measure
Specimen and Display Height	4.4	Measure
Component Size	4.7	Measure
Electrical Requirements	4.5 and 4.6	Documentation and trial
Air Supply Requirements	4.8	Documentation and trial
Limit Protection	4.9	Documentation and trial
Emergency Stop	4.10	Documentation, visual inspection, trial
Loading Machine Capacity	5.1	Independent force verification (See verification procedures below)
Load Control Capability	5.2 through 5.4	Trial tests on asphalt specimens and manufacturer provided dynamic verification device.
Platen Configuration	5.5	Visual
Platen Hardness	6.1	Test ASTM E10
Platen Dimensions	6.2	Measure
Platen Smoothness	6.3	Measure
Load Cell Range	7.1	Load cell data plate
Load Accuracy	7.2	Independent force verification (See verification procedures below)
Load Resolution	7.3	Independent force verification (See verification procedures below)
Configuration of Deflection Measuring System	8.1	Visual
Transducer Range	8.2	Independent deflection verification (See verification procedures below)
Transducer Resolution	8.3	Independent deflection verification (See verification procedures below)
Transducer Accuracy	8.4	Independent deflection verification (See verification procedures below)
Load Mechanism Compliance and Bending	8.5	Measure on steel specimens with various degrees of lack of parallelism
Configuration of Specimen Deformation Measuring System	9.1	Visual
Gauge Length of Specimen Deformation Measuring System	9.1	Measure
Transducer Range	9.2	Independent deflection verification (See verification procedures below)

Table D1. Summary of Specification Compliance Tests (Continued).

Item	Section	Method
Transducer Resolution	9.3	Independent deflection verification (See verification procedures below)
Transducer Accuracy	9.4	Independent deflection verification (See verification procedures below)
Specimen Deformation System Complexity	9.5	Trial
Confining Pressure Range	10.1 and 10.5	Independent pressure verification (See verification procedures below)
Confining Pressure Control	10.2	Trial tests on asphalt specimens
Confining Pressure System Configuration	10.3 and 10.4	Visual
Confining Pressure Resolution and Accuracy	10.5	Independent pressure verification (See verification procedures below)
Temperature Sensor	10.6 and 11.4	Independent temperature verification (See verification procedures below)
Specimen Installation and Equilibration Time	9.5, 10.7 and 11.3	Trial
Environmental Chamber Range and Control	11.1	Independent temperature verification (See verification procedures below)
Control System and Software	12	Trial
Data Analysis	13	Independent computations on trial test
Initial Calibration and Dynamic Performance Verification	14	Certification and independent verification
Calibration Mode	14.6	Trial
Verification of Normal Operation Procedures and Equipment	15	Review
On-line Documentation	16.1	Trial
Reference Manual	16.2	Review

INDEPENDENT VERIFICATION PROCEDURES FOR SIMPLE PERFORMANCE TESTING MACHINE

1.0 General

1.1 The testing machine shall be verified as a system with the load, deflection, specimen deformation, confining pressure, and temperature measuring systems in place and operating as in actual use.

1.2 System verification is invalid if the devices are removed and checked independently of the testing machine.

2.0 Load Measuring System Static Verification

2.1 Perform load measuring system verification in accordance with ASTM E-4.

2.2 All calibration load cells used for the load calibration shall be certified to ASTM E-74 and shall not be used below their Class A loading limits.

2.3 When performing the load verification, apply at least two verification runs of at least 5 loads throughout the range selected.

2.4 If the initial verification loads are within +/- 1% of reading, these can be applied as the "As found" values and the second set of verification forces can be used as the final values. Record return to zero values for each set of verification loads.

2.5 If the initial verification loads are found out of tolerance, calibration adjustments shall be made according to manufacturers specifications until the values are established within the ASTM E-4 recommendations. Two applications of verification loads shall then be applied to determine the acceptance criteria for repeatability according to ASTM E-4.

2.6 At no time will correction factors be utilized to corrected values that do not meet the accuracy requirements of ASTM E-4.

3.0 Deflection and Specimen Deformation Measuring System Static Verification

3.1 Perform verification of the deflection and specimen deformation measuring systems in accordance with ASTM D 6027 Test Method B.

3.2 The micrometer used shall conform to the requirements of ASTM E-83.

3.3 When performing verification of the deflection and strain measuring system, each transducer and associated electronics must be verified individually throughout it's intended range of use.

3.4 Mount the appropriate transducer in the micrometer stand and align it to prevent errors caused by angular application of measurements.

3.5 Apply at least 5 verification measurements to the transducer throughout it's range. Re-zero and repeat the verification measurements to determine repeatability.

3.6 If the readings of the first verification do not meet the specified error tolerance, perform calibration adjustments according to manufacturers specifications and repeat the applications of measurement to satisfy the error tolerances.

4.0 Confining Pressure Measuring System Verification

4.1 Perform verification of the confining pressure measuring system in accordance with ASTM D-5720.

4.2 All calibrated pressure standards shall meet the requirements of ASTM D-5720.

4.3 Attach the pressure transducer to the pressure standardizing device.

4.4 Apply at least 5 verification pressures to the device throughout it's range recording each value. Determine if the verification readings fall within +/- 1 % of the value applied.

4.5 If the readings are within tolerance, apply a second set of readings to determine repeatability. Record the return to zero values for each set of verification pressures.

4.6 If readings are beyond tolerance, adjust the device according to manufacturers specifications and repeat the dual applications of pressure as described above to complete verification.

5.0 Temperature Measuring System Verification

5.1 Verification of the temperature measuring system will be performed using a using a NIST traceable reference thermal detector that is readable and accurate to 0.1 ^{o}C.

5.2 A rubber band or O-ring will be used to fasten the reference thermal detector to the system temperature sensor.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

5.3 Comparisons of the temperature from the reference thermal detector and the system temperature will be made at 6 temperatures over the operating range of the environmental chamber.

5.4 Once equilibrium is obtained at each temperature setting, record the temperature of the reference thermal detector and the system temperature sensor.

5.5 Also check stability of the environmental chamber by noting the maximum and minimum temperatures during cycling at the set temperature.

6.0 Dynamic Performance Verification

6.1 The verification of the dynamic performance of the equipment will be performed after static verification of the system.

6.2 The dynamic performance verification will be performed using the verification device provided with the system by the manufacturer.

6.3 First, the verification device will be loaded statically to obtain the static relationship between force and displacement. This relationship will be compared to that provided by the manufacturer in the system documentation.

6.4 The verification device will then be used to simulate dynamic modulus test conditions. Load and displacement data will be collected on the verification device using loads of 0.6, 1.2, 3.0, and 4.8 kN at frequencies of 0.1, 1, and 25 Hz. The peak load and displacements will be determined and plotted along with the static data. The data shall plot within +/- 2 percent of the static force displacement relationship.

6.5 The verification device will also be used to check the phase difference between the load and specimen deformation measuring system. The phase difference shall be less than 1 degree.

Annex E

Minimum Testing Program For Comparison of a Non-Standard Specimen Deformation Measuring System to the Standard Specimen Deformation Measuring System

1.0 Summary

1.1 This Annex describes the minimum testing, analysis, and reporting required to demonstrate that a nonstandard specimen deformation measuring system produces the same dynamic modulus and phase angle results as the standard glued gauge point system specified in Section 9.0 of the these specifications.

1.2 The basic approach is to collect dynamic modulus and phase angle data on a single mixture using the simple performance test system with the standard glued gauge point system and the proposed alternative. Standard statistical hypothesis tests are then performed on the resulting data to verify that there is no difference in the mean and variance of the dynamic modulus and phase angles measured with the two systems.

1.3 To provide data over a wide range of modulus and phase angles, the testing will be performed for the conditions listed in Table E-1.

Table E-1. Testing Conditions.

Temperature, °C (°F)	Confinement, kPa (psi)	Frequencies, Hz
25 (77)	Unconfined	10, 1, and 0.1
45 (113)	Unconfined	10, 1, and 0.1
45 (113)	140 (20 psi)	10, 1, and 0.1

1.4 Tests on twelve independent specimens will be performed with each specimen deformation measuring system. Thus a total of 24 specimens will be fabricated and tested.

2.0 Test Specimens

2.1 The testing shall be performed on simple performance test specimens meeting the dimensional tolerances of Section 3.0 of these specifications.

2.2 Use a coarse-graded 19.0 mm nominal maximum aggregate size mixture with a PG 64-22 binder. The mixture shall meet the requirements of AASHTO MP2 for a surface course with a design traffic level of 10 to 30 million ESALs. The percent passing the 2.36 mm sieve shall be less than 35 percent. Prepare test specimens at the optimum asphalt content determined in accordance with AASHTO PP28 for a traffic level of 3 to <30 million ESALs. Mixtures shall be short term oven aged for 2 hours at the compaction temperature in accordance with AASHTO R30.

2.3 Prepare 24 test specimens within the air void content range of 3.5 to 4.5 percent. Rank the test specimens based on air void content. Group the test specimens into two subsets such that the average and standard deviation of the air void contents are approximately equal.

3.0 Dynamic Modulus Testing

3.1 Perform the dynamic modulus testing with the Simple Performance Test System in accordance with Annex C of these specifications. Repeat tests as needed to ensure that the data quality indicators are within their allowable ranges.

3.2 Perform the testing in blocks of three specimens in the order listed in Table E-2. Plan the testing such that all testing in a block will be completed on the same day.

Table E-2. Block Order Testing.

Block	Temperature, °C (°F)	Confinement, kPa (psi)	Specimen Deformation System
1	25 (77)	0	Standard
			Proposed
2	25 (77)	0	Standard
			Proposed
3	25 (77)	0	Standard
			Proposed
4	25 (77)	0	Standard
			Proposed
5	45 (113)	140 (20)	Standard
			Proposed
6	45 (113)	140 (20)	Standard
			Proposed
7	45 (113)	140 (20)	Standard
			Proposed
8	45 (113)	140 (20)	Standard
			Proposed
9	45 (113)	0	Standard
			Proposed
10	45 (113)	0	Standard
			Proposed
11	45 (113)	0	Standard
			Proposed
12	45 (113)	0	Standard
			Proposed

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 1.1
August 30, 2003

4.0 Data Analysis

4.1 For each combination of device, temperature, confining pressure, and frequency, prepare summary tables listing the measured dynamic modulus and phase angles, and the data quality indicators. A total of 18 summary tables, 9 for each measuring system will be prepared. Each of these summary tables will represent a specific combination of temperature, confining pressure, and frequency of loading.

4.2 For each summary table, compute the mean and variance of the dynamic modulus and phase angle measurements using Equations E-1 and E-2.

$$\bar{y} = \frac{\sum_{i=1}^{12} y_i}{12} \quad \text{(E-1)}$$

$$s^2 = \frac{\sum_{i=1}^{12} (y_i - \bar{y})^2}{11} \quad \text{(E-2)}$$

where:

$\bar{y}$ = sample mean
s^2 = sample variance
y_i = measured values

5.0 Statistical Hypothesis Testing

5.1 For each combination of temperature, confining pressure, and frequency of loading test the equality of variances between the standard specimen deformation system and the proposed specimen deformation measuring system using the F-test described below. In the description below, the subscript *s* refers to the standard system and the subscript *p* refers to the proposed system.

Null Hypothesis:
Variance of proposed system equals that of standard system, $\sigma_p^2 = \sigma_s^2$

Alternative Hypothesis:
Variance of proposed system is greater than that of standard system, $\sigma_p^2 > \sigma_s^2$

Test Statistic:

$$F = \frac{s_p^2}{s_s^2}$$

where

s_p^2 = computed sample variance for the proposed system
s_s^2 = computed sample variance for the standard system

Region of Rejection:
For the sample sizes specified, the test statistic must be less than 2.82 to conclude that the variances are equal.

5.2 Summarize the resulting test statistics for dynamic modulus and phase angle.

5.3 If the results conclude the variance is greater for the proposed measuring for any of the combinations of temperature, confinement, and loading frequency tested, then the proposed measuring system is unacceptable.

5.4 For combinations of temperature, confinement, and loading frequency where equality of variances is confirmed by the hypothesis test in Item 5.1, test the equality of means between the standard specimen deformation system and the proposed specimen deformation measuring system using the t-test described below. In the description below, the subscript *s* refers to the standard system and the subscript *p* refers to the proposed system.

Null Hypothesis:
Mean from the proposed system equals that from the standard system, $\mu_p{}^2 = \mu_s{}^2$

Alternative Hypothesis:
Mean from the proposed system is not equal to that from the standard system, $\mu_p{}^2 \neq \mu_s{}^2$

Test Statistic:

$$t = \frac{\left(\bar{y}_p - \bar{y}_s\right)}{\frac{n}{\sqrt{6}}}$$

where:

$$s = \sqrt{\frac{s_p{}^2 + s_s{}^2}{2}}$$

$\bar{y}_p$ = computed sample mean from the proposed system
$\bar{y}_s$ = computed sample mean from the standard system

s_p^2 = computed sample variance for the proposed system
s_s^2 = computed sample variance for the standard system

Region of Rejection:
For the sample sizes specified, the absolute value of the test statistic must be less than 2.07 to conclude that the means are equal.

5.5 Summarize the resulting test statistics for dynamic modulus and phase angle.

5.6 If the results conclude the means are not equal for any of the combinations of temperature, confinement, and loading frequency tested, then the proposed measuring system is unacceptable.

6.0 Report

6.1 Design data for the mixture used in the evaluation.

6.2 Air void contents for individual specimens and the average and standard deviations of the air void contents for the two subsets.

6.3 Tabular chronological summary of the block testing showing starting date and time and completion date and time for each block.

6.4 Summary tables of dynamic modulus, phase angle, and data quality indicators for each combination of temperature, confining pressure, and loading frequency for the two measuring systems.

6.5 Summary tables of the mean and variance of the dynamic modulus and phase angle for each combination of temperature, confining pressure, and loading frequency for the two measuring systems.

6.6 Summary tables of the hypothesis tests for the variance and mean of the dynamic modulus and phase angle for each combination of temperature, confining pressure, and loading frequency.

6.7 Conclusions concerning the acceptability of the proposed measuring system.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation