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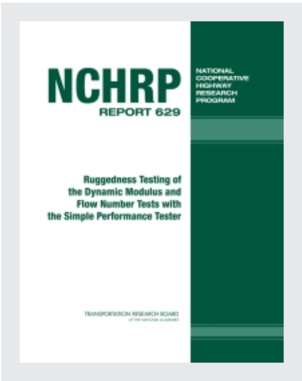

Ruggedness Testing of the Dynamic Modulus and Flow Number Tests with the Simple Performance Tester

DETAILS

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Ramon Bonaquist, Chief Operating Officer for Advanced Asphalt Technologies, LLC, served as Principal Investigator for the project and authored this report. Donald W. Christensen, Senior Engineer for Advanced Asphalt Technologies, LLC and Donald Jack, Laboratory Manager for Advanced Asphalt Technologies, LLC assisted with the equipment refinements and equipment evaluation reported in this document.

FOREWORD

By Edward T. Harrigan
Staff Officer
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NCHRP Project 9-29, "Simple Performance Tester for Superpave Mix Design," is a multi-phase effort to develop a practical, economical simple performance tester (SPT) for use in routine hot-mix asphalt (HMA) mix design and in the characterization of HMA materials for pavement structural design with the Mechanistic-Empirical Pavement Design Guide (MEPDG). In the phase of the project reported here, ruggedness testing was conducted with the SPT for the dynamic modulus and flow number tests developed in NCHRP Project 9-19 as simple performance tests for permanent deformation. Thus, the report will be of particular interest to materials and pavement structural design engineers in state highway agencies, as well as to materials suppliers.

The present HMA volumetric mix design method used by the majority of state highway agencies was developed in the asphalt component of the Strategic Highway Research Program (1987–1993). This method—standardized as AASHTO M 323 and R 35—does not include a simple, mechanical "proof" test analogous to the Marshall stability and flow tests or the Hveem stabilometer method.

Though the utility and soundness of the HMA mix design method are evident by its almost ubiquitous, present-day use, mix designers from the beginning have asked for complementary simple performance tests to quickly and easily proof-test candidate mix designs. Work sponsored by FHWA and then NCHRP in the period 1996–2006 (and reported in *NCHRP Reports 465*, *547*, and *580*) recommended three test and parameter combinations as simple performance tests for permanent deformation: (1) the dynamic modulus, E^*, determined with the triaxial dynamic modulus test; (2) the flow number, F_n, determined with the triaxial repeated load test; and (3) the flow time, F_T, determined with the triaxial static creep test. The dynamic modulus, E^*, also was chosen as the simple performance test for fatigue cracking as well as the chief HMA materials characterization test for HMA pavement design with the MEPDG.

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 an SPT for (1) proof-testing for permanent deformation and fatigue cracking in HMA mix design and (2) materials characterization for pavement structural design with the MEPDG.

In the portion (Phase V) of NCHRP Project 9-29 reported here, the research team conducted ruggedness testing for the dynamic modulus and flow number tests in the SPT. A formal ruggedness experiment was designed, conducted, and analyzed in accordance with ASTM E1169, *Standard Guide for Conducting Ruggedness Tests.* A second, *equipment effects* experiment investigated whether there are significant differences in SPT data collected with equipment from various manufacturers. Both experiments were performed separately for the dynamic modulus and flow number tests. Based on the findings from the ruggedness and equipment effects experiments, modifications to the SPT equipment specification and test procedures were made to improve the quality of the test data and reduce variability.

This report presents the full text of the contractor's final report for Phase V and six appendices, which present (1) dynamic modulus ruggedness data (Appendix A); (2) flow number ruggedness data (Appendix B); (3) dynamic modulus equipment effects data (Appendix C); (4) flow number equipment effects data (Appendix D); (5) the final version of the SPT equipment specifications (Appendix E); and (6) SPT test methods (Appendix F). Earlier work completed in Phases I through IV is presented in NCHRP *Reports 513*, *530, and 614*.

CONTENTS

SUMMARY

Ruggedness Testing of the Dynamic Modulus and Flow Number Tests with the Simple Performance Tester

In Phases I and II of NCHRP Project 9-29, a detailed purchase specification for the Simple Performance Test System (SPT) was developed and two first article devices were procured and evaluated. This evaluation concluded that the SPT is a reasonably priced, user-friendly device for testing stiffness and permanent deformation properties of asphalt concrete. Additional work, however, was needed to further refine the SPT for use in routine practice. This additional work was undertaken in Phases IV and V of NCHRP Project 9-29. These phases of the project included four major activities directed at implementation of the SPT in routine practice:

1. Enhancement of the SPT to perform dynamic modulus master curve testing required for pavement structural design and analysis.
2. Procurement and evaluation of SPTs with dynamic modulus master curve testing capability.
3. Development of equipment for rapid preparation of test specimens for the SPT.
4. Ruggedness testing for the dynamic modulus and flow number tests conducted in the SPT.

This report documents the ruggedness experiments that were performed in Phase V of the project.

Two experiments were included in the SPT ruggedness testing. The first was a formal ruggedness experiment designed, conducted, and analyzed in accordance with ASTM E1169, *Standard Guide for Conducting Ruggedness Tests*. The second was an experiment designed to investigate whether there are significant differences in SPT data collected with equipment from the three manufacturers: Interlaken Technology Corporation (ITC); IPC Global, Ltd. (IPC); and Medical Device Testing Services (MDTS). The ruggedness and equipment effects experiments were performed separately for the dynamic modulus and flow number tests. The flow number and flow time tests are very similar. Both require similar control of stresses and temperature during the tests and similar accuracy in the measurement of deformations during the test. The results from the flow number test, therefore, can also be applied to the flow time test. Based on the findings from the ruggedness and equipment effects experiments, modifications to the equipment specification and test procedure were made to improve the quality of the test data and reduce variability. A final detailed purchase specification for the SPT and test procedures for the dynamic modulus and flow number tests were developed and are included as appendices to this report.

CHAPTER 1

Introduction and Research Approach

1.1 Problem and Purpose

National Cooperative Highway Research Program (NCHRP) Project 9-19, "Superpave Support and Performance Models Management" recommended three candidate simple performance tests to compliment the Superpave volumetric mixture design method. These tests 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, and the dynamic modulus appears to have potential as a simple performance test for fatigue cracking (*1*). The dynamic modulus is also the primary material input for flexible pavement structural design in the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) completed in NCHRP Project 1-37A (*2*). The use of this test for both mixture evaluation and structural design offers a potential link between mixture design and structural analysis that has been an underlying goal of a substantial amount of past flexible pavement research.

The objective of NCHRP Project 9-29 is to stimulate the development of commercial testing equipment that is capable of performing the NCHRP Project 9-19 performance tests. It is envisioned that this equipment will be used for two purposes: (1) as a simple performance test to complement Superpave volumetric mixture design and (2) for the asphalt concrete material characterization required by the MEPDG and other similar flexible pavement structural design methods.

In Phase I of NCHRP Project 9-29, a detailed purchase specification for the Simple Performance Test System (SPT) was developed. The SPT is capable of performing the three NCHRP Project 9-19 performance tests, and it standardizes the instrumentation, data acquisition, and data analysis associated with each test. In Phase II, two first article devices were procured and evaluated. This evaluation concluded that the SPT is a reasonably priced, user-friendly device for measuring stiffness and permanent deformation properties of asphalt concrete. Additional work, however, was needed to further refine the SPT for use in routine practice. This additional work was undertaken in Phases IV and V of NCHRP Project 9-29. These phases of the project included four major activities directed at implementation of the SPT in routine practice:

1. Enhancement of the SPT to perform dynamic modulus master curve testing required for pavement structural design and analysis.
2. Procurement and evaluation of SPTs with dynamic modulus master curve testing capability.
3. Development of equipment for rapid preparation of test specimens for the SPT.
4. Ruggedness testing for dynamic modulus and flow number tests conducted in the SPT.

This report documents the ruggedness experiments that were performed in Phase V of the project.

1.2 Scope

In Phase V of NCHRP Project 9-29 a series of experiments were designed, conducted and analyzed to assess the SPT equipment and test procedures for the dynamic modulus and flow number tests. Phase V included two major experiments. The first was a formal ruggedness experiment in accordance with ASTM E1169, *Standard Guide for Conducting Ruggedness Tests.* The second was an experiment designed to investigate whether there are significant differences in SPT data collected with equipment from the three manufacturers: Interlaken Technology Corporation (ITC); IPC Global (IPC); and Medical Device Testing Services (MDTS). Although the flow time test was not formally included in the experiments, the findings from the flow number testing were also applied to the flow time test.

1.3 Ruggedness Experiments

1.3.1 Background

The purpose of ruggedness testing is to improve a test method by determining which controllable testing conditions most influence the results, and establishing limits for their control. A ruggedness evaluation should always precede an interlaboratory study for a test method. The purpose of an interlaboratory study is to establish the precision of a test method. It involves testing of multiple materials in multiple laboratories, and requires a significant commitment of time and resources. If critical testing conditions are not first identified and controlled through a ruggedness evaluation, then an interlaboratory study will likely yield poor precision for the test method. Perhaps more important than a finding of poor precision, is the fact that data from the interlaboratory study is not generally useful for determining how to improve the precision of the test. This was the unfortunate finding of an interlaboratory study that was recently completed for the dynamic modulus test (*3*). This study identified high variability in dynamic modulus data obtained from several laboratories, but was not able to establish reasons for the high variability or to identify procedural changes that would result in more acceptable testing error. By systematically varying testing conditions and quantifying their effect on the measured data, a ruggedness evaluation is able to identify important sources of testing error and help establish limits to reduce testing error to a tolerable level.

Since ruggedness testing is a critical part of the development of a test method, efficient statistical designs have been developed and standardized for ruggedness tests. ASTM E1169, *Standard Guide for Conducting Ruggedness Tests,* describes the partial factorial Plackett-Burnam designs most often used in ruggedness testing. These designs are very efficient for simultaneously evaluating the effect of changes in a number of operating conditions when there is no interaction between the operating conditions being evaluated. Inherent to this type of statistical design is the assumption that the effect of each of the operating conditions on the test result is independent. Therefore, the observed effect resulting from simultaneous variation of several operating conditions is simply the sum of the individual effects. Since ruggedness testing is concerned with the evaluation of the effect of changes in testing conditions and not necessarily the form of the effect, each testing condition is usually evaluated at only two levels. Replication should be included in the design when an estimate of the variance of a single measurement is not known.

ASTM D1067, *Standard Practice of Conducting a Ruggedness or Screening Program for Test Methods for Construction Materials,* describes the two-level, seven-factor design with replication recommended for ruggedness testing for construction materials tests. The factors to be evaluated and their two levels are determined from theoretical considerations or previous experience with the test. For this study, information obtained from testing completed in Project 9-19 and in Phase II of Project 9-29 was used to select the factors and their levels. The selection of the factors and their levels are discussed in detail later in this Chapter. Test data are collected for specific combinations of the factors and their levels as outlined in Table 1. This table uses the nomenclature from ASTM D1067. The seven factors are designated by letters ***A*** through ***G***. Capital letters indicate high levels for the factors while lower case letters indicate low levels. Thus, determination 1 will be made with factors ***A***, ***B***, and ***E*** at low levels and factors ***C***, ***D***, ***F***, and ***G*** at high levels. With replication, the experiment requires 16 tests, two for each of the specific combinations indicated in Table 1. The order of the tests should be randomized within each replication of the experiment.

Analysis of the resulting data is straightforward as described in ASTM D1067. It involves determining effects for each of the factors included in the partial factorial design, and an estimate of the variance of a single measurement. An F-test or linear regression can then be used to assess the statistical significance of the factor effects relative to the variance of a single measurement.

The major considerations in the design of a ruggedness test are (1) selection of the factors and their levels, (2) selection of a range of materials or test conditions for the evaluation, and (3) selection of an appropriate number of laboratories to participate in the ruggedness testing. The experimental design in Table 1 uses seven factors at two levels. This design is considered appropriate for the proposed ruggedness testing for the simple performance tests. ASTM D1067 recommends using three to five materials covering the expected range of properties to be measured in the test. The results from each material are analyzed separately; therefore, 16 measurements are needed for each material included in the evaluation. ASTM E1169 and ASTM D1067 differ on the number of laboratories to be included in the ruggedness testing. ASTM E1169 recommends

Table 1. Experimental design for a two level, seven factor ruggedness test.

	Determination Number							
Factor	1	2	3	4	5	6	7	8
A	a	A	A	a	A	A	A	A
B	b	B	B	B	b	B	B	B
C	C	C	C	c	C	C	C	c
D	D	D	D	d	d	D	D	D
E	e	E	E	E	E	E	E	e
F	F	F	F	F	F	F	f	F
G	G	G	G	G	g	G	G	g

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using a single laboratory that has experience with the test being evaluated, while ASTM D1067 recommends using three laboratories. Since the data from each laboratory must be evaluated separately, the use of multiple laboratories in the ruggedness testing does not improve the quality of the statistical analysis. As stated in ASTM D1067, the primary benefit obtained from the inclusion of multiple laboratories in ruggedness testing is an additional review of the validity of the test method and the need for added clarity in the operating instructions. Two laboratories were included in the ruggedness experiment. Tests were conducted in AAT's laboratory using the Interlaken SPT and in the FHWA Mobile Asphalt Laboratory using the IPC Global SPT.

1.3.2 Ruggedness Testing Plan for Dynamic Modulus

This section discusses the ruggedness testing plan that was developed for the dynamic modulus test. It discusses the selection of the materials, testing conditions and factors that were included evaluation

1.3.2.1 Materials and Testing Conditions

Temperature and loading rate are the two factors that most influence the dynamic modulus of asphalt concrete mixtures. Figure 1 presents a dynamic modulus master curve generated using the reduced testing protocol developed in Phase IV of this project (Temperatures of 4, 20, and 40°C and loading frequencies of 10, 1, 0.1, and 0.01 Hz). Aggregate type and gradation, volumetric properties, and binder grade will result in a shifting of the master curve, but the overall range will not change significantly. As shown, the range of dynamic modulus values can be covered using the following temperature and frequency combinations:

- High modulus, 4°C at 10 Hz
- Intermediate modulus, 20°C at 0.1 Hz
- Low modulus, 40°C at 0.01 Hz

Project 9-19 has suggested that confined tests may be necessary for gap- and open-graded mixtures. It is likely that the sensitivity of dynamic modulus measurements to confining pressure effects will be different for dense compared to gap- and open-graded mixtures. Therefore, two mixtures were used in the ruggedness testing: a 9.5-mm dense-graded mixture with a PG 64-22 binder, and a 12.5-mm Stone Matrix Asphalt (SMA) mixture with a PG 76-22 binder. Since, as discussed below, one of the factors to be considered in the ruggedness evaluation is air versus water for temperature conditioning, a moisture sensitive dense-graded mixture was used. Smaller nominal maximum aggregate size mixtures were selected to minimize testing error associated with specimen preparation and thereby accentuate the planned effects. Table 2 presents mixture proportions for the mixtures used in the ruggedness testing. The dense-graded mixture uses a somewhat moisture sensitive diabase from Northern Virginia having a typical tensile strength ratio of 75 percent in AASHTO T283, *Standard Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*. The SMA mixture uses a combination of diabase from Northern Virginia and Limestone from West Virginia. Tests were conducted using the

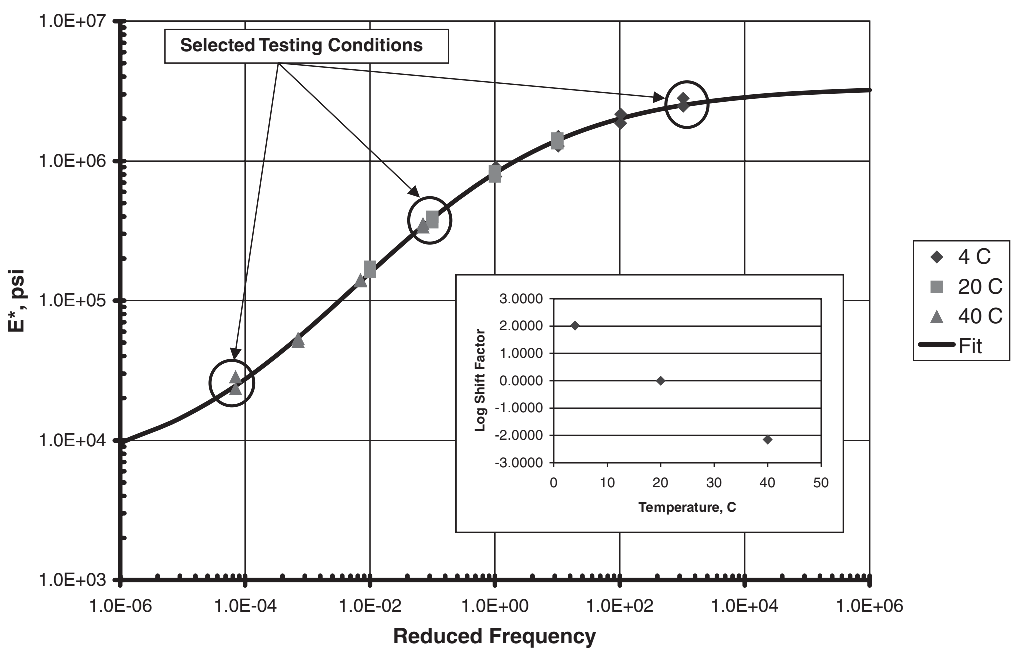

Figure 1. Typical dynamic modulus master curve.

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Table 2. Composition of the mixtures.

Property		9.5 mm Dense	12.5 mm SMA
Binder Content, %		5.7	6.5
Gradation, % passing	Sieve Size, mm		
	19	100	100
	12.5	100	97
	9.5	91	81
	4.75	68	30
	2.36	40	19
	1.18	31	15
	0.6	22	13
	0.3	12	12
	0.15	7	10
	0.075	4.8	8.3

three combinations of temperatures and frequencies listed above.

1.3.2.2 Factors and Levels

The dynamic modulus test includes a number conditions that require some level of control in order to minimize testing error. The sections below discuss the selection of factors and their levels for the ruggedness testing.

Temperature. Temperature is the most important factor affecting the mechanical properties of asphalt concrete mixtures and must be carefully controlled to obtain precise test data. For the SPT, the temperature is controlled by first equilibrating the specimen in a separate conditioning chamber to the test temperature. A dummy specimen of the same size as the test specimen with a thermocouple installed at the middle and exposed to the same thermal history as the test specimen is used to determine when temperature equilibrium is achieved. Once the specimen is equilibrated at the test temperature, a maximum time limit has been specified to instrument the specimen, install it in the test chamber, and have the test chamber return to the test temperature. The current tolerance on the temperature in the equilibration chamber is ±0.5°C from the target temperature. The time limit for transfer is 3 min. Both of these were successfully met in the Phase II evaluation testing that resulted in an acceptable coefficient of variation of 13 percent. In the ruggedness testing, the effect of increasing the equilibration tolerance and the specimen transfer time were evaluated, since less stringent control on these factors may reduce the overall testing time. A test temperature tolerance of ±1.0°C and specimen transfer times of 3 and 5 min were investigated.

A related factor that will be investigated in the ruggedness testing is the fluid for conditioning the test specimens. Currently air is specified as the fluid in the conditioning chamber, and the specimen equilibration time at each temperature may be as long as 4 hours for the temperature sequence of 4, 20, and 40°C recommended in the reduced dynamic modulus testing procedure developed in Phase IV of this project. However, it is well known that water has better thermal conductivity than air, and the overall time to complete the testing could be substantially reduced if the specimens could be equilibrated in water baths set to the testing temperatures. For example, the Marshall stability test, AASHTO T245, *Standard Method of Test for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus,* requires temperature equilibration times of 30 min in water baths and 2 hours in ovens, both set to the specified test temperature. If in the ruggedness testing the dynamic modulus is not significantly affected by the use of water as a conditioning fluid, it may be possible to complete the testing at all three temperatures required for master curves in a single day. Air versus water as conditioning fluids was, therefore, included in the ruggedness testing program.

Loading rate. Loading rate has a similar effect as temperature on the mechanical properties of asphalt concrete. In fact, this is the basis of the time-temperature superposition concept used in the development of dynamic modulus master curves. Although loading rate has a major effect on the mechanical properties of asphalt concrete, it will not be included in the ruggedness testing because the load standard error computed by SPT software is very sensitive to variations in the frequency of the applied load. Limiting the load standard error to 10 percent or less ensures that the frequency of the applied load will be the same as the specified loading frequency.

Axial strain. Research has shown the dynamic modulus to be sensitive to the applied axial strain, particularly at high temperatures or low frequencies of loading (*4*). AASHTO TP 62 has a very wide tolerance of 50 to 150 μstrain for the axial strain, which may be partially responsible for the poor test precision reported in the recently completed interlaboratory study for the dynamic modulus test (*3*). In the SPT, a control loop has been specified with a tolerance of 75 to 125 μstrain, and in the Phase II evaluation the axial strains were controlled within 80 to 110 μstrain. Axial strain level was a factor in the ruggedness testing with the factor levels set at 75 and 125 μstrain as specified in the equipment specifications for the SPT.

Confining pressure. Research has also shown the dynamic modulus at high temperatures and low frequencies of loading to be sensitive to confining pressure (*4*). Neither the Project 9-19 test methods (*1*) nor AASHTO TP 62 address confined dynamic modulus testing. Currently the SPT requires control of confining pressure to ±2 percent of the specified value. The maximum confining pressure available in the SPT is 210 kPa; therefore, the maximum deviation from the target is ±4.2 kPa. In the Phase II evaluation, this level of control was easily maintained by the two devices. The ruggedness testing included

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confined tests with confining pressures of 135 and 140 kPa to verify that the current level of confining pressure control is adequate. Unconfined tests were performed with and without the membrane to determine if the level of confinement provided by the membrane is significant. If tests at multiple confining pressures are desired, the procedure will be simplified if the membrane can remain in place during the unconfined testing.

End friction reducer. A major assumption in the dynamic modulus test is that the stresses are distributed uniformly over the specimen. Friction between the loading platen and the specimen produces shear stresses which result in a deviation from this assumption. The effects of friction can be minimized by using long specimens and making measurements near the middle. The test specimen size for the simple performance tests was determined in an extensive specimen size and geometry study conducted in Project 9-19 (*5*). The specimen diameter of 100 mm was selected to provide flow data that are independent of specimen size. The height to diameter ratio of 1.5 was selected to provide dynamic modulus and flow data that are independent of specimen height. In the Project 9-19 specimen size and geometry study, an end friction reducing element consisting of two latex sheets separated by silicon grease was used. The reduction of end friction in these tests was probably a significant factor in the conclusions concerning specimen size. The greased latex sheets are not conducive to production testing; therefore, in Project 9-29 Teflon™ sheets were used in the evaluation testing. The type of end friction reducer, greased latex versus Teflon™ was included in the ruggedness evaluation to verify that either approach is acceptable.

Specimen properties. Air void content and end parallelism are two specimen properties that must be controlled. With available specimen fabrication techniques, an air void tolerance of ±0.5 percent of the target is obtainable with careful control. It is desirable to increase the air void tolerance to minimize the number of specimens rejected. The Hirsch model, which was developed to estimate the effect of volumetric properties on the dynamic modulus can be used to assess the effect of air voids on the dynamic modulus (*6*). Figure 2 shows the potential error caused by a 1.0 percent change in air voids. As shown the error is dependent on the modulus of the mixture and varies from about 3 percent for low and high modulus values to 9 percent for intermediate modulus values. This analysis shows that variability in specimen air voids is a significant contributor to the overall test variability and that a high degree of control over air void content is needed. However, the current tolerance of ±0.5 percent is probably the tightest control obtainable using current specimen fabrication techniques. Therefore, air void content was not considered in the ruggedness testing. The current tolerance of ±0.5 percent should be used until specimen fabrication equipment is improved.

Like end friction, the degree of parallelism of the specimen ends affects the distribution of stresses in the specimen. The uniform stress distribution assumed in the analysis of the dynamic modulus data requires smooth, parallel ends. Sawed

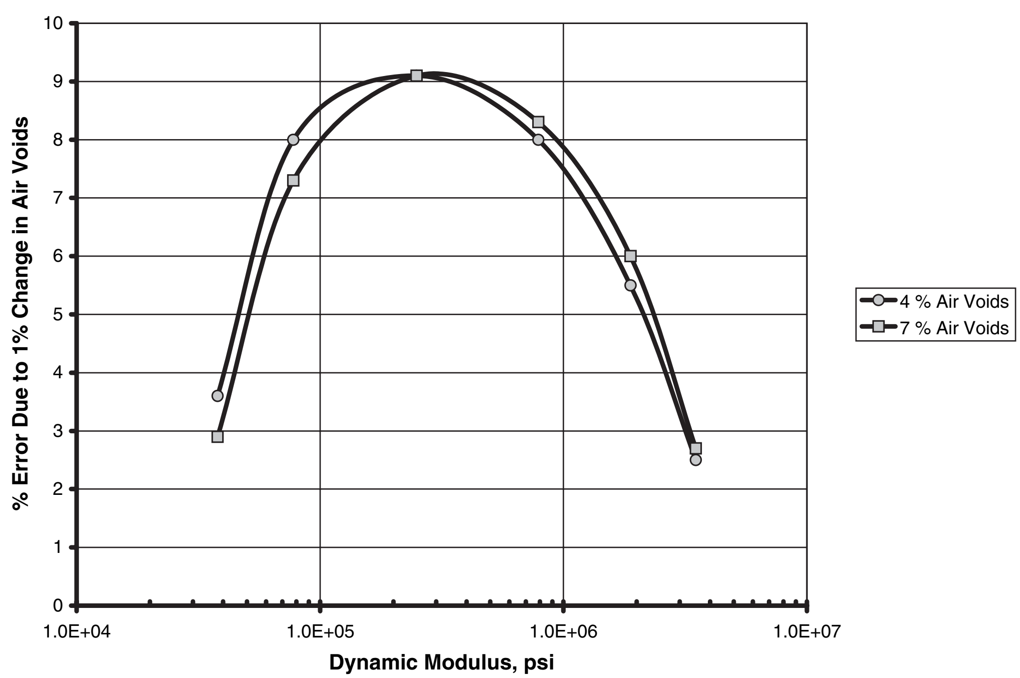

Figure 2. Estimated testing error for current air void tolerance.

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Table 3. Summary of factors and levels for the dynamic modulus ruggedness test.

Factor	Unconfined Tests		Confined Tests	
	Low	High	Low	High
Equilibrium Temperature	X – 1 °C	X + 1 °C	X – 1 °C	X + 1 °C
Specimen Transfer Time	3 min	5 min	3 min	5 min
Specimen Conditioning Fluid	Air	Water	Air	Water
Strain Level	75 µstrain	125 µstrain	75 µstrain	125 µstrain
Confining Pressure	No membrane	Membrane	135 kPa	140 kPa
Specimen End Parallelism	Milled	Sawed	Milled	Sawed
Friction Reducer	Greased latex	Teflon™	Greased latex	Teflon™

specimen ends are not perfectly smooth, nor parallel. Since the friction reducer helps minimize the effects caused by end roughness, end parallelism is the critical specimen geometry property that must be considered. Based on measurement of a number of specimens, a tolerance of 1.0 degree was established in Phase I of this project. To meet this tolerance requires careful control of the sawing operation. To verify that this level of control is acceptable, specimens with sawed ends and milled ends were included in the dynamic modulus ruggedness testing program.

1.3.2.3 Summary

Table 3 summarizes the factors and factor levels that were included in the ruggedness testing for the dynamic modulus test. Dynamic modulus tests were performed for each of the combinations of material, confinement, temperature, and loading rate listed in Table 4. Confined tests were only performed at high temperatures where past research has shown confining effects to be significant. Since the dynamic modulus is a non-destructive test, the testing program required the fabrication of 32 specimens, 16 for each mixture. Tests on these 32 specimens were performed for the four combinations of temperature and confinement listed in Table 4 in the following order, unconfined at 4°C, unconfined at 20°C, confined at 40°C then unconfined at 40°C. For each temperature/confinement combination, the order of the determinations from Table 1 was randomized. The entire ruggedness testing program was performed in two laboratories: AAT's laboratory using the ITC SPT and FHWA's Mobile Asphalt Laboratory using the IPC SPT.

Table 4. Materials and conditions for the dynamic modulus ruggedness test.

Mixture	Confinement	Temperature, °C/Frequency, Hz		
		4/1.0	20/0.1	40/0.01
Dense-graded	Unconfined	X	X	X
	Confined			X
SMA	Unconfined	X	X	X
	Confined			X

1.3.3 Ruggedness Testing Plan for the Flow Number Tests

This section discusses the ruggedness testing plan that was developed for the flow number test. It discusses the selection of the materials, testing conditions, and factors that were included in the evaluation

1.3.3.1 Materials and Testing Conditions

The ruggedness testing for the flow number test included materials and testing conditions that result in a wide range of permanent deformation properties. It also included tests on dense- and gap-graded mixtures because it is likely that the sensitivity of the flow number test to confining pressure effects will be different for dense- compared to gap-graded mixtures. To evaluate rutting resistance, the flow number test will be performed at a high pavement temperature representative of the project location and pavement layer depth to evaluate the rutting resistance of the mixture. In NCHRP Project 9-33, criteria have been developed for the flow number test based on the 50 percent reliability 7-day average maximum high pavement temperatures computed using the LTPPBind software (*7*). Table 5 summarizes these temperatures for selected cities (*8*). Based on these temperatures, mixtures in-

Table 5. LTPPBind design high pavement temperatures for 50 percent reliability.

City	50 Percent Reliability Design High Pavement Temperature, °C (*8*)	98 Percent Reliability High Temperature Grade, Fast Traffic, 3 to 10 million ESAL (*8*)
Atlanta, GA	51	64
Chicago, IL	47	64
Fairbanks, AK	38	52
Fargo, ND	46	64
Houston, TX	52	70
Indianapolis, IN	48	64
Miami, FL	51	64
Oklahoma City, OK	52	70
Phoenix, AZ	58	76
Reno, NV	51	64
Washington, DC	49	64

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Table 6. Mixture and test conditions for the ruggedness testing for the flow number tests.

Mixture	Confinement	Confining Stress, kPa	Deviator Stress, kPa	Anticipated Flow
Dense-graded	Unconfined	0	140	Low
	Confined	140	965	Moderate
SMA	Confined	140	965	High

corporating PG 64-22 binders should be tested at approximately 50 °C. A temperature of 50 °C was selected for use in the flow number ruggedness testing.

The same two mixtures selected for the dynamic modulus ruggedness were used in the ruggedness testing for the flow tests. Table 6 summarizes the testing conditions for the flow tests. Tests were performed on the dense-graded mixture with and without confinement, but only confined tests were performed on the SMA mixture. All tests were performed at 50 °C.

1.3.3.2 Factors and Levels

Many of the same factors discussed for the dynamic modulus ruggedness test were included in the ruggedness testing for the flow number test. The sections below discuss each of these factors.

Temperature. The same temperature factors: equilibrium temperature tolerance, transfer time, and conditioning fluid were included in the ruggedness testing for the flow number test. The factor levels were ±1.0 degree for equilibrium temperature, 3 min and 5 min for specimen transfer time, and air and water as conditioning fluids.

Loading rate. The duration of the load pulse and dwell time between load pulses are important factors affecting the accumulation of permanent deformation in the flow number test. The duration of the load pulse was not included in the ruggedness testing because the load standard error computed by the SPT software is very sensitive to variations in the duration of the load pulse. Limiting the load standard error to 10 percent or less ensures that the load pulse will be sinusoidal with a duration of 0.1 sec. The equipment specifications currently do not include a tolerance on the dwell time between load pulses. It is specified as 0.9 sec, and current computer control systems are very accurate allowing it to be controlled within a millisecond or less. A tolerance should be included in the specification; therefore, the dwell time was included in the ruggedness testing. The levels for this factor were set at 0.85 and 0.95 sec. Only the IPC equipment had the capability to adjust the dwell time in the flow number test.

Deviatoric stress. Research has shown that the flow number test is sensitive to the applied deviatoric stress (*9*). The equipment specifications currently apply a ±2.0 percent tolerance on the deviatoric stress. This level of control was taken from other similar tests for asphalt concrete. Deviatoric stress was included in the ruggedness tests with the factor levels set at 135 and 145 kPa for unconfined tests, and 945 and 985 kPa for confined tests.

Confining pressure. Research has also shown that the flow number test is sensitive to confining pressure (*9*). Currently the SPT specification requires control of confining pressure to ±2.0 percent of the specified value. The maximum confining pressure available in the SPT is 210 kPa; therefore, the maximum deviation from the target is ±4.2 kPa. In the Phase II evaluation, this level of control was easily maintained by the two devices. The ruggedness testing included confined tests with confining pressures of 135 and 140 kPa to verify that the current level of confining pressure control is adequate.

Contact stress. The contact stress used in the flow number test applies a small creep load to the specimen during the test. The effect of this loading has not been evaluated in past research. A contact stress of 5 percent of the deviatoric stress was recommended in the Project 9-19 test procedures (*2*). In the ruggedness testing, contact stresses of 3.7 and 7.5 percent were evaluated.

End friction reducer. A major assumption in the flow number test is that the stresses are distributed uniformly over the specimen. Friction between the loading platen and the specimen produces shear stresses which result in a deviation from this assumption. The effects of friction can be minimized by using long specimens. The test specimen size for the simple performance tests was determined in an extensive specimen size and geometry study conducted in Project 9-19 (*5*). The specimen diameter of 100 mm was selected to provide flow data that are independent of specimen size. The height to diameter ratio of 1.5 was selected to provide dynamic modulus and flow data that are independent of specimen height. In the Project 9-19 specimen size and geometry study, an end friction reducing element consisting of two latex sheets separated by silicon grease was used. The reduction of end friction in these tests was probably a significant factor in the conclusions concerning specimen size. The greased latex sheets are not conducive to production testing; therefore, in Project 9-29 Teflon™ sheets were used in the evaluation testing. The type of end friction reducer, greased latex versus Teflon™ was included in the ruggedness evaluation to verify that either approach is acceptable.

Specimen properties. Air void content and end parallelism are two specimen properties that must be controlled. With available specimen fabrication techniques, an air void tolerance of ±0.5 percent of the target is obtainable with care-

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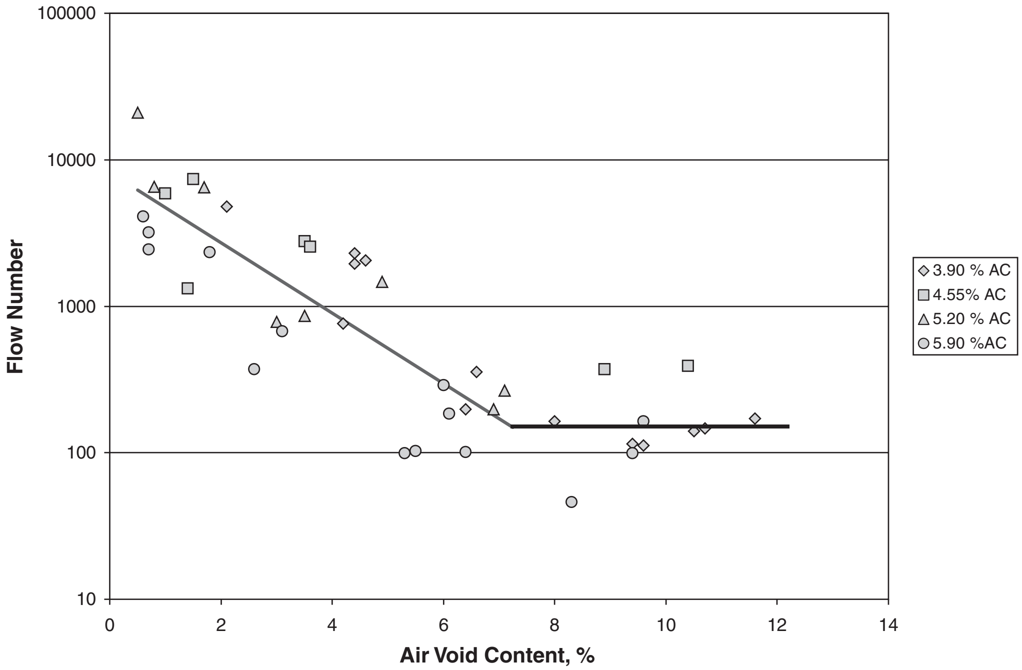

Figure 3. Effect of air voids on unconfined flow number [data from Project 9-19 (10)].

ful control. It is desirable to increase the air void tolerance to minimize the number of specimens rejected. Project 9-19 included a subset of flow number tests on mixtures with varying asphalt and air void contents (*10*). Flow number data from this study are plotted in Figure 3 and Figure 4 to show the effects of air voids. Although there is large scatter in the data, the air void content has a large effect over the 4 to 7 percent air void range likely to be used in laboratory testing. Using the trend lines shown, a 1 percent change in air voids produces a 56 percent change in the flow number for unconfined tests and a 20 percent change in flow number for confined tests. Like the dynamic modulus, this analysis shows that

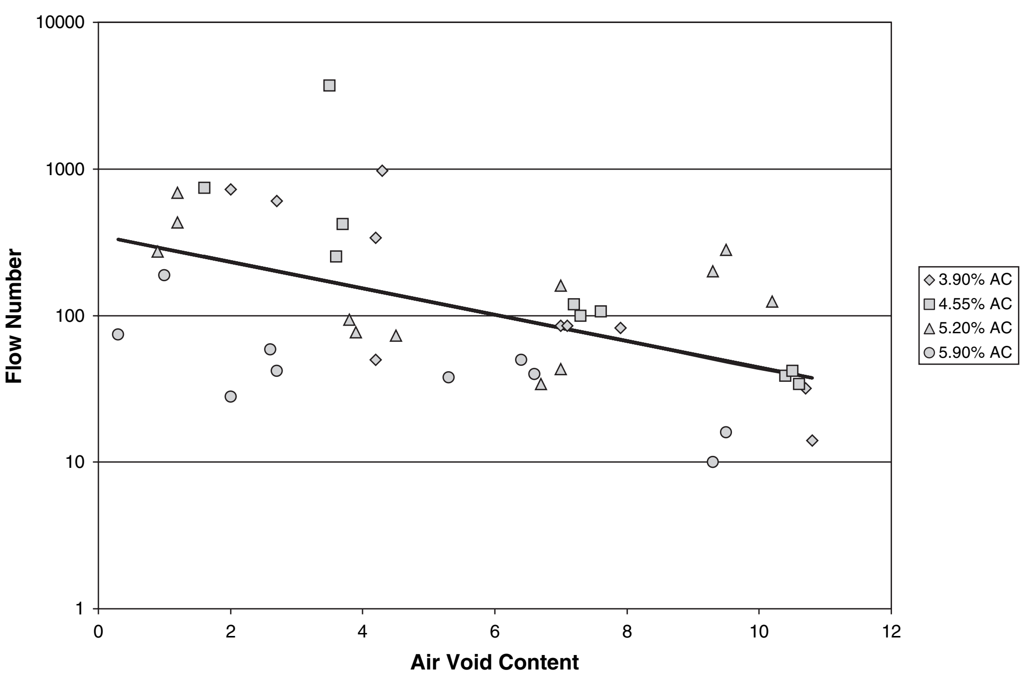

Figure 4. Effect of air voids on confined flow number [data from Project 9-19 (10)].

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variability in specimen air voids is a significant contributor to the overall test variability and that a high degree of control over air void content is needed. However, the current tolerance of ±0.5 percent is probably the tightest control obtainable using current specimen fabrication techniques. Therefore, air void content was not a factor considered in the ruggedness testing. The current tolerance of ±0.5 percent should be used until specimen fabrication equipment is improved.

As discussed for the dynamic modulus test, end parallelism was included as a factor in the ruggedness testing for the flow number test. Different conclusions concerning the effects of end parallelism may be drawn from the small strain dynamic modulus test and the large strain flow number test. Additionally, the platen configurations are different in the two tests. For the dynamic modulus test, a ball joint that allows the top platen to conform to the plane of the specimen is used. For the flow number test, the platens are fixed in a parallel arrangement. Specimens with sawed ends and milled ends were included in the dynamic modulus ruggedness testing program.

1.3.3.3 Flow Number Test Summary

Table 7 summarizes the factors and factor levels that were included in the ruggedness testing for the flow number test. As shown, dwell time and contact stress were included only in the unconfined tests. The effect of dwell time was evaluated only with the IPC equipment. The effect of contact stress was evaluated only with the ITC equipment. Flow number tests were performed at 50°C for three combinations of material and confinement: dense-graded, unconfined; dense-graded, confined; and SMA, confined. Since the flow number test is a destructive test, the testing program required the fabrication and testing of 48 specimens, 16 for each mixture/confinement combination. For each mixture/confinement combination, the order of the determinations from Table 7 was randomized. The data for each mixture/confinement combination will be analyzed separately to draw conclusions on appropriate levels of control for the individual factors. The entire ruggedness testing program was performed in two laboratories: AAT's laboratory using the ITC SPT and FHWA's Mobile Asphalt Laboratory using the IPC SPT.

1.4 Equipment Effects Experiment

Since equipment from multiple vendors will be used in future interlaboratory studies for the SPT, a study was performed after the ruggedness testing to quantify differences in data obtained with equipment from various manufacturers. The objective of this experiment was to verify that the same material properties are obtained in the dynamic modulus and flow number tests using devices from different manufacturers.

Table 8 presents the design of this experiment. For each test condition, four replicate tests were performed with each device on the 9.5-mm dense-graded mixture. Analysis of variance techniques was used to analyze the data from each column of the experiment in Table 8. This approach assumes homogeneity of variances for data obtained from the various devices. Based on the data collected in Phase II of NCHRP Project 9-29, this is a reasonable assumption. Using 4 replicates per cell provides 9 degrees of freedom for the error term, and 2 degrees of freedom for the equipment effect. As shown in Figure 5 this results in an efficient design as a larger number of replicates have only a minor effect on the critical F-statistic used in the analysis of variance to detect the significance of differences caused by equipment effects.

Since the dynamic modulus test is nondestructive, only 12 specimens, four for each device were needed to complete the dynamic modulus portion of the study. The flow number, which is a destructive test, required 24 specimens.

Table 7. Summary of factors and levels for the flow number ruggedness test.

	Unconfined Tests		Confined Tests	
Factor	**Low**	**High**	**Low**	**High**
Equilibrium Temperature	49 °C	51 °C	49 °C	51 °C
Specimen Transfer Time	3 min	5 min	3 min	5 min
Conditioning Fluid	Air	Water	Air	Water
Dwell Time (IPC only)	0.85 sec	0.95 sec	Not included	Not included
Contact Stress (ITC only)	5 kPa	10 kPa	Not included	Not included
Deviatoric Stress	135 kPa	145 kPa	945 kPa	985 kPa
Confining Stress	Not included	Not included	135 kPa	140 kPa
Specimen End Condition	Milled	Sawed	Milled	Sawed
Friction Reducer	Greased latex	Teflon™	Greased latex	Teflon™

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Table 8. Equipment effects experiment.

Condition	Dynamic Modulus Test				Flow Number Test	
Temperature, °C	10	20	35	35	50	50
Confining Stress, kPa	0	0	0	135	0	140
Deviatoric Stress, kPa	To obtain 100 μstrain				140	965
Manufacturer	Replicates					
Interlaken	4	4	4	4	4	4
IPC Global	4	4	4	4	4	4
MDTS	4	4	4	4	4	4

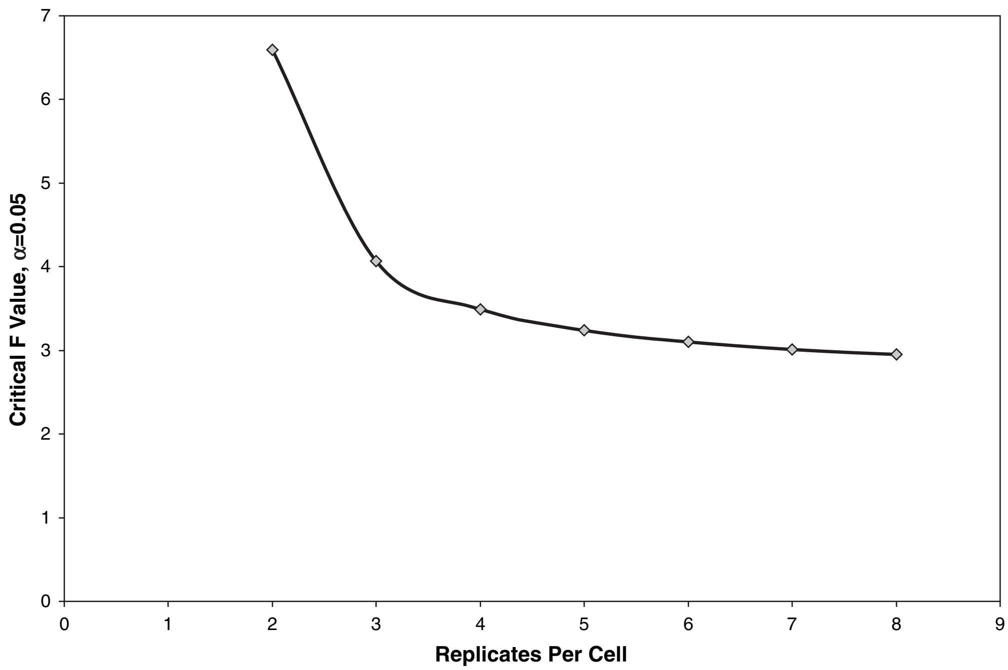

Figure 5. Effect of replicates per cell on critical F-statistic for design in Table 8.

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CHAPTER 2

Results and Analysis of Ruggedness Experiments

2.1 Analysis Approach

Linear regression is an efficient method for analyzing the ruggedness data. For each combination of mixture, laboratory, temperature, frequency, and confinement, the ruggedness test data can be fit to a linear model of the form:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 + B_6X_6 + B_7X_7 + Error \quad (1)$$

where:

Y = measured value
$X_1, X_2, X_3, X_4, X_5, X_6, X_7$ = seven factors included in the ruggedness testing
$B_0, B_1, B_2, B_3, B_4, B_5, B_6, B_7$ = model coefficients
Error = model error

From this analysis, the statistical significance of the model coefficients can be determined. For statistically significant factors, the model coefficients can then be used to estimate values for each of the factors that will keep their effect below a specified level.

2.2 Dynamic Modulus Test

The results of the dynamic modulus ruggedness testing are presented in Appendix A. The dynamic modulus ruggedness experiment included the factors listed in Table 3. The responses measured in the dynamic modulus ruggedness experiment are listed in Table 9. These include the measured dynamic modulus and phase angle, and the computed data quality indicators.

Regression equations of the form of Equation 1 were developed for each parameter listed in Table 9. The results are summarized in Table 10 through Table 13 for the dynamic modulus and phase angle. Table 10 and Table 11 present results for tests in AAT's laboratory with the ITC equipment while Table 12 and Table 13 present results for tests in FHWA's laboratory using the IPC Global equipment. These tables present p-values indicating the significance of the regression coefficients for each of the factors included in the ruggedness experiment. The p-value is the probability of rejecting the null hypothesis when it is in fact true. For this analysis, it is the probability that the regression coefficient for a particular ruggedness factor is zero when the analysis indicates that it is either greater or less than zero. Thus, low p-values indicate the regression coefficient is statistically significant and the ruggedness factor affects the results of the test.

The key to analyzing the ruggedness test in this manner is selecting critical p-values above which the regression coefficient is not significant, and it can be concluded that the ruggedness factor does not affect the test result over the range tested. It is important to keep the objective of ruggedness testing in mind when selecting critical p-values. The objective of ruggedness testing is to identify those controllable factors that *likely* affect a test, and to establish levels for their control. This is different from the usual objective of regression analysis, which is to develop a model to predict an outcome. A predictive model should only include variables that are highly related to the predicted outcome, so a very low p-value of 0.05 or less is normally used to detect significant variables for prediction models. However, for analysis of ruggedness test data, selecting a very low p-value may result in the erroneous conclusion that one or more of the ruggedness factors does not affect the test result over the range tested and controlling that factor is not important. For this analysis higher critical p-values than used in regression modeling should be selected. A critical p-value of 0.10 was used. In Table 10 through Table 13, factors with p-values less than or equal to 0.10 are shown in bold. The analysis was not performed for the unconfined 40°C data for the dense graded mixture tested in the IPC device because the quality of the data was poor. The modulus measured in the equipment for this condition was below the calibrated limit of the machine.

Table 9. Dynamic modulus test data.

Parameter	Type
Dynamic Modulus	Material Property
Phase Angle	Material Property
Load Standard Error	Data Quality Indicator
Deformation Standard Error	Data Quality Indicator
Deformation Uniformity	Data Quality Indicator
Phase Uniformity	Data Quality Indicator

2.2.1 Factors Affecting Dynamic Modulus and Phase Angle

Table 14 was constructed to combine the results from both mixtures tested in both laboratories. It presents the percentage of times a specific factor was found to be significant. The notes indicate when a factor was significant for only one laboratory or only one material.

Table 14 shows that the factors included in the ruggedness experiment were not found to be significant very often indicating that the degree of control provided for the dynamic modulus test by the SPT is reasonable. From this analysis, it is clear that the transfer time, end condition, and friction reducer have little effect on the dynamic modulus and phase angle.

The effects of the statistically significant factors are shown in Figure 6 and Figure 7 for the dynamic modulus and phase angle, respectively. In this analysis, a factor was considered significant if it was found to be statistically significant in 25 percent or more of the tests. For the factors controlled by the SPT: temperature, strain level, and confinement, these figures show the change in modulus and phase angle over the tolerance range of the SPT. For the user-selected factors: air or water as the conditioning fluid and with or without a membrane for unconfined tests, these figures show the higher modulus or phase angle condition. For example for 40°C confined tests, the dynamic modulus when water is used as the conditioning fluid is 6 percent higher than when air is used.

Data on the repeatability of the dynamic modulus test were collected in Phase II of this project (*11*). The Phase II experiment included eight replicates of two mixtures tested by single operators in two laboratories. Laboratory and mixture effects were found to not be significant, therefore, the 32 observations were pooled to obtain estimates of the repeatability of the dynamic modulus and phase angle. The coefficient of variation for the dynamic modulus obtained from this experiment was 13 percent and the standard deviation of the phase angle was 1.7 degrees. It is likely that the repeatability of the dynamic modulus test will improve in the future as specimen fabrication techniques are improved and operators become more familiar with the equipment. However due to

Table 10. Significance of dynamic modulus ruggedness test factors on dynamic modulus and phase angle for the dense mixture tested in AAT's Laboratory with the ITC SPT.

	Dynamic Modulus				Phase Angle			
Factors	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40C Confined
Equilibrium Temperature (-1 vs +1 C)	0.12	**0.10**	0.87	0.71	0.66	0.95	0.37	0.46
Transfer time (3 vs 5 min)	0.44	0.40	0.50	0.73	0.94	0.66	0.43	0.62
Conditioning Fluid (Water vs Air)	0.45	0.74	**0.04**	0.66	0.97	0.74	0.60	0.39
Strain Level	0.18	0.43	**0.03**	**0.02**	0.95	0.15	0.14	0.37
Membrane (No vs Yes)	**0.09**	0.21	0.52	NA	0.83	0.72	0.49	NA
Confinement (135 vs 145 kPa)	NA	NA	NA	0.63	NA	NA	NA	0.57
End Condition (Mill vs Saw)	0.39	0.49	0.70	0.32	0.84	0.73	0.70	0.39
Friction Reducer (Teflon vs Latex)	0.27	**0.09**	**0.00**	0.15	0.98	0.92	0.52	0.73

Table 11. Significance of dynamic modulus ruggedness test factors on dynamic modulus and phase angle for the SMA mixture tested in AAT's Laboratory with the ITC SPT.

	Dynamic Modulus				Phase Angle			
Factors	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40C Confined
Equilibrium Temperature (-1 vs +1 C)	0.59	0.17	0.99	0.66	**0.00**	0.53	0.28	**0.06**
Transfer time (3 vs 5 min)	0.50	0.43	0.68	0.79	0.33	0.89	0.91	0.69
Conditioning Fluid (Water vs Air)	0.64	0.65	0.49	0.88	0.83	0.53	0.85	0.97
Strain Level	0.90	0.99	0.35	**0.01**	0.63	0.94	0.15	**0.04**
Membrane (No vs Yes)	0.91	0.42	0.33	NA	**0.06**	0.22	**0.06**	NA
Confinement (135 vs 145 kPa)	NA	NA	NA	0.22	NA	NA	NA	**0.06**
End Condition (Mill vs Saw)	0.24	0.92	0.76	0.26	0.66	0.91	0.15	0.17
Friction Reducer (Teflon vs Latex)	0.15	0.64	0.62	0.85	0.16	0.25	0.49	0.96

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Table 12. Significance of dynamic modulus ruggedness test factors on dynamic modulus and phase angle for the dense mixture tested in FHWA's Laboratory with the IPC SPT.

Factors	Dynamic Modulus				Phase Angle			
	4 C	20 C	40 C	40 C confined	4 C	20 C	40 C	40C Confined
Equilibrium Temperature (-1 vs +1 C)	**0.02**	**0.00**		**0.03**	**0.00**	**0.06**		0.27
Transfer time (3 vs 5 min)	0.90	0.30		0.11	0.73	0.54		0.56
Conditioning Fluid (Water vs Air)	**0.05**	**0.03**		**0.02**	**0.07**	0.32		0.35
Strain Level	1.00	**0.09**		0.51	0.53	**0.01**		**0.01**
Membrane (No vs Yes)	0.36	0.22		NA	**0.00**	**0.01**		NA
Confinement (135 vs 145 kPa)	NA	NA		0.38	NA	NA		0.29
End Condition (Mill vs Saw)	0.96	0.43		0.13	0.42	0.28		0.20
Friction Reducer (Teflon vs Latex)	0.91	0.88		0.32	0.34	0.13		0.78

Table 13. Significance of dynamic modulus ruggedness test factors on dynamic modulus and phase angle for the SMA mixture tested in FHWA's Laboratory with the IPC SPT.

Factors	Dynamic Modulus				Phase Angle			
	4 C	20 C	40 C	40 C confined	4 C	20 C	40 C	40C Confined
Equilibrium Temperature (-1 vs +1 C)	**0.03**	**0.00**	**0.00**	0.82	0.15	**0.03**	0.36	0.42
Transfer time (3 vs 5 min)	0.50	0.81	0.72	0.28	0.59	0.15	0.46	0.37
Conditioning Fluid (Water vs Air)	0.87	0.80	0.45	**0.00**	0.89	0.43	0.83	**0.04**
Strain Level	0.49	0.49	0.29	0.30	0.78	0.87	0.12	0.88
Membrane (No vs Yes)	0.85	0.74	**0.05**	NA	**0.02**	**0.06**	**0.02**	NA
Confinement (135 vs 145 kPa)	NA	NA	NA	**0.10**	NA	NA	NA	**0.04**
End Condition (Mill vs Saw)	0.39	0.88	0.34	0.72	0.98	0.90	0.78	0.42
Friction Reducer (Teflon vs Latex)	0.62	0.97	0.89	0.62	0.64	0.49	0.29	0.19

the non-homogeneous nature of asphalt mixtures, it is unlikely that the repeatability will improve to that obtained with the dynamic shear rheometer (DSR) on homogeneous asphalt binder samples. The coefficient of variation for DSR measurements on original binder samples is 3.4 percent (*12*). Considering these levels of repeatability, it may be reasonable to expect the coefficient of variation for the dynamic modulus to improve to approximately 8 percent and the standard deviation of the phase angle to improve to 1.5 degrees. Using these limits, the following observations were made concerning the dynamic modulus test:

Table 14. Percentage of times each ruggedness factor was found to be significant.

Factors	Dynamic Modulus	Phase Angle
Equilibrium Temperature (-1 vs +1 °C)	47	33
Transfer time (3 vs 5 min)	0	0
Conditioning Fluid (Water vs Air)	33	13[1]
Strain Level	27	20
Membrane (No vs Yes)	18	54
Confinement (135 vs 145 kPa)	25[2]	50[3]
End Condition (Mill vs Saw)	0	0
Friction Reducer (Teflon vs Latex)	13[4]	0

Notes:

[1] FHWA Laboratory with IPC

[2] SMA in FHWA Laboratory with IPC

[3] SMA only

[4] Dense in AAT Laboratory with ITC

1. Temperature control of ±0.5°C is adequate. This range results in a change in modulus that is less than 6 percent and a change in phase angle that is less than 1 degree.
2. Confining pressure control of ±2 percent is adequate. This range results in a change in modulus that is less than 1 percent and a change in phase angle that is less than 0.5 degrees.
3. Either air or water can be used as a conditioning fluid.
4. Strain control of ±25 μstrain is adequate for unconfined tests, but not for confined tests. For unconfined tests this range results in a change in modulus that is less than 4 percent and a change in phase angle that is less than 1.7 degrees. However for confined tests, the strain control must be improved to ±15 μstrain to keep the effect on the modulus below 8 percent.
5. Unconfined tests can not be performed with the membrane in place. Either the membrane adds a level of confinement that significantly affects the modulus and phase angle at high temperatures or since the instrumentation is mounted

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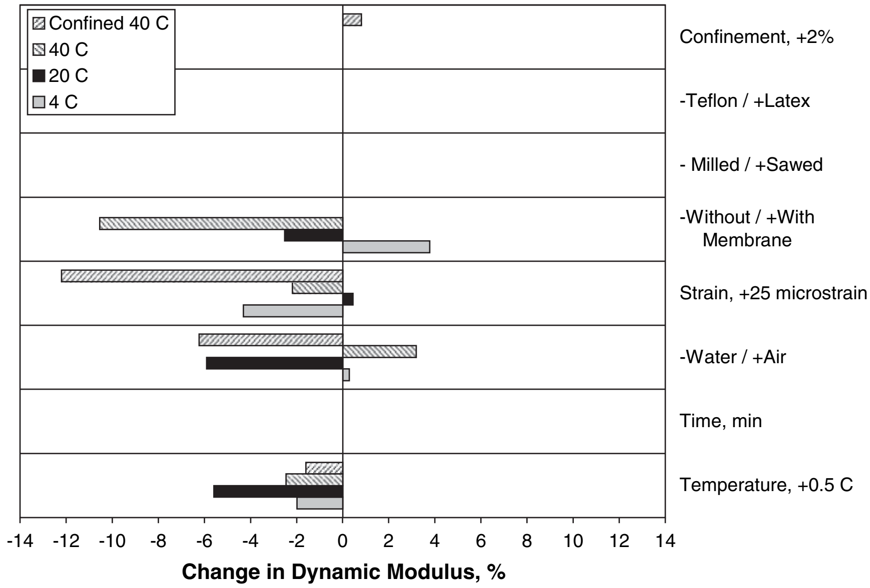

Figure 6. Effect of statistically significant ruggedness factors on the dynamic modulus.

outside the membrane, the membrane affects the deformation measurements.

2.2.2 Factors Affecting Data Quality Indicators

Similar analyses were performed for the data quality indicators. The results are summarized in Table 15 and Table 16 for tests in AAT's laboratory using the ITC equipment and in Table 17 and Table 18 for tests in the FHWA's laboratory using the IPC equipment. Like the tables for modulus and phase angle, these tables present p-values indicating the significance of the regression coefficients for each of the factors included in the ruggedness experiment. Again to highlight the important effects, p-values of 0.10 or less are shown in bold. Table 19 presents a summary table with the percentage of times a specific factor was found to be significant. The notes indicate when a factor was significant for only one laboratory or only one material. Like the measured material properties, the data quality indicators were not affected very often by the ruggedness factors. The sections that follow discuss each of the data quality indicators.

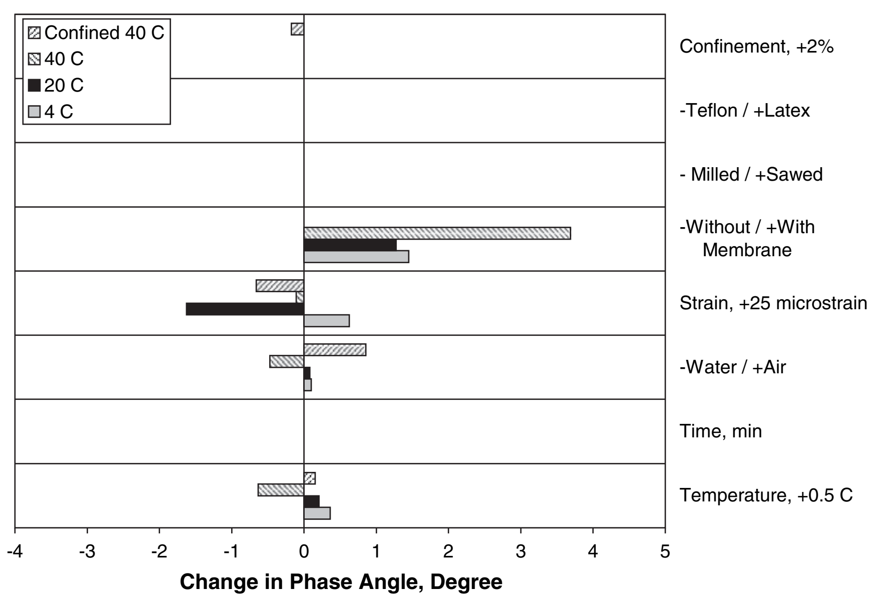

Figure 7. Effect of statistically significant ruggedness factors on the phase angle.

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Table 15. Significance of dynamic modulus ruggedness test factors on data quality indicators for the dense mixture tested in AAT's Laboratory with the ITC SPT.

Factors	Load Standard Error				Deformation Standard Error				Deformation Uniformity				Phase Uniformity			
	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4	20	40	40 C Confined
Equilibrium Temperature	0.67	0.62	0.66	0.85	0.68	**0.05**	**0.09**	0.16	**0.01**	0.50	0.78	0.71	0.98	0.94	0.69	0.97
Transfer time	0.75	0.54	0.79	0.75	0.82	0.61	0.61	0.73	0.15	0.52	0.69	0.70	0.22	0.81	**0.06**	0.76
Conditioning Fluid (Water vs Air)	1.00	0.69	0.20	0.73	0.95	**0.08**	0.54	**0.09**	0.78	0.94	0.17	0.34	0.28	0.51	**0.02**	0.38
Strain Level	**0.06**	0.30	**0.05**	0.45	**0.07**	0.13	**0.09**	**0.05**	**0.01**	0.89	**0.06**	0.74	0.46	0.35	**0.00**	**0.04**
Membrane (No vs Yes)	0.34	**0.10**	0.88	NA	0.25	**0.00**	0.72	NA	0.21	0.99	0.81	NA	0.28	0.35	0.76	NA
Confinement (135 vs 145 kPa)	NA	NA	NA	0.38	NA	NA	NA	0.41	NA	NA	NA	0.32	NA	NA	NA	0.92
End Condition (Mill vs Saw)	0.68	0.32	0.81	0.40	0.78	0.32	0.99	0.46	0.26	0.53	0.21	0.48	0.19	0.31	0.20	0.66
Friction Reducer (Teflon vs Latex)	0.84	0.37	0.56	0.97	0.76	**0.01**	0.94	0.29	0.31	0.37	0.25	0.59	0.95	0.50	0.12	**0.08**

Table 16. Significance of dynamic modulus ruggedness test factors on data quality indicators for the SMA mixture tested in AAT's Laboratory with the ITC SPT.

Factors	Load Standard Error				Deformation Standard Error				Deformation Uniformity				Phase Uniformity			
	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4	20	40	40 C Confined
Equilibrium Temperature	0.70	0.59	0.33	**0.01**	0.64	0.61	0.70	0.74	0.50	**0.07**	0.59	0.24	0.57	0.62	0.32	0.89
Transfer time	0.65	0.74	0.19	0.13	0.70	0.86	**0.07**	0.12	0.87	0.22	0.39	**0.00**	**0.07**	0.23	0.34	0.49
Conditioning Fluid (Water vs Air)	0.58	**0.09**	0.84	0.62	0.51	0.37	0.69	0.28	0.62	0.57	0.78	0.53	0.68	0.91	0.41	0.90
Strain Level	**0.06**	0.22	**0.01**	0.58	**0.08**	0.71	0.85	0.30	0.91	0.86	0.80	0.30	0.69	0.13	0.47	0.60
Membrane (No vs Yes)	0.69	0.54	0.62	NA	0.55	0.17	0.41	NA	0.68	0.84	0.94	NA	0.85	0.47	0.41	NA
Confinement (135 vs 145 kPa)	NA	NA	NA	0.46	NA	NA	NA	0.27	NA	NA	NA	**0.00**	NA	NA	NA	**0.04**
End Condition (Mill vs Saw)	0.62	0.36	0.71	0.16	0.74	0.33	0.89	**0.03**	**0.08**	0.19	0.86	**0.02**	0.92	0.26	0.36	0.52
Friction Reducer (Teflon vs Latex)	0.55	0.29	0.36	0.23	0.71	0.93	0.75	0.30	0.76	0.91	0.24	0.66	**0.07**	0.33	0.30	**0.03**

Table 17. Significance of dynamic modulus ruggedness test factors on data quality indicators for the dense mixture tested in FHWA's Laboratory with the IPC SPT.

Factors	Load Standard Error				Deformation Standard Error				Deformation Uniformity				Phase Uniformity			
	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4	20	40	40 C Confined
Equilibrium Temperature	0.33	**0.01**		0.44	0.98	**0.10**		0.79	0.90	0.76		0.35	0.33	0.53		0.15
Transfer time	0.93	0.42		0.29	0.17	**0.06**		0.62	**0.05**	0.62		0.33	0.57	0.27		**0.10**
Conditioning Fluid (Water vs Air)	0.38	0.47		0.29	0.52	0.19		**0.04**	0.74	0.33		0.38	0.38	0.54		0.86
Strain Level	0.18	**0.00**		0.24	0.33	0.14		0.43	0.26	0.87		0.73	0.46	0.51		**0.03**
Membrane (No vs Yes)	0.93	0.11		NA	0.65	0.39		NA	0.92	0.81		NA	**0.06**	0.21		NA
Confinement	NA	NA		0.28	NA	NA		0.65	**NA**	NA		0.16	NA	NA		0.37
End Condition (Mill vs Saw)	0.54	0.16		0.40	**0.08**	0.64		0.17	**0.07**	0.16		0.72	0.84	0.12		**0.02**
Friction Reducer (Teflon vs Latex)	0.53	0.11		0.30	0.42	0.79		0.34	0.27	0.62		0.34	0.31	0.18		0.17

Table 18. Significance of dynamic modulus ruggedness test factors on data quality indicators for the SMA mixture tested in FHWA's Laboratory with the IPC SPT.

Factors	Load Standard Error				Deformation Standard Error				Deformation Uniformity				Phase Uniformity			
	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4 C	20 C	40 C	40 C Confined	4	20	40	40 C Confined
Equilibrium Temperature	**0.06**	**0.08**	**0.00**	**0.09**	0.91	0.31	**0.00**	0.88	0.67	0.55	**0.10**	0.83	0.30	0.24	0.67	0.68
Transfer time	0.14	0.26	**0.03**	0.90	0.22	0.78	0.85	0.13	0.60	0.90	0.68	0.49	0.48	0.43	0.80	0.97
Conditioning Fluid (Water vs Air)	0.16	0.42	**0.01**	**0.00**	0.52	0.16	**0.01**	**0.03**	0.98	**0.10**	**0.08**	0.80	0.67	0.75	0.56	0.77
Strain Level	0.18	**0.08**	**0.00**	**0.00**	0.29	**0.04**	0.63	0.95	1.00	0.35	0.14	0.45	0.29	0.77	0.79	0.96
Membrane (No vs Yes)	0.67	0.49	**0.00**	NA	0.26	0.71	**0.00**	NA	0.24	0.19	0.21	NA	**0.09**	0.22	0.38	NA
Confinement	NA	NA	NA	**0.01**	NA	NA	NA	0.76	NA	NA	NA	0.69	NA	NA	NA	0.72
End Condition (Mill vs Saw)	0.57	0.97	**0.03**	0.44	0.83	0.25	0.75	0.44	0.26	0.83	0.90	0.65	0.26	0.54	0.75	0.96
Friction Reducer (Teflon vs Latex)	0.60	0.53	0.19	0.11	0.78	0.67	0.83	0.55	0.49	0.41	0.51	0.62	0.33	0.65	0.73	0.33

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Table 19. Percentage of times each ruggedness factor was found to be significant.

	Load Standard Error	Deformation Standard Error	Deformation Uniformity	Phase Uniformity
Equilibrium Temperature	40	27	20	0
Transfer time	7[1]	13	13	20[2]
Conditioning Fluid (Water vs Air)	20	33	13[1]	7[2]
Strain Level	53	40	13[2]	20
Membrane (No vs Yes)	18[2]	18	0	18[1]
Confinement	25[1]	0	0	25[2]
End Condition (Mill vs Saw)	7[1]	13	20	7[1]
Friction Reducer (Teflon vs Latex)	0	7[2]	0	20[2]

Notes:
[1] SMA Mixture in FHWA Laboratory with IPC
[2] AAT Laboratory with ITC

2.2.2.1 Load Standard Error

The load standard error is a measure of how well the SPT applies a sinusoidal loading to the specimen. During Phase II of this project, a maximum load standard error of 10 percent was associated with good quality data (*11*). For the load standard error, transfer time, end condition, and friction reducers did not appear to affect the results. The effects of the remaining factors are shown in Figure 8. Although some ruggedness factors were statistically significant, it is clear from Figure 8 that these have only a minor effect on the load standard error when the allowable range of 10 percent is considered.

2.2.2.2 Deformation Standard Error

The deformation standard error is a measure of how close the deformations measured in the SPT are to a sinusoid. During Phase II of this project a maximum deformation standard error of 10 percent was associated with good quality data (*11*). For the deformation standard error, transfer time, confinement, end condition, and friction reducers did not appear to affect the results. The effects of the remaining factors are shown in Figure 9. From Figure 9, it is clear that the deformation standard error for high-temperature tests is higher when water is used as the conditioning fluid and when the unconfined dynamic modulus is measured with the membrane in place. These two conditions should, therefore, be avoided.

2.2.2.3 Deformation Uniformity

The deformation uniformity is a measure of how close the individual deformation measurements made on a sample

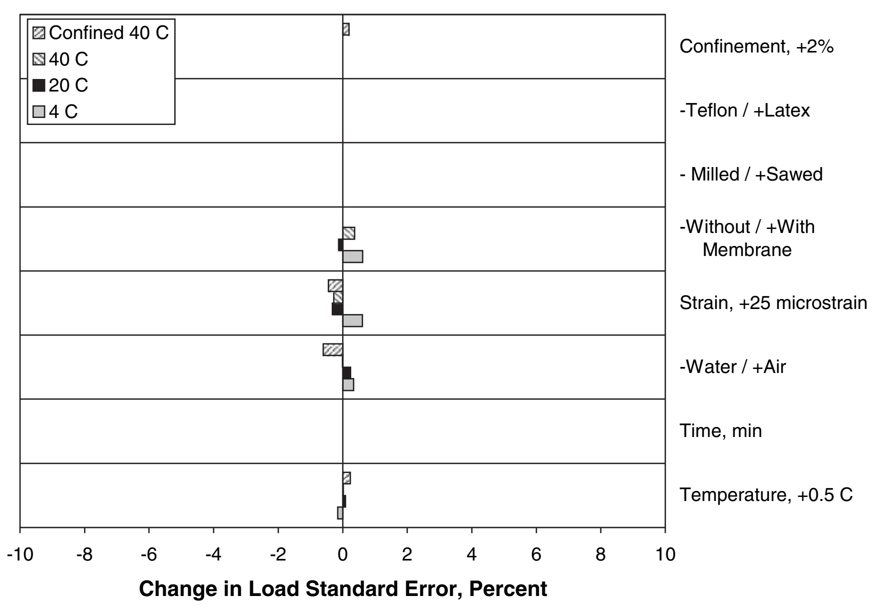

Figure 8. Effect of statistically significant ruggedness factors on the load standard error.

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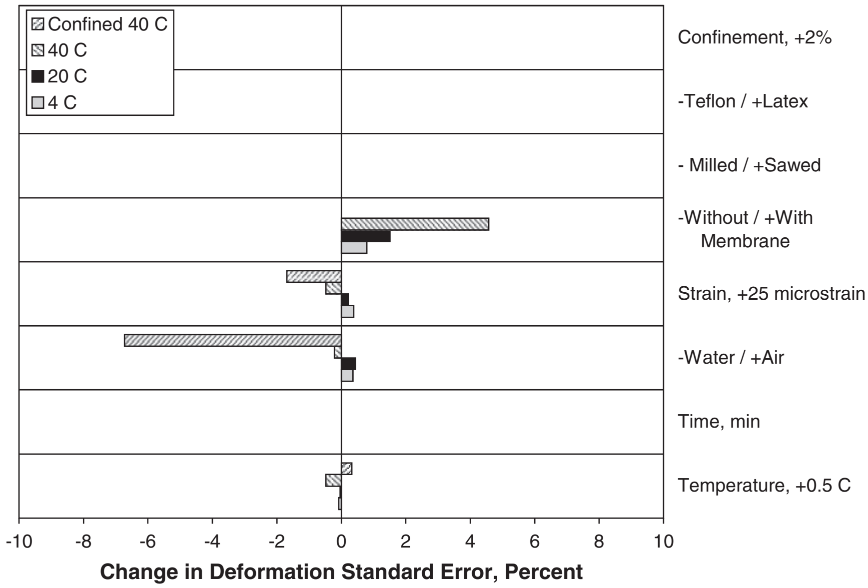

Figure 9. Effect of statistically significant ruggedness factors on the deformation standard error.

agree with one another. During Phase II of this project a maximum deformation uniformity of 20 percent was associated with good quality data (*11*). For the deformation uniformity, only the temperature and end condition were found to be statistically significant. Figure 10 shows the effect of these two factors on the deformation uniformity. The temperature effect is small considering the allowable value of 20 percent for good quality data. The end condition effect is larger, but not consistent over the temperature ranges. For unconfined tests at 4°C and confined tests at 40°C, the data from milled ends are more variable. On the other hand, the data from the sawed ends are more variable in the unconfined tests at 20°C and 40°C. Thus, the effects of the ruggedness factors on the deformation uniformity are small and not consistent.

2.2.2.4 Phase Uniformity

The phase uniformity is a measure of how close the individual phase angle measurements made on a sample agree with one another. During Phase II of this project a maximum phase uniformity of 3 degrees was associated with good quality

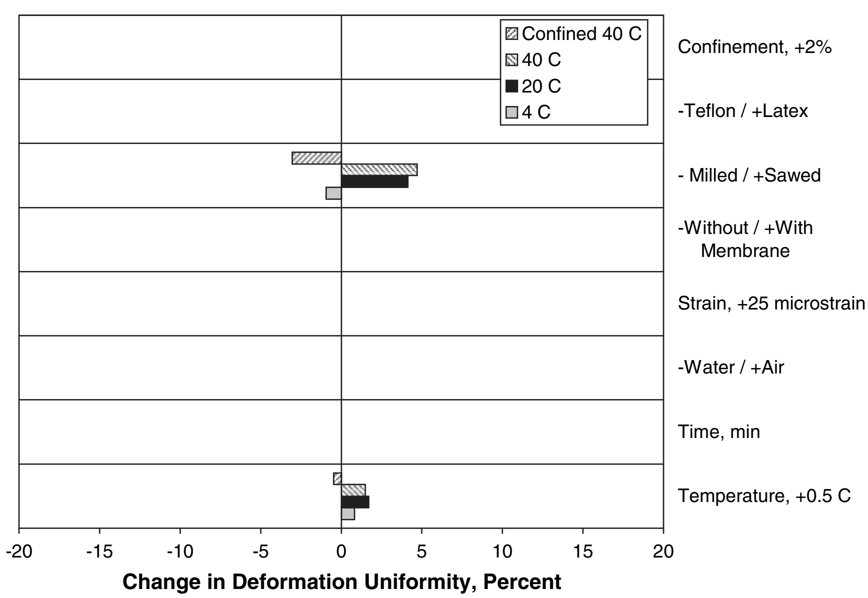

Figure 10. Effect of statistically significant ruggedness factors on the deformation uniformity.

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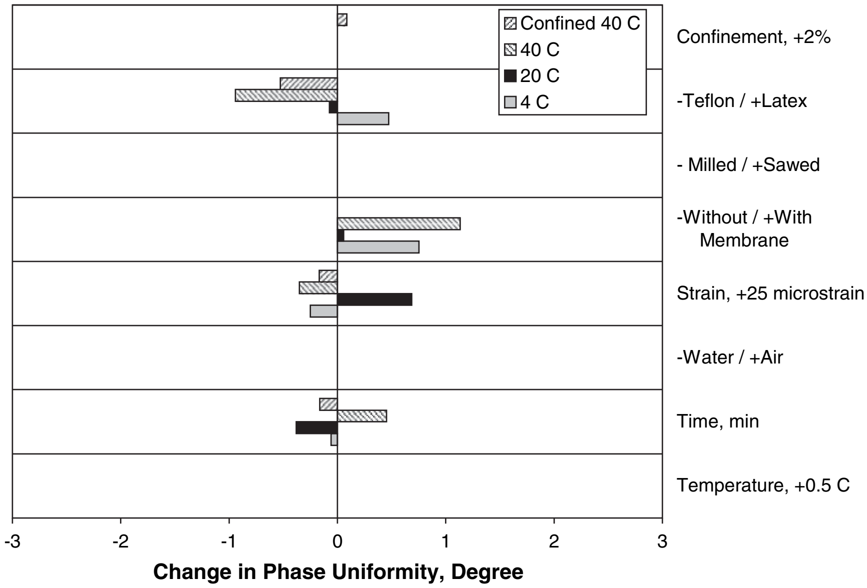

Figure 11. Effect of statistically significant ruggedness factors on the phase uniformity.

data (*11*). For phase uniformity, temperature, conditioning fluid, and end condition did not appear to affect the results. Figure 11 shows the effect of the remaining factors on the phase uniformity. The effects are generally small and not consistent over the testing conditions, except for the membrane effect. Phase angles are more variable in unconfined tests when the membrane is used.

2.2.3 Summary

Table 20 summarizes the results of the analysis of the ruggedness test data for the dynamic modulus test. For statistically significant ruggedness factors, Table 20 presents the effect of the factor on the measured modulus and phase angle and the data quality indicators. Table 20 also presents acceptable values based on anticipated test variability. The following conclusions were drawn for each of the ruggedness factors:

1. **Equilibrium temperature.** The current temperature control of ±0.5°C in SPT is acceptable. Temperature changes over this level are expected to result in less than a 6 percent change in the dynamic modulus and less than a 0.6 degree change in the phase angle.

2. **Transfer time.** The transfer time over the range of 3 to 5 min was not found to be a significant factor in the measured material properties, and had only a minor effect on the data quality. The transfer time can be increased to 5 min.

3. **Conditioning fluid.** The use of water as a conditioning fluid results in significantly poorer quality test data for confined test conditions. Air should, therefore, be used as the

Table 20. Summary of the effect of ruggedness test factors on material properties and data quality indicators in the dynamic modulus test.

Factors	Control	Dynamic Modulus	Phase Angle	Load Standard Error	Deformation Standard Error	Deformation Uniformity	Phase Uniformity
Equilibrium Temperature	0.5 °C	< 6 %	< 0.6 °	< 0.5 %	< 0.5 %	< 2 %	NS
Transfer Time	3 versus 5 min	NS	NS	NS	NS	NS	< 0.5 °
Conditioning Fluid	Air versus Water	< 6 %	< 1 °	< 0.6 %	< 0.5 % unconfined <7 % confined	NS	NS
Strain Level	25 μstrain	< 4 % unconfined < 12 % confined	< 1.6 °	< 0.6 %	< 0.5 % unconfined <1.7 % confined	NS	< 0.7 °
Membrane	Without versus With	< 11 percent	3.7 °	< 0.6 %	< 4.6 %	NS	< 1.1 °
Confinement	2 %	< 0.8 %	< 0.2 °	< 0.2 %	NS	NS	< 0.1 °
End Condition	Milled versus Sawed	NS	NS	NS	NS	< 4.7 %	NS
Friction Reducer	Greased Latex versus Teflon	NS	NS	NS	NS	NS	< 0.9 °
Acceptable		8 %	1.7 °	5 %	5 %	10 %	1.5 °

NS = not statistically significant

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conditioning fluid. If the specimens are to be conditioned in a water bath, they should be sealed in plastic to keep the water from penetrating the specimen.

4. Strain level. The current strain control of ±25 μstrain is acceptable for unconfined tests. However, the strain control should be improved to ±15 μstrain to accommodate confined testing which may be necessary for some mixture types.

5. Membrane. Unconfined tests should not be performed with the membrane on the specimen. The membrane increases the dynamic modulus and phase angle for moderate to high temperature tests. It also significantly reduces the quality of the deformation and phase angle data.

6. Confinement. The current confining pressure control of ±2 percent is acceptable in confined tests. Over this range of control, the dynamic modulus and phase angle are expected to vary by 0.8 percent and 0.2 degrees, respectively.

7. End condition. There was no significant difference in the measured material properties between milled specimen ends and sawed specimen ends. The effect of end condition on the data quality was small and not consistent. The use of sawed specimen ends is acceptable for dynamic modulus tests in the SPT.

8. Friction reducer. There was no significant difference in the measured material properties between greased latex and Teflon™ as the end friction reducer. The effect of the friction reducer on the data quality was small and not consistent. The use of either greased latex of Teflon™ as the end friction reducer is acceptable for dynamic modulus tests in the SPT.

2.3 Flow Number Test

The results of the flow number ruggedness testing are presented in Appendix B. The flow number ruggedness experiment included the factors listed in Table 7. The responses measured in the flow number ruggedness experiment included the flow number and the permanent strain after selected number of load cycles. Flow did not occur in all of the confined tests. Table 21 summarizes the data that was analyzed for the flow number tests.

Regression equations of the form of Equation 1 were developed for each of the marked cells in Table 21. The results are presented in Table 22 and Table 23 for the unconfined tests on the dense graded mixture; Table 24 and Table 25 for the confined tests on the dense graded mixture; and Table 26 and Table 27 for the confined tests on the SMA mixture. Each table presents p-values indicating the significance of the regression coefficients for each of the factors included in the ruggedness experiment. As discussed previously for the dynamic modulus, low p-values indicate the regression coefficient is statistically significant and the ruggedness factor affects the results of the test. A critical p-value of 0.10 was used in this analysis. Factors with p-values equal to or less than 0.1 are shown in bold in Table 22 through Table 27.

Table 28 and Table 29 were constructed to combine the results for the tests in both laboratories. These tables present the percentage of times a specific factor was found to be significant. Table 28 presents the results for the unconfined tests, while Table 29 presents the results for the confined tests. The sections that follow discuss the results for the flow number and the measured permanent strains.

Table 21. Flow number test data.

Parameter	Dense Unconfined	Dense Confined	SMA Confined
Flow Number	X		
ε_p at 500 cycles	X	X	X
ε_p at 1000 cycles	X	X	X
ε_p at 2000 cycles	X	X	X
ε_p at 5000 cycles			X
ε_p at 8000 cycles			X

Table 22. Significance of flow number ruggedness test factors for unconfined tests with the ITC SPT on the dense mixture.

Factors	Flow Number	Permanent Strain at 500 cycles	Permanent Strain at 1000 cycles	Permanent Strain at 2000 cycles
Equilibrium Temperature (-1 vs +1 C)	**0.06**	0.51	0.22	**0.05**
Transfer time (3 vs 5 min)	0.26	0.87	0.93	0.66
Conditioning Fluid (Water vs Air)	0.64	**0.06**	**0.02**	**0.02**
End Condition (Mill vs Saw)	0.29	**0.02**	**0.02**	**0.04**
Friction Reducer (Teflon vs Latex)	**0.02**	0.94	0.42	**0.03**
Axial Stress (135 vs 145 kPa)	0.14	0.80	0.43	0.12
Contact Stress (5 vs 10 kPa)	0.63	0.30	0.27	0.35

2.3.1 Factors Affecting Flow Number

In order to analyze the flow number, all specimens tested in both laboratories must exhibit flow. Flow occurred in all of the unconfined tests on the dense-graded mixture and about 25 percent of the confined tests on the dense-graded mixture.

Table 23. Significance of flow number ruggedness test factors for unconfined tests with the IPC SPT on the dense mixture.

Factors	Flow Number	Permanent Strain at 500 cycles	Permanent Strain at 1000 cycles	Permanent Strain at 2000 cycles
Equilibrium Temperature (-1 vs +1 C)	**0.03**	0.31	0.23	0.33
Transfer time (3 vs 5 min)	0.76	0.14	0.26	0.44
Conditioning Fluid (Water vs Air)	0.74	0.22	0.15	0.18
End Condition (Mill vs Saw)	0.99	**0.07**	0.26	0.79
Friction Reducer (Teflon vs Latex)	0.39	0.29	0.25	0.22
Axial Stress (135 vs 145 kPa)	0.98	0.77	0.74	0.64
Dwell Time (0.85 vs 0.95 sec)	0.30	0.69	0.67	0.55

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Table 24. Significance of flow number ruggedness test factors for confined tests with the ITC SPT on the dense mixture.

Factors	Flow Number	Permanent Strain at 500 cycles	1000 cycles	2000 cycles
Equilibrium Temperature (-1 vs +1 C)		**0.02**	**0.01**	**0.00**
Transfer time (3 vs 5 min)		0.14	**0.07**	**0.02**
Conditioning Fluid (Water vs Air)		0.37	0.43	0.53
End Condition (Mill vs Saw)		0.12	0.12	**0.05**
Friction Reducer (Teflon vs Latex)		**0.01**	**0.00**	**0.00**
Axial Stress (945 vs 985 kPa)		**0.07**	**0.05**	**0.02**
Confining Stress (135 vs 145 kPa)		0.21	**0.09**	**0.02**

Table 25. Significance of flow number ruggedness test factors for confined tests with the IPC SPT on the dense mixture.

Factors	Flow Number	Permanent Strain at 500 cycles	1000 cycles	2000 cycles
Equilibrium Temperature (-1 vs +1 C)		0.45	0.32	0.26
Transfer time (3 vs 5 min)		0.39	.030	0.28
Conditioning Fluid (Water vs Air)		0.58	0.82	0.95
End Condition (Mill vs Saw)		**0.01**	**0.06**	0.23
Friction Reducer (Teflon vs Latex)		**0.08**	**0.10**	0.11
Axial Stress (945 vs 985 kPa)		0.79	0.56	0.46
Confining Stress (135 vs 145 kPa)		0.35	0.39	0.41

Table 28. Significance of flow number ruggedness test factors on unconfined tests.

Factors	Flow Number	500 cycles	1000 cycles	2000 cycles
Equilibrium Temperature (-1 vs +1 C)	100	0	0	50
Transfer time (3 vs 5 min)	0	0	0	0
Conditioning Fluid (Water vs Air)	0	50	50	50
End Condition (Mill vs Saw)	0	100	50	50
Friction Reducer (Teflon vs Latex)	50	0	0	50
Axial Stress (135 vs 145 kPa)	0	0	0	0
Contact Stress (5 vs 10 kPa)[1]	0	0	0	0
Dwell[2]	0	0	0	0

Notes:
[1] ITC only
[2] IPC only

None of the SMA specimens exhibited flow in the confined tests.

Only temperature and end friction reducer were found to have a statistically significant effect on the flow number in unconfined tests. Figure 12 shows the effect of these two factors. For temperature the flow number decreases by 7.5 percent for an increase in temperature of 0.5°C while the flow number is 20 percent higher when Teflon™ is used as the end friction reducer. As expected, increasing temperature decreases the flow number. Apparently the Teflon™ end friction reducer is less effective than the greased latex membranes resulting in greater end friction and a higher flow number.

Table 26. Significance of flow number ruggedness test factors for confined tests with the ITC SPT on the SMA mixture.

Factors	Flow Number	Permanent Strain at 500 cycles	1000 cycles	2000 cycles	5000 cycles	8000 cycles
Equilibrium Temperature (-1 vs +1 C)		0.29	0.33	0.48	0.88	0.87
Transfer time (3 vs 5 min)		0.34	0.35	0.38	0.34	0.40
Conditioning Fluid (Water vs Air)		0.79	0.94	0.88	0.75	0.59
End Condition (Mill vs Saw)		0.77	0.94	0.92	0.80	0.71
Friction Reducer (Teflon vs Latex)		**0.02**	**0.07**	0.21	0.42	0.42
Axial Stress (945 vs 985 kPa)		0.88	0.85	0.68	0.74	0.98
Confining Stress (135 vs 145 kPa)		0.25	0.25	0.37	0.65	0.37

Table 27. Significance of flow number ruggedness test factors for confined tests with the IPC SPT on the SMA mixture.

Factors	Flow Number	Permanent Strain at 500 cycles	1000 cycles	2000 cycles	5000 cycles	8000 cycles
Equilibrium Temperature (-1 vs +1 C)		0.70	0.71	0.52	0.63	0.77
Transfer time (3 vs 5 min)		0.84	0.86	0.50	0.31	0.41
Conditioning Fluid (Water vs Air)		0.98	0.40	0.26	0.49	0.80
End Condition (Mill vs Saw)		0.71	0.82	0.93	0.66	0.89
Friction Reducer (Teflon vs Latex)		**0.00**	**0.00**	**0.01**	**0.08**	**0.07**
Axial Stress (945 vs 985 kPa)		0.19	0.24	0.28	0.48	0.74
Confining Stress (135 vs 145 kPa)		**0.05**	**0.05**	0.14	0.40	0.53

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Table 29. Summary of significance of ruggedness test factors on confined tests.

Factors	Permanent Strain at 500 cycles	1000 cycles	2000 cycles	5000* cycles	8000* cycles
Equilibrium Temperature (-1 vs +1 C)	25	25	25	0	0
Transfer time (3 vs 5 min)	0	25	25	0	0
Conditioning Fluid (Water vs Air)	0	0	0	0	0
End Condition (Mill vs Saw)	25	25	25	0	0
Friction Reducer (Teflon vs Latex)	100	100	50	50	50
Axial Stress (± 2 %)	25	25	25	0	0
Confining Stress (135 vs 145 kPa)	25	50	25	0	0

* SMA only

Data on the repeatability of the flow number test were collected in Phase II of this project (*11*). The Phase II experiment included eight replicates of two mixtures tested by single operators in two laboratories. Laboratory and mixture effects were found to not be significant, therefore, the 32 observations were pooled to obtain estimates of the repeatability of the flow number. The coefficient of variation for the flow number from the Phase II analysis was found to be 35 percent while the coefficient of variation for the measured permanent strain was found to be only 14 percent. The high variability of the flow number was attributed to difficulties detecting the exact point where the permanent strain rate begins to increase. Future improvements may be made to the flow point detection algorithm, but it is unlikely that the repeatability of the flow number will be less than that for the measured permanent strain. Based on this analysis, the temperature control of ±0.5°C is acceptable. However, flexibility can not be permitted in the selection of the end friction reducer. Since the greased latex membranes provide less friction and were recommended in Project 9-19, these friction reducers should be used in the flow number testing.

2.3.2 Factors Affecting Permanent Strain

Figure 13 through Figure 17 show the effects of the significant ruggedness factors on the permanent strain measured after 500, 1,000, 2,000, 5,000, and 8,000 cycles, respectively. The analysis for the permanent strain can only be performed when data are available for all specimens tested in both labs. The dense graded mixture specimens began to fail after 2,000 cycles. The SMA mixture specimens began to fail after 8,000 cycles.

Considering the permanent strain measured in the flow number test has a coefficient of variation of 14 percent, several observations can be made based on the data shown in Figure 13 through Figure 17. First, the machine control factors of temperature, axial stress, contact stress, dwell time, and confining pressure have little effect on the measured permanent strains over the control range provided by the SPT. Also

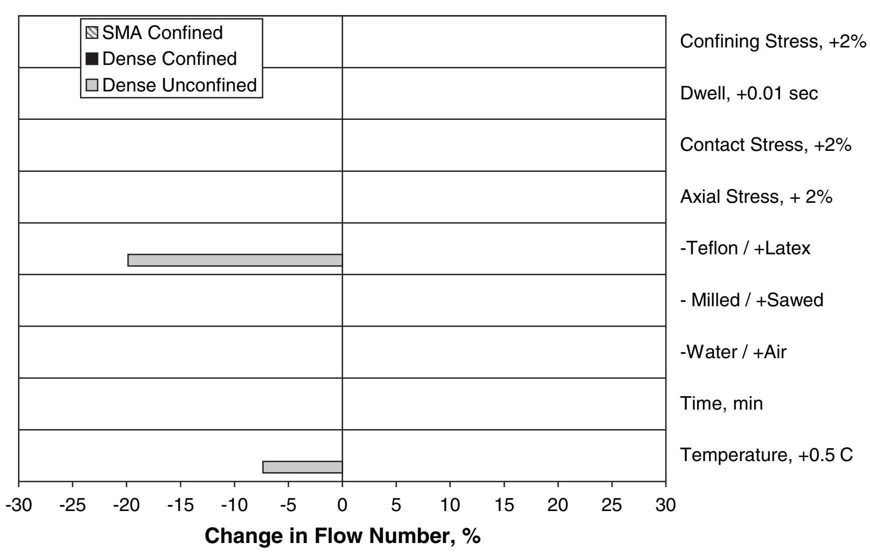

Figure 12. Effect of statistically significant ruggedness factors on the flow number.

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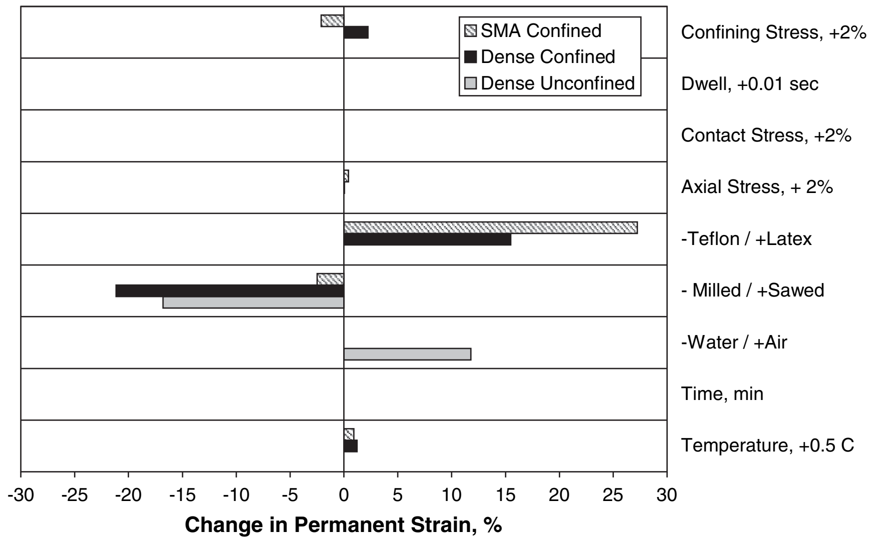

Figure 13. Effect of statistically significant ruggedness factors on the permanent strain after 500 load cycles.

the transfer time has little effect on the measured permanent strains over the range of 3 to 5 min. However, the three user-selectable factors, conditioning fluid, end condition, and end friction reducer, have a major effect on the measured permanent strains.

In unconfined tests, the permanent strain was much higher when water was used as the conditioning fluid. Recall, the dense-graded mixture that was used had marginal resistance to moisture damage when tested in accordance with AASHTO T283. Apparently water that penetrates the voids in this mixture results in some level of moisture damage during the repeated load test. The conditioning fluid was not significant in the confined tests, probably because less water entered the specimens because these specimens were conditioned with the confining membrane in-place. Although the ends were uncovered, the path for water infiltration from the ends is much longer resulting in less water absorption by the specimen during conditioning. Clearly, water can not be used as a conditioning fluid in the flow number test.

The measured permanent strains are higher when greased latex membranes are used as end friction reducers. Apparently this type of end friction reducer is more effective than Teflon™ resulting in less end friction and greater permanent deformation in the test. Flexibility can not be permitted in the selection of the end friction reducer. Since the greased latex membranes provide less friction and were specified in Project 9-19, these friction reducers should be used in the flow number testing.

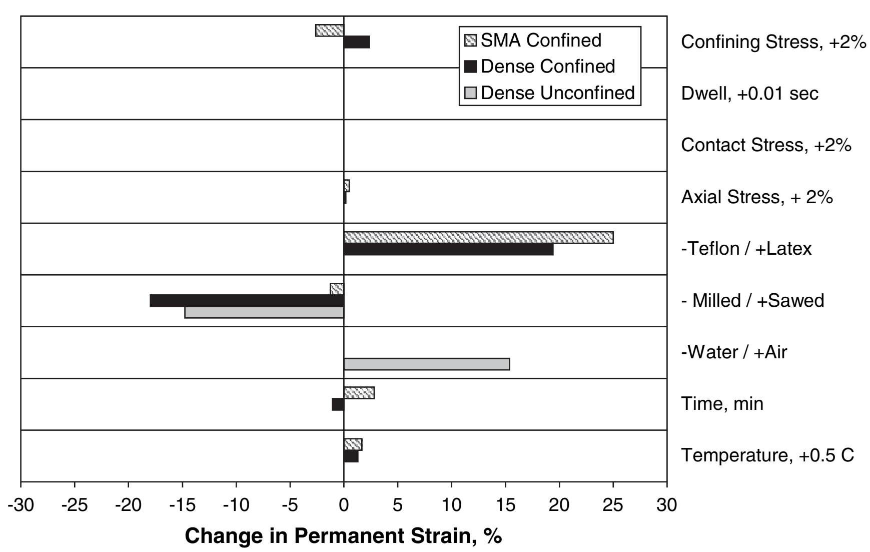

Figure 14. Effect of statistically significant ruggedness factors on the permanent strain after 1,000 load cycles.

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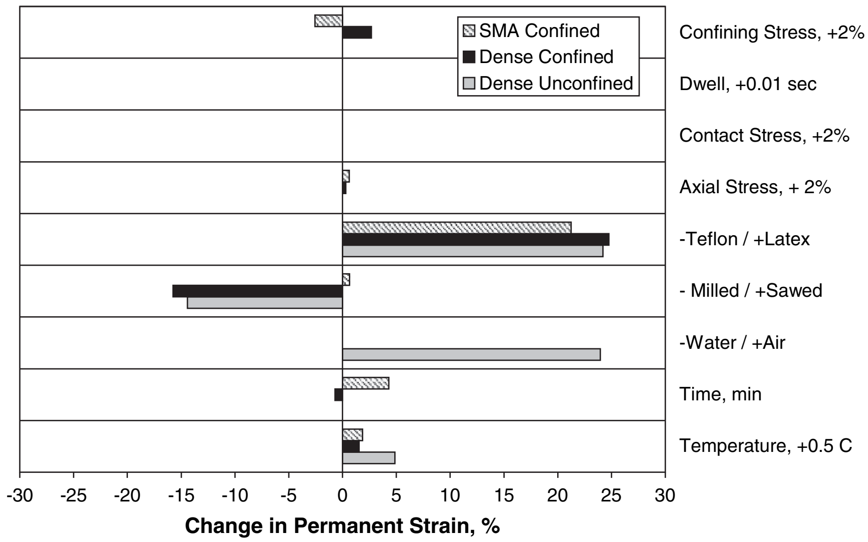

Figure 15. Effect of statistically significant ruggedness factors on the permanent strain after 2,000 load cycles.

The specimen end condition also has a major effect on the measured permanent strains in the dense-graded mixture, but not the SMA mixture. Dense-graded specimens with milled ends had consistently higher permanent strains. Apparently, the smooth, milled ends of dense-graded mixture further reduced end friction resulting in an increase in permanent deformation. Because end milling is time consuming sawed ends meeting the specimen end condition requirements in the Equipment Specification for the Simple Performance Test System should be used.

2.3.3 Summary

Table 30 summarizes the results of the analysis of the ruggedness test data for the flow number test. For statistically significant ruggedness factors, Table 30 presents the effect of the factor on the flow number and the measured permanent strains after 2,000 load cycles. Table 30 also presents acceptable values based on anticipated test variability. The following conclusions were drawn for each of the ruggedness factors:

1. Equilibrium temperature. The current temperature control of ±0.5°C in the SPT is acceptable. Temperature changes over this level are expected to result in less than a 7 percent change in the flow number and less than a 5 percent change in the permanent strain.

2. Transfer time. The transfer time over the range of 3 to 5 min was found to be a significant factor only for the

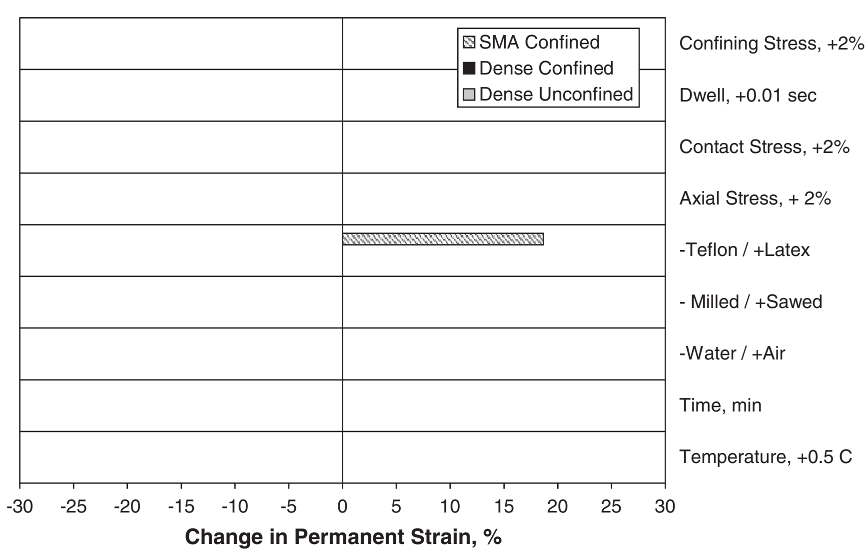

Figure 16. Effect of statistically significant ruggedness factors on the permanent strain after 5,000 load cycles.

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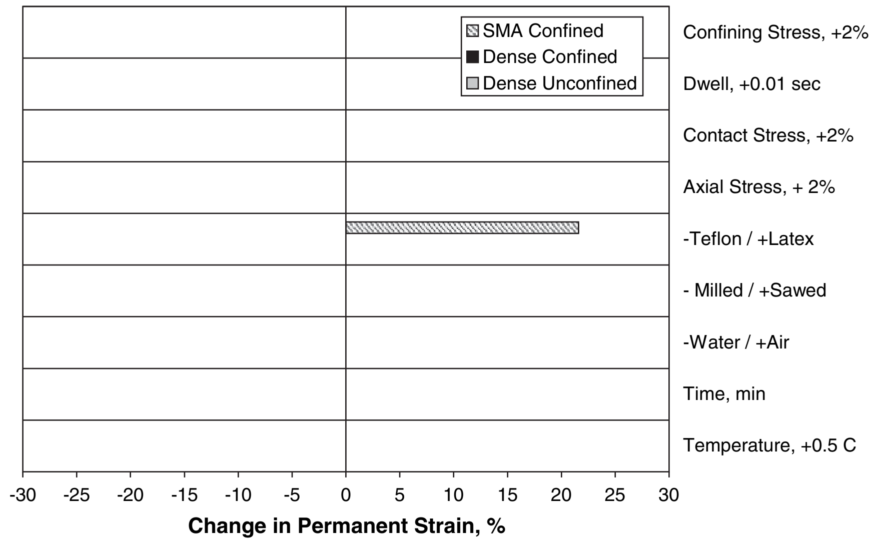

Figure 17. Effect of statistically significant ruggedness factors on the permanent strain after 8,000 load cycles.

permanent strains in the confined tests. Increasing transfer time to 5 minutes is expected to result in no change to the flow number and less than a 4 percent change in the measured permanent strain. Based on an acceptable range of 7 percent which is one-half of the coefficient of variation of the flow number test, the transfer time can be increased to 5 min.

3. Conditioning fluid. The use of water as a conditioning fluid can result in moisture damage in the specimen during repeated loading if sufficient water penetrates the specimen. Air should, therefore, be used as the conditioning fluid. If the specimens are to be conditioned in a water bath, they should be sealed in plastic to keep the water from penetrating the specimen.

4. End condition. The method of preparing the specimen ends had a major effect on the permanent strain measured in both unconfined and confined tests. Milled ends resulted in larger permanent deformations for the dense-graded mixture probably because end friction was less with the smoother milled end. Because end milling is time consuming sawed ends meeting the specimen end condition requirements in the Equipment Specification for the Simple Performance Test System should be used.

5. Friction reducer. Of all the factors included in the ruggedness testing, the end friction reducer had the greatest effect on the flow number and the measured permanent deformation. Flow numbers were much lower and permanent deformation much higher when the greased latex friction reducer

Table 30. Summary of the effect of ruggedness test factors on the flow number and permanent strain.

Factors	Control	Unconfined		Confined	
		Flow Number	ε_p, 2000 cycles	Flow Number	ε_p, 2000 cycles
Equilibrium Temperature	0.5 °C	< 7 %	< 5 %	NF	< 2%
Transfer time	3 versus 5 min	NS	NS	NF	< 4%
Conditioning Fluid	Air versus Water	NS	< 24 %	NF	NS
End Condition	Milled versus Sawed	NS	< 14 %	NF	< 15 %
Friction Reducer	Greased Latex versus Teflon	< 20 %	< 24 %	NF	< 25 %
Axial Stress	2 %	NS	NS	NF	< 1%
Contact Stress	2 %	NS	NS	NA	NA
Dwell	0.01 sec	NS	NS	NA	NA
Confinement	2 %	N A	NA	NF	< 3 %
Acceptable		10 %	7 %	10 %	7 %

NA = not included
NF = no flow detected
NS = not statistically significant

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was used. Flexibility can not be permitted in the selection of the end friction reducer. Since the greased latex membranes provide less friction and were specified in Project 9-19, these friction reducers should be used in the flow number testing.

6. Axial stress. The axial stress control of ±2 percent in the SPT is acceptable. Stress variations over this level are expected to result in no change in the flow number and less than a 1 percent change in the permanent strain.

7. Contact stress. The contact stress control of ±2 percent in the SPT is acceptable. Stress variations over this level had no significant effect on the flow number or the measured permanent strains.

8. Dwell time. Data from the flow number test was not affected by a range in dwell time of 0.1 sec. The computer control used in the SPT is capable of controlling the dwell time much more precisely at this level.

9. Confinement. The current confining pressure control of ±2 percent is acceptable in confined tests. Over this range of control, the permanent strain is expected to vary by less than 3 percent.

CHAPTER 3

Results and Analysis of Equipment Effects Experiment

3.1 Introduction

The equipment effects experiment was designed to investigate differences in dynamic modulus and flow number test data from SPTs built by the three suppliers selected for NCHRP Project 9-29. The experiment was designed as a full factorial where four independent specimens of the dense-graded mixture were tested in each device. This experimental design is conveniently analyzed using standard analysis of variance techniques.

The basic design for the equipment effects experiment was repeated for selected testing conditions. The testing conditions were selected to examine the range of capabilities of the equipment. For the dynamic modulus test, unconfined tests were conducted for 10 combinations of temperature and frequency. Confined tests were conducted only at high temperature using four frequencies. Table 31 summarizes the testing conditions used in the dynamic modulus test. The responses considered in the analysis of variance were the dynamic modulus and phase angle.

Flow number tests were conducted for unconfined and confined conditions. Table 32 summarizes the testing conditions used. The responses considered in the analysis were the measured permanent strain for each load cycle, and the flow number for the unconfined tests. Flow did not occur in the confined tests.

To minimize variability associated with specimen fabrication and testing, all specimens were fabricated by the same technician, then grouped to obtain the same average air void contents for specimens tested in the three machines. Table 33 and Table 34 summarize the air void contents for the specimens used in the dynamic modulus and flow number testing, respectively. The same experienced technician performed all of the tests. Tests with the IPC equipment were performed at the Turner-Fairbank Highway Research Center. Tests with the ITC and MDTS equipment were performed at AAT.

3.2 Dynamic Modulus

Dynamic modulus data were collected with each machine beginning at the lowest temperature and proceeding to the highest. At each temperature, the testing proceeded from the highest frequency to the lowest. At the highest temperature, the unconfined tests were performed before the confined tests. Initial graphical review of the data revealed several problems that required equipment modifications to be made by the manufacturers as discussed below.

3.2.1 Equipment Modifications

3.2.1.1 MDTS

Dynamic modulus data initially collected with the MDTS equipment were consistently 30 percent lower than that collected with the other machines. Several possible causes were investigated. This investigation led to the conclusion that the lower dynamic moduli were the result of the size of the gauge points used with the MDTS equipment. The gauge points used with this equipment exceed the size given in the specification. Apparently, the dynamic modulus test is sensitive to the size of the glued gauge point, with larger gauge points resulting in shorter effective gauge lengths and lower modulus values. The MDTS gauge points were reduced in size by grinding some of the material from the top and bottom, and the dynamic modulus tests were repeated. The modulus values at low and moderate temperatures improved. However, at high temperatures, there was not sufficient contact area to resist the moment caused by the spring force in the LVDT, and the gauge points were pried off of the specimen by the LVDT spring force.

Based on these observations, MDTS decided to completely redesign the specimen-mounted LVDT system. The redesigned system uses an LVDT in a holder that is magnetically attached to the gauge points on the specimen. With this system the moment caused by the LVDT spring force is significantly reduced. The dynamic modulus tests were repeated

Table 31. Testing conditions for the dynamic modulus equipment effects experiment.

Confining Pressure, kPa	Temperature, °C	Frequency, Hz
0	10	10
0	10	1
0	10	0.1
0	20	10
0	20	1
0	20	0.1
0	35	10
0	35	1
0	35	0.1
0	35	0.01
135	35	10
135	35	1
135	35	0.1
135	35	0.01

Table 33. Air void content for specimens used in the dynamic modulus testing.

Machine	Specimen	Air Voids, %	Average Air Voids, %
ITC	109	6.0	6.0
	114	6.1	
	115	5.9	
	118	5.8	
IPC	111	6.5	6.2
	112	6.2	
	117	5.8	
	119	6.2	
MDTS	110	6.2	6.1
	113	6.1	
	116	6.1	
	120	5.9	

using this system and these results were included in the analysis presented below.

3.2.1.2 ITC

The ITC equipment could not accurately control the loading rate for the 0.01 Hz tests at high temperatures. This problem was traced to the algorithm that ITC used to control sinusoidal loading. The method becomes less accurate as the frequency and amplitude of the sinusoidal loading decrease. Very low load levels are required during dynamic modulus testing at 0.01 Hz at high temperatures. ITC modified the control software to use a different control algorithm for low frequency loading. The high temperature testing was repeated and used in the analysis presented below.

3.2.1.3 IPC

Initial graphical analysis of the dynamic modulus data including the repeated tests with the MDTS and IITC equipment revealed that the high temperature, 0.1 and 0.01 Hz test results from the IPC equipment were much lower than those obtained with the other equipment. Further review of the data showed that the LVDT drift measured at these combinations of temperature and frequency was in the opposite direction of the applied load, indicating that the LVDT spring force was pushing the gauge points apart. The drift computation used in reducing the dynamic modulus data is intended to remove the creep caused by the non-zero mean stress that occurs in a compression haversine loading. It should not be used to subtract drift caused by the LVDT spring force moving the gauge points apart. IPC designed a set of springs to counter the LVDT spring force. The high temperature tests were repeated with substantial improvement of the data at low frequency. These data were used in the analysis presented below.

Table 32. Testing conditions for the flow number tests.

Confinement, kPa	Deviatoric Stress, kPa	Temperature, °C
0	140	35
140	965	50

3.2.2 Statistical Analysis

The dynamic modulus data from the equipment effects experiment is presented in Appendix C. It includes the measured modulus and phase angle as well as the reported data quality statistics for each test. The data were analyzed using analysis of variance, which is a statistical technique for comparing the mean values from multiple populations. In this

Table 34. Air void content for specimens used in the flow number testing.

Test	Machine	Specimen	Air Voids, %	Average Air Voids, %
Unconfined	ITC	127	6.4	6.2
		133	6.1	
		138	6.2	
		153	6.2	
	IPC	125	5.9	6.1
		131	6.2	
		147	6.4	
		154	5.9	
	MDTS	122	5.9	6.1
		134	6.2	
		140	6.1	
		148	6.3	
Confined	ITC	128	6.1	6.1
		141	6.0	
		145	6.2	
		152	6.1	
	IPC	129	6.0	6.2
		131	6.2	
		149	6.3	
		156	6.2	
	MDTS	132	6.2	6.3
		139	6.2	
		143	6.4	
		150	6.4	

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Table 35. Analysis of variance for dynamic modulus.

Temp., C	Freq., Hz	Conf., kPa	IPC		ITC		MDTS		Grand Avg	Analysis of Variance					
			Avg	SSW	Avg	SSW	Avg	SSW		SSB	MSW	MSB	F	Fcr	Conclusion
10	10	0	10687	1486055	10923	2609222	11248	13952430	10953	636155	2005301	318078	0.16	4.26	Moduli are the same
10	1	0	6795	742675	7006	869039	7318	6635076	7040	555795	916310	277898	0.30	4.26	Moduli are the same
10	0.1	0	3735	255849	3881	209442	4201	2770140	3939	456021	359492	228010	0.63	4.26	Moduli are the same
20	10	0	5723	483349	6192	142035	6194	2895315	6037	588841	391189	294421	0.75	4.26	Moduli are the same
20	1	0	3012	243403	3105	34839	3372	694325	3124	456959	103198	228480	2.21	4.26	Moduli are the same
20	0.1	0	1324	34612	1391	11249	1486	151007	1375	116224	22802	58112	2.55	4.26	Moduli are the same
35	10	0	2119	60941	1988	51075	1951	64987	2019	62052	19667	31026	1.58	4.26	Moduli are the same
35	1	0	906	11472	827	5720	745	29547	826	51642	5193	25821	4.97	**4.26**	**Moduli are different**
35	0.1	0	357	2906	397	289	281	16994	345	28190	2243	14095	6.28	**4.26**	**Moduli are different**
35	0.01	0	175	1348	245	967	148	10691	189	19831	1445	9916	6.86	**4.26**	**Moduli are different**
35	10	130	2365	37498	2556	46045	2709	281680	2543	237422	40580	118711	2.93	4.26	Moduli are the same
35	1	130	1272	6355	1396	8784	1403	82317	1357	43051	10828	21525	1.99	4.26	Moduli are the same
35	0.1	130	833	1773	946	3075	926	36549	901	29147	4600	14574	3.17	4.26	Moduli are the same
35	0.01	130	682	590	759	2478	769	29276	736	18183	3594	9092	2.53	4.26	Moduli are the same

study, it was used to compare the mean values of the dynamic modulus and phase angle data collected with the three SPTs for various combinations of confining pressure, temperature, and loading rate. The analysis of variance test as applied here is summarized below (*13*):

Null Hypothesis, H_0: $\mu_{IPC} = \mu_{ITC} = \mu_{MDTS}$
Alternative Hypothesis: The mean value from at least one of the machines is different
Test Statistic: $F = \dfrac{MS_b}{MS_w}$
Rejection Region: Reject H_0 if $F > F_{cr}$ for $(k - 1, N - k)$ degrees of freedom.

Where:

μ_{IPC} = mean for the IPC device
μ_{ITC} = mean for the ITD device
μ_{MDTS} = mean for the MDTS device
F = value of F-statistic
MS_b = mean squares between groups
MS_w = mean squares within groups
k = number of groups (3 for this experiment)
N = total number of tests (12 for this experiment)

For this experiment, the critical value of the F-statistic for a level of significance of 5 percent is 4.26. Table 35 and Table 36 present the analysis of variance for the dynamic modulus and phase angle for all testing conditions.

The data in Table 35 and Table 36 show some significant differences in the dynamic moduli and phase angles measured with the three machines. The Duncan multiple range test was used to determine which values were significantly different (*13*). This test compares the difference in the mean value between two machines to a critical value based on the mean squares within groups. If the difference exceeds the critical value, it is concluded that there is a significant difference in the property measured by the two machines. Table 37 and Table 38 present the Duncan multiple range tests for all testing conditions.

Table 36. Analysis of variance for phase angle.

Temp., C	Freq., Hz	Conf., kPa	IPC		ITC		MDTS		Grand Avg	Analysis of Variance					
			Avg	SSW	Avg	SSW	Avg	SSW		SSB	MSW	MSB	F	Fcr	Conclusion
10	10	0	16.0	0.34	15.4	0.15	15.1	1.11	15.5	1.49	0.18	0.74	4.18	4.26	Phase angles are the same
10	1	0	21.6	1.04	21.7	0.71	21.0	2.20	21.5	1.19	0.44	0.60	1.36	4.26	Phase angles are the same
10	0.1	0	27.9	2.65	27.9	1.82	26.9	6.64	27.6	2.74	1.24	1.37	1.11	4.26	Phase angles are the same
20	10	0	25.0	2.29	25.7	0.36	23.2	4.10	24.6	12.41	0.75	6.20	8.26	**4.26**	**Phase angles are different**
20	1	0	32.2	4.70	32.4	1.51	29.1	6.78	31.1	24.58	1.27	12.29	9.67	**4.26**	**Phase angles are different**
20	0.1	0	35.3	3.06	35.6	5.15	33.1	7.60	34.8	17.12	1.62	8.56	5.28	**4.26**	**Phase angles are different**
35	10	0	34.7	1.63	35.2	1.03	33.4	2.32	34.4	6.98	0.55	3.49	6.31	**4.26**	**Phase angles are different**
35	1	0	33.5	1.66	33.8	4.06	34.5	13.57	33.9	1.92	2.14	0.96	0.45	4.26	Phase angles are the same
35	0.1	0	29.9	3.66	26.7	4.29	31.0	35.43	29.2	39.52	4.82	19.76	4.10	4.26	Phase angles are the same
35	0.01	0	22.9	4.27	18.1	1.23	22.8	13.64	21.3	60.20	2.13	30.10	14.15	**4.26**	**Phase angles are different**
35	10	130	30.9	0.79	29.2	0.64	27.5	7.42	29.2	23.17	0.98	11.59	11.79	**4.26**	**Phase angles are different**
35	1	130	26.8	3.53	25.2	0.95	24.3	6.72	25.4	13.32	1.24	6.66	5.35	**4.26**	**Phase angles are different**
35	0.1	130	21.4	7.25	19.3	0.94	17.5	7.39	19.4	29.88	1.73	14.94	8.62	**4.26**	**Phase angles are different**
35	0.01	130	15.5	4.73	13.3	0.98	12.8	11.72	13.9	17.27	1.94	8.63	4.46	**4.26**	**Phase angles are different**

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Table 37. Duncan multiple range test for dynamic modulus.

Temp., C	Freq., Hz	Conf., kPa	Duncan Multiple Range Test					
			Critical	IPC-ITC	IPC-MDTS	ITC-MDTS	Conclusion	Max difference, %
10	10	0	2616	-236	-562	-326	Same	5.1
10	1	0	1769	-212	-524	-312	Same	7.4
10	0.1	0	1108	-147	-467	-320	Same	11.9
20	10	0	1156	-469	-471	-2	Same	7.8
20	1	0	594	-210	-477	-267	Same	15.3
20	0.1	0	279	-144	-239	-95	Same	17.4
35	10	0	259	131	168	37	Same	8.3
35	1	0	133	78	161	82	MDTS < IPC	19.5
35	0.1	0	88	-40	77	117	MDTS < ITC	33.9
35	0.01	0	70	-70	26	96	MDTS < ITC	50.9
35	10	130	372	-191	-344	-152	Same	13.5
35	1	130	192	-123	-130	-7	Same	9.6
35	0.1	130	125	-113	-93	20	Same	10.3
35	0.01	130	111	-77	-87	-10	Same	11.8

Table 38. Duncan multiple range test for phase angle.

Temp., C	Freq., Hz	Conf., kPa	Duncan Multiple Range Test					
			Critical	IPC-ITC	IPC-MDTS	ITC-MDTS	Conclusion	Max difference, %
10	10	0	0.78	0.55	0.85	0.30	Same	0.8
10	1	0	1.22	-0.12	0.60	0.72	Same	0.7
10	0.1	0	2.05	0.03	1.03	1.00	Same	1.0
20	10	0	1.60	-0.69	1.73	2.42	MDTS< IPC and ITC	2.4
20	1	0	2.08	-0.66	2.66	3.31	MDTS< IPC and ITC	3.3
20	0.1	0	2.35	0.16	2.61	2.45	MDTS< IPC and ITC	2.6
35	10	0	1.37	-0.54	1.28	1.82	MDTS< ITC	1.8
35	1	0	2.71	-0.26	-0.95	-0.69	Same	-0.3
35	0.1	0	4.06	3.19	-1.08	-4.28	Same	3.2
35	0.01	0	2.69	4.78	0.06	-4.72	ITC < IPC and MDTS	4.8
35	10	130	1.83	1.78	3.40	1.62	MDTS < IPC	3.4
35	1	130	2.06	1.61	2.55	0.95	MDTS < IPC	2.6
35	0.1	130	2.43	2.05	3.86	1.81	MDTS < IPC	3.9
35	0.01	130	2.57	2.26	2.76	0.49	MDTS < IPC	2.8

For the dynamic modulus, there is good agreement between the three machines except for the lower frequency tests at high temperatures. In these tests, the ITC machine yields significantly higher dynamic moduli than the MDTS machine. For the phase angle, the agreement between the three machines is somewhat poorer. The MDTS machine typically yields lower phase angles than the other machines.

Table 39 summarizes the variability of the dynamic modulus test data obtained by pooling the standard deviation of the data for each testing condition across all machines. Except for the 0.01 Hz loading at the high temperature, the variability of the test data are reasonably low with the coefficient of variation for the dynamic modulus being approximately 10 percent and the standard deviation of the phase angle being approximately 1 degree. The overall variability obtained by pooling the coefficient of variation for the dynamic modulus and the standard deviation for the phase angle over all test conditions were 11.6 percent, and 1.2 degrees, respectively.

Table 39. Grand mean and variability of dynamic modulus test data.

Temp., C	Freq., Hz	Conf., kPa	Dynamic Modulus		Phase Angle	
			Mean	COV	Mean	Standard Deviation
10	10	0	10953	12.9	15.5	0.4
10	1	0	7040	13.6	21.5	0.7
10	0.1	0	3939	15.2	27.6	1.1
20	10	0	6037	10.4	24.6	0.9
20	1	0	3124	10.3	31.1	1.1
20	0.1	0	1375	11.0	34.8	1.3
35	10	0	2019	6.9	34.4	0.7
35	1	0	826	8.7	33.9	1.5
35	0.1	0	345	13.7	29.2	2.2
35	0.01	0	189	20.1	21.3	1.5
35	10	130	2543	7.9	29.2	1.0
35	1	130	1357	7.7	25.4	1.1
35	0.1	130	901	7.5	19.4	1.3
35	0.01	130	736	8.1	13.9	1.4
		Overall		11.6		1.2

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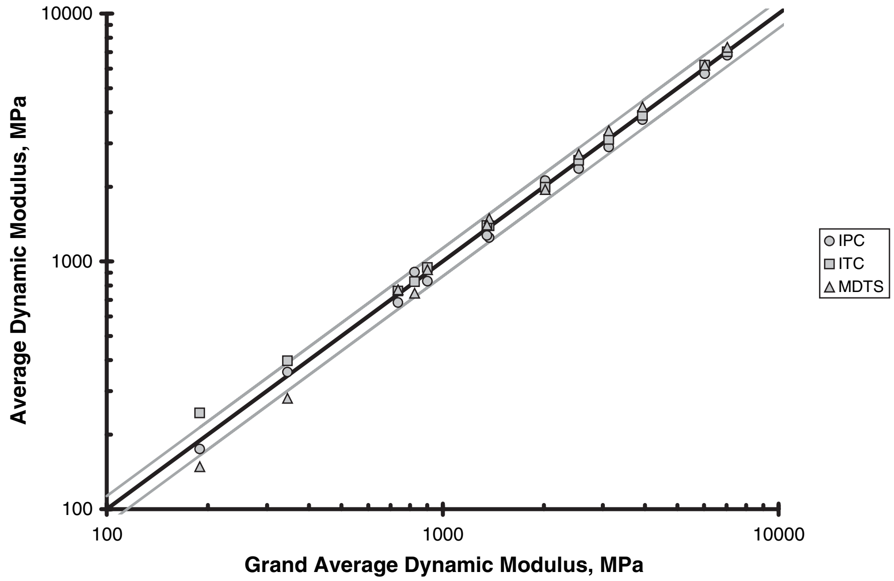

Figure 18. Comparison of mean dynamic moduli from the three machines.

These values agree well with those measured in Phase II where the coefficient of variation for the dynamic modulus was approximately 13 percent and the standard deviation of the phase angle was approximately 1.7 degrees (*11*).

Figure 18 and Figure 19 graphically depict the results discussed above. In these figures, the mean for each machine is plotted as a function of the grand mean obtained from the data for all machines. These figures also include 95 percent confidence intervals for the grand mean computed using the overall coefficient of variation for the dynamic modulus data of 11.6 percent and the overall standard deviation for the phase angle of 1.2 degrees. Significant differences occur when the data from a particular machine plot outside the 95 percent confidence intervals. For the dynamic modulus this occurs only for the low frequency tests at high temperatures, where the data for the ITC machine are significantly higher and the data for the MDTS machine are significantly lower than the grand average. Phase angles measured in with the MDTS machine tend to be lower than the grand average, while those measured with the IPC Global machine tend to be higher than the grand average. Each machine exhibits a significant difference from the grand average for various combinations of temperature, frequency, and confinement, but there does not appear to be a consistent trend for these departures.

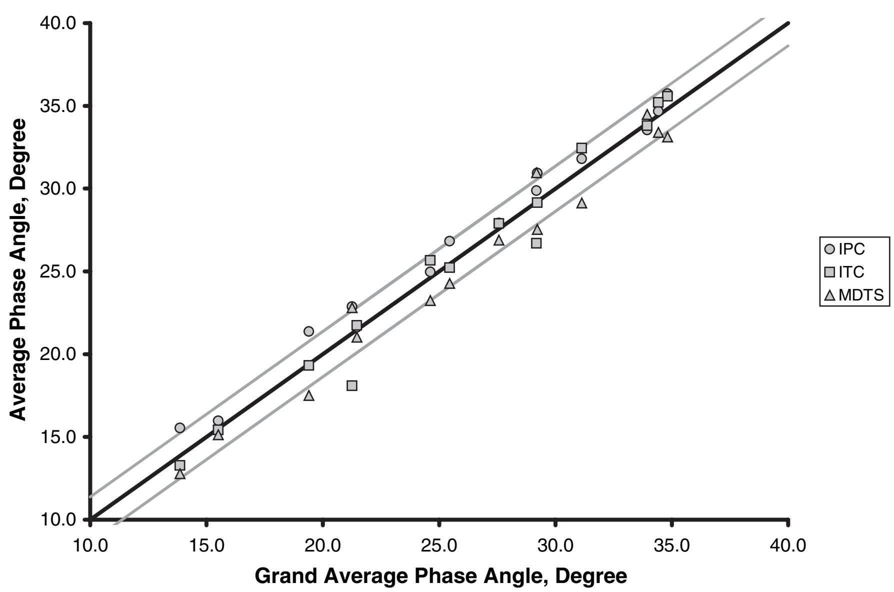

Figure 19. Comparison of mean phase angle from the three machines.

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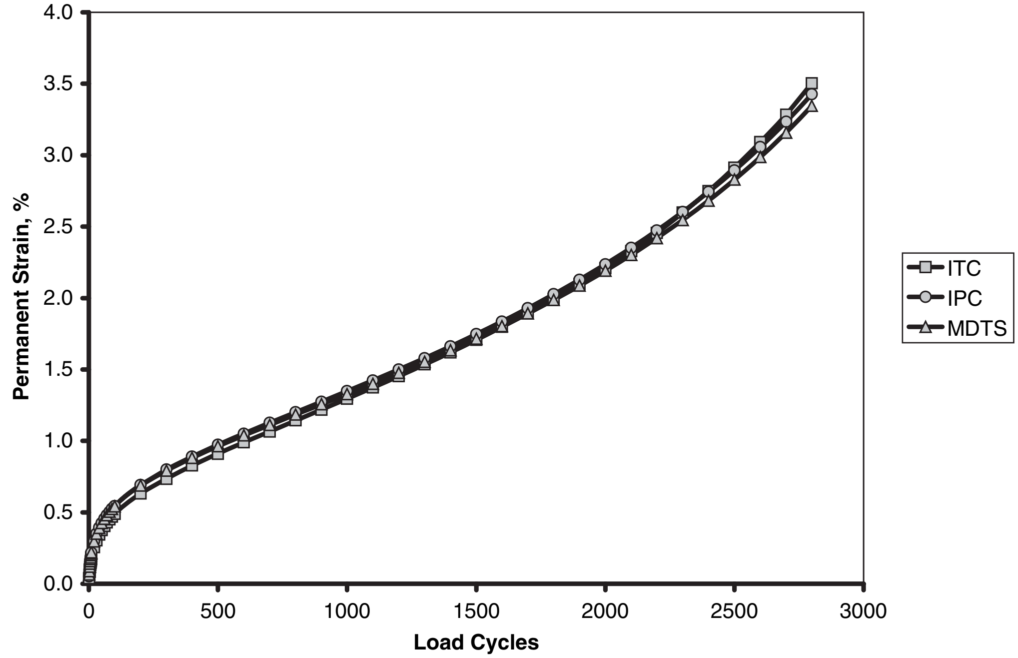

Figure 20. Average permanent strain response for unconfined repeated load tests.

3.3 Flow Number

Unconfined and confined flow number tests were performed with each machine at a temperature of 50°C. The unconfined tests used a deviatioric stress of 140 kPa. The confined tests used a confining stress of 140 kPa and a deviatoric stress of 965 kPa. Four specimens were tested in each machine. The tests were continued to 10,000 cycles or a permanent strain of 5 percent. For the confined tests with the ITC machine, the data from one sample was not included in the analysis because a leak developed in the membrane resulting in loss of confining stress and early failure of the specimen.

Figure 20 and Figure 21 present repeated load permanent deformation curves based on the average of the data for the samples tested in each machine. The complete database of the permanent deformation responses is presented in Appendix D.

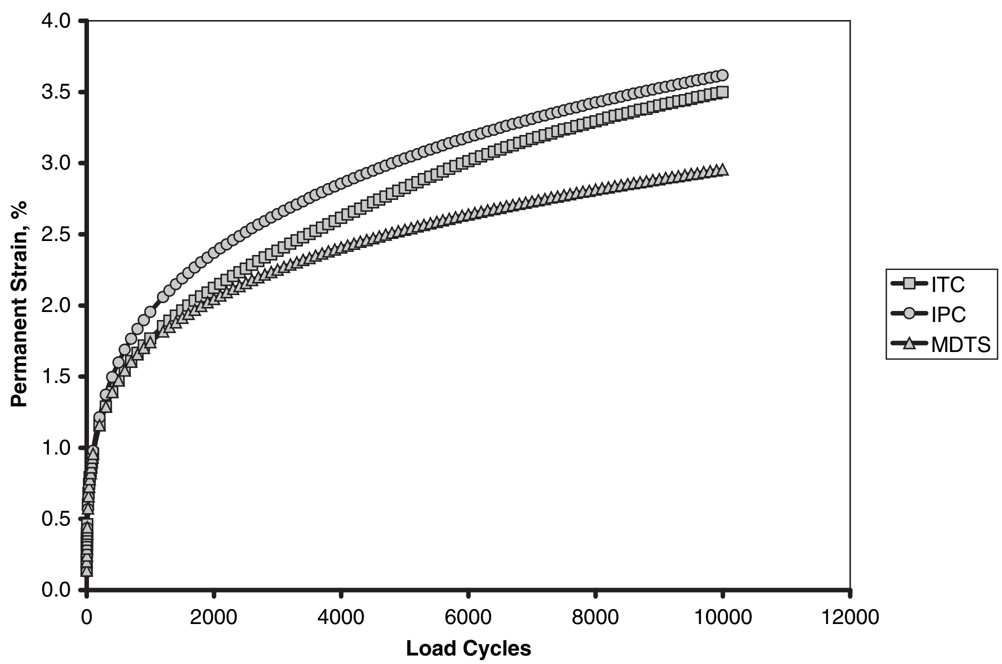

Figure 21. Average permanent strain response for confined repeated load tests.

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Table 40. Analysis of variance for unconfined repeated load permanent deformation response.

Cycle	ITC		IPC		MDTS		Grand	Pooled	Analysis of Variance					
	Avg	SSW	Avg	SSW	Avg	SSW	Avg	COV	SSB	MSW	MSB	F	Fcr	Conclusion
1	0.04	0.0000	0.05	0.0000	0.06	0.0001	0.05	6.02	0.0014	0.0000	0.0007	**55.85**	**4.26**	**Permanent strains are different**
16	0.23	0.0008	0.27	0.0002	0.27	0.0008	0.26	4.67	0.0040	0.0002	0.0020	**10.42**	**4.26**	**Permanent strains are different**
25	0.28	0.0010	0.33	0.0002	0.33	0.0012	0.31	4.54	0.0050	0.0003	0.0025	**9.36**	**4.26**	**Permanent strains are different**
40	0.34	0.0020	0.39	0.0002	0.39	0.0017	0.38	4.77	0.0063	0.0004	0.0031	**7.32**	**4.26**	**Permanent strains are different**
63	0.41	0.0026	0.46	0.0002	0.46	0.0024	0.45	4.68	0.0065	0.0006	0.0033	**5.58**	**4.26**	**Permanent strains are different**
100	0.49	0.0048	0.54	0.0003	0.54	0.0039	0.52	5.23	0.0082	0.0010	0.0041	4.10	4.26	Permanent strains are the same
160	0.58	0.0072	0.64	0.0005	0.63	0.0066	0.62	5.58	0.0088	0.0016	0.0044	2.77	4.26	Permanent strains are the same
250	0.69	0.0130	0.75	0.0007	0.74	0.0105	0.73	6.19	0.0094	0.0027	0.0047	1.75	4.26	Permanent strains are the same
400	0.83	0.0219	0.89	0.0015	0.88	0.0192	0.87	6.88	0.0090	0.0047	0.0045	0.95	4.26	Permanent strains are the same
630	1.01	0.0377	1.07	0.0032	1.06	0.0375	1.05	7.70	0.0080	0.0087	0.0040	0.46	4.26	Permanent strains are the same
1000	1.30	0.0721	1.35	0.0078	1.33	0.0871	1.32	8.91	0.0056	0.0186	0.0028	0.15	4.26	Permanent strains are the same
1600	1.80	0.1451	1.84	0.0225	1.80	0.2871	1.81	10.75	0.0034	0.0505	0.0017	0.03	4.26	Permanent strains are the same
2500	2.91	0.4842	2.89	0.0964	2.83	1.7224	2.88	15.22	0.0152	0.2559	0.0076	0.03	4.26	Permanent strains are the same

The permanent deformation curves in Figure 20 are for unconfined tests; those in Figure 21 are for confined tests. For unconfined tests, flow occurred at approximately 1,000 cycles. Flow did not occur in the confined tests. The sections below discuss the statistical analysis of these data.

3.3.1 Statistical Analysis

Analysis of variance as discussed previously in the dynamic modulus section was used to analyze differences in the permanent deformation response from different machines. The analysis for selected load cycles is presented in Table 40 for the unconfined tests and Table 41 for the confined tests.

The data in Table 40 indicate a significant difference in the permanent deformation response between devices early in the tests up to approximately 100 load cycles. Although there is a significant difference and based on the Duncan multiple range test, the permanent deformation from the ITC device is significantly lower than the other two, the difference is only 0.05 percent, which is not significant from an engineering

Table 41. Analysis of variance for confined repeated load permanent deformation response.

Cycle	IPC		ITC		MDTS		Grand	Pooled	Analysis of Variance					
	Avg	SSW	Avg	SSW	Avg	SSW	Avg	COV	SSB	MSW	MSB	F	Fcr	Conclusion
1	0.14	0.0001	0.13	0.0100	0.14	0.0009	0.13	22.83	0.0002	0.0014	0.0001	0.06	4.46	Permanent strains are the same
16	0.55	0.0032	0.52	0.2046	0.52	0.0229	0.53	26.14	0.0017	0.0288	0.0008	0.03	4.46	Permanent strains are the same
25	0.64	0.0063	0.61	0.2692	0.62	0.0304	0.63	25.58	0.0017	0.0382	0.0009	0.02	4.46	Permanent strains are the same
40	0.74	0.0082	0.72	0.3464	0.73	0.0432	0.73	24.99	0.0009	0.0497	0.0004	0.01	4.46	Permanent strains are the same
63	0.84	0.0133	0.84	0.4260	0.84	0.0602	0.84	24.40	0.0001	0.0624	0.0001	0.00	4.46	Permanent strains are the same
100	0.96	0.0191	0.98	0.5152	0.96	0.0862	0.96	23.69	0.0010	0.0776	0.0005	0.01	4.46	Permanent strains are the same
160	1.09	0.0279	1.13	0.6066	1.09	0.1218	1.10	22.88	0.0046	0.0945	0.0023	0.02	4.46	Permanent strains are the same
250	1.23	0.0394	1.30	0.6931	1.23	0.1735	1.25	22.12	0.0128	0.1133	0.0064	0.06	4.46	Permanent strains are the same
400	1.39	0.0573	1.49	0.7840	1.39	0.2531	1.43	21.37	0.0277	0.1368	0.0139	0.10	4.46	Permanent strains are the same
630	1.57	0.0713	1.71	0.9001	1.56	0.3657	1.61	20.86	0.0544	0.1671	0.0272	0.16	4.46	Permanent strains are the same
1000	1.77	0.0857	1.96	1.0391	1.74	0.4888	1.82	20.31	0.1052	0.2017	0.0526	0.26	4.46	Permanent strains are the same
1600	2.00	0.0963	2.23	1.2087	1.94	0.6473	2.06	19.77	0.1810	0.2440	0.0905	0.37	4.46	Permanent strains are the same
2500	2.26	0.0954	2.51	1.3856	2.16	0.8518	2.31	19.21	0.2682	0.2916	0.1341	0.46	4.46	Permanent strains are the same
4000	2.62	0.0746	2.85	1.5940	2.41	1.1233	2.63	18.45	0.4015	0.3490	0.2007	0.58	4.46	Permanent strains are the same
6300	3.06	0.0966	3.22	1.8747	2.67	1.4255	2.98	17.91	0.6448	0.4246	0.3224	0.76	4.46	Permanent strains are the same
10000	3.50	0.3918	3.62	2.1780	2.96	1.7957	3.36	18.23	0.9769	0.5457	0.4884	0.90	4.46	Permanent strains are the same

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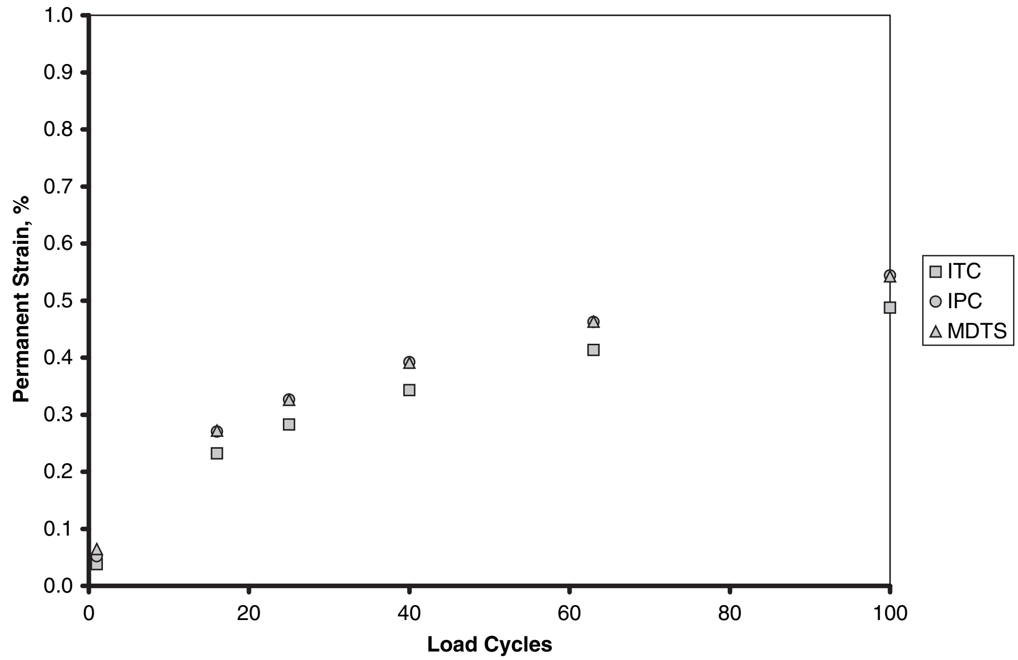

Figure 22. Comparison of permanent deformation response for the early portion of the unconfined repeated load tests.

standpoint. Figure 22 compares to early portion of the permanent deformation curves for unconfined tests with the three devices.

The data in Table 41 indicate that there is not a significant difference in the permanent deformation response for confined tests using different equipment. However, confined testing has greater variability compared to unconfined testing making significant differences more difficult to detect. Figure 23 is a plot showing the coefficient of variation for confined and unconfined tests as a function of axial strain in the specimen. The coefficient of variation plotted in this figure is a pooled value based on data from the three machines. The coefficient of variation in the unconfined test increases with increasing axial strain, while it decreases with increasing strain in confined tests. Before, the

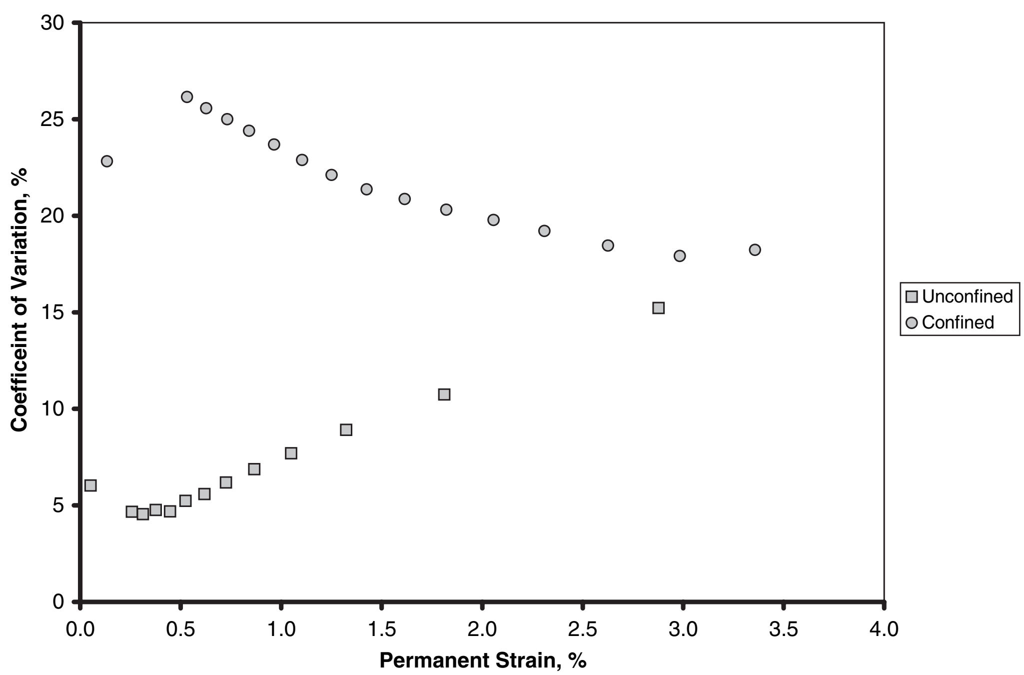

Figure 23. Coefficient of variation for unconfined and confined repeated load tests.

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Table 42. Flow numbers for unconfined tests.

Replicate	ITC	IPC	MDTS
1	1027	917	760
2	891	906	961
3	918	893	1164
4	1093	978	1106
Average	982	924	968
Standard Deviation	94.4	37.6	180.0
SSW	26723	4249	97233

flow point, the coefficient of variation in the unconfined test is less than 10 percent. At high strain levels, the coefficient of variation is similar for confined and unconfined tests.

An analysis of variance was also conducted on flow numbers obtained from unconfined repeated load permanent deformation tests. The flow number of each of these tests was computed using the improved algorithm developed at the Arizona State University (ASU) for detecting the flow number with the Franken model (*14*). The flow number data are summarized in Table 42. Table 43 presents the results of the analysis of variance for the flow numbers. The conclusion from this analysis is that the flow number is not significantly affected by the type of equipment. Figure 24 presents a bar chart showing these results. Figure 24 includes the mean flow number obtained with each device, and 95 percent confidence intervals based on the pooled standard deviation from the three devices. The pooled coefficient of variation in these tests is 10.8 percent, which is much lower than the value of 35 percent obtained for this same mixture in Phase II of the project (*11*). The lower variability reported here is the result of the improved flow number algorithm developed at ASU.

3.4 Repeatability

The data from the equipment effects experiment can be used to make initial estimates of the repeatability of the dynamic modulus and flow number tests. These estimates of repeatability can be useful in early evaluations of the equipment and in the planning of an interlaboratory study where formal statements of both the repeatability, within laboratory precision, and reproducibility, between laboratory precision, of the tests are developed.

The term "difference two standard deviation limit" or d2s is used to define the repeatability of a test method. For tests conducted within a laboratory, the difference in two measurements on the same material should not exceed the d2s

Table 43. Analysis of variance for flow number.

Source of Variation	Degree of Freedom	Sum of Squares	Mean Squares	F Statistic	Conclusion
Between	2	12273	6136	0.43< F_{cr} =4.64	Not a significant equipment effect
Within	9	128204	14245		
Total	11				

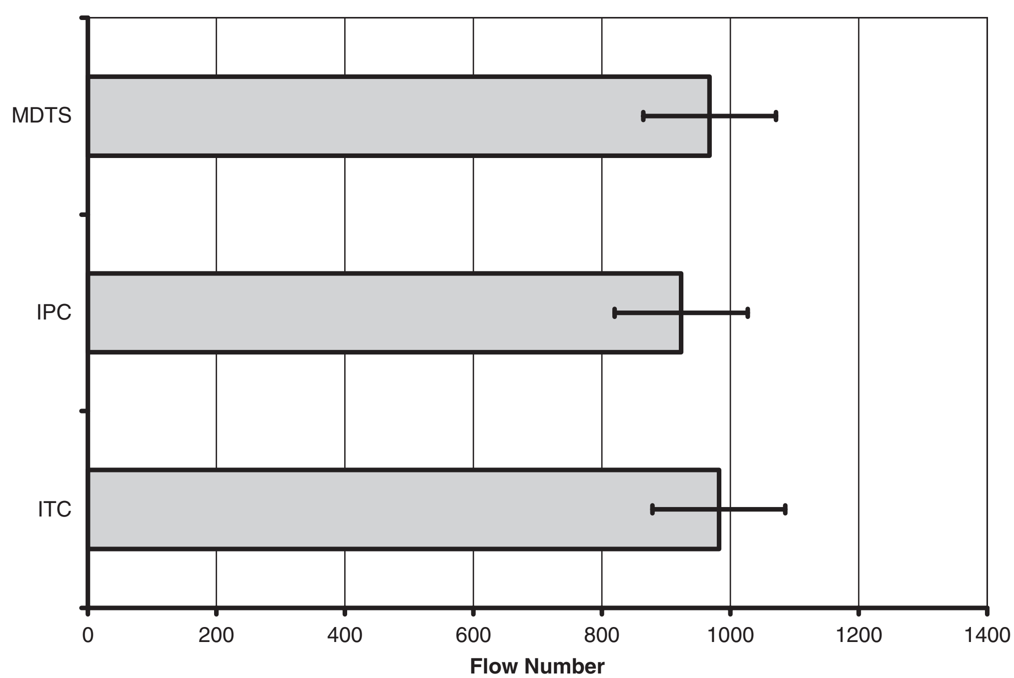

Figure 24. Bar chart for flow number.

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Table 44. Initial repeatability estimates for the dynamic modulus and flow number.

Test	Parameter	s	CV	d2s
Dynamic Modulus	Dynamic Modulus	NA	11.6%	32 %
	Phase Angle	1.2 degrees	NA	3.3 degrees
Unconfined Flow Number	Flow Number	119 cycles*	NA	320 cycles*

* For a material with a flow number of 1,000.

limit 95 percent of the time. The d2s limit is determined using Equation 2.

$$d2s = 1.960\sqrt{2}s \quad (2)$$

where:

$d2s$ = difference two standard deviation limit
s = standard deviation of the test

When the standard deviation of the test varies with test result, as it does of the dynamic modulus, the coefficient of variation is used in place of the standard deviation in Equation 2.

Table 44 summarizes estimates of single laboratory repeatability for the dynamic modulus and flow number tests. Two properly conducted tests on the same material in the same laboratory should not result in differences in the dynamic modulus greater than 32 percent or differences in the phase angle greater than 3.3 degrees. The repeatability of the flow number is likely to depend on the magnitude of the flow number and whether the test is confined or unconfined. For unconfined flow number tests on materials with a flow number of approximately 1,000, two properly conducted tests on the same material in the same laboratory should not result in differences in the flow number of more than 320 cycles.

3.5 Summary

The equipment effects experiment provided the opportunity to compare dynamic modulus and repeated load permanent deformation test data collected on the same mixture using equipment from the three manufacturers. The dynamic modulus portion of this testing revealed flaws with each device that were resolved by the respective manufacturer during the experiment. The ITC device required modification of the control software to control low frequency dynamic modulus testing at high temperatures. The IPC device required the addition of springs to the specimen-mounted deformation measuring equipment to counteract the LVDT spring force and minimize unwanted movement of the glued gauge points. Finally the MDTS device required a complete redesign of the specimen-mounted deformation measuring system.

Significant equipment effects were detected in the dynamic modulus testing. For low stiffness dynamic modulus measurements, below about 500 MPa, the dynamic modulus measured with the MDTS equipment was significantly lower and the dynamic modulus measured with the ITC equipment was significantly higher. The equipment effect was approximately 20 percent while the testing error was only approximately 12 percent. One possible cause for this difference at low stiffness levels is calibration of the low range of the load cell. The applied load levels for low stiffness dynamic modulus tests are very low, 0.5 percent or less of the capacity of the load cell of the machine. The manufacturer-supplied load cell calibrations were not verified prior to the equipment effects experiment. The calibration of the temperature sensor and the deformation measuring equipment was verified using independent NIST traceable standards immediately before conducting the equipment effects experiment. For various combinations of temperature and frequency, significant differences in phase angles were also detected. The trend that was evident in phase angle data was that the IPC equipment produces the highest phase angles and the MDTS equipment produces the lowest phase angles. The difference between these two machines averaged over the range of data collected was 1.5 degrees. The testing error for the phase angle is 1.4 degrees.

Significant equipment effects were not detected in the flow number tests. Although there was a statistical difference in the early portion of the permanent deformation in the unconfined tests, its magnitude was not of engineering significance.

Variability of the dynamic modulus data collected during this Phase of NCHRP Project 9-29 is similar to that collected during Phase II. The use of the new flow number algorithm developed at ASU appears to reduce variability in the computed flow number. This algorithm provides a more precise method for computing the derivative and inflection point in repeated load permanent deformation curves.

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CHAPTER 4

Conclusions

Several modifications to the SPT equipment specification, the SPT test methods, and the equipment supplied by the three manufacturers were made as a result of the ruggedness and equipment effects experiments. These modifications are discussed below.

4.1 SPT Equipment Specification Modifications

The ruggedness and equipment effects experiments confirmed that the SPT equipment specifications developed in NCHRP Project 9-29 are appropriate. The ruggedness testing demonstrated that the level of control required by the SPT equipment specifications provides precise data for the dynamic modulus and flow number tests. Because the flow number and flow time tests are very similar, this conclusion can also be extended to the flow time test. The equipment effects experiment demonstrated that there is little difference in dynamic modulus and flow number data collected with equipment meeting the SPT equipment specification supplied by three manufacturers. Significant differences in dynamic modulus were detected only for tests resulting in modulus values below about 500 MPa. Differences in flow number test data between machines from different manufacturers were confined to the early portion of the permanent deformation curve and were not of engineering significance.

Three SPT equipment specification changes were identified by the by the ruggedness and equipment effects experiments. First more precise control of strain is needed in confined dynamic modulus tests compared to unconfined tests. Based on the ruggedness testing, strain in confined dynamic modulus tests should be controlled to within ±15 μstrain of the 100 μstrain target. The SPT equipment specifications included a strain control tolerance of ±25 μstrain. The tolerance was reduced to within ±15 μstrain in the final version of the SPT specification. Second, the equipment effects experiment identified that the length of the gauge point in the direction of the strain measurement had a significant effect on the measured dynamic modulus. In the final version of the SPT equipment specification, a maximum dimension for the gauge point in this direction was added. Finally, the new flow number algorithm developed at ASU using the Franken model produced reduced variability in flow number test results with the SPT. The final version of the SPT equipment specification was modified to include flow number computations based on the Franken model. The final version of the SPT equipment specification is included as Appendix E.

4.2 SPT Test Methods Modifications

Two changes to the SPT test methods were also made as a result of the ruggedness and equipment effects experiments. First, the ruggedness testing clearly showed that the flow number test results were significantly affected by the type of end friction reducer used. The SPT test methods were revised to specify the use of greased latex membranes friction reducers in the flow number test. A standard method for preparing the greased latex membranes was also added. The second change to the SPT test methods was the addition of a check on the direction of the drift in the dynamic modulus test as a data quality indicator. During the equipment effects experiment, it was discovered that the spring force of the LVDTs could result in drift that tended to move the gauge points further apart. The drift compensation included in the dynamic modulus computations is not intended to remove this form of drift; therefore, a significant error in the dynamic modulus can result if the gauge points move apart during the test. The data quality check that was added is to accept only data where the drift is in the same direction as the applied load. A standard test method for conducting dynamic modulus and flow number tests in the form of an AASHTO standard is included in Appendix F.

4.3 Manufacturer Modifications

Each manufacturer made modifications to their equipment during the ruggedness and equipment effects experiments. The ITC equipment could not accurately control the loading rate for the 0.01 Hz tests at high temperatures. ITC modified the control software to use a different control algorithm for low frequency loading. The spring force in the LVDTs of the IPC equipment moved the gauge points apart at high temperatures. IPC designed a set of springs to counter the LVDT spring force. With these springs, the IPC specimen-mounted deformation measuring system can be used to higher temperatures without experiencing the gauge point drift problem. Finally poor performance of the specimen-mounted deformation measuring system for the MDTS equipment resulted in complete redesign of this component of the equipment.

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APPENDIX A

Dynamic Modulus Ruggedness Data

ID	Lab	Test Temp C	Transfer Time min	Fluid Water = 0 Air = 1	Strain μmm/mm	Confining Pressure kPa	Membrane No =0 Yes =1	End Milled =0 Sawed =1	Friction Reducer Teflon =0 Latex =1	Air Voids %	Dynamic Modulus kPa	Phase Angle Degree	Load Se %	Strain Se %	Strain Uniformity %	Phase Uniformity %
FDM2-1	AAT	3	3	0	114	0	0	0	0	6.2	12181	9.8	3.6	5.5	9.3	0.1
FDM2-2	AAT	3	3	1	113	0	1	1	1	6.4	14509	11.4	9.8	9.9	11.8	0.3
FDM2-3	AAT	3	5	0	77	0	0	1	1	6.1	14295	10.7	2.8	5.0	0.5	0.3
FDM2-4	AAT	3	5	1	72	0	1	0	0	6.0	17950	10.0	3.2	5.0	5.9	3.9
FDM2-5	AAT	5	3	0	69	0	1	0	1	5.9	17533	11.2	2.7	5.6	2.1	0.5
FDM2-6	AAT	5	3	1	72	0	0	1	0	6.1	13735	11.4	2.8	5.1	8.4	0.5
FDM2-7	AAT	5	5	0	101	0	1	1	0	5.8	14153	12.3	4.4	6.1	25.8	1.0
FDM2-8	AAT	5	5	1	105	0	0	0	1	6.1	12609	11.4	2.9	4.6	14.5	0.2
FDM3-1	AAT	3	3	0	97	0	0	0	0	5.7	17351	3.6	12.1	11.5	5.9	0.0
FDM3-2	AAT	3	3	1	104	0	1	1	1	5.6	16033	3.7	11.7	11.5	17.7	0.6
FDM3-3	AAT	3	5	0	75	0	0	1	1	5.7	14755	3.9	4.6	5.5	3.0	0.4
FDM3-4	AAT	3	5	1	80	0	1	0	0	5.9	20579	4.6	7.4	9.6	6.4	0.7
FDM3-5	AAT	5	3	0	75	0	1	0	1	5.5	12477	5.2	5.7	6.6	14.6	1.5
FDM3-6	AAT	5	3	1	75	0	0	1	0	5.7	14419	4.9	4.5	5.6	15.4	0.1
FDM3-7	AAT	5	5	0	105	0	1	1	0	5.8	15840	5.6	13.3	13.0	55.3	0.2
FDM3-8	AAT	5	5	1	121	0	0	0	1	5.7	13768	4.1	10.8	10.9	39.8	2.2
FSM4-1	AAT	3	3	0	123	0	0	0	0	6.8	10214	7.3	3.4	4.8	9.4	5.2
FSM4-2	AAT	3	3	1	110	0	1	1	1	7.0	15451	8.5	11.2	10.6	11.4	6.6
FSM4-3	AAT	3	5	0	75	0	0	1	1	6.7	14514	6.8	4.3	4.7	2.9	5.2
FSM4-4	AAT	3	5	1	80	0	1	0	0	6.8	13581	7.3	4.0	6.5	39.2	3.8
FSM4-5	AAT	5	3	0	74	0	1	0	1	6.1	13221	8.8	4.3	5.1	14.0	5.4
FSM4-6	AAT	5	3	1	74	0	0	1	0	5.8	12023	8.3	4.9	5.6	4.2	5.9
FSM4-7	AAT	5	5	0	122	0	1	1	0	6.3	12069	9.0	5.2	6.0	2.0	4.7
FSM4-8	AAT	5	5	1	121	0	0	0	1	6.5	13191	9.0	6.5	6.8	15.3	5.5
FSM7-1	AAT	3	3	0	106	0	0	0	0	5.4	15500	6.5	13.4	12.9	19.0	5.2
FSM7-2	AAT	3	3	1	103	0	1	1	1	5.8	15779	7.2	12.7	12.9	2.1	5.9
FSM7-3	AAT	3	5	0	76	0	0	1	1	6.3	14226	7.0	4.9	6.1	2.6	5.4
FSM7-4	AAT	3	5	1	73	0	1	0	0	6.1	10878	7.0	5.0	6.5	0.7	5.8
FSM7-5	AAT	5	3	0	73	0	1	0	1	5.7	13400	10.6	4.5	6.0	8.0	7.4
FSM7-6	AAT	5	3	1	77	0	0	1	0	5.5	15092	8.4	4.4	6.0	1.0	5.5

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ID	Lab	Test Temp C	Transfer Time min	Fluid Water = 0 Air = 1	Strain μmm/mm	Confining Pressure kPa	Membrane No =0 Yes =1	End Milled =0 Sawed =1	Friction Reducer Teflon =0 Latex =1	Air Voids %	Dynamic Modulus kPa	Phase Angle Degree	Load Se %	Strain Se %	Strain Uniformity %	Phase Uniformity %
FSM7-7	AAT	5	5	0	121	0	1	1	0	5.4	13454	8.7	13.5	13.3	4.3	4.7
FSM7-8	AAT	5	5	1	117	0	0	0	1	5.8	13894	8.4	12.7	12.4	9.6	5.7
FDM4-1	FHWA	3	3	0	110	0	0	0	0	5.8	15668	12.2	4.3	4.0	11.8	0.2
FDM4-2	FHWA	3	3	1	114	0	1	1	1	5.8	15101	13.9	3.5	3.9	21.2	1.1
FDM4-3	FHWA	3	5	0	76	0	0	1	1	5.8	15507	11.9	3.2	3.2	24.4	1.0
FDM4-4	FHWA	3	5	1	81	0	1	0	0	6.1	14761	14.5	2.7	4.4	12.6	1.4
FDM4-5	FHWA	5	3	0	77	0	1	0	1	5.4	14035	14.4	3.2	4.3	11.2	0.8
FDM4-6	FHWA	5	3	1	75	0	0	1	0	5.7	13469	14.2	3.4	3.4	10.3	0.2
FDM4-7	FHWA	5	5	0	111	0	1	1	0	5.5	15482	15.8	4.4	4.3	23.9	2.1
FDM4-8	FHWA	5	5	1	119	0	0	0	1	5.7	13347	13.7	2.1	4.7	22.2	0.2
FDM5-1	FHWA	3	3	0	113	0	0	0	0	5.9	14749	11.9	3.2	3.4	17.6	0.1
FDM5-2	FHWA	3	3	1	121	0	1	1	1	6.0	14294	14.6	2.9	3.4	12.3	0.9
FDM5-3	FHWA	3	5	0	73	0	0	1	1	6.0	14510	12.1	5.1	4.7	18.5	1.1
FDM5-4	FHWA	3	5	1	75	0	1	0	0	6.3	14473	14.0	4.6	4.7	22.3	1.0
FDM5-5	FHWA	5	3	0	80	0	1	0	1	5.9	14673	15.5	3.5	4.1	4.4	3.6
FDM5-6	FHWA	5	3	1	76	0	0	1	0	5.9	13042	13.8	3.8	3.6	24.2	0.6
FDM5-7	FHWA	5	5	0	124	0	1	1	0	6.3	13369	15.3	2.4	3.0	35.1	1.1
FDM5-8	FHWA	5	5	1	124	0	0	0	1	6.2	13207	14.0	2.7	4.2	15.1	1.4
FSM2-1	FHWA	3	3	0	121	0	0	0	0	6.7	13577	11.5	2.4	4.2	21.0	0.1
FSM2-2	FHWA	3	3	1	126	0	1	1	1	6.5	12985	14.3	2.7	2.9	12.5	0.7
FSM2-3	FHWA	3	5	0	77	0	0	1	1	6.2	14130	12.4	2.4	3.0	12.5	0.2
FSM2-4	FHWA	3	5	1	76	0	1	0	0	6.5	13576	13.8	2.8	2.9	22.2	1.4
FSM2-5	FHWA	5	3	0	75	0	1	0	1	6.5	11572	14.3	3.1	3.9	26.2	1.4
FSM2-6	FHWA	5	3	1	78	0	0	1	0	6.5	10678	15.2	2.9	3.1	14.2	0.5
FSM2-7	FHWA	5	5	0	127	0	1	1	0	6.4	11843	15.6	1.9	3.2	25.5	0.6
FSM2-8	FHWA	5	5	1	126	0	0	0	1	6.0	13041	13.0	2.5	3.0	25.3	1.2
FSM3-1	FHWA	3	3	0	124	0	0	0	0	6.1	13426	12.8	2.7	2.4	8.9	0.3
FSM3-2	FHWA	3	3	1	132	0	1	1	1	5.9	13191	16.8	3.8	4.0	12.4	1.5
FSM3-3	FHWA	3	5	0	75	0	0	1	1	5.9	13981	12.7	3.1	3.5	5.5	0.8
FSM3-4	FHWA	3	5	1	77	0	1	0	0	5.5	14545	16.3	3.1	3.9	21.0	2.1

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FSM3-5	FHWA	5	3	0	86	0	1	0	1	6.6	13940	20.8	2.0	4.4	10.3	7.0
FSM3-6	FHWA	5	3	1	76	0	0	1	0	6.4	13501	13.6	2.8	3.7	9.0	1.0
FSM3-7	FHWA	5	5	0	126	0	1	1	0	6.3	12187	16.4	1.8	3.2	12.6	1.3
FSM3-8	FHWA	5	5	1	128	0	0	0	1	6.5	12399	14.6	1.7	2.5	6.9	0.5
FDM2-1	AAT	19	3	0	89	0	0	0	0	6.2	1266	35.4	0.8	8.5	22.9	1.5
FDM2-2	AAT	19	3	1	114	0	1	1	1	6.4	1077	37.2	0.7	12.0	14.7	1.8
FDM2-3	AAT	19	5	0	59	0	0	1	1	6.1	1204	37.4	2.0	6.6	15.8	1.7
FDM2-4	AAT	19	5	1	55	0	1	0	0	6	1722	37.7	1.4	14.2	24.5	1.1
FDM2-5	AAT	21	3	0	75	0	1	0	1	5.9	1246	37.9	1.0	7.9	25.4	2.3
FDM2-6	AAT	21	3	1	64	0	0	1	0	6.1	1060	36.0	1.4	8.6	5.2	2.5
FDM2-7	AAT	21	5	0	83	0	1	1	0	5.8	1512	39.4	0.6	12.0	28.0	2.9
FDM2-8	AAT	21	5	1	100	0	0	0	1	6.1	835	36.1	2.8	7.1	7.8	1.6
FDM3-1	AAT	19	3	0	99	0	0	0	0	5.7	1755	32.0	1.9	11.8	11.3	4.9
FDM3-2	AAT	19	3	1	114	0	1	1	1	5.6	1645	31.2	0.5	11.8	0.1	6.4
FDM3-3	AAT	19	5	0	80	0	0	1	1	5.7	1264	33.4	2.1	6.1	6.7	6.9
FDM3-4	AAT	19	5	1	63	0	1	0	0	5.9	1601	35.4	1.9	12.3	19.2	4.8
FDM3-5	AAT	21	3	0	89	0	1	0	1	5.5	1133	29.7	2.2	8.9	4.9	0.3
FDM3-6	AAT	21	3	1	86	0	0	1	0	5.7	1168	33.3	2.1	8.1	30.0	9.8
FDM3-7	AAT	21	5	0	113	0	1	1	0	5.8	1457	31.5	0.8	10.5	15.1	4.7
FDM3-8	AAT	21	5	1	109	0	0	0	1	5.7	1450	33.0	1.3	9.4	32.0	6.1
FSM4-1	AAT	19	3	0	111	0	0	0	0	6.8	1292	27.7	0.6	6.0	12.7	5.2
FSM4-2	AAT	19	3	1	126	0	1	1	1	7	1608	29.2	2.1	9.8	15.5	8.3
FSM4-3	AAT	19	5	0	73	0	0	1	1	6.7	1613	27.3	0.9	4.6	11.5	3.1
FSM4-4	AAT	19	5	1	77	0	1	0	0	6.8	1671	27.3	1.4	13.7	3.6	4.7
FSM4-5	AAT	21	3	0	88	0	1	0	1	6.1	1346	28.7	0.8	10.5	39.4	2.9
FSM4-6	AAT	21	3	1	86	0	0	1	0	5.8	1382	26.5	1.0	4.0	61.4	8.8
FSM4-7	AAT	21	5	0	109	0	1	1	0	6.3	1369	26.7	1.5	6.2	5.4	6.2
FSM4-8	AAT	21	5	1	113	0	0	0	1	6.5	1234	28.7	1.6	6.6	1.4	5.6
FSM7-1	AAT	19	3	0	101	0	0	0	0	5.4	2825	24.2	0.9	7.1	1.8	11.2
FSM7-2	AAT	19	3	1	111	0	1	1	1	5.8	1770	27.1	1.3	6.7	35.8	8.0

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FSM7-3	AAT	19	5	0	68	0	0	1	1	6.3	1737	26.8	0.9	5.8	8.3	6.3
FSM7-4	AAT	19	5	1	94	0	1	0	0	6.1	1259	27.7	0.8	6.1	5.7	3.9
FSM7-5	AAT	21	3	0	91	0	1	0	1	5.7	1295	28.1	0.8	4.4	18.4	5.9
FSM7-6	AAT	21	3	1	70	0	0	1	0	5.5	1681	27.9	0.9	7.1	32.0	5.2
FSM7-7	AAT	21	5	0	111	0	1	1	0	5.4	1429	27.8	0.6	7.2	51.4	7.6
FSM7-8	AAT	21	5	1	110	0	0	0	1	5.8	1485	26.3	1.0	7.7	34.6	4.8
FDM4-1	FHWA	19	3	0	109	0	0	0	0	5.8	1984	34.4	1.6	9.7	11.6	0.5
FDM4-2	FHWA	19	3	1	107	0	1	1	1	5.8	1558	39.1	1.6	9.6	30.2	2.4
FDM4-3	FHWA	19	5	0	67	0	0	1	1	5.8	1714	36.5	1.8	9.5	17.5	0.7
FDM4-4	FHWA	19	5	1	69	0	1	0	0	6.1	1395	38.4	2.3	9.2	10.5	1.1
FDM4-5	FHWA	21	3	0	64	0	1	0	1	5.4	1294	36.7	2.4	11.2	14.7	6.1
FDM4-6	FHWA	21	3	1	67	0	0	1	0	5.7	1199	36.3	2.8	7.4	12.8	0.6
FDM4-7	FHWA	21	5	0	105	0	1	1	0	5.5	1423	37.2	1.9	18.6	19.5	0.8
FDM4-8	FHWA	21	5	1	106	0	0	0	1	5.7	1308	36.4	1.8	14.8	12.5	0.8
FDM5-1	FHWA	19	3	0	107	0	0	0	0	5.9	1742	35.3	1.6	9.9	8.1	1.7
FDM5-2	FHWA	19	3	1	105	0	1	1	1	6	1476	35.9	1.5	6.8	8.4	0.4
FDM5-3	FHWA	19	5	0	66	0	0	1	1	6	1477	38.7	1.9	9.5	5.1	0.5
FDM5-4	FHWA	19	5	1	66	0	1	0	0	6.3	1392	39.8	2.6	10.5	14.1	1.4
FDM5-5	FHWA	21	3	0	65	0	1	0	1	5.9	1216	42.2	3.0	10.2	4.0	1.6
FDM5-6	FHWA	21	3	1	64	0	0	1	0	5.9	1042	39.3	2.4	8.1	29.3	0.3
FDM5-7	FHWA	21	5	0	101	0	1	1	0	6.3	1079	40.1	2.1	11.0	13.1	0.3
FDM5-8	FHWA	21	5	1	108	0	0	0	1	6.2	1127	37.5	1.8	10.2	9.8	1.8
FSM2-1	FHWA	19	3	0	114	0	0	0	0	6.7	1820	30.0	2.7	7.9	10.1	0.5
FSM2-2	FHWA	19	3	1	113	0	1	1	1	6.5	1628	33.4	2.6	9.7	5.6	0.5
FSM2-3	FHWA	19	5	0	72	0	0	1	1	6.2	1740	31.9	2.6	7.5	20.3	0.4
FSM2-4	FHWA	19	5	1	69	0	1	0	0	6.5	1708	33.2	3.0	7.3	23.5	0.5
FSM2-5	FHWA	21	3	0	67	0	1	0	1	6.5	1259	32.2	3.6	4.5	43.1	1.0
FSM2-6	FHWA	21	3	1	72	0	0	1	0	6.5	1182	32.7	6.1	7.5	19.2	1.6
FSM2-7	FHWA	21	5	0	113	0	1	1	0	6.4	1135	35.1	3.0	7.1	33.0	0.7
FSM2-8	FHWA	21	5	1	116	0	0	0	1	6	1628	31.5	3.0	8.1	3.9	0.3

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FSM3-1	FHWA	19	3	0	119	0	0	0	0	6.1	1760	30.4	1.8	7.0	23.3	0.7
FSM3-2	FHWA	19	3	1	109	0	1	1	1	5.9	1835	28.4	1.7	7.7	18.1	3.9
FSM3-3	FHWA	19	5	0	74	0	0	1	1	5.9	1758	30.8	2.2	5.4	14.2	0.8
FSM3-4	FHWA	19	5	1	71	0	1	0	0	5.5	1636	32.9	2.6	6.6	13.4	0.5
FSM3-5	FHWA	21	3	0	76	0	1	0	1	6.6	1297	35.9	3.5	6.6	11.1	4.5
FSM3-6	FHWA	21	3	1	69	0	0	1	0	6.4	1426	31.6	3.1	6.5	13.1	1.6
FSM3-7	FHWA	21	5	0	111	0	1	1	0	6.3	1654	36.7	1.8	7.8	22.8	4.2
FSM3-8	FHWA	21	5	1	113	0	0	0	1	6.5	1146	33.5	2.5	6.4	7.5	1.8
FDM2-1	AAT	39	3	0	223	0	0	0	0	6.2	170	23.5	2.8	13.8	9.4	0.5
FDM2-2	AAT	39	3	1	288	0	1	1	1	6.4	131	23.0	3.2	14.8	4.3	0.3
FDM2-3	AAT	39	5	0	289	0	0	1	1	6.1	131	23.0	2.6	15.3	14.6	1.2
FDM2-4	AAT	39	5	1	234	0	1	0	0	6	162	22.4	2.7	12.8	17.2	1.3
FDM2-5	AAT	41	3	0	241	0	1	0	1	5.9	156	22.0	3.1	14.0	32.9	0.1
FDM2-6	AAT	41	3	1	235	0	0	1	0	6.1	161	22.6	3.1	16.0	30.8	0.1
FDM2-7	AAT	41	5	0	197	0	1	1	0	5.8	191	21.7	3.7	15.5	21.8	1.1
FDM2-8	AAT	41	5	1	338	0	0	0	1	6.1	112	22.3	4.0	15.8	2.8	0.4
FDM3-1	AAT	39	3	0	119	0	0	0	0	5.7	164	30.4	3.2	32.6	15.9	3.9
FDM3-2	AAT	39	3	1	176	0	1	1	1	5.6	111	34.5	3.7	34.0	82.3	6.0
FDM3-3	AAT	39	5	0	92	0	0	1	1	5.7	121	13.3	4.2	26.1	43.4	7.4
FDM3-4	AAT	39	5	1	81	0	1	0	0	5.9	138	14.6	4.7	40.7	22.4	17.6
FDM3-5	AAT	41	3	0	109	0	1	0	1	5.5	104	14.5	3.7	11.5	11.6	8.2
FDM3-6	AAT	41	3	1	78	0	0	1	0	5.7	143	11.3	4.7	13.1	55.8	8.7
FDM3-7	AAT	41	5	0	134	0	1	1	0	5.8	145	27.2	2.9	22.5	25.2	5.4
FDM3-8	AAT	41	5	1	179	0	0	0	1	5.7	108	17.5	2.9	14.9	50.8	9.6
FSM4-1	AAT	39	3	0	155	0	0	0	0	6.8	125	23.7	2.9	10.9	22.1	7.6
FSM4-2	AAT	39	3	1	142	0	1	1	1	7	138	29.1	3.2	19.4	17.2	6.1
FSM4-3	AAT	39	5	0	51	0	0	1	1	6.7	223	19.8	3.4	38.2	9.8	4.1
FSM4-4	AAT	39	5	1	81	0	1	0	0	6.8	140	20.1	4.8	45.6	22.6	4.9
FSM4-5	AAT	41	3	0	90	0	1	0	1	6.1	126	19.5	4.0	25.7	6.9	7.0
FSM4-6	AAT	41	3	1	66	0	0	1	0	5.8	172	16.8	5.3	11.6	1.8	6.9

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FSM4-7	AAT	41	5	0	135	0	1	1	0	6.3	145	27.3	2.8	26.7	41.7	19.1
FSM4-8	AAT	41	5	1	108	0	0	0	1	6.5	179	18.0	2.3	41.2	19.5	5.6
FSM7-1	AAT	39	3	0	87	0	0	0	0	5.4	221	25.4	5.7	11.0	28.0	1.5
FSM7-2	AAT	39	3	1	81	0	1	1	1	5.8	239	29.5	5.3	20.5	13.3	1.2
FSM7-3	AAT	39	5	0	74	0	0	1	1	6.3	155	21.4	6.8	15.7	1.4	0.5
FSM7-4	AAT	39	5	1	62	0	1	0	0	6.1	179	25.9	7.6	21.3	18.1	1.4
FSM7-5	AAT	41	3	0	64	0	1	0	1	5.7	159	21.3	6.8	10.1	30.7	0.8
FSM7-6	AAT	41	3	1	58	0	0	1	0	5.5	198	22.6	7.2	13.6	80.3	2.9
FSM7-7	AAT	41	5	0	102	0	1	1	0	5.4	190	30.6	2.7	24.1	3.4	1.2
FSM7-8	AAT	41	5	1	110	0	0	0	1	5.8	253	21.9	2.7	10.2	0.8	0.4
FSM2-1	FHWA	39	3	0	127	0	0	0	0	6.7	181	26.2	3.6	6.6	14.0	0.8
FSM2-2	FHWA	39	3	1	133	0	1	1	1	6.5	146	33.8	3.4	8.2	3.5	1.7
FSM2-3	FHWA	39	5	0	76	0	0	1	1	6.2	160	29.8	3.7	7.0	26.0	2.4
FSM2-4	FHWA	39	5	1	72	0	1	0	0	6.5	155	29.6	4.7	7.8	14.7	0.7
FSM2-5	FHWA	41	3	0	74	0	1	0	1	6.5	121	31.9	7.1	21.5	56.4	2.5
FSM2-6	FHWA	41	3	1	79	0	0	1	0	6.5	97	30.5	4.8	6.7	24.9	3.3
FSM2-7	FHWA	41	5	0	158	0	1	1	0	6.4	93	27.5	4.1	22.2	32.5	3.7
FSM2-8	FHWA	41	5	1	135	0	0	0	1	6	161	26.1	3.1	7.5	12.7	2.3
FSM3-1	FHWA	39	3	0	136	0	0	0	0	6.1	179	28.2	2.7	8.5	20.5	1.9
FSM3-2	FHWA	39	3	1	165	0	1	1	1	5.9	161	34.5	2.4	10.3	9.8	5.0
FSM3-3	FHWA	39	5	0	79	0	0	1	1	5.9	148	32.8	3.9	6.2	16.9	2.6
FSM3-4	FHWA	39	5	1	77	0	1	0	0	5.5	145	39.1	4.3	9.0	30.9	5.9
FSM3-5	FHWA	41	3	0	98	0	1	0	1	6.6	77	38.1	6.3	15.8	16.6	2.2
FSM3-6	FHWA	41	3	1	133	0	0	1	0	6.4	159	25.6	2.7	7.7	11.5	0.6
FSM3-7	FHWA	41	5	0	154	0	1	1	0	6.3	100	29.6	3.6	14.6	34.0	0.8
FSM3-8	FHWA	41	5	1	144	0	0	0	1	6.5	114	26.2	3.4	8.5	15.6	1.8
FDM2-1	AAT	39	3	0	196	135	0	0		6.2	189	14.0	2.1	11.2	10.7	2.6
FDM2-2	AAT	39	3	1	128	145	1	1		6.4	409	9.7	2.5	6.4	12.5	0.0
FDM2-3	AAT	39	5	0	87	135	1	1		6.1	428	8.8	1.7	6.3	0.1	0.8
FDM2-4	AAT	39	5	1	79	145	0	0		6	676	7.0	2.9	8.6	12.6	1.5

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ID	Lab	Test Temp C	Transfer Time min	Fluid Water = 0 Air = 1	Strain μmm/mm	Confining Pressure kPa	Membrane No =0 Yes =1	End Milled =0 Sawed =1	Friction Reducer Teflon =0 Latex =1	Air Voids %	Dynamic Modulus kPa	Phase Angle Degree	Load Se %	Strain Se %	Strain Uniformity %	Phase Uniformity %
FDM2-5	AAT	41	3	0	136	145	0	1		5.9	474	8.3	1.7	7.9	40.3	1.0
FDM2-6	AAT	41	3	1	187	135	1	0		6.1	198	14.5	1.6	8.4	12.8	1.5
FDM2-7	AAT	41	5	0	214	145	1	0		5.8	173	13.9	1.7	11.7	17.3	1.8
FDM2-8	AAT	41	5	1	146	135	0	1		6.1	452	5.5	1.0	8.3	7.3	0.1
FDM3-1	AAT	39	3	0	90	135	0	0		5.7	545	13.5	1.2	19.4	0.5	6.2
FDM3-2	AAT	39	3	1	77	145	1	1		5.6	253	21.9	2.6	20.9	53.3	2.2
FDM3-3	AAT	39	5	0	84	135	1	1		5.7	442	12.2	2.2	12.6	35.4	6.2
FDM3-4	AAT	39	5	1	56	145	0	0		5.9	871	9.6	1.4	7.9	84.2	10.6
FDM3-5	AAT	41	3	0	124	145	0	1		5.5	298	16.3	1.5	19.6	16.7	4.7
FDM3-6	AAT	41	3	1	76	135	1	0		5.7	648	8.4	1.8	10.1	9.3	6.0
FDM3-7	AAT	41	5	0	35	145	1	0		5.8	560	26.2	3.1	51.3	5.4	6.1
FDM3-8	AAT	41	5	1	92	135	0	1		5.7	213	17.1	2.8	10.9	48.3	1.7
FDM4-1	AAT	39	3	0	63	135	1	0	0	5.8	632	14.6	2.0	10.6	8.2	0.7
FDM4-2	AAT	39	3	1	74	145	1	1	1	5.8	668	17.5	1.6	4.7	4.8	4.3
FDM4-3	AAT	39	5	0	40	135	1	1	1	5.8	672	19.4	2.4	24.5	6.0	3.6
FDM4-4	AAT	39	5	1	45	145	1	0	0	6.1	678	15.3	1.9	4.3	5.4	0.3
FDM4-5	AAT	41	3	0	42	145	1	0	1	5.4	499	14.7	25.4	40.4	3.6	3.4
FDM4-6	AAT	41	3	1	30	135	1	1	0	5.7	557	23.1	3.0	8.4	32.3	6.5
FDM4-7	AAT	41	5	0	86	145	1	1	0	5.5	589	15.2	1.9	11.0	14.3	1.0
FDM4-8	AAT	41	5	1	68	135	1	0	1	5.7	639	17.1	1.9	5.7	20.5	3.2
FDM5-1	AAT	39	3	0	98	135	1	0	0	5.9	598	12.5	1.6	24.2	19.0	1.2
FDM5-2	AAT	39	3	1	111	145	1	1	1	6	681	11.0	1.3	6.2	13.0	0.9
FDM5-3	AAT	39	5	0	63	135	1	1	1	6	630	13.3	2.0	9.7	9.0	2.9
FDM5-4	AAT	39	5	1	49	145	1	0	0	6.3	680	14.1	2.3	17.3	9.4	0.6
FDM5-5	AAT	41	3	0	47	145	1	0	1	5.9	490	17.6	3.0	19.3	11.9	3.1
FDM5-6	AAT	41	3	1	44	135	1	1	0	5.9	710	17.4	2.3	4.7	13.2	3.5
FDM5-7	AAT	41	5	0	75	145	1	1	0	6.3	628	13.8	1.6	12.7	3.3	2.9
FDM5-8	AAT	41	5	1	75	135	1	0	1	6.2	620	15.5	1.4	15.9	5.2	1.0
FSM2-1	FHWA	39	3	0	78	135	1	0	0	6.7	528	20.0	2.5	4.4	6.8	1.3
FSM2-2	FHWA	39	3	1	127	145	1	1	1	6.5	339	24.2	1.7	6.2	12.3	0.6

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ID	Lab	Test Temp C	Transfer Time min	Fluid Water = 0 Air = 1	Strain μmm/mm	Confining Pressure kPa	Membrane No =0 Yes =1	End Milled =0 Sawed =1	Friction Reducer Teflon =0 Latex =1	Air Voids %	Dynamic Modulus kPa	Phase Angle Degree	Load Se %	Strain Se %	Strain Uniformity %	Phase Uniformity %
FSM2-3	FHWA	39	5	0	43	135	1	1	1	6.2	517	21.6	3.0	31.5	15.3	1.6
FSM2-4	FHWA	39	5	1	96	145	1	0	0	6.5	267	25.2	2.9	5.4	23.3	0.4
FSM2-5	FHWA	41	3	0	45	145	1	0	1	6.5	575	19.7	2.6	14.9	31.0	3.1
FSM2-6	FHWA	41	3	1	62	135	1	1	0	6.5	235	26.1	4.4	7.9	17.1	1.4
FSM2-7	FHWA	41	5	0	73	145	1	1	0	6.4	480	18.7	2.2	17.3	37.6	4.4
FSM2-8	FHWA	41	5	1	118	135	1	0	1	6	254	25.4	2.1	5.9	13.1	1.1
FSM3-1	FHWA	39	3	0	89	135	1	0	0	6.1	595	19.4	1.7	21.3	31.3	4.6
FSM3-2	FHWA	39	3	1	105	145	1	1	1	5.9	410	18.8	1.6	7.1	40.9	6.0
FSM3-3	FHWA	39	5	0	50	135	1	1	1	5.9	580	26.1	2.7	16.8	48.8	7.7
FSM3-4	FHWA	39	5	1	63	145	1	0	0	5.5	427	22.1	2.7	11.1	17.9	3.2
FSM3-5	FHWA	41	3	0	45	145	1	0	1	6.6	837	22.5	2.2	15.5	5.8	6.7
FSM3-6	FHWA	41	3	1	63	135	1	1	0	6.4	368	26.3	4.3	5.7	26.4	4.8
FSM3-7	FHWA	41	5	0	94	145	1	1	0	6.3	650	15.8	1.8	24.2	19.8	1.4
FSM3-8	FHWA	41	5	1	150	135	1	0	1	6.5	173	34.5	2.3	16.6	62.4	8.1
FSM4-1	FHWA	39	3	0	119	135	1	0	0	6.8	310	18.8	1.8	8.8	24.5	5.5
FSM4-2	FHWA	39	3	1	143	145	1	1	1	7	259	18.9	1.8	7.4	22.4	6.3
FSM4-3	FHWA	39	5	0	83	135	1	1	1	6.7	710	15.7	1.6	8.0	37.7	3.1
FSM4-4	FHWA	39	5	1	100	145	1	0	0	6.8	372	19.7	2.2	19.9	53.5	6.5
FSM4-5	FHWA	41	3	0	147	145	1	0	1	6.1	371	17.8	2.2	11.9	35.6	5.1
FSM4-6	FHWA	41	3	1	97	135	1	1	0	5.8	724	9.6	2.0	8.6	13.6	5.4
FSM4-7	FHWA	41	5	0	123	145	1	1	0	6.3	374	16.5	2.5	9.9	35.2	7.4
FSM4-8	FHWA	41	5	1	136	135	1	0	1	6.5	423	16.0	2.1	6.8	26.5	2.1
FSM7-1	FHWA	39	3	0	108	135	1	0	0	5.4	670	15.8	1.8	8.8	24.5	5.5
FSM7-2	FHWA	39	3	1	109	145	1	1	1	5.8	710	14.4	1.8	7.4	22.4	6.3
FSM7-3	FHWA	39	5	0	112	135	1	1	1	6.3	620	14.6	1.6	8.0	37.7	3.1
FSM7-4	FHWA	39	5	1	89	145	1	0	0	6.1	691	14.4	2.2	19.9	53.5	6.5
FSM7-5	FHWA	41	3	0	66	145	1	0	1	5.7	713	11.6	2.2	11.9	35.6	5.1
FSM7-6	FHWA	41	3	1	86	135	1	1	0	5.5	732	13.4	2.0	8.6	13.6	5.4
FSM7-7	FHWA	41	5	0	120	145	1	1	0	5.4	667	11.5	2.5	9.9	35.2	7.4
FSM7-8	FHWA	41	5	1	127	135	1	0	1	5.8	678	14.0	2.1	6.8	26.5	2.1

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APPENDIX B

Flow Number Ruggedness Data

ID	Lab	Temp C	Transfer Time Min	Fluid 0=Water 1=Air	End 0=Milled 1=Sawed	Friction Reducer 0=Teflon 1=Latex	Confining Stress kPa	Deviator Stress kPa	Contact Stress kPa	Dwell Time sec	Air Void %	Flow # Cycles	Permanent Strain, %				
													500 Cycles	1000 Cycles	2000 Cycles	5000 Cycles	8000 Cycles
FDM10-1	FHWA	49	3	0	0	0	0	144	5	0.95	6.5	1401	1.1	1.3	1.8		
FDM10-2	FHWA	49	3	1	1	1	0	144	5	0.85	6.4	1601	0.9	1.1	1.6		
FDM10-3	FHWA	49	5	0	1	1	0	135	5	0.95	6.4	1241	0.9	1.2	1.7		
FDM10-4	FHWA	49	5	1	0	0	0	134	5	0.85	6.3	1341	1.1	1.4	1.9		
FDM10-5	FHWA	51	3	0	0	1	0	135	5	0.85	6.3	641	1.2	1.6	2.7		
FDM10-6	FHWA	51	3	1	1	0	0	134	5	0.95	6.3	1001	1.1	1.5	2.5		
FDM10-7	FHWA	51	5	0	1	0	0	144	5	0.85	6.1	981	1.0	1.3	2.1		
FDM10-8	FHWA	51	5	1	0	1	0	145	5	0.95	6.2	881	1.2	1.6	2.6		
FDM11-1	FHWA	49	3	0	0	0	0	144	5	0.95	6.3	1461	1.0	1.2	1.6		
FDM11-2	FHWA	49	3	1	1	1	0	145	5	0.85	6.5	581	1.3	1.8	3.8		
FDM11-3	FHWA	49	5	0	1	1	0	135	5	0.95	6.2	1341	0.8	1.0	1.4		
FDM11-4	FHWA	49	5	1	0	0	0	134	5	0.85	6.2	1081	0.9	1.2	1.8		
FDM11-5	FHWA	51	3	0	0	1	0	144	5	0.85	6.5	961	1.2	1.5	2.2		
FDM11-6	FHWA	51	3	1	1	0	0	135	5	0.95	6.4	1081	1.0	1.3	1.8		
FDM11-7	FHWA	51	5	0	1	0	0	144	5	0.85	6.2	721	0.8	1.1	1.7		
FDM11-8	FHWA	51	5	1	0	1	0	145	5	0.95	6.3	781	1.1	1.5	2.7		
FDM12-1	AAT	49	3	0	0	0	0	145	4	0.90	6.6	1281	1.0	1.4	2.1		
FDM12-2	AAT	49	3	1	1	1	0	145	10	0.90	6.4	901	0.9	1.3	2.2		
FDM12-3	AAT	49	5	0	1	1	0	135	3	0.90	6.0	881	0.7	0.9	1.5		
FDM12-4	AAT	49	5	1	0	0	0	135	12	0.90	6.4	1121	0.9	1.2	1.9		
FDM12-5	AAT	51	3	0	0	1	0	135	10	0.90	6.3	581	0.8	1.3	2.8		
FDM12-6	AAT	51	3	1	1	0	0	135	4	0.90	6.6	1041	1.1	1.6	2.5		
FDM12-7	AAT	51	5	0	1	0	0	145	11	0.90	6.3	801	0.8	1.1	1.9		
FDM12-8	AAT	51	5	1	0	1	0	145	3	0.90	6.1	641	1.1	1.6	3.2		
FDM13-1	AAT	49	3	0	0	0	0	145	4	0.90	6.2	1021	0.9	1.2	1.7		
FDM13-2	AAT	49	3	1	1	1	0	145	10	0.90	6.1	541	0.8	1.3	2.6		
FDM13-3	AAT	49	5	0	1	1	0	135	4	0.90	6.2	781	0.8	1.1	1.9		
FDM13-4	AAT	49	5	1	0	0	0	135	12	0.90	6.1	1101	1.1	1.5	2.1		
FDM13-5	AAT	51	3	0	0	1	0	135	9	0.90	6.0	1061	1.1	1.4	2.1		
FDM13-6	AAT	51	3	1	1	0	0	135	4	0.90	6.1	881	0.8	1.1	1.8		

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ID	Lab	Temp C	Transfer Time Min	Fluid 0=Water 1=Air	End 0=Milled 1=Sawed	Friction Reducer 0=Teflon 1=Latex	Confining Stress kPa	Deviator Stress kPa	Contact Stress kPa	Dwell Time sec	Air Void %	Flow # Cycles	Permanent Strain, %				
													500 Cycles	1000 Cycles	2000 Cycles	5000 Cycles	8000 Cycles
FDM13-7	AAT	51	5	0	1	0	0	145	11	0.90	6.1	621	0.7	0.9	1.6		
FDM13-8	AAT	51	5	1	0	1	0	145	3	0.90	6.2	461	1.3	1.9	4.2		
FDM6-1	AAT	49	3	0	0	0	135	984	5	0.90	6.1		2.4	2.9	3.3		
FDM6-2	AAT	49	3	1	1	1	145	984	5	0.90	6.2		2.4	3.4	4.8		
FDM6-3	AAT	49	5	0	1	1	135	944	5	0.90	6.0		1.9	2.3	2.8		
FDM6-4	AAT	49	5	1	0	0	145	944	5	0.90	6.3		2.5	2.7	3.0		
FDM6-5	AAT	51	3	0	0	1	145	944	5	0.90	6.0		2.4	2.7	3.2		
FDM6-6	AAT	51	3	1	1	0	135	944	5	0.90	6.1		1.6	1.8	2.1		
FDM6-7	AAT	51	5	0	1	0	145	984	5	0.90	6.1		1.6	1.8	2.1		
FDM6-8	AAT	51	5	1	0	1	135	984	5	0.90	5.9		2.1	2.4	2.8		
FDM8-1	AAT	49	3	0	0	0	135	984	5	0.90	6.2		2.1	2.3	2.6		
FDM8-2	AAT	49	3	1	1	1	145	984	5	0.90	6.2		1.6	1.9	2.2		
FDM8-3	AAT	49	5	0	1	1	135	944	5	0.90	6.0		1.6	1.8	2.1		
FDM8-4	AAT	49	5	1	0	0	145	944	5	0.90	6.3		1.7	1.9	2.2		
FDM8-5	AAT	51	3	0	0	1	145	944	5	0.90	6.5		2.7	3.0	3.3		
FDM8-6	AAT	51	3	1	1	0	135	944	5	0.90	6.4		1.1	1.3	1.5		
FDM8-7	AAT	51	5	0	1	0	145	984	5	0.90	6.0		1.4	1.6	1.8		
FDM8-8	AAT	51	5	1	0	1	140	984	5	0.90	5.7		2.4	2.6	2.9		
FDM7-1	FHWA	49	3	0	0	0	135	1048	45	0.90	6.1		1.7	2.0	2.3		
FDM7-2	FHWA	49	3	1	1	1	145	1044	45	0.90	6.2		1.9	2.2	2.6		
FDM7-3	FHWA	49	5	0	1	1	135	996	45	0.90	6.2		1.6	1.9	2.4		
FDM7-4	FHWA	49	5	1	0	0	145	1009	46	0.90	6.3		1.5	1.7	2.0		
FDM7-5	FHWA	51	3	0	0	1	145	991	45	0.90	6.4		1.9	2.4	2.9		
FDM7-6	FHWA	51	3	1	1	0	135	1015	45	0.90	6.1		1.7	2.0	2.4		
FDM7-7	FHWA	51	5	0	1	0	145	1049	45	0.90	6.4		1.8	2.2	2.6		
FDM7-8	FHWA	51	5	1	0	1	135	1029	46	0.90	6.1		2.5	3.2	4.3		
FDM9-1	FHWA	49	3	0	0	0	135	1052	45	0.90	6.1		2.0	2.4	2.9		
FDM9-2	FHWA	49	3	1	1	1	145	1063	42	0.90	6.0		1.8	2.2	2.6		
FDM9-3	FHWA	49	5	0	1	1	135	1002	44	0.90	6.3		2.0	2.5	3.2		
FDM9-4	FHWA	49	5	1	0	0	145	1027	44	0.90	6.3		1.8	2.1	2.4		

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ID	Lab	Temp C	Transfer Time Min	Fluid 0=Water 1=Air	End 0=Milled 1=Sawed	Friction Reducer 0=Teflon 1=Latex	Confining Stress kPa	Deviator Stress kPa	Contact Stress kPa	Dwell Time sec	Air Void %	Flow # Cycles	Permanent Strain, %				
													500 Cycles	1000 Cycles	2000 Cycles	5000 Cycles	8000 Cycles
FDM9-5	FHWA	51	3	0	0	1	145	1010	42	0.90	6.0		2.4	3.0	3.6		
FDM9-6	FHWA	51	3	1	1	0	135	1023	45	0.90	6.3		1.9	2.3	2.8		
FDM9-7	FHWA	51	5	0	1	0	145	1052	45	0.90	6.1		2.2	2.7	3.3		
FDM9-8	FHWA	51	5	1	0	1	135	1038	42	0.90	6.1		2.6	3.4	4.6		
FSM5-1	AAT	49	3	0	0	0	135	1055	47	0.90	5.8		1.4	1.8	2.4	3.2	3.4
FSM5-2	AAT	49	3	1	1	1	145	1030	40	0.90	6.5		1.4	1.7	2.1	3.0	3.4
FSM5-3	AAT	49	5	0	1	1	135	1000	45	0.90	5.6		1.7	2.1	2.4	3.2	3.9
FSM5-4	AAT	49	5	1	0	0	145	1012	45	0.90	6.1		1.4	1.7	2.2	3.2	3.5
FSM5-5	AAT	51	3	0	0	1	145	1003	46	0.90	6.1		1.7	2.0	2.3	2.7	2.9
FSM5-6	AAT	51	3	1	1	0	135	1014	47	0.90	5.9		1.8	2.2	2.7	2.9	3.0
FSM5-7	AAT	51	5	0	1	0	145	1050	44	0.90	6.6		1.3	1.4	1.6	1.8	1.9
FSM5-8	AAT	51	5	1	0	1	135	1037	42	0.90	7.3		1.8	2.1	2.5	3.0	3.3
FSM6-1	AAT	49	3	0	0	0	135	1073	43	0.90	5.8		1.5	1.7	1.9	2.4	3.0
FSM6-2	AAT	49	3	1	1	1	145	1030	45	0.90	5.8		1.8	2.1	2.3	2.7	2.8
FSM6-3	AAT	49	5	0	1	1	135	995	44	0.90	5.7		2.1	2.5	2.9	3.6	4.2
FSM6-4	AAT	49	5	1	0	0	145	1010	47	0.90	5.8		1.4	1.5	1.7	2.1	2.5
FSM6-5	AAT	51	3	0	0	1	145	1007	45	0.90	5.6		1.9	2.1	2.4	2.9	3.4
FSM6-6	AAT	51	3	1	1	0	135	1010	46	0.90	5.4		1.3	1.4	1.7	2.4	3.2
FSM6-7	AAT	51	5	0	1	0	145	1052	47	0.90	5.8		1.8	2.2	3.1	4.4	4.6
FSM6-8	AAT	51	5	1	0	1	135	1034	44	0.90	5.4		2.3	2.8	3.4	3.8	3.9
FSM8-1	FHWA	49	3	0	0	0	135	984	5	0.90	6.0		1.2	1.3	1.4	1.5	1.6
FSM8-2	FHWA	49	3	1	1	1	145	984	5	0.90	5.8		1.5	1.7	1.8	2.0	2.1
FSM8-3	FHWA	49	5	0	1	1	135	944	5	0.90	5.5		1.5	1.6	1.9	3.2	4.3
FSM8-4	FHWA	49	5	1	0	0	145	944	5	0.90	5.6		0.9	1.1	1.3	1.7	2.0
FSM8-5	FHWA	51	3	0	0	1	145	944	5	0.90	5.4		1.4	1.6	1.7	2.1	3.0
FSM8-6	FHWA	51	3	1	1	0	135	944	5	0.90	5.7		1.1	1.4	1.6	1.9	2.1
FSM8-7	FHWA	51	5	0	1	0	145	984	5	0.90	5.4		0.9	1.0	1.1	1.2	1.3
FSM8-8	FHWA	51	5	1	0	1	135	984	5	0.90	5.5		1.9	2.2	2.7	3.5	3.7
FSM9-1	FHWA	49	3	0	0	0	135	984	5	0.90	6.5		1.5	1.6	1.8	2.2	2.8
FSM9-2	FHWA	49	3	1	1	1	145	984	5	0.90	6.2		1.6	1.8	2.3	3.3	3.9

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ID	Lab	Temp C	Transfer Time Min	Fluid 0=Water 1=Air	End 0=Milled 1=Sawed	Friction Reducer 0=Teflon 1=Latex	Confining Stress kPa	Deviator Stress kPa	Contact Stress kPa	Dwell Time sec	Air Void %	Flow # Cycles	Permanent Strain, %				
													500 Cycles	1000 Cycles	2000 Cycles	5000 Cycles	8000 Cycles
FSM9-3	FHWA	49	5	0	1	1	135	944	5	0.90	6.0		1.8	2.0	2.1	2.4	2.6
FSM9-4	FHWA	49	5	1	0	0	145	944	5	0.90	5.9		1.2	1.3	1.6	2.1	2.4
FSM9-5	FHWA	51	3	0	0	1	145	944	5	0.90	5.7		1.4	1.6	1.8	2.2	2.6
FSM9-6	FHWA	51	3	1	1	0	135	944	5	0.90	5.8		1.2	1.5	1.8	2.4	2.5
FSM9-7	FHWA	51	5	0	1	0	145	984	5	0.90	5.5		1.2	1.5	2.0	3.3	3.7
FSM9-8	FHWA	51	5	1	0	1	135	984	5	0.90	5.8		1.6	1.9	2.3	3.1	3.8

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APPENDIX C

Dynamic Modulus Equipment Effects Data

Table C1. Dynamic modulus data for ITC equipment.

Specimen	Temp C	Freq Hz	Conf Pressure KPa	Dynamic Modulus MPa	Phase Angle °	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity °
109	10	10	0	11006	15.6	3.5	134.5	6.7	24.0	0.2
109	10	1	0	7019	22.0	0.6	169.3	5.6	31.9	0.8
109	10	0.1	0	3874	28.3	0.3	203.4	4.6	33.8	1.4
114	10	10	0	11193	15.6	3.2	144.4	6.5	32.9	0.5
114	10	1	0	7106	22.3	0.5	193.4	5.8	36.6	0.3
114	10	0.1	0	3893	28.8	0.5	237.2	6.1	35.7	1.2
115	10	10	0	9636	15.3	4.0	127.5	6.3	12.2	0.5
115	10	1	0	6297	21.3	0.9	153.4	5.1	9.9	0.6
115	10	0.1	0	3555	27.3	0.7	174.2	5.6	16.1	1.0
118	10	10	0	11857	15.2	2.9	140.4	6.1	11.6	0.1
118	10	1	0	7602	21.4	0.5	187.6	5.3	10.5	0.1
118	10	0.1	0	4202	27.2	1.3	243.0	5.3	4.8	0.2
109	20	10	0	5959	25.4	5.5	357.4	22.0	36.4	0.0
109	20	1	0	3038	31.9	1.4	359.0	14.9	33.2	0.0
109	20	0.1	0	1376	34.3	1.4	262.5	5.9	22.4	0.3
114	20	10	0	6128	25.3	5.1	355.5	22.5	44.9	0.2
114	20	1	0	3152	31.8	1.3	333.2	15.2	47.1	2.0
114	20	0.1	0	1429	34.7	2.8	193.9	7.5	43.5	3.8
115	20	10	0	6202	25.9	5.4	384.4	20.5	15.9	0.5
115	20	1	0	2997	32.9	1.4	444.9	15.8	15.2	0.9
115	20	0.1	0	1312	36.4	4.0	359.4	8.4	15.0	1.8
118	20	10	0	6481	26.1	5.1	413.6	21.8	16.3	0.3
118	20	1	0	3233	33.2	1.4	477.8	16.2	22.5	0.1
118	20	0.1	0	1448	36.9	4.4	433.4	11.2	31.3	0.8
109	35	10	0	1864	34.6	7.4	268.4	11.5	15.7	0.6
109	35	1	0	782	32.3	2.5	114.6	5.7	8.3	1.0
109	35	0.1	0	383	25.0	5.5	55.0	7.3	1.1	1.3
109	35	0.01	0	255	17.2	3.2	31.3	6.2	10.1	1.6
114	35	10	0	2036	35.1	7.9	316.0	12.4	14.6	0.8
114	35	1	0	846	33.7	2.2	176.9	5.6	6.4	0.7
114	35	0.1	0	404	26.8	4.5	96.6	6.5	1.7	0.1
114	35	0.01	0	222	18.4	3.2	27.5	5.8	13.8	0.2
115	35	10	0	1902	35.3	8.8	350.2	12.4	0.5	1.2
115	35	1	0	802	34.1	2.5	242.9	6.4	4.1	2.0
115	35	0.1	0	399	27.1	5.0	197.2	6.2	10.2	2.0
115	35	0.01	0	262	18.2	3.2	83.5	6.2	30.4	0.1
118	35	10	0	2149	36.0	8.3	368.4	13.3	29.2	1.1
118	35	1	0	879	35.1	2.8	219.3	6.8	20.8	0.5
118	35	0.1	0	404	27.8	4.6	136.5	6.2	11.1	0.3
118	35	0.01	0	240	18.6	2.6	51.6	4.8	12.5	1.7
109	35	10	140	2535	29.7	7.7	180.6	9.9	43.7	1.4
109	35	1	140	1370	26.0	1.8	115.0	6.5	50.4	1.7

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Table C1. (Continued).

Specimen	Temp C	Freq Hz	Conf Pressure KPa	Dynamic Modulus MPa	Phase Angle °	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity °
109	35	0.1	140	923	20.1	4.4	103.8	7.4	52.5	2.0
109	35	0.01	140	733	14.1	1.2	79.8	6.9	54.6	1.9
114	35	10	140	2410	28.6	7.1	151.8	8.4	17.2	1.0
114	35	1	140	1342	24.7	1.7	100.5	5.2	8.1	1.6
114	35	0.1	140	918	18.8	2.8	87.0	4.6	0.5	1.0
114	35	0.01	140	742	13.1	1.5	70.3	5.4	2.4	0.1
115	35	10	140	2570	29.2	7.2	167.9	8.9	3.5	1.3
115	35	1	140	1403	25.0	1.7	100.9	5.3	5.3	1.7
115	35	0.1	140	953	19.4	1.7	87.3	5.0	13.1	0.9
115	35	0.01	140	762	13.2	8.1	67.7	10.0	17.8	0.7
118	35	10	140	2711	29.2	8.0	158.8	10.2	17.4	0.8
118	35	1	140	1468	25.2	2.1	91.4	6.6	10.5	1.0
118	35	0.1	140	988	19.1	5.0	80.7	8.2	5.1	0.3
118	35	0.01	140	798	12.8	15.6	60.1	17.9	1.8	0.2

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Table C2. Dynamic modulus data for IPC equipment.

Specimen	Temp C	Freq Hz	Conf Pressure kPa	Dynamic Modulus MPa	Phase Angle °	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity °
111	10	10	0	10268	16.1	3.4	-114.7	4.0	1.4	0.4
111	10	1	0	6527	21.9	2.8	-192.5	4.0	1.8	0.6
111	10	0.1	0	3611	28.1	1.6	-247.6	4.4	0.8	0.8
112	10	10	0	11044	15.6	3.2	-106.3	3.5	3.5	0.0
112	10	1	0	7107	20.8	8.6	-149.0	5.0	3.5	0.1
112	10	0.1	0	3955	26.5	1.6	-180.2	3.0	3.4	0.2
117	10	10	0	11486	15.9	3.7	-115.0	3.8	15.6	0.4
117	10	1	0	7307	21.7	2.6	-201.9	3.7	16.9	0.5
117	10	0.1	0	3992	28.4	1.7	-280.5	4.4	18.5	0.6
119	10	10	0	9949	16.3	4.0	-115.7	5.1	1.8	0.2
119	10	1	0	6237	22.1	2.8	-200.7	4.6	0.8	0.4
119	10	0.1	0	3380	28.6	1.7	-271.2	5.4	1.5	0.5
111	20	10	0	5299	26.0	2.8	-328.1	6.0	21.1	1.0
111	20	1	0	2594	32.9	1.5	-432.0	6.0	18.6	1.3
111	20	0.1	0	1113	36.5	1.3	-373.1	5.1	17.8	1.5
112	20	10	0	5938	23.9	4.1	-277.1	6.0	4.5	0.3
112	20	1	0	3092	30.4	1.5	-357.9	5.4	2.0	0.6
112	20	0.1	0	1360	34.6	1.2	-299.8	4.9	1.5	0.7
117	20	10	0	6171	25.0	4.7	-323.6	6.7	11.0	0.7
117	20	1	0	3127	32.1	1.4	-421.9	5.9	13.8	0.9
117	20	0.1	0	1335	36.0	1.3	-364.3	5.0	15.4	1.1
119	20	10	0	5485	25.0	3.2	-300.7	5.5	14.8	1.0
119	20	1	0	2767	31.8	1.5	-400.0	5.7	11.8	1.3
119	20	0.1	0	1180	35.8	1.3	-346.6	5.3	10.2	1.5
111	35	10	0	1952	34.9	5.4	-448.5	14.3	3.9	0.8
111	35	1	0	824	33.8	3.3	-156.0	5.1	4.2	1.5
111	35	0.1	0	313	30.0	3.6	-40.8	4.5	8.5	2.9
111	35	0.01	0	148	23.5	2.1	-4.6	6.8	19.0	4.7
112	35	10	0	2186	33.6	4.6	-369.2	11.7	8.4	1.0
112	35	1	0	942	32.5	3.0	-135.3	4.4	9.8	1.6
112	35	0.1	0	383	28.7	3.2	-35.1	5.7	12.3	2.3
112	35	0.01	0	191	22.2	1.8	14.4	6.8	19.3	3.7
117	35	10	0	2277	35.2	5.1	-506.4	14.7	5.1	0.4
117	35	1	0	963	34.3	2.9	-208.9	5.3	6.0	0.2
117	35	0.1	0	361	31.4	3.6	-73.3	4.9	6.3	0.8
117	35	0.01	0	168	24.2	1.9	-47.3	7.0	8.8	2.9
119	35	10	0	2059	35.0	4.9	-484.3	13.0	12.9	0.7
119	35	1	0	894	33.7	3.1	-211.1	5.4	12.1	1.0
119	35	0.1	0	372	29.5	3.2	-74.6	4.2	17.1	2.3
119	35	0.01	0	192	21.6	1.8	-35.8	6.5	28.7	6.4
111	35	10	140	2483	30.9	3.0	-345.2	8.3	13.8	1.1

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Table C2. (Continued).

Specimen	Temp C	Freq Hz	Conf Pressure kPa	Dynamic Modulus MPa	Phase Angle °	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity °
111	35	1	140	1336	27.1	2.5	-204.6	4.4	14.4	0.8
111	35	0.1	140	868	21.9	2.0	-199.1	5.7	13.9	0.9
111	35	0.01	140	698	16.0	0.9	-147.5	6.1	12.5	1.1
112	35	10	140	2268	31.6	5.2	-402.1	9.8	6.9	0.7
112	35	1	140	1233	28.2	2.5	-248.8	5.0	4.9	0.8
112	35	0.1	140	820	23.1	1.7	-181.6	5.1	4.0	0.9
112	35	0.01	140	685	16.8	0.8	-102.3	6.5	3.6	0.8
117	35	10	140	2438	30.9	3.3	-228.5	8.1	11.3	1.0
117	35	1	140	1275	25.8	2.1	-58.7	2.6	11.8	0.8
117	35	0.1	140	829	19.4	1.4	-30.4	2.9	11.5	0.7
117	35	0.01	140	679	13.8	0.8	-29.7	5.8	10.3	0.8
119	35	10	140	2271	30.4	2.8	-321.2	8.4	9.4	0.7
119	35	1	140	1245	26.2	2.0	-182.3	4.1	9.2	0.7
119	35	0.1	140	813	21.2	1.8	-140.0	4.7	9.4	0.6
119	35	0.01	140	664	15.6	0.8	-101.5	7.9	9.3	0.6

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Table C3. Dynamic modulus data for MDTS equipment.

Specimen	Temp C	Freq Hz	Conf Pressure kPa	Dynamic Modulus MPa	Phase Angle °	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity °
111	10	10	0	11336	16.8	0.4	51.2	2.3	18.8	0.9
111	10	1	0	7556	22.2	0.1	165.5	5.3	18.2	1.7
111	10	0.1	0	4178	26.8	0.0	221.3	5.4	9.7	4.5
113	10	10	0	13150	16.6	0.3	144.0	6.4	16.3	2.7
113	10	1	0	7841	24.7	0.2	186.6	4.2	0.4	1.9
113	10	0.1	0	3792	30.4	0.0	182.4	4.2	19.9	0.7
116	10	10	0	11961	16.6	0.5	115.6	2.8	21.6	4.4
116	10	1	0	7637	22.3	0.1	252.3	6.3	19.3	3.7
116	10	0.1	0	4242	27.4	0.0	257.4	7.2	16.6	4.3
120	10	10	0	11010	14.0	0.4	60.6	1.8	35.3	2.3
120	10	1	0	7610	22.4	0.1	156.2	3.7	28.6	0.3
120	10	0.1	0	3918	27.3	0.0	229.4	5.4	8.1	2.9
111	20	10	0	6359	21.2	0.7	129.3	4.1	22.7	0.7
111	20	1	0	3676	29.8	0.2	140.2	5.2	25.4	0.9
111	20	0.1	0	1694	32.8	0.1	87.6	4.6	24.5	1.3
113	20	10	0	6660	21.3	0.7	140.3	3.2	28.4	1.5
113	20	1	0	3002	30.4	0.3	221.4	6.2	5.6	0.6
113	20	0.1	0	1546	33.3	0.1	157.3	6.9	7.1	0.8
116	20	10	0	5818	18.3	0.7	85.7	2.5	32.8	4.7
116	20	1	0	3052	27.7	0.3	219.2	5.9	14.9	7.4
116	20	0.1	0	1417	32.1	0.1	136.0	6.1	6.8	4.7
120	20	10	0	5235	17.5	0.7	122.4	2.4	19.0	2.1
120	20	1	0	3307	27.6	0.3	174.3	3.6	15.9	0.0
120	20	0.1	0	1713	30.6	0.1	166.9	4.9	18.7	0.8
111	35	10	0	2138	32.2	1.3	157.3	2.7	2.3	6.5
111	35	1	0	850	32.0	0.7	76.7	4.9	2.9	8.4
111	35	0.1	0	399	27.5	0.3	50.4	6.1	24.0	1.2
111	35	0.01	0	234	22.1	0.3	100.5	10.3	46.6	5.2
113	35	10	0	2165	35.0	1.3	236.7	6.5	7.7	7.3
113	35	1	0	821	36.7	0.7	62.0	5.5	7.5	3.8
113	35	0.1	0	404	32.0	0.3	33.6	6.2	18.8	6.8
113	35	0.01	0	262	25.2	0.3	49.5	12.8	33.2	11.0
116	35	10	0	2033	32.9	1.4	324.1	11.3	4.0	6.5
116	35	1	0	890	32.1	1.0	80.5	6.1	2.6	0.9
116	35	0.1	0	392	27.3	0.3	59.7	6.3	6.0	3.5
116	35	0.01	0	236	21.1	0.3	80.2	11.3	16.0	7.5
120	35	10	0	1788	34.4	1.8	347.9	9.8	14.1	0.9
120	35	1	0	755	34.4	0.8	288.7	10.3	13.7	1.7
120	35	0.1	0	312	32.0	0.3	268.5	8.1	0.1	3.5
120	35	0.01	0	127	32.3	0.5	152.5	10.8	29.1	3.0
111	35	10	140	2240	30.4	1.0	137.7	3.3	4.8	1.2

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Table C3. (Continued).

Specimen	Temp C	Freq Hz	Conf Pressure kPa	Dynamic Modulus MPa	Phase Angle °	Load Standard Error %	Deformation Drift %	Deformation Standard Error %	Deformation Uniformity %	Phase Uniformity °
111	35	1	140	1123	26.8	0.3	10.8	2.6	12.4	0.7
111	35	0.1	140	714	19.8	0.1	13.2	2.9	13.7	0.5
111	35	0.01	140	555	13.8	0.1	24.2	3.8	12.2	0.3
113	35	10	140	2390	29.3	0.9	179.9	3.7	17.2	1.0
113	35	1	140	1196	26.1	0.4	131.0	3.0	22.3	2.1
113	35	0.1	140	780	19.4	0.1	98.2	3.5	23.5	2.4
113	35	0.01	140	680	15.2	0.6	106.0	15.1	41.1	4.4
116	35	10	140	2149	31.2	1.1	237.4	3.6	17.1	1.2
116	35	1	140	991	28.0	0.5	45.4	2.7	17.1	2.0
116	35	0.1	140	597	22.8	0.1	18.9	4.0	11.1	1.8
116	35	0.01	140	493	17.5	0.1	46.5	4.8	2.8	1.4
120	35	10	140	2190	31.7	1.3	203.3	4.2	4.1	2.4
120	35	1	140	1153	27.4	0.4	76.3	2.5	9.7	2.1
120	35	0.1	140	765	20.7	0.1	71.0	3.0	11.2	1.7
120	35	0.01	140	672	19.2	0.4	90.6	41.8	80.0	3.6

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APPENDIX D

Flow Number Equipment Effects Data

Table D1. Unconfined flow number data.

Cycle	Permanent Axial Strain, %											
	ITC				IPC				MDTS			
	127	133	138	153	125	131	147	154	122	134	140	148
1	0.04	0.04	0.04	0.04	0.05	0.05	0.06	0.05	0.06	0.07	0.06	0.06
2	0.06	0.06	0.07	0.06	0.08	0.08	0.09	0.08	0.09	0.07	0.09	0.09
3	0.08	0.08	0.09	0.08	0.11	0.11	0.12	0.11	0.12	0.13	0.11	0.12
4	0.10	0.10	0.11	0.09	0.13	0.13	0.14	0.13	0.14	0.15	0.13	0.14
5	0.11	0.11	0.12	0.11	0.15	0.15	0.16	0.15	0.16	0.17	0.15	0.16
6	0.13	0.13	0.14	0.13	0.17	0.16	0.18	0.16	0.17	0.19	0.16	0.17
7	0.15	0.14	0.16	0.14	0.18	0.18	0.19	0.18	0.17	0.20	0.17	0.19
8	0.16	0.15	0.17	0.15	0.20	0.19	0.20	0.19	0.20	0.21	0.18	0.20
9	0.17	0.16	0.19	0.16	0.21	0.20	0.22	0.20	0.21	0.23	0.20	0.21
10	0.18	0.18	0.20	0.18	0.22	0.21	0.23	0.21	0.22	0.24	0.20	0.22
20	0.25	0.25	0.28	0.24	0.30	0.29	0.30	0.29	0.30	0.32	0.27	0.30
30	0.30	0.30	0.33	0.28	0.36	0.35	0.36	0.34	0.36	0.37	0.32	0.35
40	0.34	0.34	0.38	0.32	0.40	0.39	0.40	0.38	0.40	0.41	0.36	0.39
50	0.37	0.37	0.41	0.35	0.43	0.42	0.43	0.41	0.44	0.45	0.38	0.43
60	0.40	0.40	0.44	0.37	0.46	0.45	0.46	0.44	0.47	0.48	0.41	0.46
70	0.42	0.43	0.47	0.40	0.49	0.48	0.48	0.47	0.50	0.51	0.43	0.48
80	0.44	0.45	0.49	0.42	0.51	0.50	0.51	0.49	0.52	0.53	0.46	0.50
90	0.45	0.46	0.52	0.43	0.53	0.53	0.53	0.51	0.55	0.55	0.47	0.52
100	0.47	0.49	0.54	0.45	0.55	0.55	0.55	0.53	0.57	0.57	0.49	0.54
200	0.60	0.64	0.71	0.58	0.70	0.70	0.69	0.67	0.73	0.72	0.62	0.68
300	0.70	0.74	0.83	0.67	0.80	0.82	0.80	0.77	0.86	0.82	0.70	0.78
400	0.78	0.84	0.94	0.75	0.89	0.91	0.90	0.86	0.97	0.92	0.78	0.87
500	0.85	0.92	1.04	0.82	0.97	1.00	0.98	0.94	1.06	1.00	0.84	0.94
600	0.92	1.01	1.14	0.89	1.04	1.09	1.06	1.01	1.16	1.08	0.91	1.01
700	0.99	1.09	1.23	0.95	1.12	1.17	1.14	1.08	1.25	1.15	0.96	1.08
800	1.05	1.17	1.32	1.02	1.19	1.25	1.21	1.15	1.35	1.22	1.02	1.14
900	1.13	1.26	1.40	1.09	1.26	1.33	1.29	1.22	1.44	1.29	1.08	1.21
1000	1.19	1.34	1.50	1.15	1.33	1.41	1.37	1.29	1.54	1.37	1.13	1.28
1100	1.26	1.43	1.59	1.22	1.40	1.49	1.45	1.36	1.64	1.44	1.18	1.34
1200	1.33	1.51	1.67	1.29	1.47	1.57	1.53	1.43	1.74	1.52	1.24	1.41
1300	1.40	1.61	1.77	1.37	1.55	1.66	1.61	1.51	1.85	1.59	1.29	1.47
1400	1.48	1.69	1.86	1.44	1.62	1.75	1.70	1.58	1.96	1.67	1.35	1.55
1500	1.55	1.80	1.96	1.52	1.70	1.84	1.79	1.66	2.08	1.76	1.41	1.62
1600	1.63	1.89	2.06	1.60	1.79	1.93	1.88	1.74	2.21	1.84	1.47	1.69
1700	1.72	2.00	2.17	1.68	1.88	2.03	1.98	1.83	2.34	1.93	1.53	1.76
1800	1.80	2.11	2.28	1.77	1.97	2.13	2.09	1.91	2.49	2.02	1.59	1.84
1900	1.89	2.22	2.41	1.86	2.06	2.24	2.20	2.01	2.64	2.12	1.66	1.93
2000	1.99	2.35	2.53	1.96	2.16	2.36	2.32	2.11	2.80	2.22	1.73	2.01
2100	2.09	2.48	2.68	2.06	2.27	2.48	2.44	2.21	2.98	2.33	1.80	2.10
2200	2.20	2.63	2.83	2.17	2.39	2.61	2.58	2.32	3.18	2.44	1.87	2.19
2300	2.32	2.79	2.99	2.30	2.51	2.74	2.72	2.44	3.39	2.56	1.94	2.29
2400	2.45	2.97	3.15	2.42	2.64	2.89	2.88	2.56	3.62	2.70	2.02	2.39

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Table D1. (Continued).

Cycle	Permanent Axial Strain, %											
	ITC				IPC				MDTS			
	127	133	138	153	125	131	147	154	122	134	140	148
2500	2.59	3.16	3.35	2.55	2.79	3.04	3.05	2.69	3.87	2.84	2.10	2.50
2600	2.74	3.37	3.54	2.71	2.94	3.21	3.23	2.84	4.15	2.99	2.19	2.62
2700	2.91	3.61	3.76	2.86	3.11	3.40	3.43	3.00	4.46	3.15	2.27	2.75
2800	3.10	3.86	4.00	3.06	3.29	3.60	3.65	3.17	4.81	3.33	2.37	2.88
2900	3.31	4.15	4.27	3.29	3.48	3.82	3.90	3.35		3.53	2.46	3.02
3000	3.55	4.48	4.57	3.56	3.70	4.05	4.18	3.56		3.74	2.56	3.17

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Table D2. Confined flow number data.

	Permanent Axial Strain, %											
	ITC				IPC				MDTS			
Cycle	128	141	145	152	129	131	149	156	150	132	143	139
1	0.14		0.13	0.13	0.05	0.16	0.17	0.13	0.14	0.15	0.15	0.11
2	0.22		0.20	0.20	0.06	0.25	0.27	0.20	0.21	0.22	0.22	0.16
3	0.28		0.26	0.26	0.07	0.32	0.34	0.25	0.26	0.27	0.28	0.16
4	0.33		0.29	0.30	0.08	0.37	0.40	0.30	0.30	0.31	0.32	0.23
5	0.37		0.33	0.33	0.09	0.42	0.45	0.33	0.33	0.35	0.36	0.25
6	0.40		0.36	0.35	0.09	0.46	0.49	0.36	0.36	0.38	0.39	0.27
7	0.43		0.38	0.38	0.10	0.49	0.52	0.39	0.38	0.41	0.43	0.29
8	0.45		0.41	0.40	0.11	0.52	0.55	0.41	0.41	0.43	0.45	0.29
9	0.48		0.43	0.42	0.11	0.54	0.58	0.43	0.43	0.46	0.48	0.32
10	0.50		0.45	0.44	0.12	0.57	0.60	0.45	0.44	0.48	0.50	0.34
20	0.66		0.58	0.57	0.17	0.74	0.78	0.58	0.57	0.63	0.65	0.45
30	0.75		0.66	0.64	0.21	0.85	0.90	0.66	0.65	0.72	0.76	0.50
40	0.82		0.72	0.69	0.24	0.93	0.99	0.72	0.71	0.80	0.83	0.56
50	0.88		0.77	0.73	0.28	1.00	1.07	0.77	0.76	0.86	0.89	0.60
60	0.92		0.81	0.77	0.31	1.06	1.13	0.82	0.80	0.91	0.94	0.64
70	0.96		0.84	0.80	0.33	1.11	1.18	0.85	0.84	0.96	0.99	0.66
80	1.00		0.88	0.83	0.36	1.16	1.23	0.89	0.87	1.00	1.04	0.69
90	1.04		0.90	0.85	0.38	1.20	1.28	0.92	0.90	1.03	1.07	0.71
100	1.07		0.94	0.88	0.41	1.24	1.32	0.94	0.92	1.07	1.11	0.73
200	1.29		1.14	1.04	0.59	1.51	1.62	1.14	1.10	1.32	1.35	0.87
300	1.45		1.27	1.15	0.72	1.69	1.81	1.26	1.20	1.49	1.51	0.96
400	1.57		1.37	1.23	0.84	1.83	1.96	1.35	1.28	1.62	1.63	1.03
500	1.66		1.46	1.31	0.93	1.94	2.09	1.43	1.35	1.73	1.73	1.08
600	1.74		1.53	1.37	1.01	2.04	2.20	1.50	1.40	1.83	1.82	1.13
700	1.81		1.60	1.42	1.08	2.13	2.30	1.55	1.45	1.91	1.89	1.17
800	1.87		1.66	1.47	1.14	2.21	2.38	1.60	1.49	1.97	1.97	1.20
900	1.93		1.71	1.52	1.20	2.28	2.46	1.65	1.52	2.02	2.03	1.23
1000	1.98		1.76	1.57	1.25	2.35	2.53	1.69	1.56	2.07	2.09	1.26
1200	2.07		1.85	1.64	1.35	2.46	2.65	1.77	1.62	2.15	2.19	1.31
1300	2.11		1.88	1.68	1.39	2.52	2.71	1.80	1.64	2.18	2.24	1.33
1400	2.15		1.92	1.72	1.43	2.57	2.76	1.84	1.67	2.22	2.29	1.36
1500	2.19		1.96	1.75	1.47	2.62	2.81	1.87	1.69	2.25	2.33	1.38
1600	2.22		1.99	1.78	1.51	2.66	2.85	1.90	1.71	2.28	2.37	1.40
1700	2.26		2.03	1.81	1.54	2.70	2.90	1.92	1.74	2.31	2.41	1.42
1800	2.29		2.06	1.84	1.57	2.74	2.94	1.95	1.76	2.34	2.45	1.44
1900	2.31		2.09	1.87	1.61	2.78	2.98	1.97	1.78	2.37	2.48	1.46
2000	2.34		2.12	1.90	1.64	2.82	3.02	2.00	1.80	2.40	2.52	1.47
2100	2.38		2.15	1.93	1.67	2.86	3.05	2.03	1.81	2.42	2.55	1.49
2200	2.40		2.18	1.95	1.69	2.89	3.08	2.05	1.83	2.45	2.59	1.51
2300	2.43		2.21	1.98	1.72	2.93	3.12	2.07	1.85	2.48	2.62	1.52

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Table D2. (Continued).

	Permanent Axial Strain, %											
	ITC				IPC				MDTS			
Cycle	128	141	145	152	129	131	149	156	150	132	143	139
2400	2.45		2.24	2.01	1.75	2.96	3.15	2.09	1.87	2.50	2.65	1.53
2500	2.47		2.27	2.04	1.77	3.00	3.18	2.11	1.88	2.52	2.68	1.55
2600	2.50		2.30	2.06	1.80	3.03	3.21	2.13	1.90	2.55	2.71	1.56
2700	2.52		2.33	2.09	1.82	3.06	3.23	2.15	1.91	2.57	2.73	1.58
2800	2.54		2.35	2.11	1.85	3.09	3.26	2.17	1.93	2.59	2.76	1.59
2900	2.56		2.38	2.14	1.87	3.12	3.29	2.19	1.94	2.61	2.79	1.60
3000	2.59		2.41	2.16	1.89	3.15	3.31	2.21	1.95	2.63	2.81	1.61
3100	2.60		2.43	2.18	1.91	3.18	3.34	2.23	1.97	2.65	2.84	1.63
3200	2.63		2.46	2.21	1.93	3.21	3.36	2.25	1.98	2.67	2.86	1.64
3300	2.64		2.49	2.24	1.95	3.23	3.39	2.26	1.99	2.69	2.89	1.65
3400	2.66		2.52	2.26	1.98	3.26	3.41	2.28	2.00	2.70	2.91	1.66
3500	2.68		2.54	2.28	2.00	3.29	3.44	2.29	2.01	2.72	2.93	1.67
3600	2.70		2.57	2.30	2.02	3.31	3.46	2.31	2.03	2.73	2.95	1.69
3700	2.71		2.60	2.33	2.04	3.34	3.48	2.33	2.04	2.75	2.97	1.70
3800	2.73		2.63	2.35	2.06	3.36	3.50	2.34	2.05	2.77	2.99	1.71
3900	2.75		2.65	2.38	2.07	3.38	3.52	2.36	2.06	2.78	3.01	1.72
4000	2.76		2.68	2.40	2.09	3.41	3.55	2.37	2.07	2.80	3.03	1.73
4100	2.78		2.71	2.42	2.11	3.43	3.57	2.39	2.08	2.81	3.05	1.74
4200	2.80		2.74	2.44	2.13	3.45	3.59	2.40	2.09	2.83	3.07	1.75
4300	2.81		2.76	2.46	2.15	3.47	3.61	2.42	2.10	2.84	3.09	1.76
4400	2.82		2.79	2.49	2.16	3.49	3.63	2.43	2.11	2.86	3.11	1.77
4500	2.84		2.82	2.51	2.18	3.52	3.65	2.44	2.12	2.87	3.13	1.77
4600	2.85		2.85	2.53	2.19	3.54	3.67	2.46	2.13	2.88	3.14	1.78
4700	2.87		2.88	2.55	2.21	3.56	3.69	2.47	2.14	2.90	3.16	1.79
4800	2.88		2.90	2.57	2.23	3.57	3.71	2.48	2.15	2.91	3.18	1.80
4900	2.89		2.93	2.59	2.24	3.59	3.73	2.49	2.16	2.92	3.19	1.81
5000	2.91		2.96	2.61	2.26	3.61	3.75	2.51	2.17	2.94	3.21	1.82
5100	2.92		2.98	2.63	2.27	3.63	3.77	2.52	2.18	2.95	3.22	1.83
5200	2.93		3.01	2.65	2.29	3.65	3.79	2.53	2.18	2.96	3.24	1.83
5300	2.95		3.04	2.67	2.30	3.67	3.81	2.54	2.19	2.97	3.25	1.84
5400	2.96		3.06	2.69	2.32	3.68	3.83	2.56	2.20	2.99	3.27	1.85
5500	2.97		3.08	2.71	2.33	3.70	3.84	2.57	2.21	3.00	3.28	1.85
5600	2.98		3.11	2.73	2.34	3.72	3.86	2.58	2.22	3.01	3.30	1.86
5700	3.00		3.14	2.75	2.36	3.73	3.88	2.59	2.23	3.02	3.31	1.87
5800	3.01		3.16	2.76	2.37	3.75	3.89	2.60	2.24	3.04	3.33	1.88
5900	3.02		3.19	2.78	2.38	3.77	3.91	2.61	2.24	3.05	3.34	1.89
6000	3.03		3.21	2.80	2.39	3.78	3.92	2.62	2.25	3.06	3.35	1.89
6100	3.05		3.23	2.81	2.41	3.80	3.94	2.64	2.26	3.07	3.37	1.90
6200	3.06		3.26	2.83	2.42	3.82	3.95	2.65	2.27	3.08	3.38	1.91
6300	3.07		3.28	2.84	2.43	3.83	3.97	2.66	2.28	3.09	3.39	1.91
6400	3.08		3.30	2.85	2.44	3.84	3.99	2.67	2.28	3.10	3.41	1.92
6500	3.09		3.33	2.87	2.46	3.86	4.00	2.68	2.29	3.11	3.42	1.93
6600	3.10		3.35	2.88	2.47	3.87	4.02	2.69	2.30	3.12	3.43	1.93
6700	3.11		3.37	2.89	2.48	3.89	4.03	2.70	2.31	3.13	3.45	1.94

(continued on next page)

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Table D2. (Continued).

	Permanent Axial Strain, %											
	ITC				IPC				MDTS			
Cycle	128	141	145	152	129	131	149	156	150	132	143	139
6800	3.12		3.39	2.91	2.49	3.90	4.04	2.71	2.31	3.14	3.46	1.95
6900	3.13		3.42	2.92	2.50	3.92	4.06	2.72	2.32	3.15	3.47	1.95
7000	3.14		3.44	2.93	2.51	3.93	4.07	2.73	2.33	3.16	3.48	1.96
7100	3.15		3.46	2.93	2.52	3.94	4.09	2.74	2.33	3.17	3.49	1.97
7200	3.16		3.48	2.95	2.54	3.96	4.10	2.75	2.34	3.18	3.50	1.97
7300	3.17		3.50	2.95	2.55	3.97	4.11	2.75	2.35	3.19	3.52	1.98
7400	3.18		3.52	2.96	2.56	3.99	4.13	2.76	2.35	3.20	3.53	1.98
7500	3.19		3.54	2.97	2.57	4.00	4.14	2.77	2.36	3.21	3.54	1.99
7600	3.20		3.56	2.98	2.58	4.01	4.15	2.78	2.37	3.22	3.55	1.99
7700	3.21		3.58	2.99	2.59	4.03	4.17	2.79	2.37	3.23	3.56	2.00
7800	3.22		3.60	2.99	2.60	4.04	4.18	2.80	2.38	3.24	3.57	2.01
7900	3.23		3.62	3.00	2.61	4.05	4.19	2.81	2.39	3.24	3.58	2.01
8000	3.23		3.64	3.01	2.62	4.06	4.20	2.82	2.39	3.25	3.59	2.02
8100	3.24		3.66	3.02	2.63	4.08	4.21	2.83	2.40	3.26	3.60	2.02
8200	3.26		3.68	3.02	2.64	4.09	4.23	2.84	2.40	3.27	3.62	2.03
8300	3.26		3.70	3.03	2.65	4.10	4.24	2.84	2.41	3.28	3.63	2.03
8400	3.27		3.72	3.04	2.65	4.11	4.25	2.85	2.42	3.29	3.63	2.04
8500	3.28		3.73	3.04	2.67	4.12	4.26	2.86	2.42	3.30	3.65	2.04
8600	3.29		3.75	3.05	2.67	4.14	4.27	2.87	2.43	3.31	3.65	2.05
8700	3.30		3.77	3.06	2.68	4.15	4.28	2.88	2.43	3.31	3.66	2.05
8800	3.30		3.79	3.06	2.69	4.16	4.30	2.88	2.44	3.32	3.67	2.06
8900	3.31		3.81	3.07	2.70	4.17	4.30	2.89	2.45	3.33	3.68	2.06
9000	3.32		3.82	3.07	2.71	4.18	4.32	2.90	2.45	3.34	3.69	2.07
9100	3.33		3.84	3.08	2.72	4.19	4.33	2.91	2.46	3.35	3.70	2.07
9200	3.33		3.86	3.08	2.73	4.20	4.34	2.91	2.46	3.36	3.71	2.08
9300	3.34		3.87	3.09	2.74	4.21	4.35	2.92	2.47	3.36	3.72	2.08
9400	3.35		3.89	3.09	2.74	4.23	4.36	2.93	2.47	3.37	3.73	2.09
9500	3.36		3.90	3.10	2.75	4.23	4.37	2.94	2.48	3.38	3.74	2.09
9600	3.36		3.92	3.10	2.76	4.25	4.38	2.94	2.49	3.38	3.75	2.10
9700	3.37		3.94	3.10	2.77	4.25	4.39	2.95	2.49	3.39	3.75	2.10
9800	3.38		3.96	3.11	2.78	4.27	4.40	2.96	2.50	3.40	3.76	2.11
9900	3.38		3.97	3.12	2.79	4.28	4.41	2.97	2.50	3.41	3.77	2.11
9997	3.39		3.99	3.12	2.79	4.29	4.42	2.97	2.51	3.42	3.78	2.12

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APPENDIX E

Final Version of the SPT Equipment Specifications

NCHRP
Project 9-29

Simple Performance Tester for Superpave Mix Design

Equipment Specification For The Simple Performance Test System

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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

Note: This equipment specification represents a revision of the equipment requirements contained in NCHRP Report 465 and AASHTO TP62. The requirements of this specification supersede those contained in NCHRP Report 465 and AASHTO TP62.

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.

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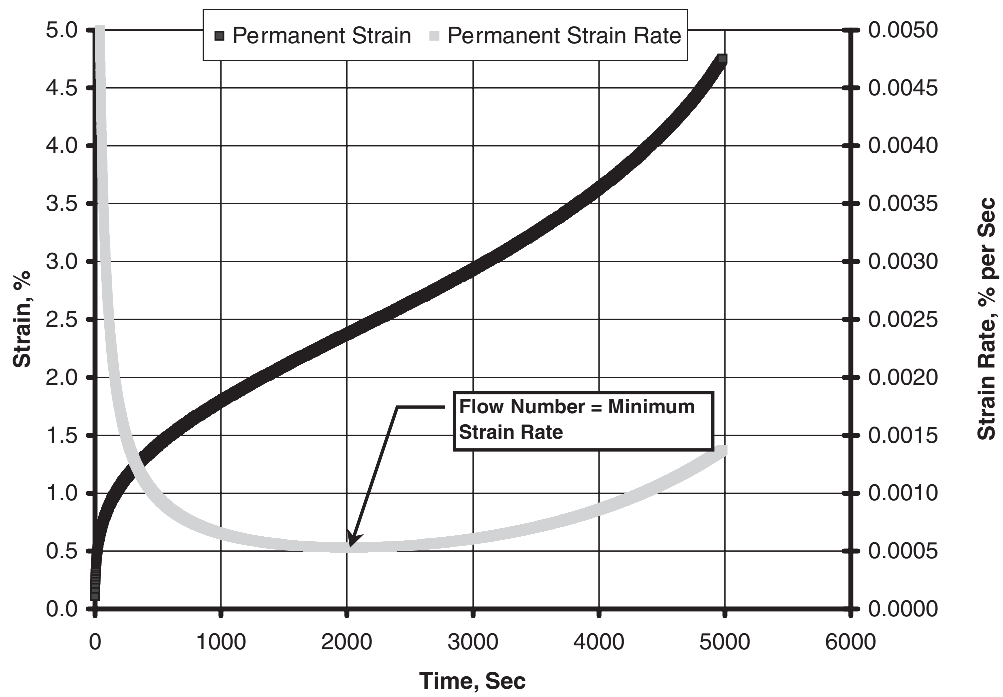

Figure 1. Schematic of Flow Time Test Data.

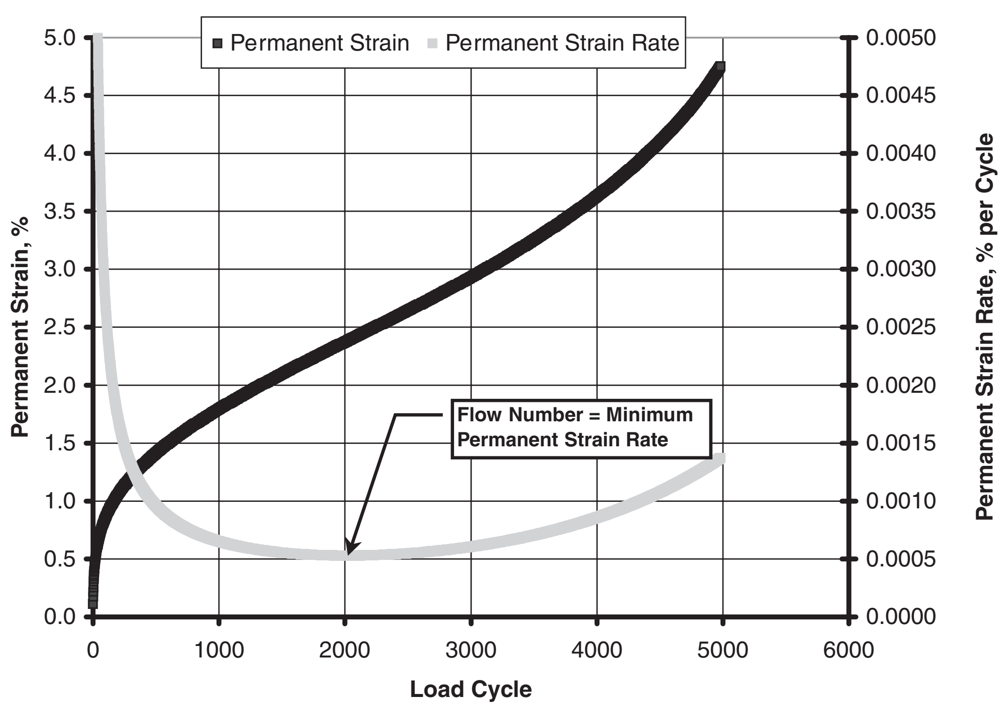

Figure 2. Schematic of Flow Number Test Data.

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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

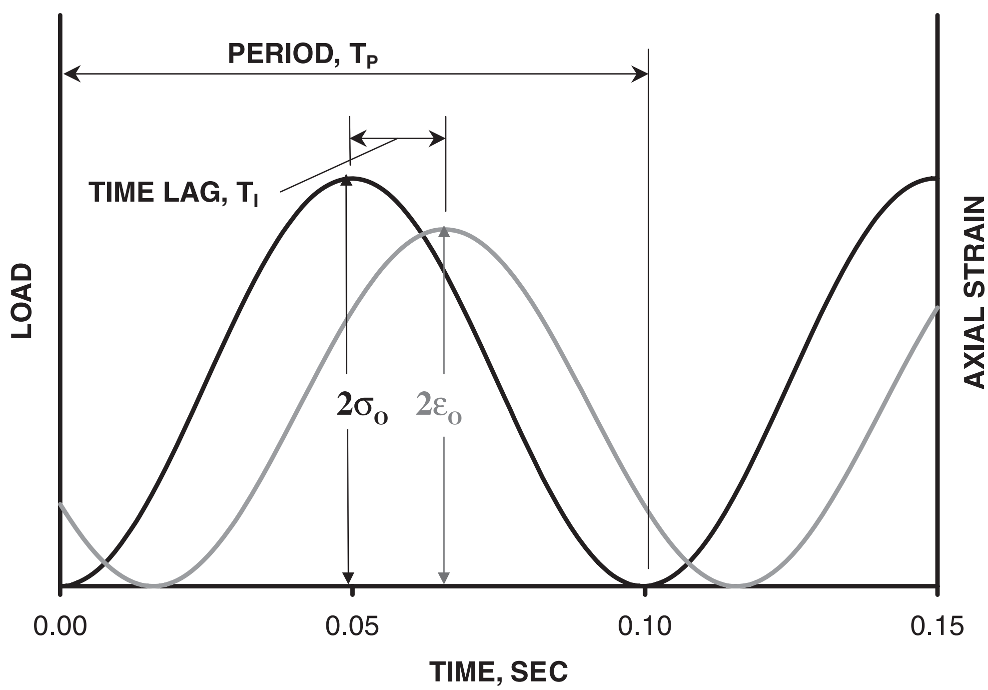

Figure 3. Schematic of Dynamic Modulus Test Data.

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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	Note
Specimen Dimensions	Average Diameter	100 mm to 104 mm	1
	Standard Deviation of Diameter	0.5 mm	1
	Height	147.5 mm to 152.5 mm	2
	End Flatness	0.5 mm	3
	End Perpendicularity	1.0 mm	4

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Notes:	1. Using calipers, measure the diameter at the center and third points of the test specimen along axes that are 90 ° apart. Record each of the six measurements to the nearest 0.1 mm. Calculate the average and the standard deviation of the six measurements. 2. Measure the height of the test specimen in accordance with Section 6.1.2 of ASTM D 3549. 3. Using a straightedge and feeler gauges, measure the flatness of each end. Place a straight edge across the diameter at three locations approximately 120 ° apart and measure the maximum departure of the specimen end from the straight edge using tapered end feeler gauges. For each end record the maximum departure along the three locations as the end flatness. 4. Using a combination square and feeler gauges, measure the perpendicularity of each end. At two locations approximately 90 ° apart, place the blade of the combination square in contact with the specimen along the axis of the cylinder, and the head in contact with the highest point on the end of the cylinder. Measure the distance between the head of the square and the lowest point on the end of the cylinder using tapered end feeler gauges. For each end, record the maximum measurement from the two locations as the end perpendicularity.

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 tests.

4.2 Appendix A 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.

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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	13.5 kN (3.0 kips)	0.01 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.

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

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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 13.5 kN (3.0 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.

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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^2 ± 10 mm^2
Dimension of the gauge point in the direction of the guage length	10mm ± 2mm
Mass of mounting system and transducer	80 g max
Transducer spring force	1 N max

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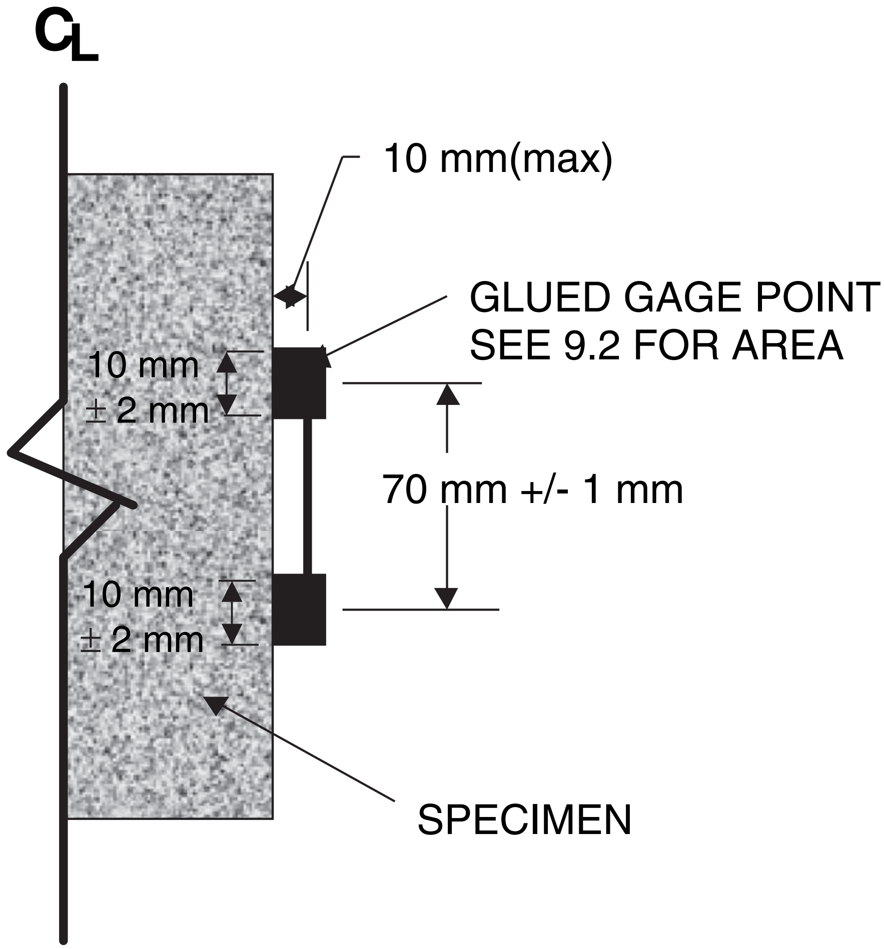

Figure 4. Schematic of Standard Specimen Mounted Deformation Measuring System.

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.

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 5 minutes over the complete range of temperatures.

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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 2,200,000 psi). Appendix B describes the minimum testing and analysis required for a non-standard 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.

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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 0 to 60 ^{o}C (32 to 140 ^{o}F), and be readable and accurate to the nearest 0.25 ^{o}C. (0.5 ^{o}F). For confined testss 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 5 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 4 to 60 °C (39 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 5 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 0 to 60 ^{o}C (32 to 140 ^{o}F), and be readable and accurate to the nearest 0.25 ^{o}C (0.5 ^{o}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.

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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 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.

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

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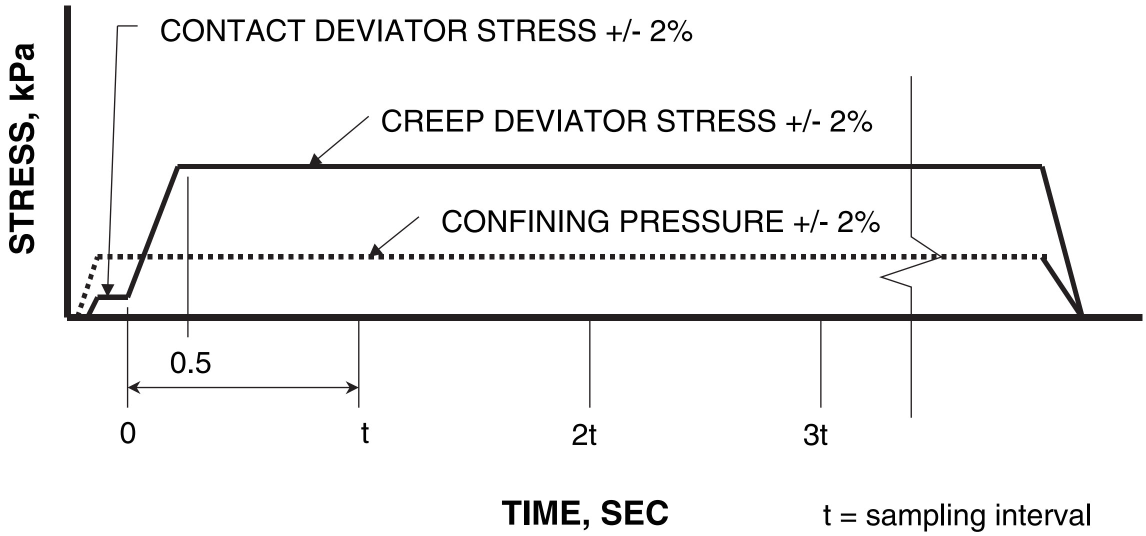

Figure 5. Schematic of Loading and Data Acquisition.

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, collect and store data.
6. Post test remarks.
7. Remove tested specimen.

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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.

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 ^{o}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. Sum of errors squared between measured and fitted axial strain.
5. Axial strain at the flow time.
6. Average temperature during the test.
7. Average confining stress during the test.
8. Time and corresponding measured deviator stress, measured confining pressure, measured temperature, measured axial strain, and computed rate of change of strain.
9. Warnings
10. 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. Sum of errors squared between measured and fitted axial strain.
5. Axial strain at the flow time.
6. Average temperature during the test.
7. Average confining stress during the test.
8. Warnings

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9. Post test remarks
10. Plot of measured axial strain versus time.
11. Plot of fitted axial strain versus time
12. 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.

12.4.6 Figure 6 presents a schematic of the specified loading and data acquisition.

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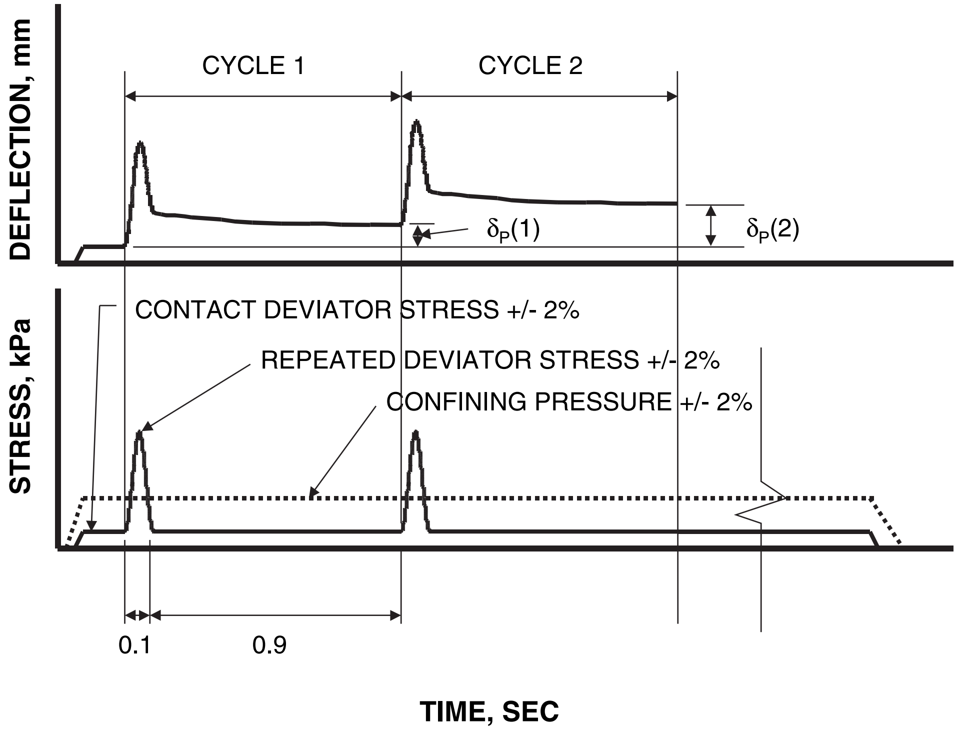

Figure 6. Schematic of Loading and Data Acquisition for Flow Time Test.

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.

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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, and 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 ^{o}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. Sum of errors squared between measured and fitted axial strain.
5. Axial strain at the flow number.
6. Average temperature during the test.
7. Average confining stress during the test.
8. Average peak deviator stress.
9. Average contact stress.
10. Maximum standard error of the applied load.
11. 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.

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12. Warnings
13. 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. Sum of errors squared between measured and fitted axial strain.
5. Axial strain at the flow number.
6. Average temperature during the test.
7. Average confining stress during the test.
8. Average peak deviator stress.
9. Average contact stress.
10. Maximum load standard error.
11. Warnings.
12. Post test remarks.
13. Plot of measured permanent axial strain versus load cycles.
14. Plot of fitted permanent axial strain versus load cycles.
15. 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 85 to 115 µstrain. Adjustment of the dynamic stress shall be performed during the ten conditioning cycles at each loading frequency.

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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.

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Response	Tolerance
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 ^{o}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 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. Strain amplitude
4. Average temperature during the test.
5. Average confining pressure.
6. 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.

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7. Time and corresponding measured axial stress, individual measured axial strains, measured confining pressure, and measured temperature,
8. Warnings
9. 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. Strain amplitude.
6. Average temperature during the test.
7. Average confining pressure during the test.
8. 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.

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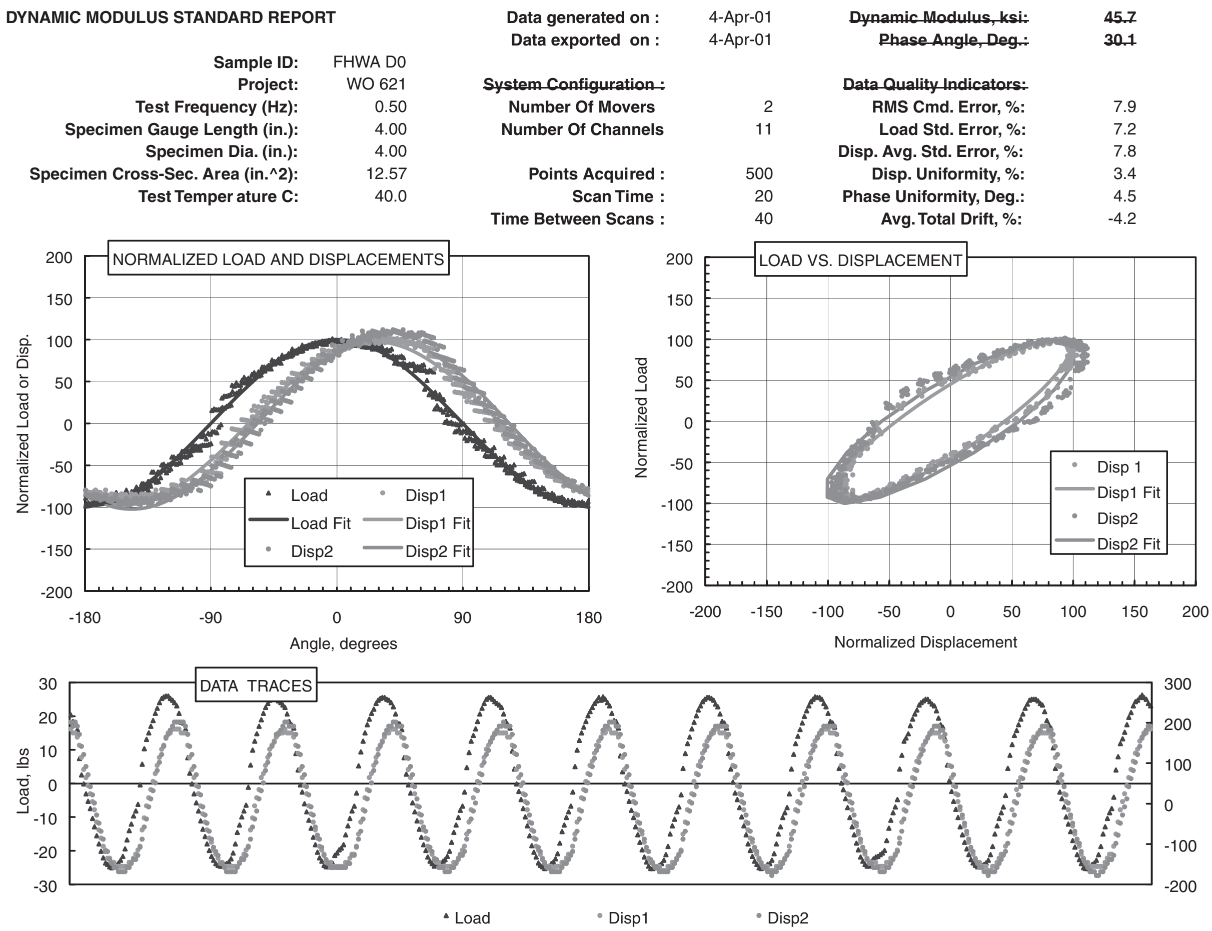

Figure 7. Example Dynamic Modulus Output.

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. The flow time is found by fitting the model described in Section 13.1.2 to the axial strain data using nonlinear least squares, then determining the inflection point from the second derivative of the model described in section 13.1.4.

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13.1.2 Axial strain model:

$$\varepsilon = At^{B} - C(e^{Dt} - 1) \quad (4)$$

where:

ε = axial strain
t = time
A, B, C, and D = fitting coefficients

13.1.3 First derivative (Strain Rate):

$$\frac{d\varepsilon}{dt} = ABt^{B-1} + CDe^{Dt} \quad (5)$$

13.1.4 Second derivative:

$$\frac{d^{2}\varepsilon}{dt^{2}} = AB(B-1)t^{B-2} + CD^{2}e^{Dt} \quad (6)$$

13.1.5 Fitting of Equation 4 shall produce a sum of squared errors between measured and fitted axial strain that is less than 0.5% when the strains are expressed in units of percent.

13.1.6 The Flow Time is reported as the time when the second derivative of the axial strain model, Equation 6, changes from negative to positive.

13.2 Flow Number Test

13.2.1 The Flow Number is defined as the cycle corresponding to the minimum rate of change of axial permanent strain during a repeated load test. The flow number is found by fitting the model described in Section 13.2.2 to the permanent axial strain data using nonlinear least squares, then determining the inflection point from the second derivative of the model described in section 13.2.4.

13.2.2 Permanent axial strain model:

$$\varepsilon_{p} = An^{B} + C(e^{Dn} - 1) \quad (7)$$

where:

ε_p = permanent axial strain
n = number of cycles
A, B, C, and D = fitting coefficients

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13.2.3 First derivative (Permanent Axial Strain Rate)

$$\frac{d\varepsilon_p}{dn} = ABn^{B-1} + CDe^{Dn} \tag{8}$$

13.2.4 Second derivative

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{B-2} + CD^2e^{Dn} \tag{9}$$

13.2.5 Fitting of Equation 7 shall produce a sum of squared errors between measured and fitted axial strain that is less than 0.5% when the strains are expressed in units of percent.

13.2.6 The Flow Number is reported as the cycle when the second derivative of the permanent axial strain model, Equation 9, changes from negative to positive.

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.

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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:

$$Y_{ji}' = Y_{ji} - \overline{Y_j} \tag{10}$$

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:

$$[X'X] = \begin{bmatrix} N & \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} \cos(\omega_0 t_i) & \sum_{i=1}^{n} \sin(\omega_0 t_i) \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 & \sum_{i=1}^{n} t_i \cos(\omega_0 t_i) & \sum_{i=1}^{n} t_i \sin(\omega_0 t_i) \\ \sum_{i=1}^{n} \cos(\omega_0 t_i) & \sum_{i=1}^{n} t_i \cos(\omega_0 t_i) & \sum_{i=1}^{n} \cos^2(\omega_0 t_i) & \sum_{i=1}^{n} \cos(\omega_0 t_i)\sin(\omega_0 t_i) \\ \sum_{i=1}^{n} \sin(\omega_0 t_i) & \sum_{i=1}^{n} t_i \sin(\omega_0 t_i) & \sum_{i=1}^{n} \cos(\omega_0 t_i)\sin(\omega_0 t_i) & \sum_{i=1}^{n} \sin^2(\omega_0 t_i) \end{bmatrix} \tag{11}$$

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:

$$(X'Y)_j = \begin{bmatrix} \sum_{i=1}^{n} Y_{ji}' \\ \sum_{i=1}^{n} Y_{ji}' t \\ \sum_{i=1}^{n} Y_{ji}' \cos(\omega_0 t) \\ \sum_{i=1}^{n} Y_{ji}' \sin(\omega_0 t) \end{bmatrix} \tag{12}$$

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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:

$$\begin{bmatrix} A_{j0} \\ A_{j1} \\ A_{j2} \\ B_{j2} \end{bmatrix} = [X'X]^{-1}[X'Y_j] \tag{13}$$

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

$$\hat{Y}_{ji} = A_{j0} + A_{j1}t_i + A_{j2}\cos(\omega_0 t_i) + B_{j2}\sin(\omega_0 t_i) + \varepsilon_{ji} \tag{14}$$

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:

$$\theta_j = \arctan\left(-\frac{B_{j2}}{A_{j2}}\right) \tag{15}$$

$$|Y_j{*}| = \sqrt{A_{j2}^2 + B_{j2}^2} \tag{16}$$

$$\Delta Y_j = \frac{A_{j1}t_N}{|Y_j{*}|} \times 100\% \tag{17}$$

$$se(Y_j) = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_{ji}' - Y_{ji}'\right)^2}{n-4}}\left(\frac{100\%}{|Y_j{*}|}\right) \tag{18}$$

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

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$\hat{Y}_{ji}$' ' = 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:

$$\overline{\theta}_D = \frac{\sum_{j=2}^{m} \theta_j}{m-1} \tag{19}$$

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:

$$\theta(\omega) = \overline{\theta_D} - \theta_P \tag{20}$$

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:

$$\left|\overline{Y}_D *\right| = \frac{\sum_{j=2}^{m} \left|Y_j *\right|}{m-1} \tag{21}$$

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

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

$$\left| E^*(\omega) \right| = \frac{\left| Y_P^* \right| L_g}{\left| \bar{Y}_D^* \right| A} \tag{22}$$

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:

$$\Delta \bar{Y}_D = \frac{\sum_{j=2}^{m} A_{j1} t_N}{\sum_{j=2}^{m} \left| Y_j^* \right|} \times 100\% \tag{23}$$

$$se(Y_D) = \frac{\sum_{j=2}^{m} se(Y_j)}{m-1} \tag{24}$$

$$U_A = \sqrt{\frac{\sum_{j=2}^{m} \left(\left| Y_j^* \right| - \left| \bar{Y}_D^* \right| \right)^2}{m-1}} \left(\frac{100\%}{\left| \bar{Y}_D^* \right|} \right) \tag{25}$$

$$U_\theta = \sqrt{\frac{\sum_{j=2}^{m} \left(\theta_j - \bar{\theta}_D \right)^2}{m-1}} \tag{26}$$

Where:

$\Delta \bar{Y}_D$ = 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

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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 0.5, 4.5, 8.5, and 12.5 kN (0.1, 1.0, 1.9, and 2.8 kips) at frequencies of 0.1, 1, and 10 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

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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.

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Appendix A
Specification Compliance Test Methods for the Simple Performance Test System

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Table A1. 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)

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Table A1. 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

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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.

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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.

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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 0.5, 4.5, 8.5, and 12.5 kN (0.1, 1.0, 1.9, and 2.8 kips) at frequencies of 0.1, 1, and 10 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.

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Appendix B

Minimum Testing Program For Comparison of a Non-Standard Specimen Deformation Measuring System to the Standard Specimen Deformation Measuring System

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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 B-1.

Table B-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.

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3.0 Dynamic Modulus Testing

3.1 Perform the dynamic modulus testing with the Simple Performance Test System in accordance with the Standard Test Method for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test. 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 B-2. Plan the testing such that all testing in a block will be completed on the same day.

Table B-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

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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 B-1 and B-2.

$$\bar{y} = \frac{\sum_{i=1}^{12} y_i}{12} \tag{B1}$$

$$s^2 = \frac{\sum_{i=1}^{12} (y_i - \bar{y})^2}{11} \tag{B2}$$

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, $\sigma_p^2 > \sigma_s^2$

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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:

$$s = \sqrt{\frac{s_p^2 + s_s^2}{2}}$$

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$\bar{y}_p$ = 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.

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APPENDIX F

SPT Test Methods

Proposed Standard Test Method for

Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System

NCHRP 9-29: PT 01

1. SCOPE

1.1 This standard describes test methods for measuring the dynamic modulus and flow number for hot-mix asphalt mixtures using the Simple Performance Test System. This practice is intended for dense- and gap- graded mixtures with nominal maximum aggregate sizes to 37.5 mm.

1.2 *This standard may involve hazardous materials, operations, and equipment, This standard does not purport to address all of the 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 its use.*

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards*

- NCHRP 9-29 PP 01, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor
- NCHRP 9-29 PP 02, Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System

2.2 *Other Publications*

- Equipment Specification for the Simple Performance Test System, Version 3.0, Prepared for National Cooperative Highway Research Program (NCHRP), October 16, 2007.

3. TERMINOLOGY

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.

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

3.3 *Permanent Deformation* – Non-recovered deformation in a repeated load test.

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

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

3.6 *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 THE TEST METHODS

4.1 This test method describes procedures for measuring the dynamic modulus and flow number for HMA.

4.2 In the dynamic modulus procedure an HMA 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.

4.3 In the flow number procedure an HMA 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 the load cycles 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.

5. SIGNIFICANCE AND USE

5.1 The dynamic modulus is a performance related property that can be used for mixture evaluation and for characterizing the stiffness of HMA for mechanistic-empirical pavement design.

5.2 The flow number is a property related to the resistance of HMA mixtures to permanent deformation. It can be used to evaluate mixtures and to design mixtures with specific resistance to permanent deformation.

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6. APPARATUS

6.1 *Specimen Fabrication Equipment* - Equipment for fabricating dynamic modulus test specimens as described in NCHRP 9-29 PP 01, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.

6.2 *Dynamic Modulus Test System* - A dynamic test system meeting the requirements of Equipment Specification for the Simple Performance Test System, Version 3.0.

6.3 *Conditioning Chamber* - 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 4 to 60 °C (39 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate the number of specimens to be tested plus a dummy specimen with a temperature sensor mounted in the center for temperature verification.

6.4 *Teflon Sheet* - 0.25 mm (0.01 in) thick to be used as friction reducer between the specimen and the loading platens in the dynamic modulus test.

6.5 *Latex Membranes* – 100 mm (4 in) diameter by 0.3 mm (0.012 in) thick for use in confined tests and for manufacturing "greased double latex" friction reducers to be used between the specimen and the loading platens in the dynamic modulus and flow number tests.

6.6 *Silicone Grease* – Dow Corning Stopcock Grease or equivalent for manufacturing "greased double latex" friction reducers.

6.7 *Balance* – Balance capable of weighing to the nearest 0.01 g. The balance is used to weigh silicone grease during fabrication of "greased double latex" friction reducers.

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7. HAZARDS

7.1 This practice and associated standards involve handling of hot asphalt binder, aggregates and asphalt mixtures. It also includes the use of sawing and coring machinery and servo-hydraulic testing equipment. Use standard safety precautions, equipment, and clothing when handling hot materials and operating machinery.

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8. STANDARDIZATION

8.1 Items associated with this practice that require calibration are included in the documents referenced in Section 2.2 Refer to the pertinent section of the referenced documents for information concerning calibration.

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9. PROCEDURE A - DYNAMIC MODULUS TEST

9.1 *Test Specimen Fabrication*

9.1.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with NCHRP 9-29 PP 01, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.

9.1.2 Prepare at least two test specimens to the target air void content and aging condition in accordance with NCHRP 9-29 PP 01, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.

Note 1 – A reasonable air void tolerance for test specimen fabrication is ± 0.5 %.

Note 2 – The coefficient of variation for properly conducted dynamic modulus tests is approximately 13 %. The coefficient of variation of the mean dynamic modulus for tests on multiple specimens is given by Table 1.

Table 1. Coefficient of Variation for the Mean of Dynamic Modulus Test on Replicate Specimens.

Specimens	Coefficient of Variation For the Mean, %
2	9.2
3	7.5
4	6.5
5	5.8
6	5.3
7	4.9
8	4.6
9	4.3
10	4.1

Use Table 1 to select an appropriate number of specimens based on the uncertainty that can be tolerated in the analysis.

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9.2 *Test Specimen Instrumentation (Standard Glued Gauge Point System)*

9.2.1 Attach the gauge points to the specimen in accordance with the manufacturer's instructions.

9.2.2 Confirm that the gauge length is 70 mm (2.76 in) ± 1 mm (0.04 in) measured center to center of the gage points.

9.3 *Loading Platens and End Friction Reducers*

9.3.1 For the dynamic modulus test, the top platen shall be free to rotate.

9.3.2 Either "greased double latex" or Teflon end friction reducers can be used in the dynamic modulus test.

9.3.2.1 Teflon end friction reducers are made from 0.25 mm (0.01 in) thick Teflon sheet cut to slightly larger than the loading platen.

9.3.2.2 "Greased double latex" friction reducers are fabricated from 0.3 mm (0.012 in) thick latex membranes as described in Appendix A.

9.4 *Procedure*

9.4.1 <u>Unconfined Tests</u>

9.4.1.1 Place the specimens to be tested in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

9.4.1.2 Place platens and friction reducers inside the testing chamber. 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.

9.4.1.3 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen from the conditioning chamber, and quickly place it in the testing chamber.

9.4.1.4 Assemble the specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom friction reducer, specimen, top friction reducer, and top loading platen.

9.4.1.5 Install the specimen mounted deformation measuring system on the gauge points per the manufacturer's instructions. Ensure that the deformation measuring system is within its calibrated range. Make sure that the top loading platen is free to rotate during loading.

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9.4.1.6 Close the testing chamber and allow the chamber temperature to return to testing temperature.

9.4.1.7 Steps 9.4.1.3 through 9.4.1.6 including return of the test chamber to the target temperature shall be completed in 5 minutes.

9.4.1.8 Enter the required identification and control information into the Dynamic Modulus Software.

9.4.1.9 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.

9.4.1.10 Review the data quality indicators as discussed in Section 9.5 of this test procedure. Retest specimens with data quality indicators above the values specified in Section 9.5.

9.4.1.11 Once acceptable data have been collected, open the test chamber, and remove the tested specimen.

9.4.1.12 Repeat steps 9.4.1.3 through 9.4.1.11 for the remaining test specimens.

9.4.2 Confined Tests

9.4.2.1 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.

9.4.2.2 Encase the dummy specimen in a membrane.

9.4.2.3 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.

9.4.2.4 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.

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9.4.2.5 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.

9.4.2.6 Install the specimen mounted deformation measuring system outside the membrane on the gauge points per the manufacturer's instructions. Ensure that the deformation measuring system is within its calibrated range. Make sure that the top loading platen is free to rotate during loading.

9.4.2.7 Close the testing chamber and allow the chamber temperature to return to testing temperature.

9.4.2.8 Steps 9.4.2.5 through 9.4.2.7 including return of the test chamber to the target temperature shall be completed in 5 minutes.

9.4.2.9 Enter the required identification and control information into the Dynamic Modulus Software.

9.4.2.10 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.

9.4.2.11 Review the data quality indicators as discussed in Section 9.5 of this test procedure. Retest specimens with data quality indicators above the values specified in Section 9.5.

9.4.2.12 Once acceptable data have been collected, open the test chamber, and remove the tested specimen.

9.4.2.13 Repeat steps 9.4.2.3 through 9.4.2.12 for the remaining test specimens.

9.5 *Computations and Data Quality*

9.5.1 The calculation of dynamic modulus, phase angle, and the data quality indicators is performed automatically by the Simple Performance Test System software.

9.5.2 Accept only test data meeting the data quality statistics given in Table 2. Table 3 summarizes actions that can be taken to improve the data quality statistic. Repeat tests as necessary to obtain test data meeting the data quality statistics requirements.

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Table 2. Data Quality Statistics Requirements.

Data Quality Statistic	Limit
Deformation Drift	In direction of applied load
Peak to Peak Strain	75 to 125 μstrain unconfined tests 85 to 115 μstrain confined tests
Load standard error	10 %
Deformation standard error	10 %
Deformation uniformity	30 %
Phase uniformity	3 degrees

Note 3 – The data quality statistics in Table 2 are reported by the Simple Performance Test System software. If a dynamic modulus test system other than the Simple Performance Test System is used, refer to Equipment Specification for the Simple Performance Test System, Version 3.0 for algorithms for computation of dynamic modulus, phase angle, and data quality statistics.

Table 3. Troubleshooting Guide for Data Quality Statistics.

Item	Cause	Possible Solutions
Deformation Drift not in direction of applied load.	Gage points are moving apart.	Reduce LVDT spring force. Add compensation springs. Reduce test temperature.
Peak to Peak Strain too high.	Load level too high.	Reduce load level.
Peak to Peak Strain too low.	Load level too low.	Increase load level.
Load Standard Error > 10 %.	Applied load not sinusoidal.	Adjust tuning of hydraulics.
Deformation Standard Error > 10 %.	1. Deformation not sinusoidal 2. Loose gage point. 3. Excessive noise on deformation signals. 4. Damaged LVDT.	1. Adjust tuning of hydraulics. 2. Check gage points. Reinstall if loose. 3. Check wiring of deformation sensors. 4. Replace LVDT.
Deformation Uniformity > 30 %.	1. Eccentric loading. 2. Loose gage point. 3. Sample ends not parallel. 4. Poor gage point placement. 5. Non-uniform air void distribution.	1. Ensure specimen is properly aligned. 2. Check gage points. Reinstall if loose. 3. Check parallelism of sample ends. Mill ends if out of tolerance. 4. Check for specimen non-uniformity (segregation, air voids). Move gage points. 5. Ensure test specimens are cored from the middle of the gyratory specimen.
Phase Uniformity > 3 degrees.	1. Eccentric loading. 2. Loose gage point. 3. Poor gage point placement. 4. Damaged LVDT.	1. Ensure specimen is properly aligned. 2. Check gage points. Reinstall if loose. 3. Check for specimen non-uniformity (segregation, air voids). Move gage points. 4. Replace LVDT.

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9.6 *Reporting*

9.6.1 For each specimen tested, report the following:

9.6.1.1 Test temperature.

9.6.1.2 Test frequency.

9.6.1.3 Confining stress level.

9.6.1.4 Dynamic modulus.

9.6.1.5 Phase angle.

9.6.1.6 Data quality statistics.

9.6.2 Attach Simple Performance Test System dynamic modulus test summary report for each specimen tested.

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10. PROCEDURE B – FLOW NUMBER TEST

10.1 *Test Specimen Fabrication*

10.1.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with NCHRP 9-29 PP 01, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.

10.1.2 Prepare at least three test specimens to the target air void content and aging condition in accordance with NCHRP 9-29 PP 01, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor.

Note 4 – A reasonable air void tolerance for test specimen fabrication is ± 0.5 %.

Note 5 – The coefficient of variation for the permanent deformation before flow in the flow number test is approximately 15 %. The coefficient of variation for the flow number is approximately 20 %. The coefficient of variation of the mean for tests on multiple specimens is given by Table 4.

10.2 *Loading Platens and End Friction Reducers*

10.2.1 For the flow number test, the top platen shall not be free to rotate.

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10.2.2 Prepare two "greased double latex" end friction reducers for each specimen that will be tested using the procedure specified in Appendix A. It is recommended that new friction reducers be used for each test.

Table 4. Coefficient of Variation for the Mean of Properties From the Flow Number Test

	Coefficient of Variation for the Mean, %	
Specimens	**Permanent Deformation Before Flow**	**Flow Number**
2	10.6	14.1
3	8.7	11.5
4	7.5	10.0
5	6.7	8.9
6	6.1	8.2
7	5.7	7.6
8	5.3	7.1
9	5.0	6.7
10	4.7	6.3

Use Table 4 to select an appropriate number of specimens based on the uncertainty that can be tolerated in the analysis.

10.3 Unconfined Tests

10.3.1 Place the specimens to be tested in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

10.3.2 Place platens and "greased double latex" friction reducers inside the testing chamber. 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.

10.3.3 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen from the conditioning chamber, and quickly place it in the testing chamber.

10.3.4 Assemble each specimen to be tested with platens in the following order from bottom to top. Bottom loading platen, bottom "greased double latex" friction reducer, specimen, top "greased double latex" friction reducer, and top loading platen.

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10.3.5 Close the testing chamber and allow the chamber temperature to return to testing temperature. Make sure that the top loading platen is not permitted to rotate during loading.

10.3.6 Steps 10.3.3 and 10.3.5 including return of the test chamber to the target temperature shall be completed in 5 minutes.

10.3.7 Enter the required identification and control information into the Flow Number Software.

10.3.8 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.

10.3.9 Upon completion of the test, open the test chamber, and remove the tested specimen.

10.3.10 Repeat steps 10.3.4 through 10.3.9 for the remaining test specimens.

10.4 Confined Tests

10.4.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom "greased double latex" 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 "greased double latex" friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

10.4.2 Encase the dummy specimen in a membrane.

10.4.3 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.

10.4.4 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.

10.4.5 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.

10.4.6 Close the testing chamber and allow the chamber temperature to return to testing temperature. Make sure that the top loading platen is not permitted to rotate during loading.

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10.4.7 Steps 10.4.5 and 10.4.6 including return of the test chamber to the target temperature shall be completed in 5 minutes.

10.4.8 Enter the required identification and control information into the Flow Number Software.

10.4.9 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete.

10.4.10 Upon completion of the test, open the test chamber, and remove the tested specimen.

10.4.11 Repeat steps 10.4.5 through 10.4.10 for the remaining test specimens.

10.5 *Calculations*

10.5.1 The calculation of the permanent strain for each load cycle and the flow number for individual specimens is performed automatically by the Simple Performance Test System software.

10.5.2 Compute the average and standard deviation of the flow numbers for the replicate specimens tested.

10.5.3 Compute the average and standard deviation of the permanent strain at the load cycles of interest.

10.6 *Reporting*

10.6.1 Report the following:

10.6.1.1 Test temperature.

10.6.1.2 Average applied deviatoric stress.

10.6.1.3 Average applied confining stress.

10.6.2 Average and standard deviation of flow numbers for the specimens tested.

10.6.3 Average and standard deviation of the permanent strain at the load cycles of interest.

10.6.4 Attach Simple Performance Test System flow number test summary report for each specimen tested.

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11. KEYWORDS

11.1 Dynamic modulus, phase angle, flow number, permanent deformation, repeated load testing.

APPENDIX A. METHOD FOR PREPARING GREASED DOUBLE LATEX END FRICTION REDUCERS FOR THE FLOW NUMBER TEST (MANDATORY INFORMATION)

A1. PURPOSE

A1.1 This Appendix presents a procedure for fabricated "greased double latex" end friction reducers for the flow number test.

A1.2 These end friction reducers are mandatory for the flow number test.

A2. SUMMARY

A2.1 "Greased double latex" end friction reducers are fabricated by cutting two circular latex sheets from a latex membrane used for confining specimens, applying a specified weight of silicone grease evenly over one of the latex sheets, then placing the second latex sheet over the first.

A3. PROCEDURE

A3.1 Cut a 0.3 mm (0.012 in) thick latex membrane along its long axis to obtain a rectangular sheet of latex. The sheet will be approximately 315 mm (12.5 in) by 250 mm (10 in).

A3.2 Trace the circumference of the loading platen on the sheet of latex, then cut along the tracing to form circular latex sheets that are slightly larger than the loading platen. Four are needed to fabricate friction reducers for the top and bottom of the specimen.

A3.3 Place one circular latex sheet on the balance and weigh 0.25 ± 0.5 g of silicone grease onto the middle of the latex sheet.

A3.4 Spread the silicone grease evenly over the latex sheet by rubbing in a circular motion from the center to the outside of the sheet.

A3.5 Place the second circular latex sheet on top of the silicone grease.

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A3.6 If the friction reducer will be used in confined tests, cut or punch a hole through both latex sheets at the location of the vent in the loading platen.

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
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	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
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
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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