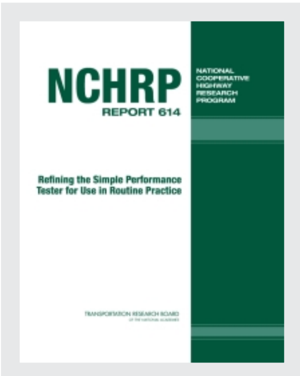


Refining the Simple Performance Tester for Use in Routine Practice

DETAILS

142 pages | | PAPERBACK
ISBN 978-0-309-09938-7 | DOI 10.17226/14158

AUTHORS

Ramon Bonaquist; Transportation Research Board

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 614

Refining the Simple Performance Tester for Use in Routine Practice

Ramon Bonaquist
ADVANCED ASPHALT TECHNOLOGIES, LLC
Sterling, VA

Subject Areas
Maintenance

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2008
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 614

Project 9-29
ISSN 0077-5614
ISBN: 978-0-309-09938-7
Library of Congress Control Number 2008928656

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

CRP STAFF FOR NCHRP REPORT 614

Christopher W. Jenks, *Director, Cooperative Research Programs*
Crawford F. Jencks, *Deputy Director, Cooperative Research Programs*
Edward T. Harrigan, *Senior Program Officer*
Eileen P. Delaney, *Director of Publications*
Margaret B. Hagood, *Editor*

NCHRP PROJECT 09-29 PANEL
Field of Materials and Construction—Area of Bituminous Materials

Larry L. Michael, *Hagerstown, MD* (Chair)
Ronald Cominsky, *Pennsylvania Asphalt Pavement Association, Harrisburg, PA*
Gary A. Frederick, *New York State DOT, Albany, NY*
Cindy LaFleur, *Callanan Industries, Inc., Albany, NY*
Dean A. Maurer, *Pennsylvania DOT, Harrisburg, PA*
Murari M. Pradhan, *Arizona DOT, Phoenix, AZ*
John "Jack" Weigel, Jr., *Payne & Dolan, Inc., Waukesha, WI*
Thomas Harman, *FHWA Liaison*
Leslie Ann McCarthy, *FHWA Liaison*
Audrey Copeland, *Other Liaison*
John D'Angelo, *Other Liaison*
Frederick Hejl, *TRB Liaison*

AUTHOR ACKNOWLEDGMENTS

The research reported here was performed under NCHRP Project 9-29 by Advanced Asphalt Technologies, LLC. The Simple Performance Test Systems evaluated in this report were developed by Industrial Process Controls, Ltd, Interlaken Technology Corporation and Medical Device Testing Systems. The Simple Performance Test Specimen Fabrication System evaluated in this report was developed by Shedworks, Inc.

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.

F O R E W O R D

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents the findings of a research project to develop a practical, economical simple performance tester (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, version 1.0 available for evaluation at www.trb.org/mepdg). In the work reported here, the effectiveness and efficiency of the SPT were substantially improved for its use in routine, day-to-day pavement structural design with the MEPDG. 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. In 1996, work sponsored by the Federal Highway Administration began at the University of Maryland—College Park to identify and validate simple performance tests for permanent deformation and fatigue cracking. In 1999, this effort was transferred to Task C of NCHRP Project 9-19, "Superpave Support and Performance Models Management," with major activity conducted at Arizona State University as well as the University of Maryland.

NCHRP Project 9-19 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 time, F_T, determined with the triaxial static creep test; and (3) the flow number, F_n, determined with the triaxial repeated load test. The dynamic modulus, E^*, also was chosen as the simple performance test for fatigue cracking.

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 of NCHRP Project 9-29 reported here, the research team conducted two major tasks aimed at continued development of the SPT. In the first task, an abbreviated testing protocol for developing dynamic modulus master curves for use in routine mixture evaluation and flexible pavement design was developed and validated. The abbreviated testing protocol is based on analysis of numerous dynamic modulus master curves produced using AASHTO TP62. Details of the analysis are presented in Chapter 2 and a recommended Standard Practice for developing dynamic modulus master curves for routine mixture evaluation and flexible pavement design is presented in Appendix A.

The abbreviated testing protocol includes testing at three temperatures between 39.2 and 115°F using four frequencies of loading between 0.01 and 10 Hz. The low temperature required some modification of the SPT developed earlier in NCHRP Project 9-29 to permit master curve testing, viz., (1) improved cooling capacity, (2) additional load capacity, and (3) software modification to include 0.01 Hz load control. Cost estimates from potential vendors indicated that the additional cooling and loading capacity would only add approximately 5 percent to the cost of the SPT.

In the second task, the SPT equipment specification was revised to produce a device capable of performing dynamic modulus master curves using the abbreviated protocol described above. This version of the SPT maintains the capability to perform the flow number and flow time testing. The revised equipment specification is presented in Appendix B and was used to (1) upgrade the first-article devices that were purchased and evaluated earlier in the project and (2) procure and evaluate additional production units from several vendors.

This report presents the full text of the contractor's final report and three appendices, which present (1) proposed standard practices for (a) developing dynamic modulus master curves and (b) preparing cylindrical test specimens for use with the SPT (Appendix A); (2) a revised SPT purchase specification (Appendix B); and (3) a specification for an SPT test specimen fabrication system (Appendix C).

CONTENTS

SUMMARY

Refining the Simple Performance Tester for Use in Routine Practice

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.

The ruggedness experiments were performed in Phase V of the project. This report documents the work completed in Phase IV.

During Phase IV, a methodology was developed to construct dynamic modulus master curves for pavement structural design using an abbreviated testing protocol. With this protocol, it is not necessary to perform dynamic modulus testing at the lowest temperature included in AASHTO TP62. Eliminating the low temperature testing offers three advantages. First, the cost of environment control capabilities is substantially less. Second, smaller, less expensive actuators can be used since the load required for dynamic modulus testing depends on the stiffness of the material that increases with decreasing temperature. Third, testing below 32°F is difficult and more variable due to potential icing of the instrumentation. Using the abbreviated protocol and the SPT, it is possible for highway agencies to routinely collect dynamic modulus data for the Mechanistic-Empirical Pavement Design Guide (MEPDG) and other applications.

A recommended standard practice was developed to implement the abbreviated dynamic modulus protocol. This standard practice provides recommended testing temperatures and frequencies. It also describes how to fit the dynamic modulus master curve to the measured data and how to compute input data for Level 1 analysis in the MEPDG.

The equipment specification for the Simple Performance Test System was modified to specify a device capable of performing the three simple performance tests and developing dynamic modulus master curves using the abbreviated testing protocol. The first article

SPTs purchased in Phase II of the project were upgraded to meet the revised specification. Two new devices meeting the revised specification were purchased in Phase IV of the project. SPTs meeting the revised specification currently are available from three sources: Interlaken Technology Corporation, IPC Global, and Medical Device Testing Systems. The three devices are very similar. All are relatively small, bottom-loading, servo-hydraulic machines with automated testing chambers that serve as a confining pressure cell and temperature control chamber. The primary differences are in the hardware and software used for temperature control, the user friendliness of the equipment, and the operational details of the control software.

Test specimen preparation for the SPT is a multi-step process. A recommended standard practice for SPT specimen fabrication was prepared. This standard practice addresses each step of the fabrication process in detail, and includes two important appendices that provide additional guidance for preparing SPT specimens. The first is a procedure for obtaining the target air void content for specimens from mixtures the technician is not familiar with. The second appendix provides a method for evaluating the uniformity of air void contents within SPT test specimens.

In evaluating the specimen preparation process, it was determined that an automated system for coring and sawing the specimens would be beneficial to the future implementation of the SPT. A prototype automated coring and sawing system called FlexPrep™ was developed by Shedworks, Inc. to meet specifications developed in NCHRP 9-29. The development of this equipment proved to be more difficult than the SPT systems, requiring approximately five years to complete. The machine is capable of preparing SPT specimens in less than 15 minutes with little technician intervention. While the FlexPrep™ is a promising prototype, additional development work must be completed before production models of the design can be made available.

CHAPTER 1

Introduction and Research Approach

1.1 Problem and Purpose

NCHRP Project 9-19: Superpave Support and Performance Models Management recommended three candidate simple performance tests to compliment the Superpave volumetric mixture design method. These are: flow time, flow number, and dynamic modulus. The recommended tests are conducted in uniaxial or triaxial compression on cylindrical specimens that are sawed and cored from over-height gyratory compacted samples. Data from all three candidates were shown to correlate well with observed rutting in field pavements, 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 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 compliment 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 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.

The ruggedness experiments were performed and documented in Phase V of the project. This report documents the work completed in Phase IV of the project.

1.2 Scope and Research Approach

1.2.1 Simple Performance Test System

Phase IV included two major tasks aimed at continued development of the SPT. The first of these was the development of an abbreviated testing protocol for developing dynamic modulus master curves for use in routine mixture evaluation and flexible pavement design. AASHTO TP62, *Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*, is the recommended standard describing the testing and analysis required to develop dynamic modulus master curves for the MEPDG. This standard requires testing at five temperatures

(14, 40, 70, 100, and 130 °F) and six frequencies of loading (0.1, 0.5, 1.0, 5.0, 10, and 25 Hz). It is desirable that equipment for performing such testing be available to highway agencies at a reasonable cost, and that the test procedure be appropriate for agency laboratories. A recently completed FHWA pooled fund study identified several issues associated with the test protocol, and concluded that the overall time required to perform the testing must be shortened if highway agencies are going to use it for routine testing (*3*). The most efficient approach to reducing the time requirements for dynamic modulus master curve testing is to minimize the number of temperatures used in the testing. The current low temperature testing requirement of 14 °F significantly increases the cost of the environmental system and increases the loading capacity and cost of the testing equipment. If testing at this temperature can be eliminated, the cost of the equipment, the complexity of the procedure, and the overall time required to develop a master curve can be significantly reduced. In Phase IV of NCHRP Project 9-29, an abbreviated testing protocol for developing dynamic modulus master curves was developed based on analysis of numerous dynamic modulus master curves produced using AASHTO TP62. Details of this analysis are presented in Chapter 2 and a recommended standard practice for developing dynamic modulus master curves for routine mixture evaluation and flexible pavement design is presented in Appendix A.

The abbreviated testing protocol includes testing at three temperatures between 39.2 and 115 °F using four frequencies of loading between 0.01 and 10 Hz. The low temperature required some modification of the SPT developed in Phases I and II of NCHRP Project 9-29. To minimize costs, the SPT was originally designed for testing only at room temperature and above. The modifications required for master curve testing were: (1) improved cooling capacity, (2) additional load capacity, and (3) software required modification to include 0.01 Hz load control. Cost estimates from potential vendors indicated that the additional cooling and loading capacity would only add approximately 5 percent to the cost of the SPT.

In the second task to continue the development of the SPT, the equipment specification was revised to produce a device capable of performing dynamic modulus master curves using the abbreviated protocol. This equipment also maintains the capability to perform the flow number and flow time testing. The revised equipment specification is presented in Appendix B. The revised equipment specification was used to upgrade the First Article devices that were purchased and evaluated in Phase II of the project and to procure and evaluate additional production units. New equipment was procured from Industrial Process Controls, Ltd. and Medical Device Testing Services, Inc. Chapter 3 includes details of the evaluation of the First Article upgrades and the production units.

1.2.2 Simple Performance Test Specimen Fabrication System

A major criticism of the NCHRP Project 9-19 performance tests is the size of the specimen used in the testing. To ensure that fundamental properties are measured, a 3.94 in. diameter by 5.91 in. tall test specimen must be used. These test specimen dimensions were determined through an extensive specimen size and geometry study conducted during NCHRP Project 9-19 (*4*). Test specimens are obtained by first manufacturing gyratory specimens that are 5.91 in. diameter by 6.5 to 6.9 in. tall. The test specimen is then obtained by cutting a 3.94 in. diameter core from the middle of the gyratory sample, and sawing the ends to produce a test specimen 5.91 in. tall with smooth, parallel ends. Many engineers and technicians consider this multi-step test specimen fabrication process a significant obstacle to implementation of the SPT in routine practice.

In Phase I of NCHRP Project 9-29, workshops were held with potential users and manufacturers of the SPT. Both users and manufacturers agreed that a low-cost, automated system for test specimen fabrication would enhance the SPT. An equipment specification for such a system was developed in Phase I of the project. The primary purpose of the specification for the Simple Performance Test Specimen Fabrication System was to encourage equipment manufacturers to develop equipment for test specimen fabrication that speeds the process of preparing the required test specimen. The specification provided tolerances for critical specimen dimensions and required that the test specimen be fabricated from an existing gyratory sample in 15 minutes or less. In Phase II of the project, Shedworks' Inc. was awarded a contract for final design and fabrication of an innovative device where the gyratory specimen is gripped by a chuck similar to that used in a lathe. Automated diamond-tipped cutoff blades saw the gyratory specimen to length, and an automated diamond-core barrel then cores the test specimen from the gyratory specimen.

Shedworks encountered many problems during final design and fabrication of the equipment in Phase II; therefore, delivery of the first-article device was extended to Phase IV of the project. Chapter 4 presents the results of a series of specification compliance tests that were performed on the Shedworks device. Appendix C presents the equipment specification for the Simple Performance Test Specimen Fabrication System. A Recommended Standard Practice for preparing SPT specimens is included in Appendix A. This practice is a generic procedure for SPT specimen fabrication that does not require use of the Simple Performance Test Specimen Fabrication System.

CHAPTER 2

Abbreviated Dynamic Modulus Master Curve Testing

2.1 Introduction

An abbreviated dynamic modulus master curve testing and analysis procedure was developed in Phase IV of NCHRP Project 9-29 to reduce the effort and equipment costs associated with developing dynamic modulus master curves for pavement structural design. The dynamic modulus test protocol was developed in NCHRP Projects 9-19 and 1-37A and has been standardized as AASHTO Provisional Standard TP62, *Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures.* The recommended test sequence in AASHTO TP62 for the development of a master curve for pavement structural design consists of testing a minimum of two replicate specimens at temperatures of 14, 40, 70, 100, and 130 °F at loading frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. This testing provides a database of 60 dynamic modulus measurements from which the parameters of the master curve are determined by numerical optimization.

It is desirable that equipment for performing such testing be available to highway agencies at a reasonable cost and the test procedure be appropriate for agency laboratories. A recently completed FHWA pooled-fund study identified several issues associated with the test protocol and concluded that the overall time required to perform the testing must be shortened if highway agencies are going to use it for routine testing (*3*). NCHRP Project 9-19 included a study of the minimum testing required to develop the dynamic modulus master curves and concluded that reasonable master curves can be developed using tests at three temperatures: 14, 70, and 130°F at loading frequencies of 33, 2.22, 0.15, and 0.01 Hz (*5*). This reduced sequence still requires testing at 14°F that the FHWA pooled fund study found difficult due to moisture condensation and ice formation (*3*). Additionally, low temperature testing significantly increases the cost of the environmental chamber and increases the loading capacity and cost of the testing equipment. If testing at this temperature can be eliminated, the cost of the equipment, the complexity of the procedure, and the overall time required to develop a master curve can be significantly reduced.

The approach taken in this project takes advantage of the fact that all asphalt binders reach approximately the same glassy modulus at very low temperatures (*6*). Using this binder modulus and recently developed relationships to predict mixture dynamic modulus from binder modulus and volumetric data, an estimate of the limiting maximum modulus of the mixture can be made and used in the development of the dynamic modulus master curve (*7*).

2.2 MEPDG Dynamic Modulus Master Curve

To account for temperature and rate of loading effects on the modulus of asphalt concrete, the MEPDG uses asphalt concrete moduli obtained from a master curve constructed at a reference temperature of 70°F (*2*). Master curves are constructed using the principle of time-temperature superposition. First a standard reference temperature is selected, in this case 70°F, then data at various temperatures are shifted with respect to loading frequency until the curves merge into a single smooth function. The master curve of modulus as a function of frequency formed in this manner describes the frequency dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. Thus, both the master curve and the shift factors are needed for a complete description of the rate and temperature effects. Figure 1 presents an example of a master curve constructed in this manner. The shift factors are presented in the inset figure.

In the MEPDG, the sigmoidal function in Equation 1 is used to describe the frequency dependency of the modulus master curve.

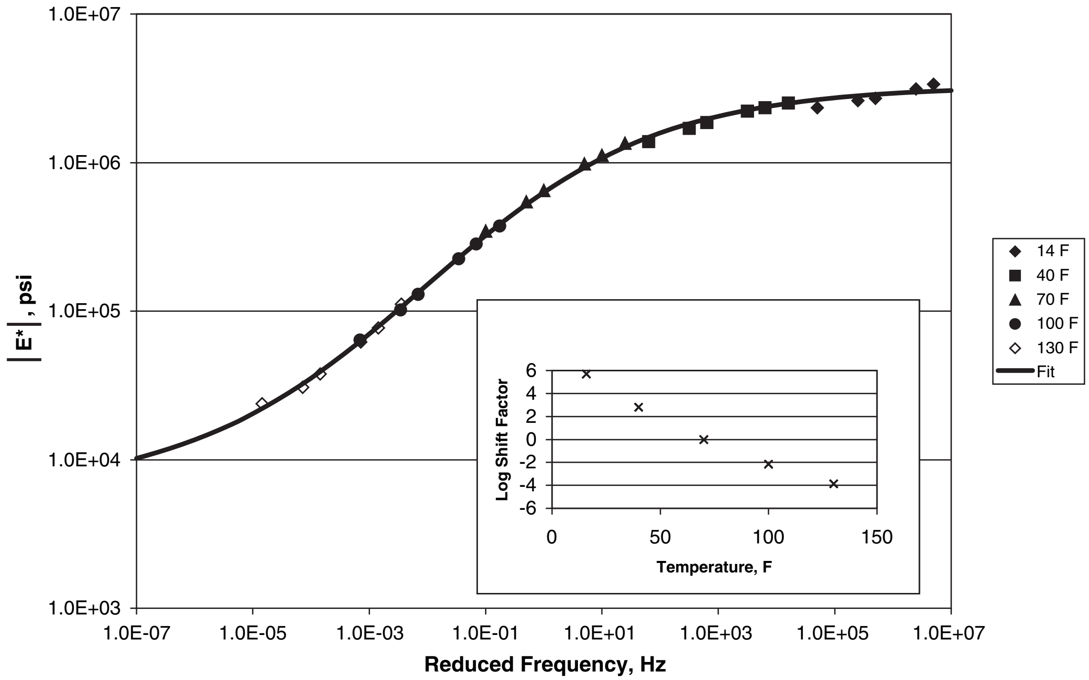


Figure 1. Example dynamic modulus master curve and shift factors.

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

where

$|E^*|$ = dynamic modulus;

ω_r = reduced frequency, Hz;

δ = minimum value of $|E^*|$;

$\delta+\alpha$ = maximum value of $|E^*|$; and

β, γ = parameters describing the shape of the sigmoidal function.

Research has shown that the fitting parameters δ and α depend on aggregate gradation, binder content, and air void content. The fitting parameters β and γ depend on the characteristics of the asphalt binder and the magnitude of δ and α.

The temperature dependency of the modulus is incorporated in the reduced frequency parameter, ω_r, in Equation 1. Equation 2 defines the reduced frequency as the actual loading frequency multiplied by the time-temperature shift factor, $a(T)$.

$$\omega_r = a(T) \times \omega \tag{2a}$$

$$\log(\omega_r) = \log(\omega) + \log[a(T)] \tag{2b}$$

where

ω_r = reduced frequency, Hz;

ω = loading frequency, Hz;

$a(T)$ = shift factor as a function of temperature; and

T = temperature.

The shift factors are a function of temperature. Various equations such as the Arrhenius function and the Williams-Landel-Ferry equation have been recommended in an attempt to provide a rational explanation for the temperature dependency of the shift factors (*6*). In the MEPDG, the shift factors were expressed as a function of the binder viscosity to allow aging over the life of the pavement to be considered using the Global Aging Model developed by Mirza and Witczak (*8*). Equation 3 presents the shift factor relationship used in the MEPDG (*2*).

$$\log[a(T)] = c[\log(\eta) - \log(\eta_{70RTFOT})] \tag{3}$$

where

$a(T)$ = shift factor as a function of temperature and age

η = viscosity at the age and temperature of interest

$\eta_{70RTFOT}$ = viscosity at the reference temperature of 70 °F, AASHTO T240 residue

c = fitting parameter

The viscosity as a function of temperature can be expressed using the viscosity-temperature relationship given in ASTM D 2493.

$$\log\log\eta = A + VTS\log T_R \tag{4}$$

where

η = viscosity, cP;

T_R = temperature, Rankine;

A = regression intercept; and

VTS = regression slope of viscosity-temperature relationship.

Combining Equations 3 and 4 yields the shift factor as a function of temperature relationship used in the MEPDG for the construction of dynamic modulus master curves from laboratory test data.

$$\log[a(T)] = c[10^{A+VTS\log T_R} - \log(\eta_{70RTFOT})] \quad (5)$$

where

$a(T)$ = shift factor as a function of temperature;
T_R = temperature, Rankine;
$\eta_{70RTFOT}$ = viscosity at the reference temperature of 70 °F, AASHTO T240 residue;
A, VTS = viscosity-temperature parameters for AASHTO T240 residue; and
c = fitting parameter.

Substituting Equation 5 into Equation 2b and the result into Equation 1 yields the form of the dynamic modulus master curve relationship used in the MEPDG for the development of master curves from laboratory test data.

$$\log|E|^* = \delta + \frac{\alpha}{1+e^{\beta+\gamma\left\{\log(\omega)+c\left[10^{A+VTS\log T_R}-\log(\eta_{70RTFOT})\right]\right\}}} \quad (6)$$

where

$|E^*|$ = dynamic modulus;
ω = loading frequency, Hz;
T_R = temperature, Rankine;
$\eta_{70RTFOT}$ = viscosity at the reference temperature of 70 °F, AASHTO T240 residue;
A, VTS = viscosity-temperature parameters for AASHTO T240 residue;
c = fitting parameter;
δ = limiting minimum value of $|E^*|$;
$\delta + \alpha$ = limiting maximum value of $|E^*|$; and
β, γ = parameters describing the shape of the sigmoidal function.

The fitting parameters (α, β, δ, γ, and c) are determined through numerical optimization of Equation 6 using mixture test data collected in accordance with AASHTO TP62. Due to equipment limitations, neither the limiting maximum nor limiting minimum modulus can be measured directly; therefore, these parameters are estimated through the curve fitting process.

2.3 Proposed Dynamic Modulus Master Curve Modification

The modification proposed in this project is to estimate the limiting maximum modulus based on binder stiffness and mixture volumetric data using the Hirsch model developed in NCHRP Projects 9-25 and 9-31 (*7*). For a known limiting maximum modulus, the MEPDG master curve relationship given in Equation 6 reduces to:

$$\log|E^*| = \delta + \frac{(Max-\delta)}{1+e^{\beta+\gamma\left\{\log(\omega)+c\left[10^{A+VTS\log T_R}-\log(\eta_{70RTFOT})\right]\right\}}} \quad (7)$$

where

$|E^*|$ = dynamic modulus;
ω = loading frequency, Hz;
T_R = temperature, Rankine;
$\eta_{70RTFOT}$ = viscosity at the reference temperature of 70 °F, AASHTO T240 residue;
A, VTS = viscosity-temperature parameters for AASHTO T240 residue;
Max = specified limiting maximum modulus; and
α, β, γ and c-fitting parameters.

The four unknown fitting parameters are still estimated using numerical optimization of the test data, but since the limiting maximum modulus is specified, data at low test temperatures are no longer needed.

Equations 8 and 9 present the Hirsch model, which allows estimation of the modulus of the mixture from binder stiffness data and volumetric properties of the mixture.

$$|E^*|_{mix} = P_c\left[4,200,000\left(1-\frac{VMA}{100}\right)+3|G^*|_{binder}\left(\frac{VFA\text{ x }VMA}{10,000}\right)\right] + \frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4,200,000}+\frac{VMA}{3VFA|G^*|_{binder}}\right]} \quad (8)$$

where

$$P_c = \frac{\left(20+\frac{VFA\times 3|G^*|_{binder}}{VMA}\right)^{0.58}}{650+\left(\frac{VFA\times 3|G^*|_{binder}}{VMA}\right)^{0.58}} \quad (9)$$

$|E^*|$ = dynamic modulus of the mixture, psi;
VMA = Voids in mineral aggregates, %;
VFA = Voids filled with asphalt, %; and
$|G^*|_{binder}$ = dynamic shear modulus of binder, psi.

Based on research conducted during the Strategic Highway Research Program (SHRP), all binders reach a maximum shear modulus of approximately 1 GPa or 145,000 psi (*6*). Substituting this value into Equations 8 and 9 yields the recommended equation for estimating the limiting maximum modulus of asphalt concrete mixtures from volumetric data.

$$|E^*|_{max} = P_c\left[4,200,000\left(1-\frac{VMA}{100}\right) + 435,000\left(\frac{VFA\times VMA}{10,000}\right)\right] + \frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4,200,000}+\frac{VMA}{435,000(VFA)}\right]} \quad (10)$$

where

$$P_c = \frac{\left(20 + \frac{435{,}000(\text{VFA})}{\text{VMA}}\right)^{0.58}}{650 + \left(\frac{435{,}000(\text{VFA})}{\text{VMA}}\right)^{0.58}} \tag{11}$$

$|E^*|_{max}$ = limiting maximum mixture dynamic modulus;
VMA = voids in mineral aggregates, %; and
VFA = voids filled with asphalt, %.

Figure 2 presents limiting maximum moduli computed using Equation 10 for VMA ranging from 10 to 20 percent, and VFA ranging from 55 to 85 percent. For this wide range of volumetric properties, the limiting maximum modulus varies from about 3,000,000 to 3,800,000 psi. These limiting maximum modulus values appear very rational. For conditions with low VMA and high VFA, the limiting maximum modulus approaches 4,000,000 psi, which is often assumed for the modulus of portland cement concrete.

2.4 Comparison of Master Curves Using Complete and Reduced Data Sets

This section presents comparisons of master curves fitted to actual laboratory test data using the complete AASHTO TP62 data and a reduced data set where test data at the lowest temperature are eliminated and replaced with an estimate of the limiting maximum modulus from the Hirsch model. For the comparison, the database of dynamic modulus measurements assembled for NCHRP Project 9-19 was used (*9*). This database includes test data from replicate samples tested at temperatures of 15.8, 40, 70, 100, and 130°F and frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. Table 1 summarizes pertinent properties of the mixtures included in the evaluation. The mixtures include 5 mixtures from the MNRoad project, 11 mixtures from the FHWA Pavement Testing Facility, and 6 mixtures from the WesTrack project. This combination of mixtures includes a range of nominal maximum aggregate sizes, binders, and volumetric properties.

For each mixture included in Table 1, master curves were developed using the MEPDG master curve. Data from all temperatures were used to develop the AASHTO TP62 master curves, while the reduced data set excluded the data at 15.8°F and included an estimate of the limiting maximum modulus from the Hirsch model. The master curves then were compared graphically. The rationality of the master curve parameters also was considered.

Figure 3 and Figure 4 present examples of the master curves generated. Figure 3 is for Lane 2 at the FHWA Pavement Testing Facility and is an example of the worst agreement between the two methods. The limiting maximum modulus from the reduced data set at 3,236,868 psi is much lower than the 6,714,030 psi limiting maximum modulus from the AASHTO TP62 data set. The difference in the limiting maximum modulus also affects the limiting minimum modulus because the sigmoidal master curve is symmetrical. The limiting minimum modulus from the reduced data set is

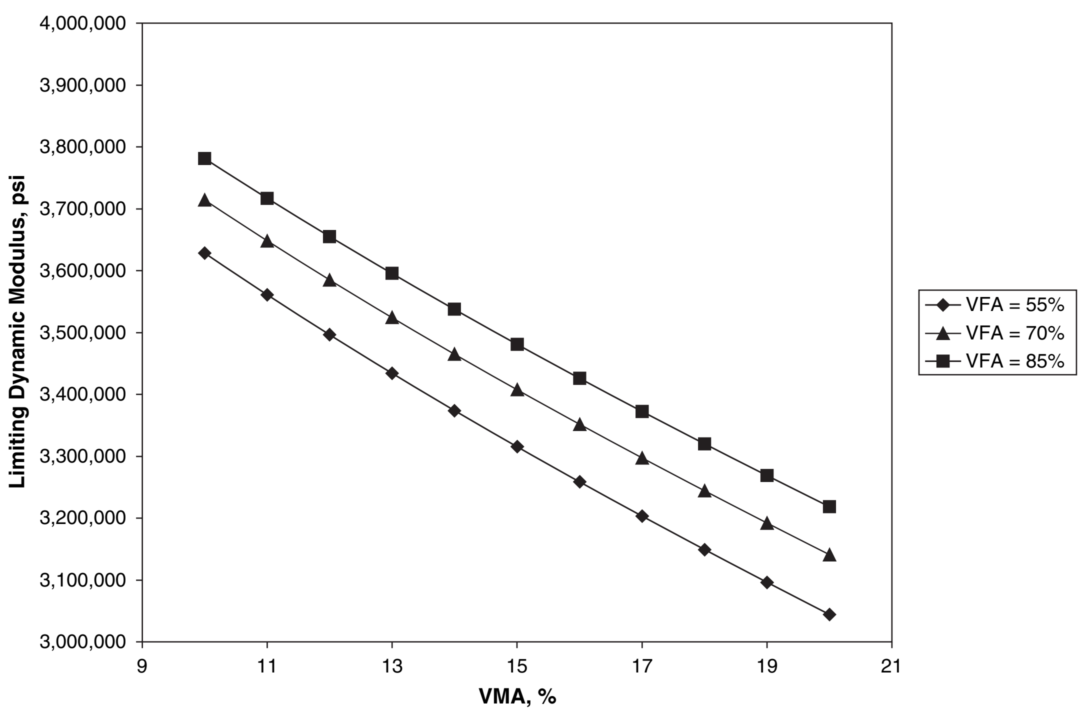


Figure 2. Limiting maximum dynamic modulus values from the Hirsch model.

Table 1. Properties of mixtures used in the master curve comparison study.

Description				Mix Volumetric Properties				AASHTO T240 Residue Binder Properties		
Project	Project ID	Binder	Mix Type	AC, %	Va, %	VMA, %	VFA, %	A	VTS	$\eta_{70_{RTFOT}}$, cP
MNRoad	Cell 16	AC-20	Fine 9.5 mm	5.08	8.2	18.0	54.4	10.7826	-3.6065	1.22E+09
MNRoad	Cell 17	AC-20	Fine 9.5 mm	5.45	7.7	18.2	57.6	10.7826	-3.6065	1.22E+09
MNRoad	Cell 18	AC-20	Fine 9.5 mm	5.83	5.6	17.1	67.2	10.7826	-3.6065	1.22E+09
MNRoad	Cell 20	120/150 Pen	Fine 9.5 mm	6.06	6.3	18.3	65.6	10.8101	-3.6254	3.96E+08
MNRoad	Cell 22	120/150 Pen	Fine 9.5 mm	5.35	6.5	16.9	61.5	10.8101	-3.6254	3.96E+08
ALF	Lane 1	AC-5	Fine 19 mm	4.75	6.1	16.9	63.9	10.6766	-3.5740	5.35E+08
ALF	Lane 2	AC-20	Fine 19 mm	4.85	6.5	17.3	62.5	10.6569	-3.5594	1.38E+09
ALF	Lane 3	AC-5	Fine 19 mm	4.75	7.7	18.3	57.9	10.6766	-3.5740	5.35E+08
ALF	Lane 4	AC-20	Fine 19 mm	4.9	9.7	20.3	52.1	10.6569	-3.5594	1.38E+09
ALF	Lane 5	AC-10	Fine 19 mm	4.8	8.6	19.0	54.7	10.7805	-3.6116	5.72E+08
ALF	Lane 7	Styrelf	Fine 19 mm	4.9	11.9	22.1	46.2	8.9064	-2.9089	4.02E+09
ALF	Lane 8	Novophalt	Fine 19 mm	4.7	11.9	21.6	45.0	8.8136	-2.8817	1.58E+09
ALF	Lane 9	AC-5	Fine 19 mm	4.9	7.7	18.4	58.1	10.6766	-3.5740	5.35E+08
ALF	Lane 10	AC-20	Fine 19 mm	4.9	9.3	19.8	53.0	10.6569	-3.5594	1.38E+09
ALF	Lane 11	AC-5	Fine 37.5 mm	4.05	6	14.2	57.9	10.6766	-3.5740	5.35E+08
ALF	Lane 12	AC-20	Fine 37.5 mm	4.05	7.4	15.5	52.3	10.6569	-3.5594	1.38E+09
WesTrack	Sec 2	PG 64-22	Fine 19 mm	5.02	10.4	17.3	39.9	11.0757	-3.7119	1.63E+09
WesTrack	Sec 4	PG 64-22	Fine 19 mm	5.24	6.6	14.3	53.8	11.0757	-3.7119	1.63E+09
WesTrack	Sec 7	PG 64-22	Coarse 19 mm	6.28	6.9	15.9	56.6	11.0757	-3.7119	1.63E+09
WesTrack	Sec 15	PG 64-22	Fine 19 mm	5.55	8.7	16.9	48.4	11.0757	-3.7119	1.63E+09
WesTrack	Sec 23	PG 64-22	Coarse 19 mm	5.78	4.9	13.0	62.3	11.0757	-3.7119	1.63E+09
WesTrack	Sec 24	PG 64-22	Coarse 19 mm	5.91	7.2	15.4	53.2	11.0757	-3.7119	1.63E+09

higher, 16,826 psi compared to 2,222 psi for the AASHTO TP62 data set. Both approaches fit the measured data well over the temperature range from 40 to 130°F and the shift factors for the two approaches are essentially the same.

Figure 4 is for Cell 17 at the MNRoad project, and is an example of best agreement between the two methods. In this case, the two approaches yield essentially the same master curves.

To compare master curves for all of the mixtures, dynamic moduli were calculated for temperatures ranging from −30 to 150°F using loading rates of 25, 10, 1, 0.1, and 0.01 Hz. The results are shown in Figure 5. As shown, the two approaches

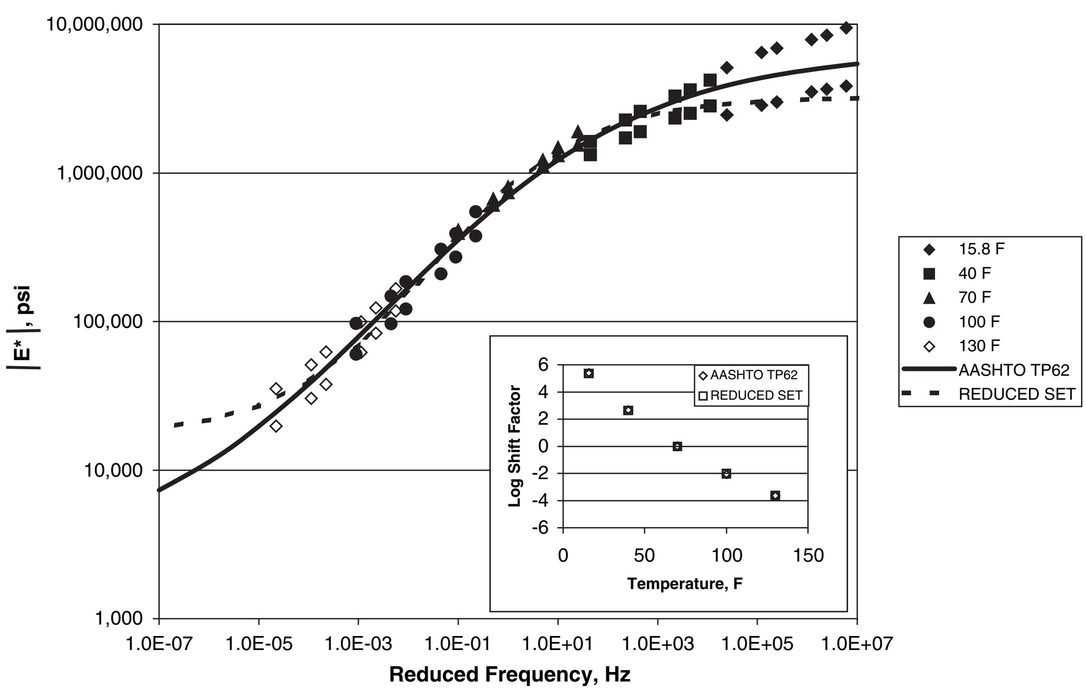


Figure 3. Comparison of fitted master curves for Lane 2 from the FHWA Pavement Testing Facility

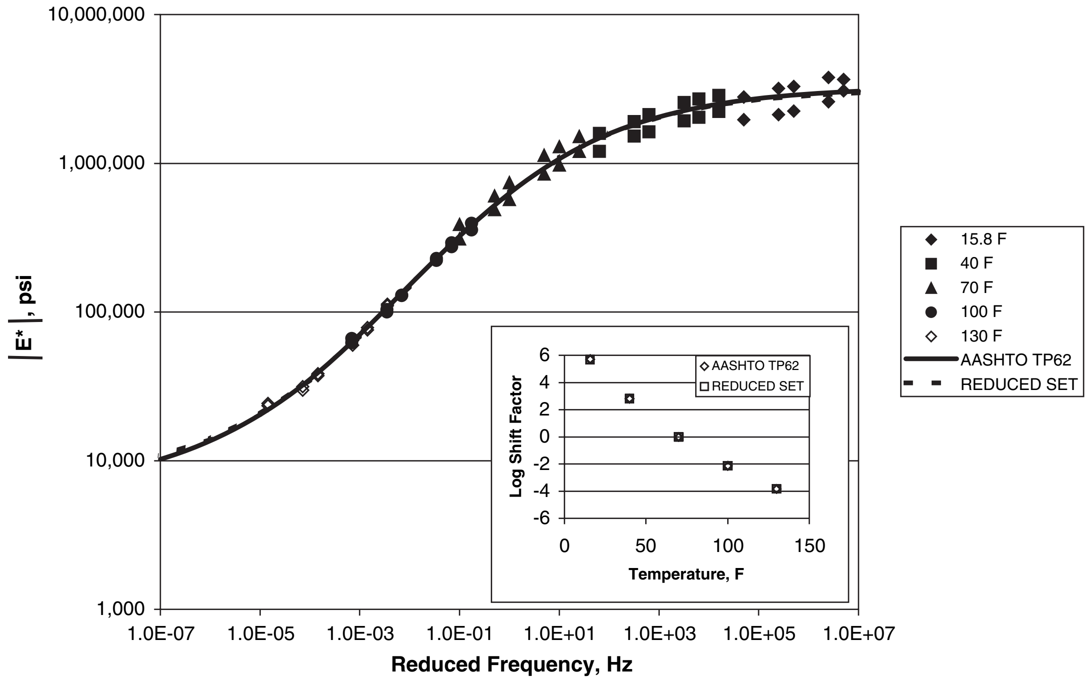


Figure 4. Comparison of fitted master curves for Cell 17 from the MNRoad.

yield the same moduli over the range of the measured data, but sometimes yield differences at high and low moduli primarily due to differences caused by the maximum limiting modulus.

Figure 6 compares limiting maximum moduli from the two data sets. As shown, the AASHTO TP62 data set yields unrealistically high moduli in four cases, ALF 2, ALF 3, ALF 10, and ALF 11. It also yields unrealistically low values in two cases, ALF 8 and WSTR 2. Table 2 summarizes limiting maximum modulus values averaged over similar mixtures. As shown, the two data sets produce reasonably similar average limiting maximum modulus values except for the ALF mixtures, which had four unrealistically high values in the AASHTO TP62 data set. The quality of the data for the low temperature test condition has a major impact on the limiting maximum modulus in the MEPDG master curve equation. Pellinen reported significantly greater variability for data collected at 15.8 °F and 130°F as summarized Table 3 (*9*). As reported by Pellinen, strain levels for the 15.8°F data were significantly lower than those at other

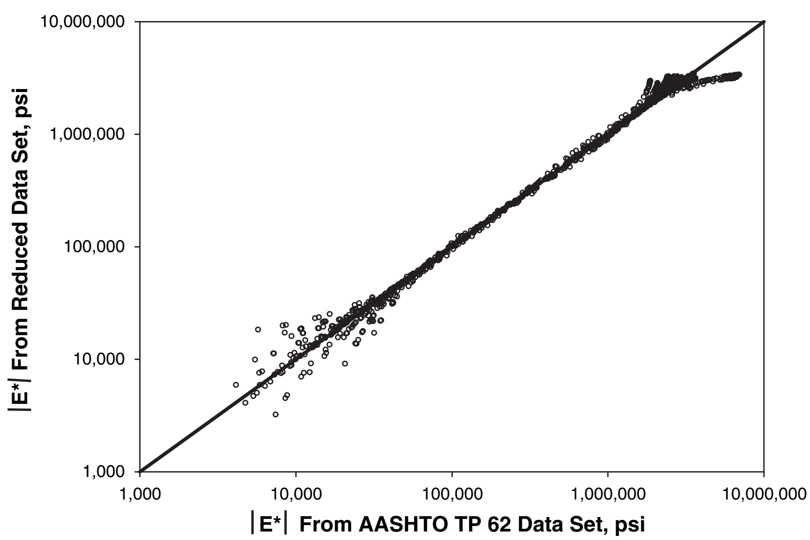


Figure 5. Comparison of dynamic moduli computed from master curves.

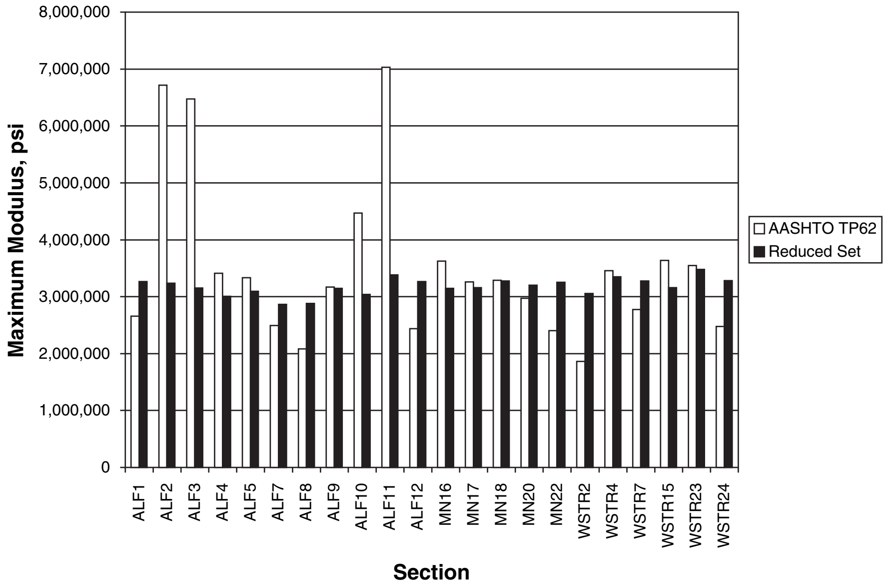


Figure 6. Comparison of limiting maximum moduli.

temperatures (*9*). This coupled with potential friction in the linearly variable differential transformer (LVDT) guide rod used included in the AASHTO TP62 recommended instrumentation is the most likely cause of the high variability in the low temperature measurements. This probably also explains the unrealistically high moduli measured for four of the ALF mixtures.

The limiting maximum modulus also affects the limiting minimum modulus because of the symmetry inherent to the MEPDG dynamic modulus master curve. Figure 7 compares limiting minimum modulus values from the two data sets for individual mixtures. As shown the largest differences between the two occur for the same mixtures that have the largest differences in the limiting maximum modulus. Table 4 summarizes limiting minimum modulus values averaged over similar mixtures. The two data sets produce reasonably similar average limiting minimum modulus values. The limiting minimum modulus represents the stiffness of the aggregate structure in the absence of binder. Both procedures provide the same rankings for the mixtures compared in this evaluation.

Table 2. Limiting maximum modulus values averaged over mixture type.

Mixture	Number	Limiting Maximum Modulus, psi	
		AASHTO TP62	Reduced Set
MNRoad	5	3,109,668	3,206,382
ALF 19 mm	9	3,867,636	3,077,348
ALF 25 mm	2	4,735,721	3,324,313
WesTrack 19 mm Fine	3	2,985,757	3,187,770
WesTrack 19 mm Coarse	3	2,934,664	3,345,151
All Mixtures	22	3,526,808	3,180,702

2.5 Abbreviated Dynamic Modulus Master Curve Testing Conditions

The previous section showed that reasonable dynamic modulus master curves can be obtained using an estimated limiting maximum modulus and data collected at temperatures of 40, 70, 100, and 130°F and frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. However, these temperatures and loading rates are not optimal for use with the estimated limiting maximum modulus approach. This section presents an analysis of the temperatures and loading rates that should be used in combination with an estimated limiting maximum modulus to develop dynamic modulus master curves.

The optimum approach for fitting the S shaped sigmoidal function is to obtain data defining the limiting maximum modulus, the limiting minimum modulus, and the slope over the middle portion of this range on a log scale. Unfortunately, the limiting moduli cannot be obtained directly by testing as these would require tests at extremely low and high temperatures. Therefore, the approach taken in AASHTO TP62 is to collect data over a wide temperature range and essentially

Table 3. Dynamic modulus variability reported by Pellinen (*9*).

Temperature, °F	Pooled Between Specimen Coefficient of Variation, %	
	12.5 mm Mixtures	19.0 mm Mixtures
15.8	16.7	25.4
40.0	12.8	19.0
70.0	14.2	9.4
100.0	14.5	20.3
130.0	28.1	22.7

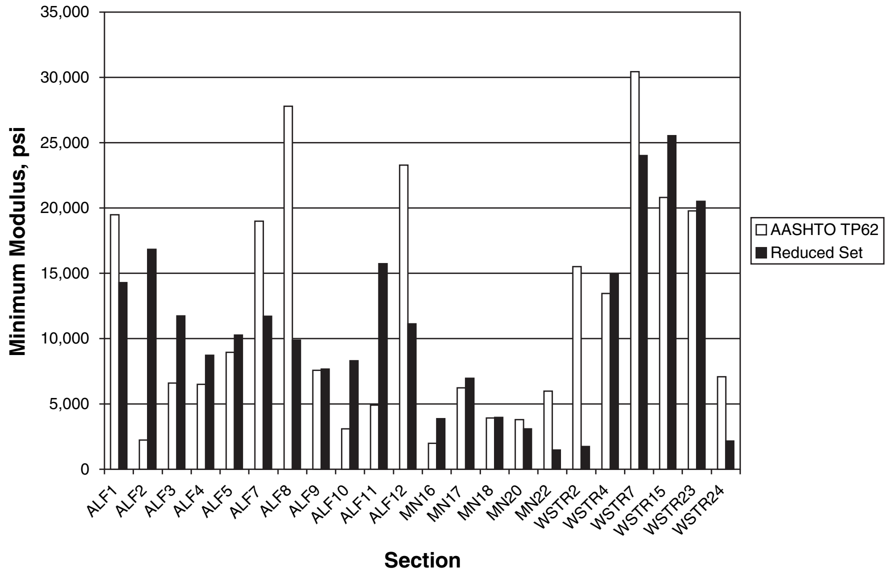


Figure 7. Comparison of limiting minimum moduli.

extrapolate these data to define the limiting maximum and minimum moduli. As shown in this evaluation, the AASHTO TP62 approach is sensitive to the quality of the data at the lowest temperature, which is often variable, and potentially inaccurate due to testing difficulties. For the same intermediate- and high-temperature data, high-limiting maximum moduli result in lower limiting minimum moduli while low-limiting maximum moduli result in higher limiting minimum moduli due to the symmetry of the MEPDG master curve equation.

In the alternate approach developed in Phase IV of NCHRP Project 9-29, a reasonable, rational estimate of the limiting maximum modulus is provided by the Hirsch model. This eliminates the need for testing at low temperatures, and the potential inaccuracies caused by these difficult testing conditions. To provide an accurate estimate of the limiting minimum modulus, data should be collected to the slowest reduced frequency possible. From Equation 2, the reduced frequency is a function of both temperature and frequency of loading. High temperature, slow frequency dynamic modulus tests result in the lowest reduced frequency values. The AASHTO TP62 testing conditions yielded minimum reduced frequencies for the mixtures studied ranging from 10^{-3} to 10^{-4} Hz. The most efficient way to decrease the reduced frequency in the testing program is to increase temperature; however, for the glued gage point instrumentation used in the dynamic modulus test, the maximum testing temperature appears to be approximately 104°F. Above this temperature, the gage points may loosen, particularly when the gage points are attached to the matrix of fine aggregate and binder. Higher temperatures may be possible when stiff modified binders are used or the gage points are attached to the coarse aggregate, but this can not be assured in most mixtures. Figure 8 presents experimentally determined shift factors for the mixtures included in this evaluation. As shown, the shift factors for the maximum recommended testing temperature of 104°F range from about $10^{-1.8}$ to $10^{-2.5}$. From Equation 2, this results in a loading frequency of approximately 0.03 to 0.06 Hz at 104 °F to obtain reduced frequencies ranging from 10^{-3} to 10^{-4} Hz. Thus, the use of a loading rate of 0.01 Hz at 104°F will provide somewhat lower reduced frequencies than obtained with 0.1 Hz at 130°F as specified in AASHTO TP62.

Because the shift factor relationship is not linear, a minimum of three temperatures spaced as widely as possible should be used in the testing program. This will provide a reasonable estimate of the coefficient, *c*, in the shift factor relationship, Equation 3. A low testing temperature of 40°F would allow reasonable priced environmental chambers to be used, and will eliminate the icing problems that occur when testing at temperatures below freezing.

The recommended testing temperatures for the abbreviated dynamic modulus master curve testing are 40, 70, and 104°F. Based on the performance of typical LVDT deformation systems, the maximum frequency of loading should be limited to 10 Hz. Using loading frequencies of 10, 1, 0.1, and 0.01 Hz at each of the temperatures results in well spaced data in reduced frequency with a minimum of overlap. This

Table 4. Limiting minimum modulus values averaged over mixture type.

Mixture	Number	Limiting Minimum Modulus, psi	
		AASHTO TP62	Reduced Set
MNRoad	5	4,383	3,873
ALF 19 mm	9	11,247	11,044
ALF 25 mm	2	14,092	13,426
WesTrack 19 mm Fine	3	16,589	14,077
WesTrack 19 mm Coarse	3	19,101	15,569
Overall	22	11,745	10,662

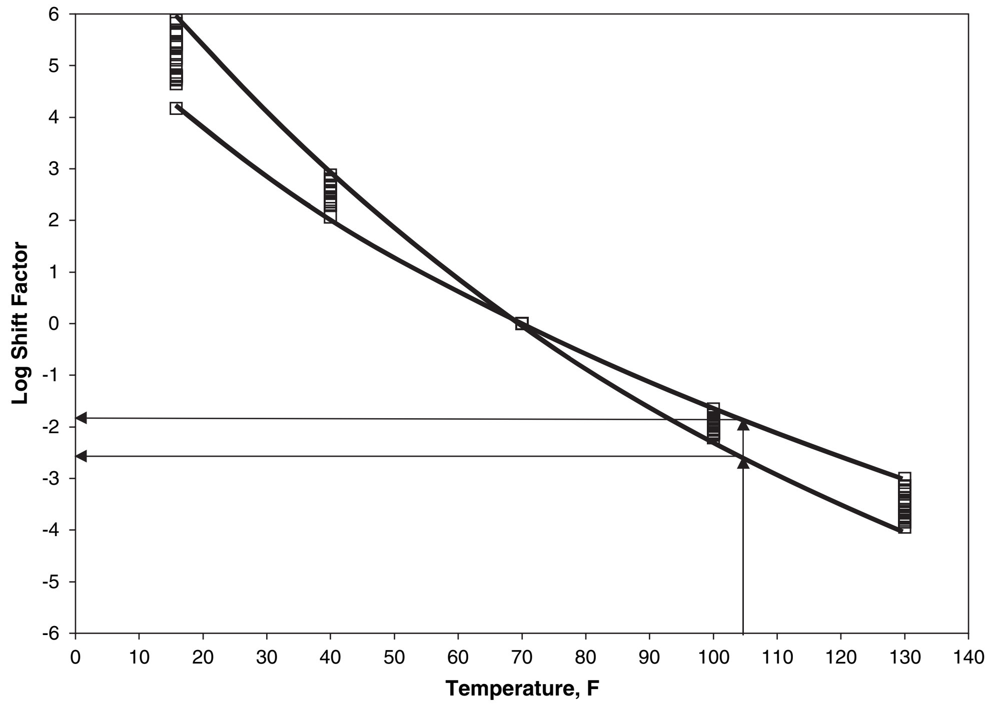


Figure 8. Shift factors as a function of temperature for the mixtures in Table 2.

is shown in Figure 9, based on the average shift factors at 40 and 104°F shown in Figure 8. The recommended testing temperatures and frequencies for the abbreviated dynamic modulus master curve testing result in data over the range of reduced frequency at 70°F from approximately 10^{-4} to 10^{5} with a small overlap of the high and low temperature data with the reference temperature data.

The SPT software applies 20 cycles at each loading frequency. The first 10 cycles are used to adjust the load to produce strains within the specified 75 to 125 μstrain range. The data from the

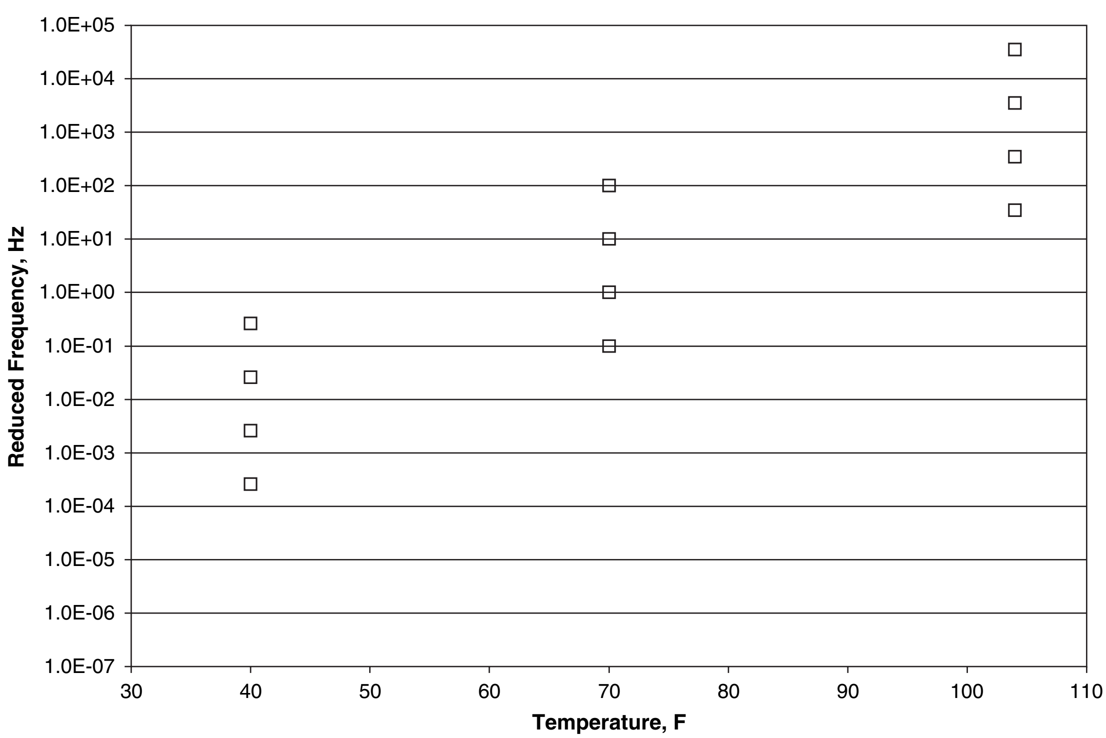


Figure 9. Approximate reduced frequencies for abbreviated dynamic modulus master curve testing sequence.

second 10 cycles are then collected and used to compute the dynamic modulus and phase angle. The loading frequencies recommended in this document will require approximately 40 min per specimen at each testing temperature, including time for specimen instrumentation and chamber temperature equilibrium. Thus, a testing program including three replicate specimens will require approximately 2 hours per temperature for data collection.

2.6 Arrhenius Shift Factor Relationship

Equation 7 presented the modified form of the MEPDG master curve equation used to generate a dynamic modulus master curve using the proposed abbreviated testing. This equation requires knowledge of the viscosity-temperature relationship of the binder used in the mixture. For mixture evaluation, the binder viscosity-temperature relationship may not be known. A dynamic modulus master curve can still be developed using an alternative shift factor relationship based on the Arrhenius equation given in Equation 12.

$$\log[a(T)] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{12}$$

where
$a(T)$ = shift factor at temperature T;
T_r = reference temperature, °K;
T = test temperature, °K; and
ΔE_a = activation energy (treated as a fitting parameter).

Using Equation 12 for the shift factors, the dynamic modulus master curve equation for use with proposed abbreviated testing procedure becomes:

$$\log|E^*| = \delta + \frac{(\text{Max} - \delta)}{1 + e^{\beta + \gamma\left\{\log\omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \tag{13}$$

where
$|E^*|$ = dynamic modulus;
ω = loading frequency, Hz;
T_r = reference temperature, °K;
T = test temperature, °K;
Max = specified limiting maximum modulus; and
δ, β, γ and ΔE_a = fitting parameters.

2.7 Example Using the Abbreviated Dynamic Modulus Master Curve Testing

This section illustrates the development of master curves using the proposed procedure. The mixture that was tested was a coarse graded 9.5 mm limestone mixture made with a PG 70-22 binder. The viscosity-temperature susceptibility parameters for the binder were: A= 10.299 and VTS = −3.426. The test specimens were compacted at the optimum asphalt content of 5.5 percent to 4.0 percent air voids. For this condition, the percent VMA was 15.8 and the percent voids filled with asphalt was 76.2. Table 5 presents dynamic modulus data measured on replicate samples using the combination of temperatures and loading rates recommended in the abbreviated testing protocol.

The first step for fitting the master curve is to estimate the limiting maximum modulus using Equation 10. For a mixture with a VMA of 15.8 percent and a VFA of 76.2 percent, the limiting maximum modulus from Equation 10 is 3,376,743 psi. Using this value of the limiting maximum modulus, the viscosity-temperature susceptibility parameters, and the measured data, the master curve parameters can be obtained through numerical optimization of Equation 7. The optimization can be performed using the Solver function in Microsoft EXCEL®. This is done by setting up a spreadsheet to compute the sum of the squared errors between the logarithm of the measured dynamic moduli and the values predicted by Equation 7. The Solver function is used to minimize the sum of the squared errors by varying the fitting parameters in Equation 7. The following initial estimates are recommended: $\delta = 0.5$, $\beta = -1.0$, $\gamma = -0.5$, and $c = 1.2$. The master curve developed from this example data is shown in Figure 10. The goodness of fit statistics show Equation 7 provides an excellent fit to the measured data with an R^2 greater than 0.99 and an Se/Sy less than 0.04. Using the abbreviated temperatures and loading rates, the measured data cover approximately 80 percent of the range defined by the fitted limiting minimum and computed limiting maximum moduli.

2.8 Summary and Draft Standard Practice

An abbreviated testing protocol for developing dynamic modulus master curves for routine mixture evaluation and flexible pavement design was developed in Phase IV of NCHRP

Table 5. Dynamic modulus test data collected using the abbreviated dynamic modulus master curve testing.

Temp, F	Frequency, Hz	Specimen 1 Modulus, ksi	Specimen 1 Phase, Degree	Specimen 2 Modulus, ksi	Specimen 2 Phase, Degree
40	0.01	771.6	25.0	901.1	23.7
40	0.1	1274.9	19.0	1496.1	17.9
40	1	1861.7	13.9	2164.1	12.8
40	10	2458.2	9.6	2811.0	8.6
70	0.01	161.0	30.0	174.6	29.6
70	0.1	362.7	29.2	398.3	29.2
70	1	771.7	24.5	844.4	24.3
70	10	1332.1	18.0	1446.0	18.0
104	0.01	23.3	24.4	28.3	22.9
104	0.1	50.8	27.8	53.4	27.9
104	1	137.8	29.4	140.9	29.5
104	10	336.2	29.7	352.8	29.9

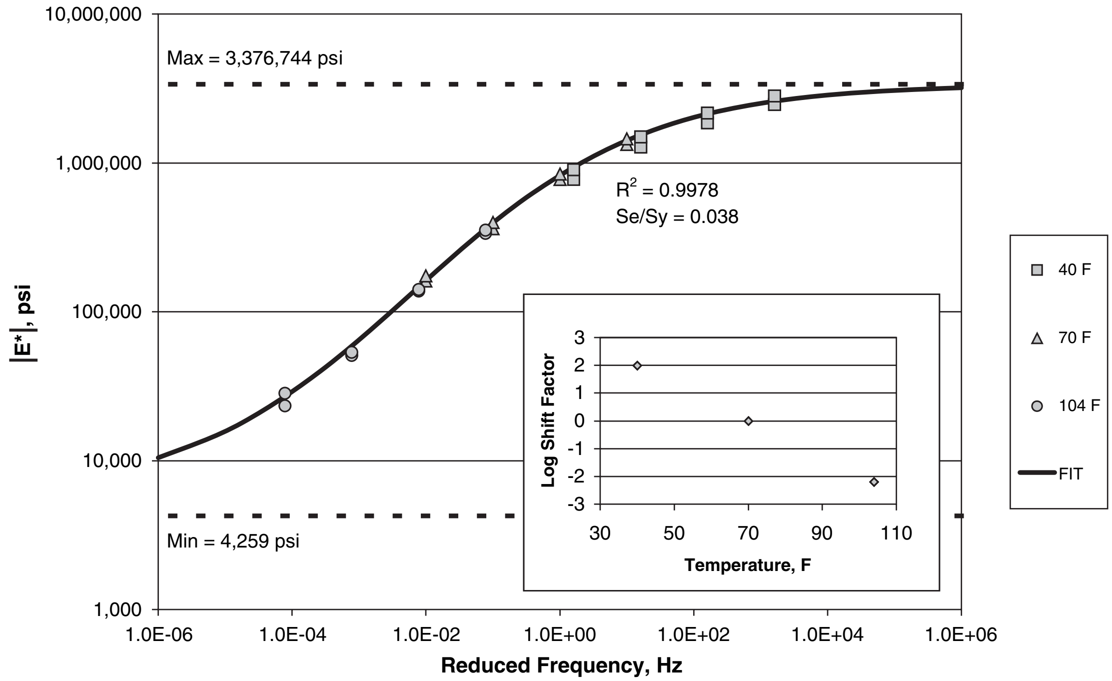


Figure 10. Example master curve using abbreviated testing sequence.

Project 9-29. This abbreviated testing protocol requires testing at 40, 70, and 104°F using loading frequencies of 10, 1, 0.1, and 0.01 Hz. The data can be fit to the MEPDG dynamic modulus equation after an estimate of the limiting maximum modulus is made using the Hirsch model. The abbreviated dynamic modulus master curve testing protocol eliminates the lowest temperature in the AASHTO TP62 testing sequence and optimizes the temperatures and loading frequencies for minimal overlap to the modulus data. Testing at the lowest temperature in the AASHTO TP62 sequence, 14 °F, greatly increases the cost of the environmental chamber for the testing system, and increases the complexity of testing. Moisture condensation and icing make testing at this temperature challenging even for highly experienced technicians.

To aid in implementation of the abbreviated dynamic modulus testing protocol, a draft standard practice titled "Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System" was prepared. This draft standard practice is presented in Appendix A.

CHAPTER 3

Revised Simple Performance Test System

3.1 Revised Simple Performance Test System Equipment Specification

Equipment to perform the abbreviated dynamic modulus master curve testing presented in Chapter 2 requires additional low temperature and loading capabilities compared to the SPT developed in Phases I and II. Table 6 compares the requirements for the SPT developed in Phases I and II, a testing device to produce dynamic modulus master curves using the abbreviated testing protocol, and a device to produce dynamic modulus master curves using AASHTO TP62. Table 6 also includes an estimate of the cost of each system. The primary differences in the equipment are the temperature range and the required dynamic loading capacity. The substantial difference in the low-temperature range of the environmental chamber is responsible for the increase in the estimated cost of the equipment. The increased dynamic loading capacity results in a nominal increase in the estimated cost of the equipment.

The equipment specification developed in Phases I and II (*10*) was revised to specify a device capable of performing the three simple performance tests and developing dynamic modulus master curves using the abbreviated testing protocol developed during this phase of the project. This specification was designated as Version 2.0 and is reproduced in Appendix B. It was produced by modifying Version 1.1 of the specification developed in Phase II of the project to include the 39°F temperature control, the increased dynamic load capacity, and the 0.01 Hz load control needed for master curve testing. Version 1.1 of the specification included the improvements identified by the first article evaluation.

3.2 Simple Performance Test System Procurement and Evaluation

3.2.1 Procurement

Version 2.0 of the Equipment Specification for the SPT was used to upgrade the first article devices purchased in Phase II of the project to meet the revised requirements for master curve testing and to procure new SPTs. Contracts for upgrade work were negotiated directly with Interlaken Technology Corporation, Inc. and IPC Global.

The process used in Phase II of this project to procure the first article equipment was used to procure the new equipment in Phase IV. A request for proposal (RFP) was issued to manufacturers who expressed interest in providing equipment under NCHRP Project 9-29. Table 7 lists the manufacturers that provided an RFP package consisting of Version 2.0 of the equipment specification and a copy of the Phase II evaluation report (*10*). The RFP required the manufacturers to submit a detailed proposal describing the proposed equipment and providing supporting documentation that the proposed equipment meets the specification requirements. Additionally, the manufacturers were asked to identify unique features offered in their equipment and to provide a firm fixed price for the equipment delivered to Sterling, VA. Four manufacturers submitted complete proposals in response to the Phase IV RFP:

- Interlaken Technology Corporation,
- IPC Global,
- James Cox and Sons, Inc., and
- Medical Device Testing Services, Inc.

Cooper Research Technology, Ltd submitted an incomplete proposal, and Shedworks, Inc. submitted a document describing a more general system capable of performing the tests required by the SPT specification as well as other tests.

The four complete proposal were evaluated, and three were selected for award. The following criteria were used in the evaluation, listed in order of importance:

1. Documented ability of the proposed equipment to meet the specification requirements,
2. Unique advantages offered by the proposed equipment, and
3. Cost of the proposed equipment.

Table 6. Comparison of dynamic modulus testing devices.

Item	Simple Performance Test System for Rutting	Simple Performance Test System for Rutting and Abbreviated Master Curve Testing	AASHTO TP62 Master Curves for Structural Design
Temperature Range	20 to 60 °C (68 to 140 °F)	4 to 60 °C (39 to 140 °F)	-10 to 60 °C (14 to 140 °F)
Temperature Control	± 0.5 °C (± 1.0 °F)	± 0.5 °C (± 1.0 °F)	± 0.5 °C (± 1.0 °F)
Dynamic Load Capacity	6 kN (1.3 kips)	12.5 kN (2.8 kips)	22.5 kN (5.0 kips)
Loading Rates	0.1 to 25 Hz	0.01 to 10 Hz	0.1 to 25 Hz
Confining Pressure	YES	YES	NO
Estimated Cost	$45,000	$60,000	$100,000

The equipment proposed by the four manufacturers was similar to the first article devices evaluated in Phase II of the project. All were relatively small, bottom-loading, servo-hydraulic machines with automated testing chambers that serve as a confining pressure cell and temperature control chamber. No manufacturer proposed an alternative to the standard glued gage point system with LVDTs for measuring specimen deformations in the dynamic modulus test. Version 2.0 of the specification allows alternatives to be considered provided the manufacturer can demonstrate that the alternative produces deformation measurements that are the same as the standard glued gage point system. Interlaken, Cox, and Medical Device Testing proposed equipment with two LVDTs spaced 180° apart on the specimen. IPC Global proposed equipment with three LVDTs spaced 120° apart. Because they were selected as the first article manufacturers in Phase II of the project, the IPC Global and Interlaken proposals included specifications and photographs of completed equipment. The Cox and Medical Device Testing proposals included detailed design drawings for the major components of the system.

Costs for the proposed equipment ranged from approximately $52,000 to $68,000. Table 8 presents the proposed costs. The Cox and Medical Device Testing proposals indicated that the proposed prices included initial development costs of approximately $18,000 and that future production units would cost approximately $50,000. A contract was awarded to IPC Global as the lowest bidder. Considering that one of the overall objectives of NCHRP Project 9-29 is to stimulate the development of commercial equipment, it was decided to award contracts to James Cox and Sons, Inc. and Medical Device Testing Services, Inc. even though they did not provide the lowest prices. Through these two Phase IV contracts and the Phase II first article contracts, seed funding was made available to four equipment manufacturers: IPC Global, Interlaken Technology Corporation, James Cox and Sons, Inc., and Medical Device Testing Services, Inc. Unfortunately James Cox and Sons, Inc. was not able to complete

Table 7. Equipment manufacturers receiving Phase IV RFP.

Manufacturer	Address	Phone	Contact
Cooper Research Technology, Ltd	Technical Centre 11 High Holborn Road Codnor Gate Business Park Ripley Derbyshire DE5 3NW ENGLAND	44 (1) 773 512174	Andrew Cooper
Interlaken Technology Corporation	8175 Century Boulevard Chaska, MN 55318	(952) 856-4210	Tom Driggers
Instron Corporation	825 University Ave. Norwood, MA 02062-2643	(800) 473 7838	Leslie Dixon
IPC Global	4 Wadhurst Drive Boronia Vic 3155 Australia	61 (0) 3 9800 2200	Con Sinadinos
James Cox and Sons, Inc.	1085 Alpine Way Colfax, CA 95713	(530) 346-8322	James Cox
Medical Device Testing Services, Inc.	6121 Baker Road, Suite 101 Minnetonka, MN 55345	(952) 933-1152	Kent Vilendrer
MTS Systems Corporation	14000 Technology Drive Eden Prairie, MN 55344	(952) 937-4000	Scott Johnson
Shedworks, Inc.	2151 Harvey Mitchell Parkway, S. Suite 320 College Station, TX 77840-5244	(979) 695-8416	Bill Crockford

Table 8. Proposed costs for SPTs.

Manufacturer	Proposed Cost
IPC Global	$52,136
Interlaken Technology Corporation	$62,000
Medical Device Testing Services, Inc	$67,500
James Cox and Sons, Inc.	$68,000

development of their device and at their request, the contract was cancelled. Therefore, new devices were purchased from IPC Global and Medical Device Testing Services in Phase IV of the project.

3.2.2 Upgraded First Article Devices

In Phase II of the project, first article devices were purchased from Shedworks/IPC Global and Interlaken Technology Corporation. When these devices were purchased, it was envisioned that the SPT would be used only for fatigue and rutting evaluations at intermediate and high pavement temperatures. After the abbreviated dynamic modulus master curve testing procedure was developed, it became apparent that the SPT also could serve as equipment for the development of dynamic modulus master curves for pavement structural design. Only two modifications were needed to make the first article devices comply with Version 2.0 of the equipment specification: expand the low temperature control to 39°F and modify the control software to include 0.01 Hz loading. The estimated cost of these upgrades was small relative to the cost of new equipment. Contracts were negotiated with IPC Global and Interlaken Technology Corporation to upgrade the first article equipment to meet Version 2.0 of the equipment specification.

3.2.2.1 Shedworks/IPC Global First Article

One of the first article devices evaluated in Phase II of the project was purchased from Shedworks, Inc. The equipment was manufactured by IPC Global and Shedworks represented IPC Global in the United States. Shedworks and IPC Global discontinued their relationship before Phase IV of the project; therefore, the contract for the first article upgrade was negotiated with IPC Global.

The 39°F temperature requirement presented a minor problem for the Shedworks/IPC Global first article device. The refrigeration unit needed to reach this temperature was too large for the first article frame and enclosure. The plan for upgrading this device, therefore, involved removing the electronics, test cell, and hydraulics from the first article and reinstalling them in a new frame and enclosure sized for the new refrigeration unit. The upgrade was estimated to require 4 to 6 weeks to ship the first article to Australia, remove the salvageable components, reassemble the upgraded machine, and return it to the United States. Since the first article was being used extensively by the FHWA Mobile Asphalt Laboratory to demonstrate the SPT, it was decided that the upgrade should not be performed until another unit became available from the project for use in the FHWA Mobile Asphalt Laboratory. The upgrade was delayed several times because the other manufacturers failed to deliver their equipment on time. IPC Global eventually offered to replace the Shedworks/IPC Global first article device with a new unit and credit the project approximately 70 percent of the original purchase price of the first article. This offer was accepted and the new unit was installed in the FHWA Mobile Asphalt Laboratory on November 15, 2006. The first article will be used by IPC Global for training.

3.2.2.2 Interlaken Technology Corporation First Article

The Interlaken first article device did not fully comply with Version 1.1 of the specification. Version 1.1 incorporated several changes that resulted from the first article evaluation that was completed in Phase II of the project. The test chamber and the deformation measuring system for the dynamic modulus test were the two major elements for the Interlaken first article that were not in compliance with Version 1.1 of the specification. The test chamber for the Interlaken first article was a large metal enclosure with a thick site glass that provided only limited view of the specimen and instrumentation during testing. Users of the equipment found this to be a major limitation during testing. The problem was exacerbated by the lack of lighting in the cell. Because of this experience during the first article testing, Version 1.1 of the specification included a requirement that the specimen, platens, and instrumentation must be clearly visible during testing. To comply with this requirement, the test chamber for the Interlaken first article had to be replaced. Second, the Interlaken first article included a unique extensometer system that was pushed into contact with the specimen by small pneumatic cylinders. This unique deformation measuring system was one of the factors leading to the selection of Interlaken to supply a first article device. The first article evaluation revealed that there was some slip between the specimen and the extensometer system. As a result, Version 1.1 of the specification included a standard glued gage point system for specimen deformation measurements. To comply with this requirement, Interlaken had to design and install a new specimen deformation measuring system. In addition to these major elements, the Interlaken first article also had some unresolved software bugs. Thus, the Interlaken first article upgrade completed in Phase IV addressed the following:

1. Replacement of the test chamber with an acrylic chamber that provided full view of the specimen, instrumentation, and loading platens.
2. Replacement of the original automated extensometer system with a glued gage point system. This included the design of the gage point system as well as auxiliary equipment to automate gluing of the gage points on the specimen.
3. Replacement of the original temperature control system with a new system designed to allow testing over the temperature range of 39 to 140°F.
4. Various software modifications to control temperature, apply 0.01 Hz loading during the dynamic modulus test and to resolve outstanding software bugs.

The first article was returned to Interlaken in November, 2003. Interlaken took approximately one year to complete the upgrade work and return the upgraded device to Advanced Asphalt Technology (AAT).

The upgraded Interlaken first article is shown in Figure 11. The equipment is fairly large and operates on single phase 230 V power. Compressed air also is required for confined testing. The Interlaken SPT consists of (1) a main wheeled cabinet (63 in. wide by 76 in. high by 31 in. deep) that houses the test chamber, the hydraulic pump, the hydraulic actuators, and associated control electronics; (2) a separate standard laboratory bath (16 in. wide by 26 in. high by 17 in. deep) that provides temperature control for the test cell; and (3) a desk top computer for controlling the machine and collecting and analyzing test data. Separate 230 V power supplies are needed for the main cabinet and the laboratory bath. The laboratory bath is shown to the left of the test cell in Figure 11; the computer is located to the right of the main cabinet in Figure 11.

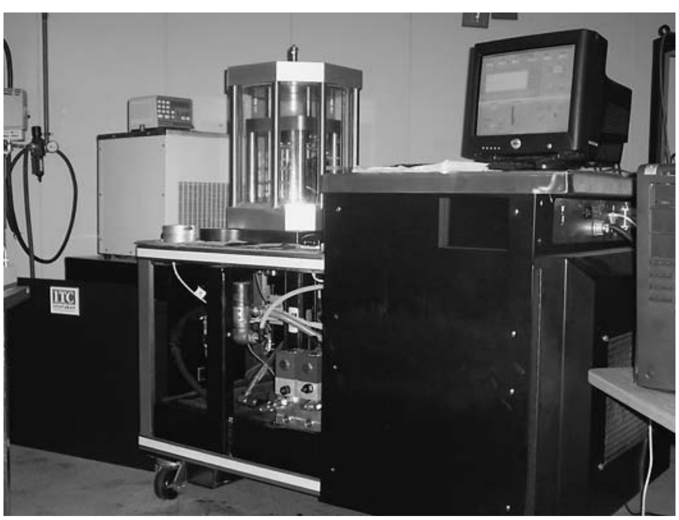


Figure 11. Overall view of upgraded Interlaken SPT (main cabinet removed to show system hydraulics).

Figure 12 shows the interior of the test chamber. The heat exchanger and associated fan are located at the back of the test chamber. The test chamber is large, measuring 15 in. diameter by 21 in. high. It is raised and lowered by two hydraulic actuators. Two hand switches are provided as a safety feature. Hand contact must be made with both of these switches for the test chamber to close.

Strains for the dynamic modulus test are measured by two magnetic LVDT extensometers mounted 180° apart as shown in Figure 13. Each extensometer includes two very flexible springs that allow only vertical movement of the ends. Each extensometer includes a pin that centers the measuring system. When the pin is released, the extensometer is activated. To quickly and accurately mount the glued gage points to the specimen, Interlaken designed the gluing apparatus shown in Figure 14. This system has mechanical links that use the weight of the specimen to press the gage points against the specimen at the correct gage length at the center of the specimen.

Because several major changes were made during the upgrade of the Interlaken first article, all of the specification

Figure 12. Open test chamber for the upgraded Interlaken SPT.

Figure 13. Interlaken specimen mounted extensometer system.

compliance tests detailed in Version 2.0 of the specification were performed. Table 9 summarizes the items included in the specification compliance testing. The specification compliance testing revealed several deficiencies with the upgraded equipment summarized in Table 10. Most of the deficiencies were related to the control and analysis software. Table 10 also summarizes the changes made to resolve the deficiencies. Substantial effort was expended by both the research team and Interlaken to resolve the deficiencies. All of the deficiencies were addressed, and the upgraded device was accepted in December, 2006.

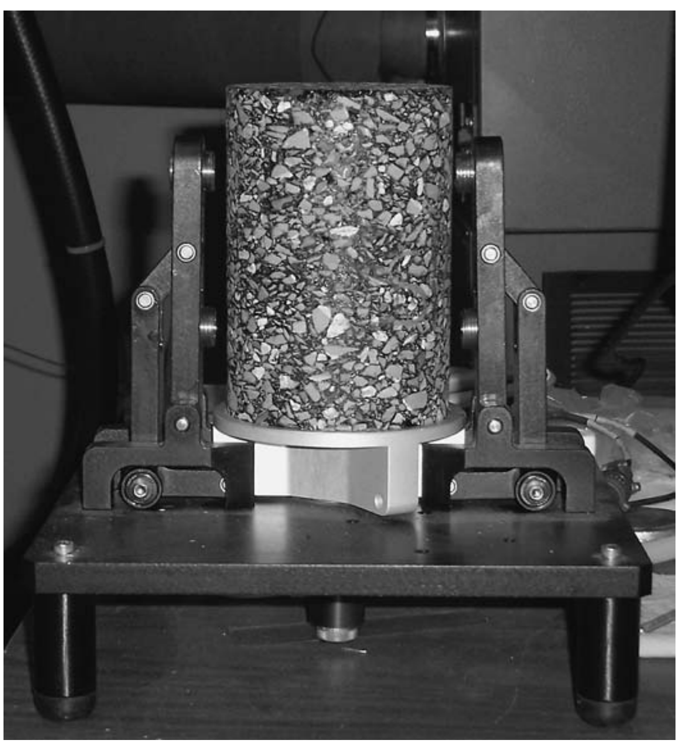


Figure 14. Interlaken gluing apparatus.

3.2.3 Medical Device Testing Services First Article

The Medical Device Testing Services (MDTS) first article is shown in Figure 15. The equipment is relatively small. It consists of (1) a main wheeled cabinet (26 in. wide by 76 in. high by 24 in. deep) that houses the test chamber, the hydraulic pump, the hydraulic actuator, and associated control electronics; (2) a separate heat exchanger (16 in. wide by 23 in. high by 20 in. deep) that provides temperature control for the test cell; and (3) laptop computer for controlling the machine and collecting and analyzing test data. The heat exchanger is under the laptop computer table in Figure 15. An interesting feature of the MDTS SPT is the hydraulic system operates on 115 V AC power, and the hydraulic pump only operates intermittently, which makes the unit very quiet during operation. The heat exchanger requires single phase 208–230 V AC power. The unit also requires compressed air to raise and lower the test chamber and apply confining pressure.

Figure 16 shows the MDTS SPT with the test chamber open, and a specimen inserted for confined testing. The test chamber is relatively small, only 10 in. in diameter by 21 in. high. The reaction posts are located in an awkward position, making installation of the instrumentation on the specimen for dynamic modulus testing difficult. The test cell heat exchangers and associated fans are mounted in the top of the test chamber. The test chamber is insulated; a sight glass and lighting are provided to allow the operator to view the specimen during testing. The chamber is opened and closed by a manually controlled pneumatic actuator located at the back of the machine as shown in Figure 17. It is locked in the closed position by a manual ring locking mechanism that has position switches that are interlocked with the pressure and load control.

The specimen mounted deformation system consists of two magnetic LVDT extensometers mounted 180° apart as shown in Figure 18. Each extensometer includes two very flexible springs that allow only vertical movement of the ends. Each extensometer includes a pin that centers the measuring system. When the pin is released, the extensometer is activated. These extensometers are similar to those developed by Interlaken. This deformation measuring system is the third system that was developed by MDTS for the SPT. The other two systems did not function properly during the ruggedness testing. To quickly and accurately mount the glued gage points to the specimen, MDTS designed the gluing apparatus shown in Figure 19. This system has pneumatic actuators that press the gage points against the specimen at the correct gage length at the center of the specimen.

Table 9. Summary of specification compliance tests.

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

Table 10. Interlaken deficiencies and solutions.

Deficiency	Solution
Slow temperature recovery.	Modified the temperature control software to switch control from the test chamber probe to the bath probe when the chamber is opened, then back to the test chamber probe when the chamber is closed.
Cooling fluid leaks.	Replaced plastic hose clamps with steel band hose clamps.
Units for temperature control.	Modified software to use both U.S. customary and SI units.
Test chamber binding.	Lubricated actuator shaft and realign chamber.
Test chamber air leaks.	Added temporary seal to affected areas.
0.01 Hz loading for dynamic modulus.	Modified software to allow user to test at 0.01 Hz loading.
Irregular first cycle data during dynamic modulus testing.	Modified software to collect additional cycles that are not stored. Only the last 10 cycles are stored and analyzed.
Incorrect computation of dynamic modulus data quality statistics.	Modified software to correct computations.
Poor dynamic load control at high temperatures.	Added a tuning algorithm to allow user to develop and store templates with servo-hydraulic gains.
Software occasionally crashes when maximum strain is reached during flow number testing.	Modified strain limit shut down algorithm.
Incomplete documentation.	Provide required documentation

Final design, fabrication, and shop testing of the MDTS SPT required approximately 18 months. MDTS was given authorization to proceed with the machine on February 6, 2004. The machine was delivered on September 14, 2005. Upon delivery, the specification compliance testing summarized in Table 9 was performed. The specification compliance testing and the ruggedness testing revealed several deficiencies with the equipment, which are summarized in Table 11. Most of the deficiencies were related to the control and analysis software. Table 11 also summarizes the changes made to

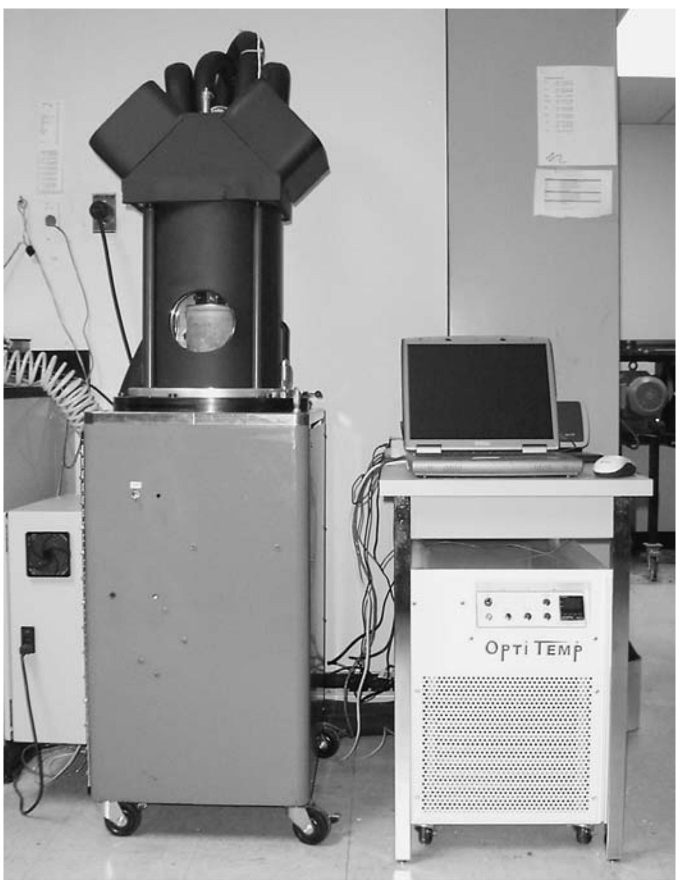


Figure 15. Overall view of MDTS SPT.

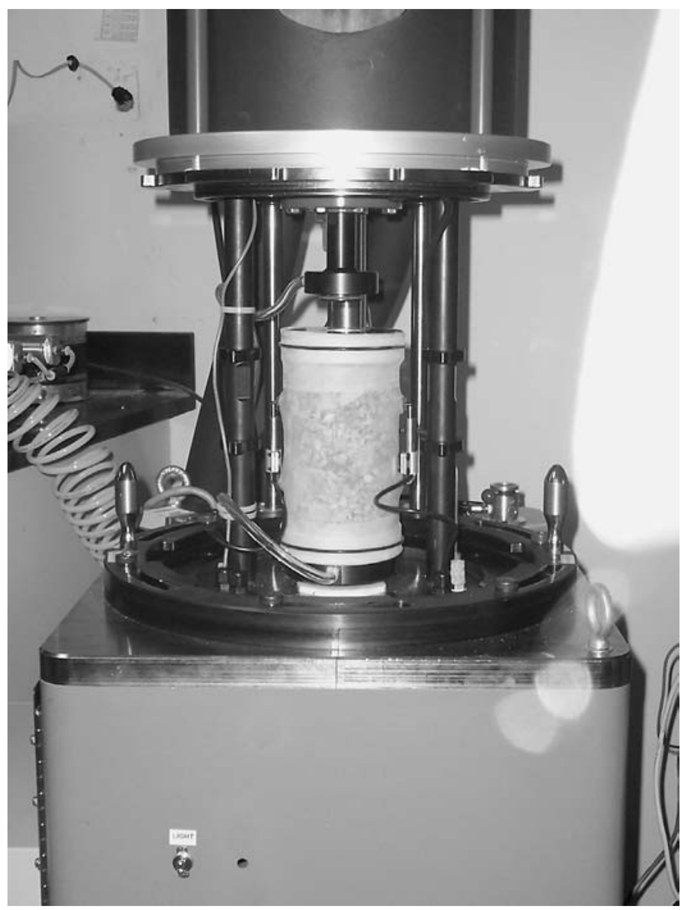


Figure 16. Open test chamber for the MDTS SPT.

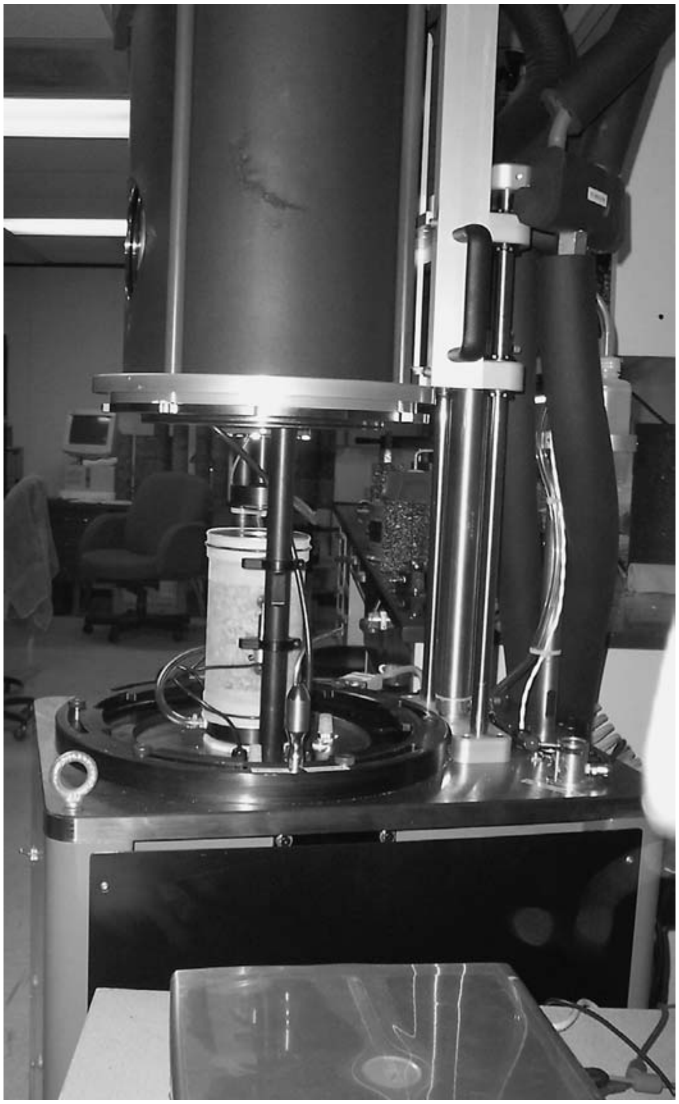


Figure 17. Test chamber lift mechanism for the MDTS SPT.

Figure 18. MDTS specimen mounted deformation measuring system.

Figure 19. MDTS gluing apparatus.

resolve the deficiencies. Substantial effort was expended by both the research team and MDTS to resolve the deficiencies. All of the deficiencies were addressed, and the upgraded device was accepted in January, 2007.

3.2.4 IPC Global Production Unit

The IPC Global production unit is shown in Figure 20. This unit is very similar to the first article device evaluated in Phase II of the project. The machine is slightly larger than the first article to accommodate the larger refrigeration unit needed for testing at 39°C and a second acrylic cell was added around the test chamber to provide insulation. IPC Global also made a modification to improve the holders for the LVDTs for the specimen mounted deformation measuring system used in the dynamic modulus test.

The IPC Global SPT is relatively small. It consists of (1) a cabinet (44 in. wide by 53 in. high by 25 in. deep) that includes the test chamber, the hydraulic pump and actuator, the heating and refrigeration unit, and associated power and control electronics; and (2) a desktop computer for controlling the machine and collecting and analyzing test data. The system operates on single phase 208–230 V AC power.

Figure 21 shows the IPC Global SPT with the test chamber open and a specimen inserted for unconfined testing. The test chamber is relatively small, only 8.5 in. in diameter by 14 in. high. Since temperature control is provided by conditioned air circulated through the test cell, there are no heat exchangers inside the test cell to interfere with test specimen installation and instrumentation. The test chamber is opened and closed by pneumatic actuators. Two hand switches are provided as a safety feature. Hand contact must be made with both of these switches for the test chamber to close. The test chamber is insulated by a second acrylic cell that hangs on the

Table 11. MDTS deficiencies and solutions.

Deficiency	Solution
Specimen mounted deformation measuring system glued contact size exceeded specification.	Reduced glued contact size.
Moment on glued gage points too high resulting in gage point failure at high temperatures.	Revised specimen mounted deformation measuring system by removing LVDT spring and modifying the connection to decrease distance from the specimen.
Temperature control is difficult to use to manufacturer supplied offsets.	Removed manufacturer supplied offsets. User must develop a table of offsets.
Confining pressure control did not function properly in the flow number and flow time tests.	Modified the software to properly control the confining pressure during these tests.
Auto strain control in the dynamic modulus test does not function correctly.	Modified auto strain control algorithm.
Incorrect computation of some dynamic modulus data quality statistics	Modified the software to correctly compute the data quality statistics.
Some data quality statistics not included in dynamic modulus reports.	Modified the software to include all data quality statistics in the reports.
Raw data, not normalized data, used in the plots in the dynamic modulus reports.	Modified the software to use the normalized data in the report plots.
Summary report not provided.	Modified the software to include the summary report.
Strain rate computations for the flow number are shifted forward by one line.	Modified the software to correctly report the strain rate
Strain not set to zero at the beginning of the flow time test.	Modified the software to set the strain to zero at the time specified in the software.
Strain rate computations for the flow time are shifted forward by one line.	Modified the software to correctly report the strain rate

automated test chamber. The specimen mounted deformation system consists of three spring-loaded LVDTs mounted 120° apart as shown in Figure 22. IPC Global designed a unique holder for the LVDTs that can be used for unconfined and confined testing. Each holder has a stiff spring that grips the glued gage points. The spring was designed to highly compress the latex membranes to minimize errors during confined testing.

The ruggedness testing revealed that at high temperatures, creep of the LVDT gauge points can occur, and when this happens, erroneous dynamic modulus data are obtained. The spring force for the IPC Global LVDTs is the highest of the three machines tested, and this machine was the only device to exhibit gauge point creep at the temperatures used in the ruggedness testing. IPC Global designed springs to counter the LVDT spring force and minimize gauge point creep. Figure 23 shows the counter springs on the IPC Global LVDT holders. These counter springs should be used when LVDT gauge point creep is detected in high temperature dynamic modulus tests. Gauge point creep occurred in the ruggedness testing at 95°F when testing specimens made with PG 64-22 binder.

To quickly and accurately mount the glued gage points to the specimen, IPC Global designed the gluing apparatus shown in Figure 24. This system has pneumatic actuators that press the gage points against the specimen at the correct gage length at the center of the specimen. It also includes a membrane stretcher to assist with membrane installation for confined tests.

Final design, fabrication, and shop testing of the IPC Global SPT required approximately 6 months. IPC Global was given authorization to proceed with the machine on February 6, 2004. The machine was delivered on July 29, 2004. Upon delivery, the specification compliance testing summarized in Table 9 was performed. The specification compliance testing revealed a small temperature effect on the LVDTs used in the dynamic modulus testing over the temperature range of 39 to 140°F. IPC Global investigated this problem and determined that the temperature effect was caused by an incorrect excitation frequency being used with the LVDTs. Apparently the LVDT manufacturer provided IPC Global an incorrect optimum excitation frequency. IPC Global subsequently replaced the LVDT conditioners to resolve this problem. The machine was accepted in October, 2004 and delivered to the Turner-Fairbank Highway Research Center, where it has been used extensively on several research projects.

Figure 20. Overall view of the IPC Global SPT.

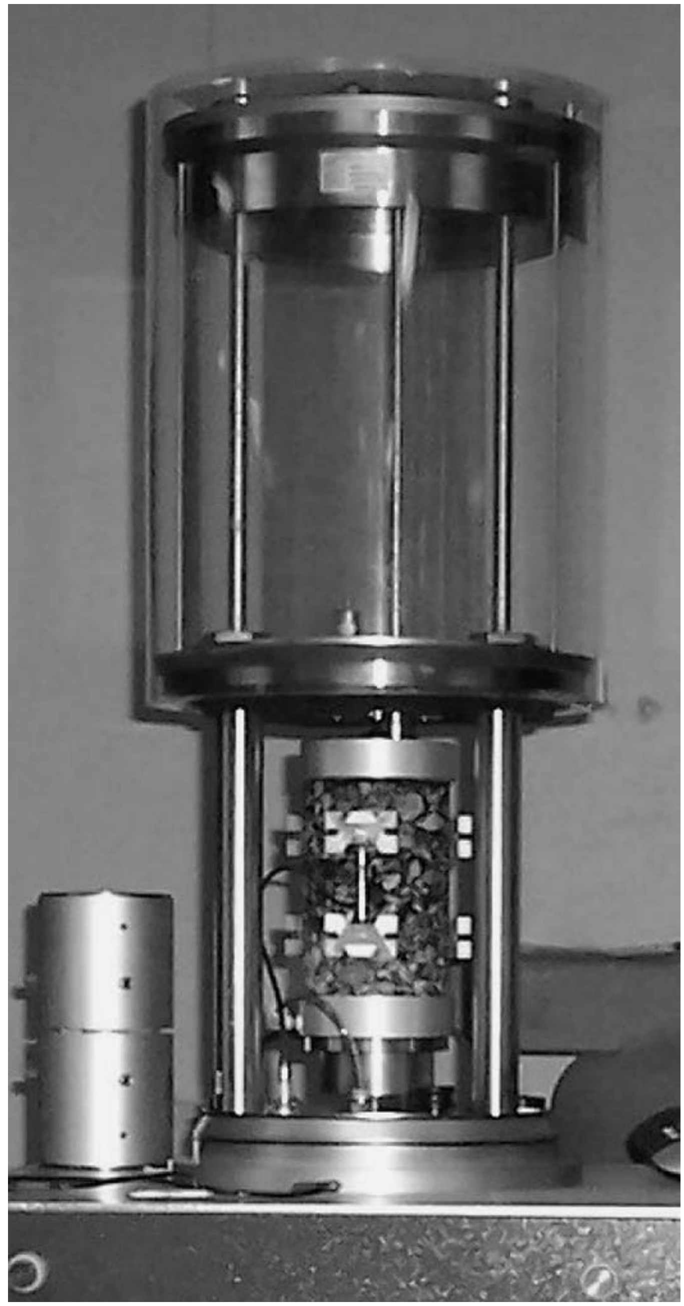


Figure 21. Open test chamber for the IPC Global SPT.

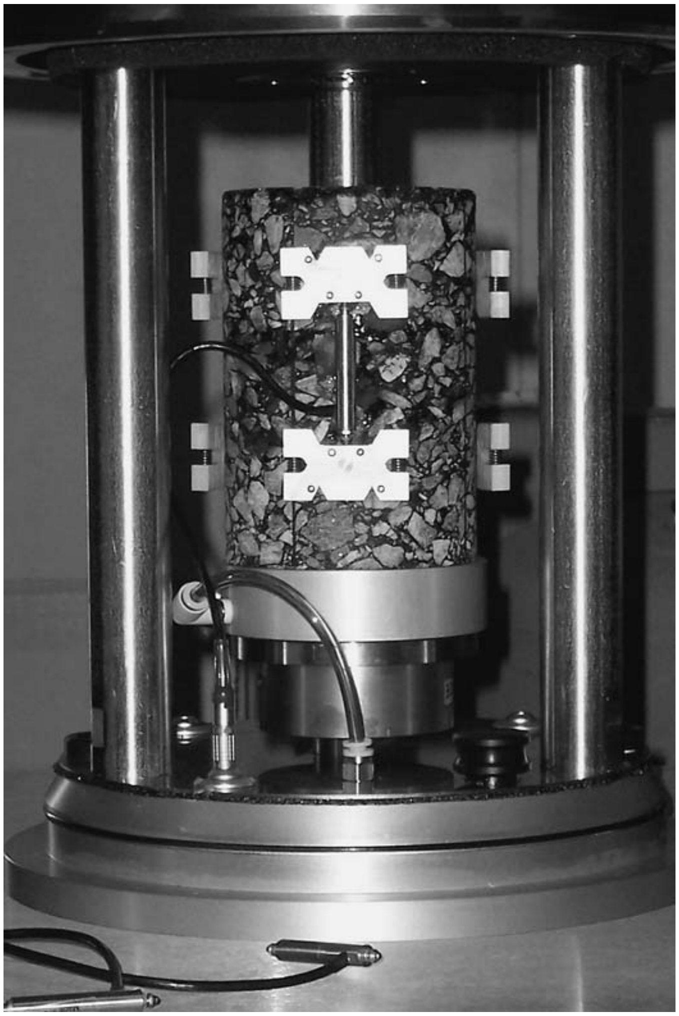


Figure 22. IPC Global specimen mounted deformation measuring system.

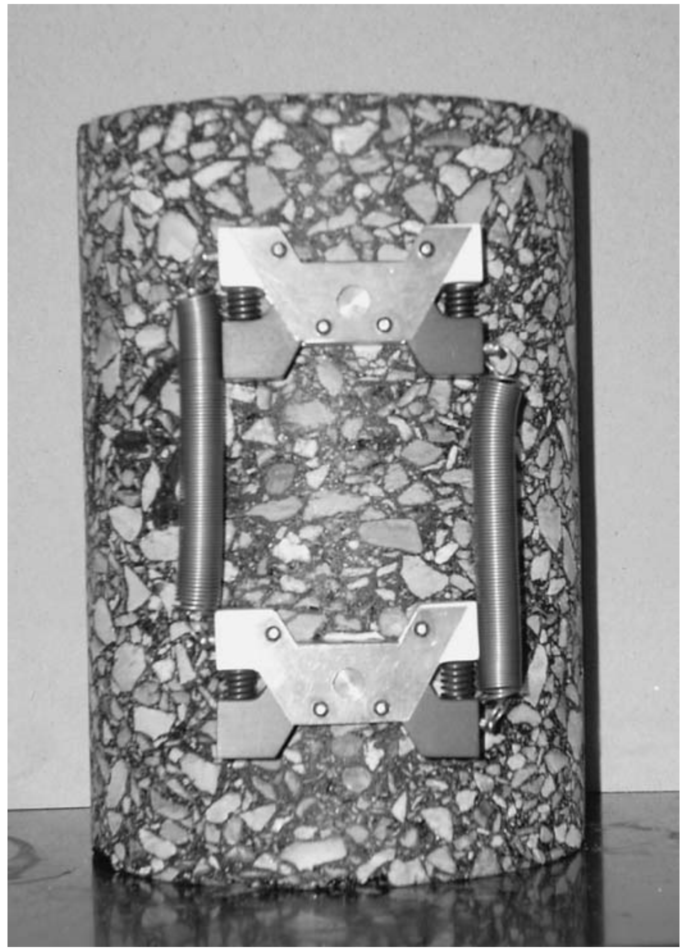


Figure 23. Additional springs to minimize gauge point creep at high temperatures.

Figure 24. IPC Global gluing apparatus and membrane stretcher

CHAPTER 4

Simple Performance Test Specimen Fabrication System

4.1 Recommended Standard Practice for Performance Test Specimen Fabrication

A recommendation made by several reviewers of AASHTO TP62 was that the test specimen fabrication procedures should be removed from AASHTO TP62 and moved to a separate standard practice so that additional guidance on specimen fabrication could be provided. Since NCHRP Project 9-29 was developing equipment for specimen fabrication, it was logical that a recommended standard practice of performance test specimen fabrication be developed by the project team. The resulting practice is contained in Appendix A. Major items addressed in this practice include:

- HMA mixture preparation;
- Over-sized gyratory specimen preparation;
- SPT test specimen preparation;
- SPT test specimen air void content; and
- SPT test specimen storage.

The recommended practice also includes two important appendices that provide additional guidance for preparing SPT specimens. The first is a procedure for obtaining the target air void content for specimens from mixtures that the technician is not familiar with. This procedure was developed at Arizona State University during NCHRP Project 9-19. The second appendix provides a method for evaluating the uniformity of air void contents within SPT test specimens. The appendix is intended help identify the gyratory specimen height that yields the most uniform air voids for a given laboratory.

4.2 Automated Specimen Fabrication Equipment

The remainder of this chapter documents the development of the automated coring and sawing device for the SPT. This device was developed to simplify and automate test specimen fabrication for the SPT. Based on a thorough specimen size and geometry study conducted during NCHRP Project 9-19, the required test specimen for the SPT is a 100 mm (4 in.) diameter by 150 mm (6 in.) tall cylindrical specimen that is cut and cored from a larger 150 mm (6 in.) diameter by 175 mm (6.9 in.) gyratory specimen prepared in a Superpave Gyratory Compactor (*4*). The specimen size, 100 mm (4 in.) in diameter with a height to diameter ratio of 1.5, is needed to ensure that fundamental material properties are measured in the SPT. The test specimen is sawed and cored from a larger gyratory compacted specimen to minimize air void gradients in the specimen, and to provide smooth sides for attaching instrumentation and flat, parallel ends to minimize end effects during testing. Specimens prepared in the Superpave gyratory compactor have higher air void contents near the ends and circumference of the specimen.

Test specimen preparation for the SPT is a multi-step process. Appendix A presents a draft standard practice for preparing SPT test specimens. First, tall gyratory specimens must be prepared to an air void content that is 1 to 2 percent higher than the desired air void content of the test specimen. During this step, it is critical that the mold be loaded in a manner that minimizes segregation in the specimen. Next, the 100 mm (4 in.) diameter test specimen must be cored from the larger gyratory specimen. Finally, the test specimen is cut to the appropriate length by sawing approximately 12.5 mm (1/2 in.) from each end of the specimen. During the coring and sawing operations, it is critical the test specimen be properly clamped and the cutting be performed at the proper rate to ensure a smooth specimen with flat parallel ends is prepared.

In evaluating the specimen preparation process, it was determined that an automated system for coring and sawing the specimens would be beneficial to the future implementation of the SPT. Such a system would reduce the amount of skilled labor needed to prepare test specimens. It also would minimize the potential for errors in the coring and sawing operations that result in specimen rejection due to noncompliance with the SPT specimen dimensional tolerances.

4.2.1 Equipment Selection Process

General requirements for an automated coring and sawing device were set forth in the First Article Equipment Specification for the Simple Performance Test Specimen Fabrication System developed by the research team based on experience with the fabrication of many SPT specimens for other research projects. The major requirements of this specification are given in Table 12.

Proposals were solicited from several manufacturers that expressed interest in building the equipment during a workshop held in Phase I of the project. Only two manufacturers responded to the RFP issued on January 2, 2002 for the system: Shedworks, Inc. and Pine Instrument Company. Shedworks proposed an innovative approach where the gyratory specimen is gripped by a chuck similar to that used in a lathe. Automated diamond-tipped cutoff blades saw the gyratory specimen to length, and an automated diamond-core barrel then cores the test specimen from the gyratory specimen. Pine's system included a portable laboratory core drill, a specially designed clamp to hold the gyratory specimen during the coring operation, and a milling machine to cut the cored test specimen to the appropriate length. Based on a comprehensive evaluation of the two proposals, the equipment proposed by Shedworks was selected for purchase in NCHRP Project 9-29. Although the Shedworks approach was considered to be more risky, it had the potential to automate and simplify the specimen fabrication operations and thereby accelerate the implementation of the SPT. The system proposed by Pine represented only a marginal improvement over available equipment, and did not address the primary objective of the Simple Performance Test Specimen Fabrication System, which was to automate and simplify the specimen fabrication operations.

4.2.2 Equipment Development

A purchase order for the equipment was issued to Shedworks, Inc. on March 9, 2002. A five month schedule was provided for final design, fabrication, and delivery of the equipment. After completing the design, Shedworks, Inc. elected to subcontract the fabrication of the automated chuck components to another company. The automated chuck was designed to tighten against the specimen when rotated. This aspect of the design was not only important for automating the specimen fabrication process, but it also

Table 12. First Article Specimen Requirements.

Requirement	Specification		
Assembled Size	No larger than 60 in. by 96 in. by 72 in. high.		
Maximum Component Size	No wider than 30 in.		
Electrical Power	Single phase 115 or 230 VAC		
Cutting Fluid	Air or Water		
Air Supply	125 psi max pressure, 10.6 cfm max volume		
Specimen Preparation Time	Less than 15 min.		
Specimen Dimensions	Item	Specification	Note
	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
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 straightedge across the diameter at three locations approximately 120 ° apart and measure the maximum departure of the specimen end from the straightedge 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.		

allowed the chuck to adjust for creep that occurs in asphalt concrete under sustained loads. With this design, the gyratory specimen will not loosen during the sawing and coring operations as a result of the self-tightening action. Unfortunately, the chuck components were complex, and the subcontractor was not able to satisfactorily fabricate the components. In an attempt to keep the project on schedule and within budget, Shedworks fabricated a manual chuck that held the gyratory specimen in place using screws that were manually tightened. This allowed Shedworks to assemble the device and shop test it in early November 2002. This version of the device was powered by a small single phase electric motor, used air to cool the cutting blades and the core barrel, and pneumatic actuators to automate the sawing and coring. The shop testing revealed several serious problems with this design as summarized in Table 13. Shedworks requested and was granted additional time to resolve the problems.

Over the next 15 months, Shedworks designed and fabricated modifications to address each of the problems identified during the November 2002 shop test. The following major modifications were made:

1. Cooling fluid: The cooling fluid was change from air to water.
2. Motor size: The motor was increased to a 3 hp 208/230 V three phase motor. The phase conversion is done internal to the machine so that only a single phase supply is needed.
3. Actuator fluid: The actuator fluid was changed from air to a hybrid air/hydraulic system to provide better control over the cutting and coring forces and speeds.

In some cases these modification resulted in changes to other components in the device. For example, the decision to change to water as the cooling fluid required that the chuck bearing seals be redesigned to be watertight and that corrosion resistant materials or finishes be used on all parts that would be exposed to water.

In July, 2004, Shedworks delivered the first version of the Shedworks FlexPrep™ system. This unit, shown in Figure 25, incorporated the improvements listed above, but still used the manual screw chuck. During testing by the research team, it was determined that this chuck was not acceptable. Gyratory specimens loosened in the chuck approximately 50 percent of the time, and when this occurred, a test specimen could not be obtained. Additionally, the core barrel tended to break through the specimen leaving a ragged edge at the top. The chuck failure rate was greatest for samples made with softer binders and harder aggregates. When the specimen did not loosen in the chuck, a specimen meeting the tolerances in Table 12 was obtained except at the top edge where the breakthrough was occurring. Because the FlexPrep™ system showed promise, Shedworks was granted additional time and funding to develop an improved chuck and a back-up plate to eliminate the breakthrough.

The breakthrough problem was resolved by adding a back-up plate. The back-up plate is held tight against the top of the specimen by a pneumatic actuator. Shedworks considered many alternatives for the chuck, ultimately deciding that the original concept was the only acceptable alternative. Several design changes were made to simplify the chuck mechanism, and in July, 2005 Shedworks produced a prototype version of the chuck that functioned as designed. The major issue that remained was to develop seals to keep water and grit from entering the bearings and operating mechanism of the chuck. This required a number of iterations. Finally a slinger-type seal was developed and the self-tightening chuck and seals were installed on the FlexPrep™ System. This final version of

Table 13. Operational problems identified during November, 2002 shop testing.

Problem	Possible Cause	Possible Solution
Saw Blade Flexure. The saw blades flexed after approximately ½ in deep cut. Cutting was stopped to avoid blade damage.	Actuator force or speed too high.	Add blade bearing strips to support the saw blade against flexure
Core barrel able to stall motor when cutting at appropriate coring force.	Motor size too small	1. Increase motor size. Will require 208/230 V single phase power. 2. Switch to a hydraulic motor.
Heat build-up when cutting at reduced coring force melted binder and caused specimen to slip in the chuck.	Inefficient cutting due to reduced coring force. Air cooling may not be adequate.	1. Increase motor size to allow higher coring force. 2. Use coarser diamond blades and core barrels to provide greater heat dissipation. 3. Use water for cooling.
Actuator control. Current pneumatic actuators functioned smoothly under no load conditions. There is concern that control under load when completing cuts may not be acceptable.	Compressibility of air.	Switch to hydraulic actuators.

Figure 25. Shedworks, Inc. FlexPrep™ System, serial number 001.

the device was delivered in September 2006 and subjected to the specification compliance testing as described below.

4.2.3. Specification Compliance Testing

Table 12 summarized the requirements contained in the first article equipment specification. The size, electrical power, air supply, and specimen preparation time were checked through measurements or information contained on component label plates. A small experimental plan was developed to check the dimension of specimens prepared with the device. This plan was based on 20 gyratory specimens that included the following variables:

- Aggregate type: limestone and granite.
- Nominal maximum aggregate size: 9.5 mm and 19.0 mm.
- Binder grade: PG 58-28 and PG 64-22.
- Air void content: 4 and 7 percent.
- Height: 165 and 175 mm.

The sections that follow present the findings of the specification compliance testing.

4.2.3.1 Physical and Operational Requirements

The FlexPrep™ is very compact measuring 37 in. wide by 30 in. deep by 44 in. high and weighing approximately 400 lb. The system operates on single phase 208/230 V AC power and according to the manufacturer's specifications requires only a modest air-flow of 3 cfm at 60 psi pressure. For the specification compliance testing, the equipment was operated with 208 V power with air pressure regulated at 75 psi. The machine is capable of completing the sawing and coring operations within the specified time of 15 min.

The first step in preparing a test specimen with the FlexPrep™ is to secure the gyratory specimen in the chuck of the machine. This is done by opening the top door and moving the specimen back-up plate to the open position as shown in Figure 26. The chuck is opened (See Figure 27) by turning the motor in the reverse direction using a socket wrench while the chuck is held stationary by an air actuated pin. The reverse force on the chuck opens the chuck mechanism, which has springs to ensure a minimum contact pressure when closed. Once the chuck is opened, the gyratory specimen is dropped into the chuck as shown in Figure 28. The core barrel is used to center the specimen vertically in the chuck as shown in Figure 29. When the gyratory specimen is centered, the chuck is closed by turning the motor in the forward direction with the socket wrench. The back-up plate is secured as shown in

Figure 26. Top view of FlexPrep™ chuck with upper door and specimen back-up plate open.

Figure 27. Opening chuck using a socket wrench.

Figure 30, then the top and front doors are closed, and the machine is ready to prepare the SPT test specimen.

The FlexPrep™ system automatically performs the sawing and coring operations. First, the cutoff blades are advanced to trim the specimen ends. Once the ends are trimmed, the cutoff blades retract, and the core barrel advances from the bottom to core the test specimen. The finished specimen is removed from the core barrel by removing a cap on the bottom of the core barrel as shown in Figure 31. The waste ring is removed by opening the chuck mechanism as described above. Figure 32 shows the finished specimen after removal from the core barrel.

Figure 28. Inserting gyratory specimen in the FlexPrep™ chuck.

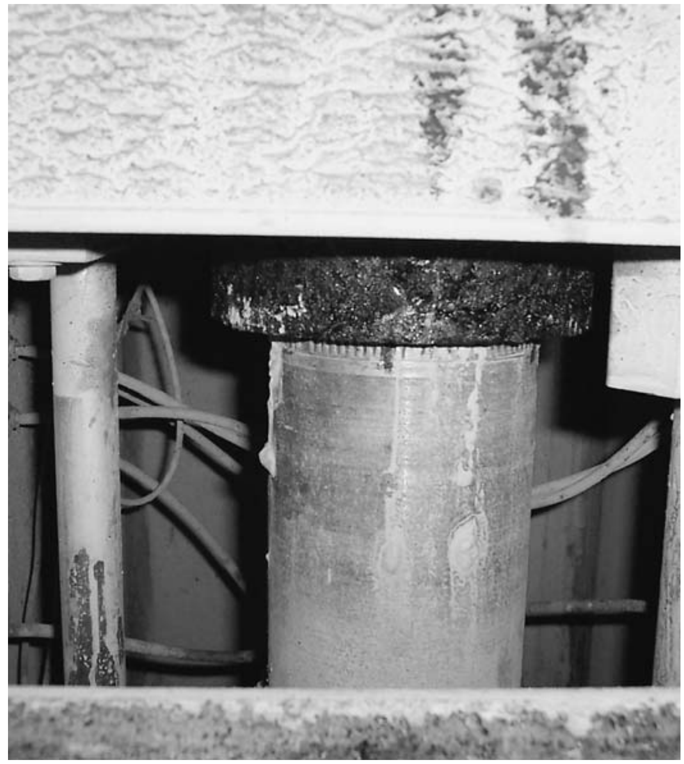


Figure 29. Centering the gyratory specimen vertically using the core barrel.

Figure 30. Securing the back-up plate.

Figure 31. Removing finished test specimen from the bottom of the core barrel.

Figure 32. Finished test specimen.

The operator can adjust the speed of the cutoff blades and the core barrel using controls on the machine. The feed rates should be adjusted to obtain smooth cuts, generally slower for harder aggregates. Additionally the feed rates must be such that the current draw for the motor remains below 10 amps, otherwise the motor circuit breaker will trip. An amp meter is provided to aid in setting the feed rates.

The FlexPrep™ circulates the cooling water. The system includes a pump and settling tank under the machine as shown in Figure 33 to capture then circulate the cooling water.

4.2.3.2 Specimen Dimensions

One of the objectives of the specification compliance testing was to investigate the effect of several specimen variables on the finished dimensions of specimens fabricated with the FlexPrep™ system. The planned experiment included different binder grades, different nominal maximum aggregate sizes and aggregate hardness, high and low air void content specimens, and gyratory specimens compacted to two heights. Twenty test specimens were fabricated, and the dimensions of the test specimens were measured and compared to the tolerances listed in Table 12. Table 14 summarizes the measurements. As shown, all of the specimens meet the SPT specification requirements for diameter, height, and end perpendicularity. The top of several specimens fail the flatness requirement. The failing specimens are highlighted in bold. All of these specimens had aggregate torn from the top end near the middle of the specimen as shown in Figure 34. As the cutoff blade moves through the specimen, it tends to lift the waste material from the specimen as it cuts. If the cutting speed it too fast or there is an air void near the middle of the specimen, the waste material breaks from the specimen. If it breaks below the plane of the cutting blade, a divot is

Figure 33. Water circulation system.

Table 14. Dimensions of specimens prepared using the FlexPrep™ system.

Specimen Characteristics						Diameter		Height	Flatness		Perpendicularity	
No.	Mix Size, mm	Aggregate Type	Binder Grade	Gyratory Height, mm	Air Voids, %	Average, mm	Standard Deviation, mm	Average, mm	Top, mm	Bottom, mm	Top, mm	Bottom, mm
1	9.5	Limestone	58	165	7	101.3	0.1	149.5	0.25	0.05	0.05	0.05
2	9.5	Limestone	58	165	7	100.7	0.2	148.3	0.30	0.05	0.10	0.05
3	19	Granite	58	175	7	100.8	0.1	149.5	0.30	0.10	0.05	0.30
4	9.5	Limestone	64	165	7	101.3	0.1	149.8	0.45	0.05	0.15	0.05
5	9.5	Limestone	64	165	7	101.1	0.1	149.9	0.45	0.05	0.15	0.05
6	9.5	Limestone	64	165	4	101.3	0.0	149.8	0.20	0.05	0.15	0.05
7	9.5	Limestone	64	165	4	101.1	0.1	149.7	0.25	0.10	0.10	0.05
8	9.5	Limestone	64	165	7	101.0	0.1	149.9	0.15	0.05	0.05	0.15
9	9.5	Limestone	58	165	7	101.0	0.1	148.0	0.10	0.05	0.05	0.30
10	19	Granite	64	165	7	101.4	0.1	149.3	0.30	0.25	0.10	0.10
11	19	Granite	64	165	7	101.3	0.1	150.0	0.30	0.30	0.15	0.10
12	19	Granite	64	175	4	101.1	0.1	150.3	**1.00**	0.15	0.15	0.15
13	19	Granite	64	165	4	101.0	0.1	150.5	**0.85**	0.05	0.50	0.10
14	9.5	Limestone	64	165	4	101.2	0.1	150.6	**0.90**	0.10	0.50	0.10
15	9.5	Limestone	58	165	4	101.0	0.0	149.8	**0.90**	0.05	0.40	0.30
16	9.5	Limestone	64	175	4	101.2	0.1	150.5	0.45	0.05	0.30	0.10
17	9.5	Limestone	64	175	7	101.3	0.1	150.5	**1.45**	0.45	0.40	0.10
18	19	Granite	64	175	7	101.2	0.1	150.6	**1.25**	0.15	0.30	0.05
19	19	Granite	58	165	7	100.8	0.1	149.9	**0.80**	0.15	0.25	0.20
20	19	Granite	58	165	4	101.1	0.0	150.7	**1.25**	0.20	0.30	0.20

created as shown in Figure 34. None of the variables included in the experiment affected the top end flatness failure rate.

Although both the top and bottom cutoff blades have the same shape, the failures only occurred on the top of the specimen. This is likely the result of the air void gradient produced by the Interlaken compactor used to fabricate the gyratory specimens for this study. The Interlaken compactor produces high air voids at the top of the specimens and low air voids at the bottom. It is likely that the higher air voids at the top are the reason the failures always occurred at that end during the specification compliance testing.

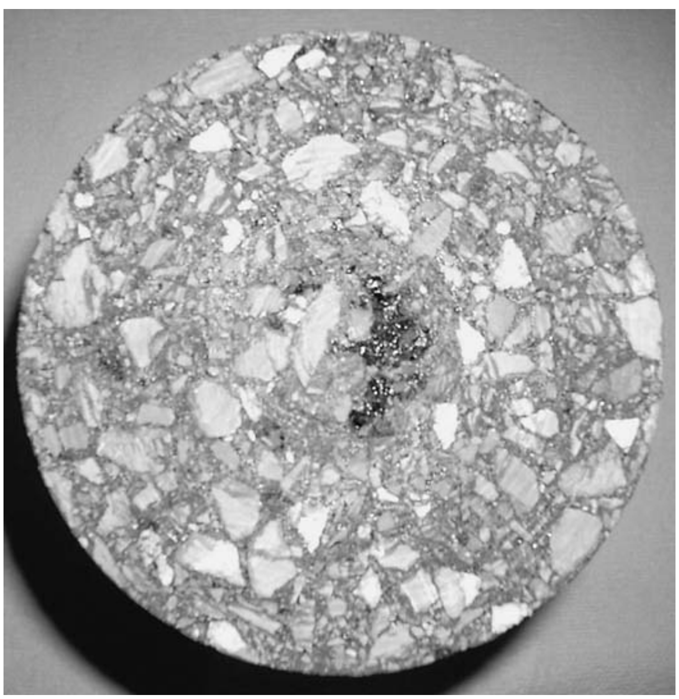


Figure 34. Divot in top of specimens created by the FlexPrep™ system.

The effect of not meeting the specimen end tolerance on the measured properties of the specimens was not evaluated in this study. The defects may not significantly affect the measured properties because the instrumentation is located far from the specimen end and aggregate interlock, and the resulting redistribution of stress and strain likely produces more uniform conditions at the center of the specimen. Additionally, it may be possible to fill the defects with plaster or some other material without significantly affecting the measured material properties.

4.2.4 Needed Improvements

The FlexPrep™ System was found to be in substantial compliance with the first article equipment specification and was accepted by the research team. The machine complies with the physical size and power requirements. It can produce specimens meeting the dimensional tolerances for specimens for the SPT. The cycle time for cutting and coring test specimens is less than the specified 15 minutes.

Although the FlexPrep™ System was accepted under NCHRP Project 9-29, the specification compliance testing identified several improvements that should be made in future production units. These are summarized below:

- Cutoff blade**.** Shedworks should perform additional development work to improve the cutoff blades and their control to minimize the potential for aggregate being torn from the specimen.
- Controls**.** The control system requires further improvement. In some cases, the limit switches that detect the completion of the cutting or the coring failed to trip. When this occurs, there is no manual override that allows the program to continue from its current point. The only alternative is to reset the machine and restart the cutting and coring operation from the beginning. Restarting from the beginning wastes time and increases the possibility that the test specimen will not meet the dimensional tolerances.
- Water circulation system**.** The settling tank is undersized and requires frequent cleaning. Additionally the cooling water heats-up after several specimens are cut in succession. The water heats sufficiently that specimens made with soft binders and high air void contents may creep beyond the range of the self-tightening chuck or break while being cored.
- Test specimen removal**.** It is difficult to remove the cap on the core barrel to remove the test specimen. A different type of core barrel cap is needed.
- Front doors**.** The machine has a wide front door that provides access for removing the test specimen and cleaning the system. This door is made from a polycarbonate material. It is relatively wide and split horizontally in the middle. A spring loaded pin-type latch is included in the top half of the door to close it. This door is difficult to use particularly when coring grit builds up on the door. Additionally, the door leaks at the bottom as shown in Figure 33.

CHAPTER 5

Conclusions and Recommendations

5.1 Dynamic Modulus Master Curves

A methodology was developed to construct dynamic modulus master curves for pavement structural design using an abbreviated testing protocol. In this approach, the limiting maximum modulus is estimated from mixture volumetric properties and a limiting binder modulus of 145,000 psi. When a reasonable estimate of the limiting maximum modulus is available, it is not necessary to perform dynamic modulus testing at the lowest temperature included in AASHTO TP62. Eliminating the low temperature testing offers three advantages. First, the cost of environment control capabilities is substantially less. Second, smaller, less expensive actuators can be used since the load required for dynamic modulus testing depends on the stiffness of the material that increases with decreasing temperature. Third, testing below 32°F is difficult and more variable due to potential icing of the instrumentation. Using the abbreviated dynamic modulus methodology and the SPT, it is possible for highway agencies to routinely collect dynamic modulus data for the MEPDG.

A recommended standard practice was developed to implement the abbreviated dynamic modulus protocol, and is included in Appendix A. This standard practice provides recommended testing temperatures and frequencies. It also describes how to fit the dynamic modulus master curve to the measured data and to compute input data for Level 1 analysis in the MEPDG.

5.2 Simple Performance Test Systems

The Simple Performance Test System Specification was modified to specify a device capable of performing the three simple performance tests and developing dynamic modulus master curves using the abbreviated testing protocol. The revised equipment specification is presented in Appendix B.

The first article SPTs purchased in Phase II of the project were upgraded to meet the revised specification. Two new devices meeting the revised specification were purchased in Phase IV of the project. SPTs meeting the revised specification currently are available from three sources: Interlaken Technology Corporation, IPC Global, and Medical Device Testing Services. The three devices are very similar. All are relatively small, bottom-loading, servo-hydraulic machines with automated testing chambers that serve as a confining pressure cell and temperature control chamber. The primary differences are in the hardware and software used for temperature control, the user friendliness of the equipment, and the operational details of the control software. Hopefully competition generated by these suppliers will lead to improvements to the equipment.

5.3 Simple Performance Test Specimen Fabrication

Test specimen preparation for the SPT is a multi-step process. First, tall gyratory specimens must be prepared to an air void content that is 1 to 2 percent higher than the desired air void content of the test specimen. Next, the 100 mm (4 in.) diameter test specimen must be cored from the larger gyratory specimen. Finally, the test specimen is cut to the appropriate length by sawing approximately 12.5 mm (1/2 in.) from each end of the specimen.

A recommended standard practice for SPT specimen fabrication was prepared. This standard practice is included in Appendix A. It addresses each step of the fabrication process in detail, and includes two important appendices that provide additional guidance for preparing SPT specimens. The first is a procedure for obtaining the target air void content for specimens from mixtures that the technician is not familiar with. The second appendix provides a method for evaluating the uniformity of air void contents within SPT test specimens.

In evaluating the specimen preparation process, it was determined that an automated system for coring and sawing the specimens would be beneficial to the future implementation of the SPT. Such a system would reduce the amount of skilled labor needed to prepare test specimens. It also would minimize the potential for errors in the coring and sawing operations that result in specimen rejection due to noncompliance with the SPT specimen dimensional tolerances. A prototype automated coring and sawing system, called FlexPrep™, was developed by Shedworks, Inc. in NCHRP 9-29. The equipment specification that the FlexPrep™ was designed to meet is included in Appendix C. The development of this equipment proved to be more difficult than the SPT systems, requiring approximately five years to complete. The machine is capable of preparing SPT specimens in less than 15 minutes with little technician intervention. While the FlexPrep™ is a promising prototype, additional development work must be completed before production models of the design can be made available.

References

1. Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus, H. *NCHRP Report 465: Simple Performance Test for Superpave Mix Design*. TRB, National Research Council, Washington, D.C., 2002.
2. ARA, Inc., ERES Consultants Division. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Final report prepared for the National Cooperative Highway Research Program, March, 2004.
3. Dougan, C., Stephens, J., Mahoney, J. and Hansen, G. *E**-Dynamic Modulus Test Protocol—Problems and Solutions. Report Number: CT-SPR-0003084-F03-3. Connecticut Department of Transportation and Federal Highway Administration, 2003.
4. Witczak, M.W., Bonaquist, R., Von Quintus, H., and Kaloush, K. Specimen Geometry and Aggregate Size Effects in Uniaxial Compression and Constant Height Shear Tests. *Journal of the Association of Asphalt Paving Technologists*, Vol. 69, 2000, pp. 733–782.
5. Witczak, M.W. NCHRP 9-19 Video Conference. Presentation to the National Cooperative Highway Research Program, November 7, 2003.
6. Christensen, D.W., and Anderson, D.A. Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements. *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992, pp. 67–116.
7. Christensen, D.W., Pellinen, T.K., and Bonaquist, R.F. Hirsch Model for Estimating the Modulus of Asphalt Concrete. *Journal of the Association of Asphalt Paving Technologists*, Vol. 72, 2003, 97–121.
8. Mirza, M. W. and Witczak, M.W. Development of a Global Aging System for Short and Long Term Aging of Asphalt Cements. *Journal of the Association of Asphalt Paving Technologists,* Vol. 64, 1995, 393–430.
9. Pellinen, T. K. *Investigation of the Use of Dynamic Modulus as An Indicator of Hot-Mix Asphalt Performance*. PhD dissertation, Arizona State University, May, 2001.
10. Bonaquist, R.F., Christensen, D.W., and Stump, W. NCHRP Report 513: Simple Performance Tester of Superpave Mix Design: First-Article Development and Evaluation. Transportation Research Board of the National Academies, Washington, D.C., 2003.

Glossary

Dynamic Modulus: The absolute value of the complex modulus of a viscoelastic material calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

Dynamic Modulus Master Curve: A composite curve constructed at a reference temperature by shifting dynamic modulus data from various temperatures along the log frequency axis.

First Article Devices: Prototype equipment produced primarily for evaluation.

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

Flow Time: The time corresponding to the minimum rate of change of axial strain during a creep test.

Extensometer: Self contained device that measures strain or deformation over a fixed gauge length.

Level 1 Analysis: The Mechanistic-Empirical Pavement Design Guide provides the option to choose between three levels for input data. Level 1 is the most extensive input data requiring measured material properties or traffic data.

Linearly Variable Differential Transformer: Electronic device consistent of a coil and a core that measures displacement. The signal from the device varies linearly with the position of the core in the coil.

Mechanistic-Empirical Pavement Design Guide: The mechanistic-empirical pavement design procedure developed in National Cooperative Highway Research Program Project 1-37A.

Reduced Frequency: The computed frequency at the reference temperature equivalent to the actual loading frequency at the test temperature.

Reference Temperature: The temperature at which the master curve is constructed.

Servo-hydraulic: A closed-loop hydraulic testing machine that responds to minimize the difference between the command signal and the feedback signal from a transducer attached to the test specimen.

Shift Factor: Shift in frequency associated with a shift from a test temperature to the reference temperature.

Simple Performance Tests: Mechanical tests for asphalt concrete mixtures that are related to pavement performance and can be used in the mixture design process to evaluate the performance of a mixture.

Simple Performance Test Specimen Fabrication System: An automated device for preparing test specimens for the Simple Performance Test System.

Simple Performance Test System: Commercial testing equipment developed in National Cooperative Highway Research Program Project 9-29 to perform the Simple Performance Tests.

Solver™: A function included in Microsoft Excel™ that performs nonlinear optimization. This function can be used to assemble dynamic modulus master curves.

Superpave Volumetric Mixture Design: Volumetric design procedure for dense-graded hot-mix asphalt that was developed during the Strategic Highway Research Program.

APPENDIX A

Proposed Standard Practices

Proposed Standard Practice for

Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System

NCHRP 9-29: PP 02

---

1. SCOPE

1.1 This practice describes testing and analysis for developing a dynamic modulus master curve for hot-mix asphalt concrete 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 PT 01, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) 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 Master Curve* – a composite curve constructed at a reference temperature by shifting dynamic modulus data from various temperatures along the log frequency axis.

3.2 *Reduced Frequency* – The computed frequency at the reference temperature equivalent to the actual loading frequency at the test temperature.

3.3 *Reference Temperature* – The temperature at which the master curve is constructed.

3.4 *Shift Factor*- Shift in frequency associated with a shift from a test temperature to the reference temperature.

4. SUMMARY OF PRACTICE

4.1 This practice describes the testing and analysis needed to develop a dynamic modulus master curve for hot-mix asphalt concrete mixtures. It involves collecting dynamic modulus test data at specified temperatures and loading rates, then manipulating the test data to obtain a continuous function describing the dynamic modulus as a function of frequency and temperature.

5. SIGNIFICANCE AND USE

5.1 Dynamic modulus master curves can be used for mixture evaluation and for characterizing the modulus of hot-mix asphalt concrete for mechanistic-empirical pavement design.

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 *Analysis Software* – Software capable of performing numerical optimization of non-linear equations.

Note 1 - The Solver Tool included in Microsoft Excel® is capable of performing the numerical optimization required by this practice.

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.

8. STANDARDIZATION

8.1 Items associated with this practice that require calibration are included in the documents referenced in Section 2. Refer to the pertinent section of the referenced documents for information concerning calibration.

9. DYNAMIC MODULUS TEST DATA

9.1 *Test Specimen Fabrication*

9.1.1 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 2 – A reasonable air void tolerance for test specimen fabrication is ± 0.5 %.

Note 3 – 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.

9.1.2 Record the following volumetric properties for each test specimen:

- Voids in the mineral aggregate (VMA)

- Voids filled with asphalt concrete (VFA)

9.2 *Testing Conditions*

9.2.1 Measure the dynamic modulus and phase angle of each specimen using the dynamic modulus test system at each of the temperatures and loading frequencies given in Table 2. Begin testing at the lowest temperature and highest frequency. Test all frequencies in descending order before moving to the next highest temperature.

Table 2. Recommended Testing Temperatures and Loading Frequencies.

PG 58-XX and softer		**PG 64-XX & PG 70-XX**		**PG 76 –XX and stiffer**	
Temperature °C	Loading Frequencies Hz	Temperature °C	Loading Frequencies Hz	Temperature °C	Loading Frequencies Hz
4	10, 1, 0.1	4	10, 1, 0.1	4	10, 1, 0.1
20	10, 1, 0.1	20	10, 1, 0.1	20	10, 1, 0.1
35	10, 1, 0.1, and 0.01	40	10, 1, 0.1, and 0.01	45	10, 1, 0.1, and 0.01

Note 4 – The dynamic modulus testing may be performed with or without confinement. The same confining stress conditions must be used at all temperatures and loading rates. An unconfined dynamic modulus master curve is typically used in mechanistic-empirical pavement analysis methods.

9.2.2 Accept only test data meeting the data quality statistics given in Table 3. Repeat tests as necessary to obtain test data meeting the data quality statistics requirements.

Table 3. Data Quality Statistics Requirements.

Data Quality Statistic	**Limit**
Load standard error	10 %
Deformation standard error	10 %
Deformation uniformity	30 %
Phase uniformity	3 degrees

Note 5 – The data quality statistics in Table 3 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.

9.3 *Dynamic Modulus Data Summary*

9.3.1 Prepare a summary table of the dynamic modulus data. At each temperature and frequency, compute:

1. Average dynamic modulus
2. Average phase angle
3. Dynamic modulus coefficient of variation
4. Standard deviation of phase angle

Figure 1 presents an example summary data sheet.

Conditions		Specimen 1		Specimen 2		Specimen 3		Average	Modulus	Average	Std Dev
Temperature	Frequency	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	CV	Phase	Phase
C	Hz	Ksi	Degree	Ksi	Degree	Ksi	Degree	Ksi	%	Deg	Deg
4	0.1	1170.9	18.8	1214.8	19.6	1443.2	18.5	1276.3	11.5	19.0	0.5
4	1	1660.8	12.0	1743.5	12.5	2027.0	11.6	1810.5	10.6	12.0	0.4
4	10	2107.3	8.1	2245.6	8.4	2596.1	8.2	2316.3	10.9	8.2	0.2
20	0.1	259.1	33.9	289.9	33.5	315.2	34.6	288.1	9.8	34.0	0.6
20	1	604.1	27.4	657.3	26.8	711.2	27.0	657.5	8.1	27.1	0.3
20	10	1065.1	21.0	1181.5	18.8	1231.4	19.8	1159.3	7.4	19.9	1.1
40	0.01	17.2	18.6	16.5	18.8	18.8	19.2	17.5	6.7	18.9	0.3
40	0.1	26.5	24.8	26.4	26.1	30.6	26.0	27.8	8.6	25.6	0.7
40	1	62.9	31.5	63.9	32.1	74.5	32.7	67.1	9.6	32.1	0.6
40	10	180.1	35.2	197.6	35.1	220.6	35.2	199.4	10.2	35.2	0.1

Figure 1. Example Dynamic Modulus Summary Sheet.

---

10. DATA ANALYSIS

10.1 *Dynamic Modulus Master Curve Equation*

10.1.1 General Form. The general form of the dynamic modulus master curve is a modified version of the dynamic modulus master curve equation included in the Mechanistic Empirical Design Guide (MEDG) (Applied Research Associates, Inc., 2004)

$$\log|E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma \log f_r}} \tag{1}$$

where:

$|E^*|$ = dynamic modulus, psi
f_r = reduced frequency, Hz
Max = limiting maximum modulus, psi
δ, β, and γ = fitting parameters

10.1.2 Reduced Frequency. The reduce frequency in Equation 1 is computed using the Arrhenius equation.

$$\log f_r = \log f + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{2}$$

where:

f_r = reduced frequency at the reference temperature, Hz
f = loading frequency at the test temperature, Hz

T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as a fitting parameter)

10.1.3 Final Form. The final form of the dynamic modulus master curve equation is obtained by substituting Equation 2 into Equation 1.

$$\log|E^*| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log\omega + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \tag{3}$$

10.2 *Shift Factors.* The shift factors at each temperature are given by Equation 4,

$$\log[a(T)] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{4}$$

where:

a(T) = shift factor at temperature T
T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as a fitting parameter)

10.3 *Limiting Maximum Modulus.* The maximum limiting modulus is estimated from mixture volumetric properties using the Hirsch model (Christensen, et. al, 2003) and a limiting binder modulus of 1 GPa (145,000 psi), Equations 5 and 6.

$$|E^*|_{max} = P_c\left[4{,}200{,}000\left(1 - \frac{VMA}{100}\right) + 435{,}000\left(\frac{VFA\ x VMA}{10{,}000}\right)\right] + \frac{1 - P_c}{\left[\frac{\left(1 - \frac{VMA}{100}\right)}{4{,}200{,}000} + \frac{VMA}{435{,}000(VFA)}\right]} \tag{5}$$

where

$$P_c = \frac{\left(20 + \frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650 + \left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \tag{6}$$

$|E^*|_{max}$ = limiting maximum mixture dynamic modulus, psi
VMA = Voids in mineral aggregates, %
VFA = Voids filled with asphalt, %

10.4 *Fitting the Dynamic Modulus Master Curve*

10.4.1 Step 1. Estimate Limiting Maximum Modulus

10.4.1.1 Using the average VMA and VFA of the specimens tested, compute the limiting maximum modulus using Equations 5 and 6.

10.4.1.2 Compute the logarithm of the limiting maximum modulus and designate this as *Max*

10.4.2 Step 2. Select a the Reference Temperature

10.4.2.1 Select the reference temperature for the dynamic modulus master curve and designate this as T_r. Usually 20 °C (293.15 °K) is used as the reference temperature.

10.4.3 Step 3. Perform Numerical Optimization

10.4.3.1 Substitute *Max* computed in Section 10.4.1.2 and T_r selected in Section 10.4.2.1 into Equation 3.

10.4.3.2 Determine the four fitting parameters of Equation 3 (δ, β, γ, and ΔE_a) using numerical optimization. The optimization can be performed using the Solver function in Mircosoft EXCEL®. This is done by setting up a spreadsheet to compute the sum of the squared errors between the logarithm of the average measured dynamic moduli at each temperature/frequency combination and the values predicted by Equation 3. The Solver function is used to minimize the sum of the squared errors by varying the fitting parameters in Equation 3. The following initial estimates are recommended: $\delta = 0.5$, $\beta = -1.0$, $\gamma = -0.5$, and $\Delta E_a = 200{,}000$.

10.4.4 Step 4. Compute Goodness of Fit Statistics

10.4.4.1 Compute the standard deviation of the logarithm of the average measured dynamic modulus values for each temperature/frequency combination. Designate this value as S_y.

10.4.4.2 Compute the standard error of estimate using Equation 7.

$$S_e = \left[\frac{1}{6} \sum_{1}^{10} \left(\log\left|\hat{E}^*\right|_i - \log\left|E^*\right|_i \right)^2 \right]^{0.5} \quad (7)$$

where:

S_e = standard error of estimate

$\log\left|\hat{E}^*\right|_i$ = value predicted by Equation 3 after optimization for each temperature/frequency combination

$\log\left|E^*\right|_i$ = logarithm of the average measured dynamic modulus for each temperature/frequency combination.

10.4.4.3 Compute the explained variance, R^2, using Equation 8.

$$R^2 = 1 - \frac{8S_e^2}{9S_y^2} \tag{8}$$

where:

R^2 = explained variance
S_e = standard error of estimate from Equation 7.
S_y = standard deviation of the logarithm of the average dynamic modulus values

10.5 *Evaluate Fitted Master Curve*

10.5.1 The ratio of S_e to S_y should be less than 0.05

10.5.2 The explained variance should exceed 0.99

10.6 *Determine AASHTO Mechanistic-Empirical Pavement Design Guide Inputs*

10.6.1 Substitute the logarithm of the limiting maximum modulus (*Max*) determined in Section 10.4.1.2 and the fitting parameters (δ, β, γ, and ΔE_a) determined in Section 10.4.3.2 into Equation 3 and compute the dynamic modulus at the following temperatures and loading frequencies. A total of 30 dynamic modulus values will be calculated.

Temperatures	Frequencies
-10, 4.4, 21.1, 37.8, and 54.4 °C (14, 40, 70, 100, 130, °C)	25, 10, 5, 1, 0.5, and 0.1 Hz

---

11. REPORT

11.1 Mixture identification

11.2 Measured dynamic modulus and phase angle data for each specimen at each temperature/frequency combination

11.3 Average measured dynamic modulus and phase angle at each temperature/frequency combination

11.4 Coefficient of variation of the measured dynamic modulus data at each temperature/frequency combination

11.5 Standard deviation of the measured phase angle data at each temperature/frequency combination.

11.6 VMA and VFA of each specimen tested

11.7 Average VMA and VFA for the specimens tested

11.8 Reference temperature

11.9 Parameters of the fitted master curve (Max, δ, β, γ, and ΔE_a)

11.10 Goodness of fit statistics for the fitted master curve (S_e, S_y, S_e/S_y, R^2)

11.11 Plot of the fitted dynamic modulus master curve as a function of reduced frequency showing average measured dynamic modulus data

11.12 Plot of shift factors as a function of temperature

11.13 Plot of average phase angle as a function of reduced frequency.

11.14 Tabulated temperature, frequency, and dynamic modulus for input into MEPDG

12. KEYWORDS

12.1 Dynamic modulus, phase angle, master curve

13. REFERENCES

13.1 Applied Research Associates, Inc., ERES Consultants Division *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, Final Report Prepared for the National Cooperative Highway Research Program, March, 2004.

13.2 Christensen, D.W., Pellinen, T.K., Bonaquist, R.F., "Hirsch Model for Estimating the Modulus of Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists*, Vol 72, 2003.

Proposed Standard Practice for

Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor

NCHRP 9-29: PP 01

---

1. SCOPE

1.1 This practice covers the use of a Superpave gyratory compactor to prepare 100 mm diameter by 150 mm tall cylindrical test specimens for use in a variety of axial compression and tension performance tests. This practice in intended for dense-, gap-, and open-graded hot mix asphalt concrete 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*

- T 312, Preparation and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor.
- R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
- T 166, Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens.
- T 209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures.
- T 269, Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures.

2.1.1 *ASTM Standards*

- D 3549, Thickness or Height of Compacted Bituminous Paving Mixture Specimens.

3. TERMINOLOGY

3.1 *Gyratory Specimen* – Nominal 150 mm diameter by 170 mm high cylindrical specimen prepared in a Gyratory compactor meeting the requirements of AASHTO T 312.

3.2 *Test Specimen* – Nominal 100 mm diameter by 150 mm high cylindrical specimen that is sawed and cored from the gyratory specimen.

3.3 *End Perpendicularity* - The degree to which an end surface departs from being perpendicular to the axis of the cylindrical test specimen. This is measured using a combination square with the blade touching the cylinder parallel to its axis, and the head touching the highest point on the end of the cylinder. The distance between the head of the square and the lowest point on the end of the cylinder is measured with feeler gauges.

3.4 *End Planeness* – Maximum departure of the specimen end from a plane. This is measured using a straight edge and feeler gauges.

4. SUMMARY OF PRACTICE

4.1 This practice presents methods for preparing 100 mm diameter by 150 mm tall cylindrical test specimens for use in a variety of axial compression and tension performance tests.

5. SIGNIFICANCE AND USE

5.1 This practice should be used to prepare specimens for the following standard tests:

- AASHTO TP 62, Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures
- NCHRP 9-29 PP 03, Determining the Dynamic Modulus and Flow Number for Hot-Mix Asphalt (HMA) Using the Simple Performance Test System

5.2 This practice may also be used to prepare specimens for other non-standard tests requiring 100 mm diameter by 150 mm tall cylindrical test specimens.

6. APPARATUS

6.1 *Superpave Gyratory Compactor* - A compactor meeting the requirements of AASHTO T 312 and capable of preparing finished 150 mm diameter specimens that a minimum of 170 mm tall.

Note 1 - Research completed to date has not determined if it is critical that the compactor maintain the internal angle specified in AASHTO T 312 when compacting 170 mm tall specimens. Until additional work is completed compactors meeting either the external or internal angle requirements of AASHTO T 312 may be used.

6.2 *Mixture Preparation Equipment* – Balances, ovens, thermometers, mixer, pans, and other miscellaneous equipment needed to prepare gyratory specimens in accordance with AASHTO T 312 and make specific gravity measurements in accordance with AASHTO T 166, T 209, and T 269.

6.3 *Core Drill* – An air or water cooled diamond bit core drill capable of cutting nominal 100 mm diameter cores meeting the dimensional requirements of Section 9.5.3. The core drill shall be equipped with a fixture for holding 150 mm diameter gyratory specimens.

Note 2 – Core drills with fixed and adjustable rotational speed have been successfully used to prepare specimens meeting the dimensional tolerances given in Section 9.5.3. Rotational speeds from 450 – 750 RPM have been used.

Note 3 – Core drills with automatic and manual feed rate control have been successfully used to prepare specimens meeting the dimensional tolerances given in Section 9.5.3.

6.4 *Masonry Saw* – An air or water cooled diamond bladed masonry saw capable of cutting specimens to a nominal length of 150 mm and meeting the tolerances for end perpendicularity and end flatness given in Section 9.5.3.

Note 4 – Single and double bladed saws have been successfully used to prepare specimens meeting the dimensional tolerances given in Section 9.5.3. Both types of saws require a fixture to securely hold the specimen during sawing, and control of the feed rate.

Note 5 – In National Cooperative Highway Research Project 9-29, a machine that performs both the sawing and coring operation within the tolerances specified in Section 9.5.3 was developed. Contact: Shedworks, Inc., 2151 Harvey Mitchell Parkway, S., Suite 320, College Station, TX 77840-5244, Phone (979) 695-8416, Fax 695-9629, email wwc@shedworks.com.

6.5 *Square* – Combination square with a 300 mm blade and 100 mm head.

6.6 *Feeler Gauges* – Tapered leaf feeler gauges in 0.05 mm increments.

6.7 *Metal Ruler*– Metal ruler capable of measuring nominal 150 mm long specimens to the nearest 1 mm.

6.8 *Calipers* – Calipers capable of measuring nominal 100 mm diameter specimens to the nearest 0.1 mm.

7. HAZARDS

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

8. STANDARDIZATION

8.1 Items associated with this practice that require calibration are included in the AASHTO Standards referenced in Section 2. Refer to the pertinent section of the referenced standards for information concerning calibration.

9. PROCEDURE

9.1 *HMA Mixture Preparation*

9.1.1 Prepare HMA mixture for each test specimen and a companion maximum specific gravity test in accordance with Section 8 of AASHTO T 312.

9.1.2 The mass of mixture needed for each specimen will depend on the gyratory specimen height, the specific gravity of the aggregate, the nominal maximum aggregate size and gradation (coarse or fine), and the target air void content for the test specimens. Appendix A describes a trial and error procedure developed in NCHRP Project 9-19 for determining the mass of mixture required to reach a specified test specimen target air void content for gyratory specimens prepared to a height of 170 mm.

Note 6 – Test specimens with acceptable properties have been prepared from gyratory specimens ranging in height from 165 to 175 mm. The height of the gyratory specimen that should be used depends on the air void gradient produced by the specific compactor, and the capabilities of the sawing equipment.

9.1.3 Perform mixture conditioning for the test specimens and companion maximum specific gravity test in accordance with Section 7.2 of AASHTO R-30, *Short-Term Conditioning for Mixture Mechanical Property Testing.*

9.2 *Gyratory Specimen Compaction*

9.2.1 Compact the gyratory specimens in accordance with Section 9 of AASHTO T 312.

9.2.2 Compact the gyratory specimens to the target gyratory specimen height.

Note 7 – Each laboratory should determine a target gyratory specimen height based on the procedure for evaluating test specimen uniformity given in Appendix B, and an evaluation of the ability of the sawing equipment to maintain the dimensional tolerances given in Section 9.5.3.

9.3 *Long-Term Conditioning (Optional)*

9.3.1 If it is desired to simulate long-term aging, condition the gyratory specimen in accordance with Sections 7.3.4 through 7.3.6 of AASHTO R-30.

9.3.2 To obtain accurate volumetric measurements on the long-term conditioned specimens, also condition a companion sample of short-term conditioned loose mix meeting the sample size requirements of AASHTO T 209 in accordance with Sections 7.3.4 through 7.3.6 of AASHTO R-30.

9.4 *Gyratory Specimen Density and Air Voids (Optional)*

9.4.1 Determine the maximum specific gravity of the mixture in accordance with AASHTO T 209 (If long-term conditioning has been used, determine the maximum specific gravity on the long-term conditioned loose mix sample). Record the maximum specific gravity of the mixture.

9.4.2 For dense- and gap-graded mixtures, determine the bulk specific gravity of the gyratory specimen in accordance with AASHTO T 166. Record the bulk specific gravity of the gyratory specimen.

9.4.3 For open-graded mixtures, determine the bulk specific gravity of the gyratory specimen in accordance with Section 6.2 of AASHTO T 269.

9.4.4 Compute the air void content of the gyratory specimen in accordance with AASHTO T 269. Record the air void content of the gyratory specimen.

Note 8 – Section 9.4 is optional because acceptance of the test specimen for mechanical property testing is based on the air void content of the test specimen, not the gyratory specimen. However, monitoring gyratory specimen density can identify improperly prepared specimens early in the specimen fabrication process. Information on gyratory specimen air voids and test specimens air voids will also assist the laboratory in establishing potentially more precise methods than Appendix A for preparing test specimens to a target air void content.

9.5 *Test Specimen Preparation*

9.5.1 Drill a nominal 100 mm diameter core from the center of the gyratory specimen. Both the gyratory specimen and the drill shall be adequately supported to ensure that the resulting core is cylindrical with sides that are smooth, parallel, and meet the tolerances on specimen diameter given in Section 9.5.3.

9.5.2 Saw the ends of the core to obtain a nominal 150 mm tall test specimen. Both the core and the saw shall be adequately supported to ensure that the resulting test specimen meets the tolerances given in Section 9.5.3 for height, end flatness and end perpendicularity.

Note 9 – With most equipment, it is better to perform the coring before the sawing. However, these operations may be done in either order as long as the dimensional tolerances in Section 9.5.3 are met.

9.5.3 Test specimens shall meet the dimensional tolerances given in Table 1.

Table 1. Test Specimen Dimensional Tolerances.

Item	Specification	Method
Average Diameter	100 mm to 104 mm	9.5.3.1
Standard Deviation of Diameter	0.5 mm	9.5.3.1
Height	147.5 mm to 152.5 mm	9.5.3.2
End Flatness	0.5 mm	9.5.3.3
End Perpendicularity	1.0 mm	9.5.3.4

9.5.3.1 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. The standard deviation shall be less than 0.5 mm. Reject specimens not meeting the average and standard deviation requirements listed in Table 1. The average diameter, reported to the nearest 0.1 mm, shall be used in all material property calculations.

9.5.3.2 Measure the height of the test specimen in accordance with Section 6.1.2 of ASTM D 3549. Reject specimens with an average height outside the height tolerance listed in Table 1. Record the average height.

9.5.3.3 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. Reject specimens with end flatness exceeding 0.5 mm.

9.5.3.4 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. Reject specimens with end perpendicularity exceeding 1.0 mm.

9.6 *Test Specimen Density and Air Voids*

9.6.1 Determine the maximum specific gravity of the mixture in accordance with AASHTO T 209 (If long-term conditioning has been used, determine the maximum specific gravity on the long-term conditioned loose mix sample). Record the maximum specific gravity of the mixture.

9.6.2 For dense- and gap-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with AASHTO T 166. Record the bulk specific gravity of the test specimen.

Note 10 – When wet coring and sawing methods are used, measure the immersed mass followed by the surface dry mass followed by the dry mass to minimize drying time and expedite the specimen fabrication process.

9.6.3 For open-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with Section 6.2 of AASHTO T 269. Record the bulk specific gravity of the test specimen.

9.6.4 Compute the air void content of the test specimen in accordance with AASHTO T 269. Record the air void content of the test specimen. Reject test specimens exceeding the air void tolerances specified in the appropriate Standard Method of Test.

9.7 *Test Specimen Storage*

9.7.1 Mark the test specimen with a unique identification number.

9.7.2 Store the test specimen on end on a flat shelf in a room with temperature controlled between 15 and 27 °C until tested.

Note 11 – Definitive research concerning the effects of test specimen aging on various mechanical property tests has not been completed. Some users wrap specimens in Saran wrap and minimize specimen storage time to two weeks.

10. REPORTING

10.1 Unique test specimen identification number.

10.2 Mixture design number for link to pertinent mixture design data including design compaction level and air void content, asphalt binder type and grade, binder content, binder specific gravity, aggregate types and bulk specific gravitities, consensus aggregate properties, and maximum specific gravity.

10.3 Type of aging used.

10.4 Maximum specific gravity for the aged condition.

10.5 Gyratory specimen target height (Optional).

10.6 Gyratory specimen bulk specific gravity (Optional).

10.7 Gyratory specimen air void content (Optional).

10.8 Test specimen average height.

10.9 Test specimen average diameter.

10.10 Test specimen bulk specific gravity.

10.11 Test specimen air void content.

10.12 Test specimen end flatness for each end.

10.13 Test specimen end parallelism for each end.

10.14 Remarks concerning deviations from this standard practice.

11. KEYWORDS

Performance test specimens; gyratory compaction

APPENDIX A METHOD FOR ACHIEVING TARGET AIR VOID CONTENT (NONMANDATORY INFORMATION)

A1. PURPOSE

A1.1 This Appendix presents a procedure for estimating the mass of mixture required to produce test specimens at a target air void content. It was developed to reduce the number of trial specimens needed obtain a target air void content for a specific mixture.

A1.2 This procedure can be used with either plant produced or laboratory prepared mixture.

A2. SUMMARY

A2.1 Trial test specimens are prepared as described in this standard practice from gyratory specimens produced with a standard mass of 6,650 g and compacted to a standard height of 170 mm.

A2.2 Based on the air void content of the trial specimens, the mass of mixture required to produce test specimens at a target air void content is estimated using a regression equation. Background information regarding the regression equation is presented in Section A4.

A2.3 To use this method, it is critical that all gyratory specimens are prepared to a standard height of 170 mm. The approach described in Section A4 can be used to develop a similar equation for other gyratory specimen heights.

A3. PROCEDURE

A3.1 Prepare trial test specimen 1 and trial test specimen 2 following this standard practice from gyratory specimens produced with a standard mass of 6,650 g and compacted to a standard height of 170 mm.

A3.2 Determine the air void content of trial test specimen 1 and trial test specimen 2.

A3.3 Calculate the average air void content of the two specimens and designate this as Va_s.

A3.4 Estimate the mass of mixture, W_t, required to produce test specimens with a target air void content of Va_t using Equation A1.

$$W_t = 7175 - (525)\frac{Va_t}{Va_s} \quad \text{(A1)}$$

where:

W_t = estimated mass of mixture required to produce a gyratory specimen for a test specimen with a target air void content of Va_t, g

Va_t = target air void content for the test specimen, vol %

Va_s = test specimen air void content produced with a gyratory mass of 6,650 g, vol %

A3.5 Prepare trial test specimen 3 following this standard practice from a gyratory specimen produced with the target mass estimated in Section A3.4 and compacted to the standard height of 170 mm.

A3.6 Determine the air void content of trial test specimen 3.

A3.7 If the air void content of trial test specimen 3 is within ± 0.5 percent of the target, use the mass determined in A3.4 as the target mass for test specimen production.

A3.8 If the air void content of trial test specimen 3 is not within ± 0.5 percent of the target, prepare trial specimen 4 using 50g less than calculated in A3.4 and trial test specimen 5 using 50g more than calculated in A3.4.

A3.9 Determine the air void content of trial test specimen 4 and trial test specimen 5.

A3.10 Plot the air void content of trial test specimens 3, 4, and 5 (y) against the mass of mixture used to prepare the gyratory specimen (x), and draw the best-fit line through the three data points.

A3.11 From the best-fit line, determine the mass of mixture needed to produce a test specimen with the target air void content.

A3.12 Use the mass determined in A3.11 as the target mass for test specimen production.

A4. BACKGROUND

A4.1 The method described in this Appendix was developed by the Arizona State University during NCHRP Project 9-19. It is based on analysis of 38 different mixtures, where test specimens were prepared to varying target air void contents representative of in-situ conditions.

A4.2 For a given mixture, when gyratory specimens are prepared to a specific height, the relationship between the mixture mass used to prepare the gyratory specimen and the air void content of the test specimens was found to be linear.

$$Va = I + S(W) \quad \text{(A2)}$$

where:

Va = test specimen air void content, vol %
W = mass of mixture used to produce the gyratory specimen
I = intercept of the regression line
S = slope of the regression line

A4.3 When a wide range of mixtures is considered, the intercepts and slopes for individual mixtures were also found to be linearly related.

$$I = -C(S) \quad \text{(A3)}$$

where:

I = intercept of individual mixture regression lines
S = slope of individual mixture regression lines
C = constant

A4.4 In the NCHRP Project 9-19 research, the constant, C, was found to be 7,175 for gyratory specimens prepared to a standard height of 170 mm. Substituting this constant into Equation A3, then substituting Equation A3 into Equation A2 and simplifying, yields an equation relating the air void content of the test specimen to the mass of mixture used to prepare the gyratory specimen to the standard height of 170 mm.

$$Va = S(W - 7175) \quad \text{(A4)}$$

A4.5 If gyratory specimens are compacted using a standard mass, W_s, and the air void contents for the resulting test specimens are determined to be Va_s, then Equation A4 can be solved for the slope.

$$S = \frac{Va_s}{W_s - 7175} \quad \text{(A5)}$$

where:

Va_s = test specimen air void content produced with a gyratory mass of W_s, vol %
W_s = mass of mixture used to produce the gyratory specimen, g
S = slope of the regression line

A4.6 Using the slope from Equation A5, the target gyratory specimen mass, W_t, required to produce a test specimen with a specific air void content, Va_t, can be estimated by substituting Equation A5 into Equation A4 and simplifying.

$$W_t = 7175 + \frac{Va_t}{Va_s}\left(W_s - 7175\right) \quad \text{(A6)}$$

where:

W_t = estimated mass of mixture required to produce a gyratory specimen for a test specimen with a target air void content of Va_t, g

Va_t = target air void content for the test specimen.

Va_s = test specimen air void content produced with a gyratory mass of W_s, vol %

W_s = mass of mixture used to produce the gyratory specimen

A4.7 For a standard mixture mass of 6,650 g, which was the average mass used in the NCHRP 9-19 study, Equation A6 reduces to.

$$W_t = 7175 - (525)\frac{Va_t}{Va_s} \quad \text{(A6)}$$

where:

W_t = estimated mass of mixture required to produce a gyratory specimen for a test specimen with a target air void content of Va_t, g

Va_t = target air void content for the test specimen.

Va_s = test specimen air void content produced with a gyratory mass of W_s, vol %

W_s = mass of mixture used to produce the gyratory specimen

APPENDIX B TEST SPECIMEN UNIFORMITY (NONMANDATORY INFORMATION)

B1. PURPOSE

B1.1 This Appendix presents a procedure for assessing the uniformity of the air void content in test specimens produced using this standard practice.

B1.2 The approach tests the significance of the difference in mean bulk specific gravity between the top and bottom third of the specimen relative the middle third.

B1.3 The procedure can be used to determine the height for preparing gyratory specimens with a specific compactor to minimize within sample variations in air voids.

B2. SUMMARY

B2.1 Three test specimens are prepared as described in this standard practice from gyratory specimens produced with the same mixture mass and compacted to the same height.

B2.2 The test specimens are cut into three slices of equal thickness and the bulk specific gravity or each slice is determined.

B2.3 A statistical hypothesis test is conducted to determine the significance of differences in the mean bulk specific gravity of the top and bottom slices relative to the middle.

B3. PROCEDURE

B3.1 Prepare three test specimens following this standard practice to a target air void content of 5.5 percent. All three specimens shall have air void contents within the range of 5.0 to 6.0 percent.

B3.2 Label the top, middle, and bottom third of each specimen, then saw the specimens at the third points.

B3.3 Determine the bulk specific gravity of each of the nine test section slices in accordance with AASHTO T 166 for dense- and gap-graded mixtures or AASHTO T 269 for open-graded mixtures.

B3.4 Assemble a summary table of the bulk specific gravity data where each column contains data for a specific slice, and each row contains the data from a specific core.

B3.5 For each column, compute the mean and variance of the bulk specific gravity measurements using Equations B1 and B2.

$$\bar{y} = \frac{\sum_{i=1}^{3} y_i}{3} \tag{B1}$$

$$s^2 = \frac{\sum_{i=1}^{3} (y_i - \bar{y})^2}{2} \tag{B2}$$

where:

$\bar{y}$ = slice mean
s^2 = slice variance
y_i = measured bulk specific gravities

B3.6 *Statistical Comparison of Means*- Compare the mean bulk specific gravity of the top and bottom slices to the middle slice using the hypothesis tests described below. In the descriptions below, subscripts "*t*", "*m*", and "*b*" refer to the top, middle, and bottom slices, respectively.

B3.6.1 Check the top relative to the middle.

Null Hypothesis:
The mean bulk specific gravity of the top slice equals the mean bulk specific gravity of the middle slice, $\mu_t^2 = \mu_m^2$

Alternative Hypothesis:
The mean bulk specific gravity of the top slice is not equal the mean bulk specific gravity of the middle slice, $\mu_t^2 \neq \mu_m^2$

Test Statistic:

$$t = \frac{(\bar{y}_t - \bar{y}_m)}{0.8165(s)} \tag{B3}$$

where:

$$s = \sqrt{\frac{s_t^2 + s_m^2}{2}} \tag{B4}$$

$\bar{y}_t$ = computed mean for the top slices

$\bar{y}_m$ = computed mean for the middle slices
s_t^2 = computed variance for the top slices
s_m^2 = computed variance for the middle slices

Region of Rejection:
For the sample sizes specified, the absolute value of the test statistic must be less than 2.78 to conclude that bulk specific gravity of the top and middle slices are equal.

B3.6.2 Check the bottom relative to the middle.

Null Hypothesis:
The mean bulk specific gravity of the bottom slice equals the mean bulk specific gravity of the middle slice, $\mu_b^2 = \mu_m^2$

Alternative Hypothesis:
The mean bulk specific gravity of the bottom slice is not equal the mean bulk specific gravity of the middle slice, $\mu_b^2 \neq \mu_m^2$

Test Statistic:

$$t = \frac{(\bar{y}_b - \bar{y}_m)}{0.8165(s)} \tag{B5}$$

where:

$$s = \sqrt{\frac{s_b^2 + s_m^2}{2}} \tag{B4}$$

$\bar{y}_b$ = computed mean for the bottom slices
$\bar{y}_m$ = computed mean for the middle slices
s_b^2 = computed variance for the bottom slices
s_m^2 = computed variance for the middle slices

Region of Rejection:
For the sample sizes specified, the absolute value of the test statistic must be less than 2.78 to conclude that bulk specific gravity of the bottom and middle slices are equal.

B4. ANALYSIS

B4.1 Significant differences in the bulk specific gravity of the top and bottom slices relative to the middle indicate a systematic variation in density within the specimen.

B4.2 Specimens with differences for the top and/or bottom slices relative to the middle slices on the order of 0.025 have performed satisfactorily in the dynamic modulus, flow number, flow time, and continuum damage fatigue tests.

B4.3 Changing the height of the gyratory specimen can improve the uniformity of the density in the test specimen.

APPENDIX B

Revised Simple Performance Test System Specification

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Table of Contents

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

1.0 Summary

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

Test Method For Static Creep/Flow Time of Asphalt Concrete Mixtures in Compression

Test Method for Repeated Load Testing of Asphalt Concrete Mixtures in Uniaxial Compression

Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Permanent Deformation

Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Fatigue Cracking

Test Methods for each of these tests using the equipment described in this specification are presented in Annexes A, B, and C of this equipment specification. The testing system can also be used in conjunction with AASHTO TP62 to develop a dynamic modulus master curve for pavement structural design using the reduced testing protocol described in Annex D.

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.

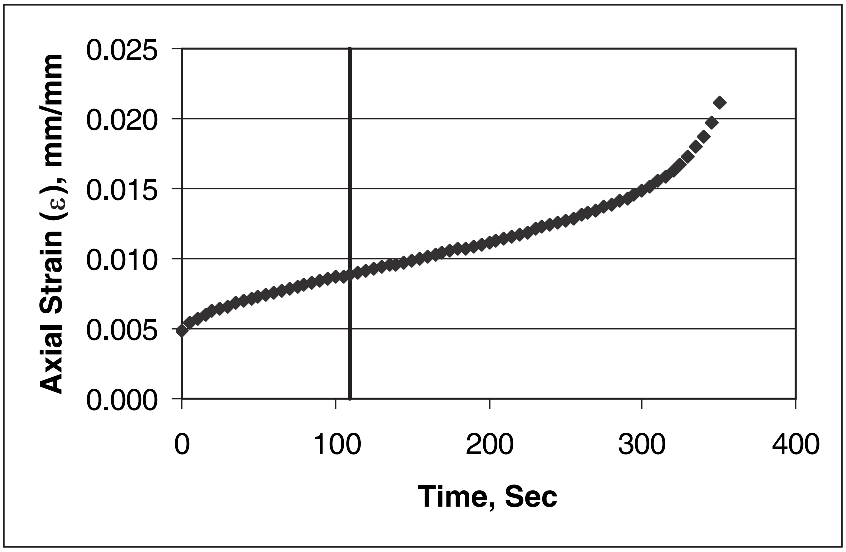
1.2 The testing system shall be capable of performing three compressive tests on nominal 100 mm (4 in) diameter, 150 mm (6 in) high cylindrical specimens. The tests are briefly described below.

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.

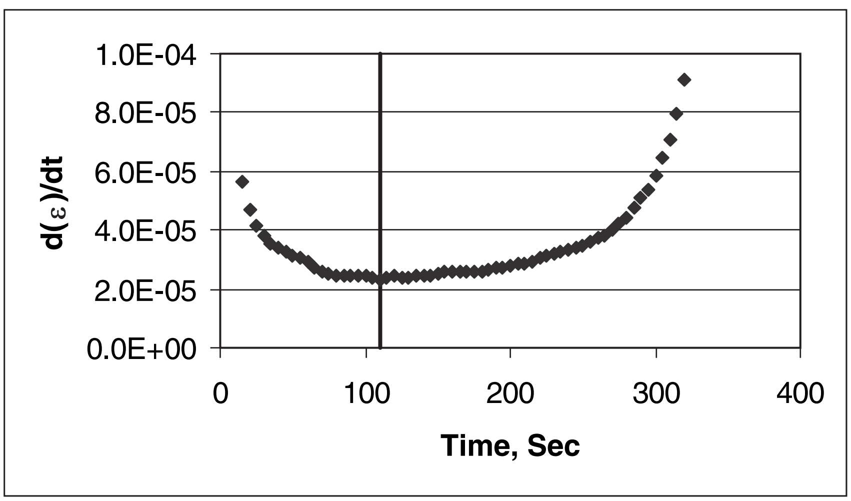
1.4 **Flow Number Test.** In this test, the specimen, at a specific test temperature, is subjected to a repeated haversine axial compressive load pulse of 0.1 sec every 1.0 sec. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

number of load cycles corresponding to the minimum rate of change of permanent axial strain. This is shown schematically in Figure 2.



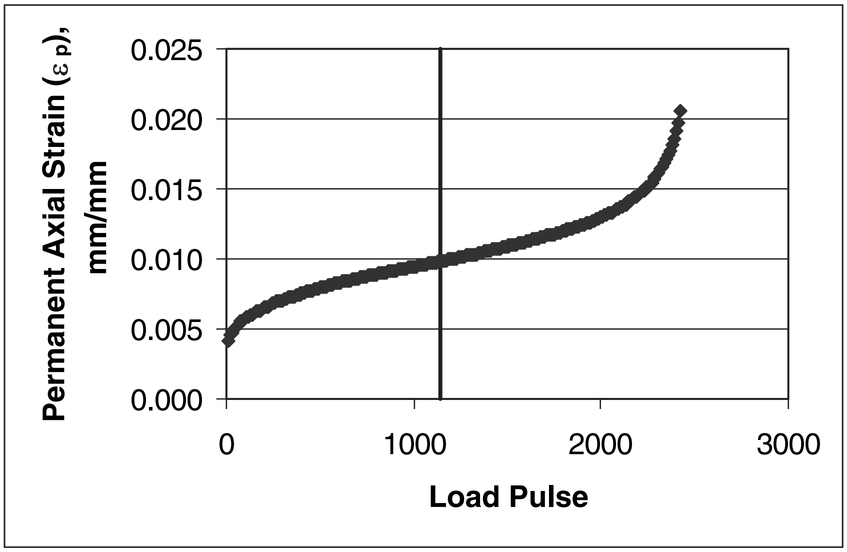
a. Axial Strain in Flow Time Test.



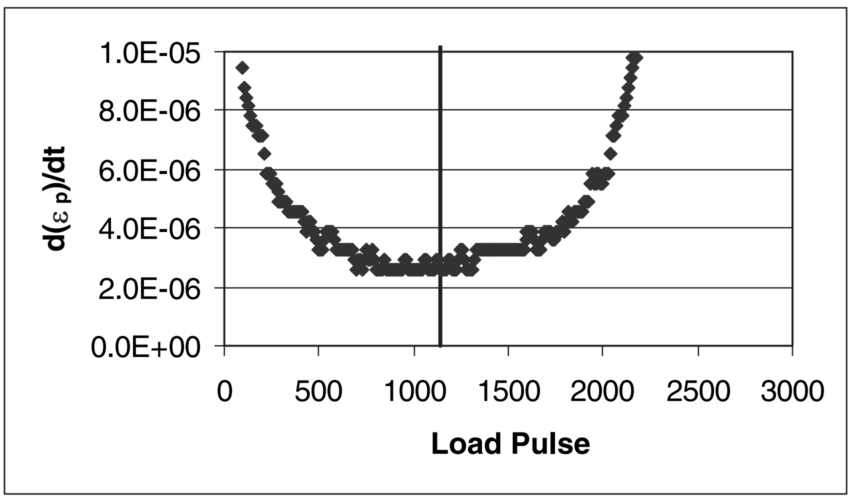
b. Rate of Change of Axial Strain.

Figure 1. Schematic of Flow Time Test Data.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004



a. Permanent Axial Strain in Flow Number Test.



b. Rate of Change of Permanent Axial Strain.

Figure 2. Schematic of Flow Number Test Data.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

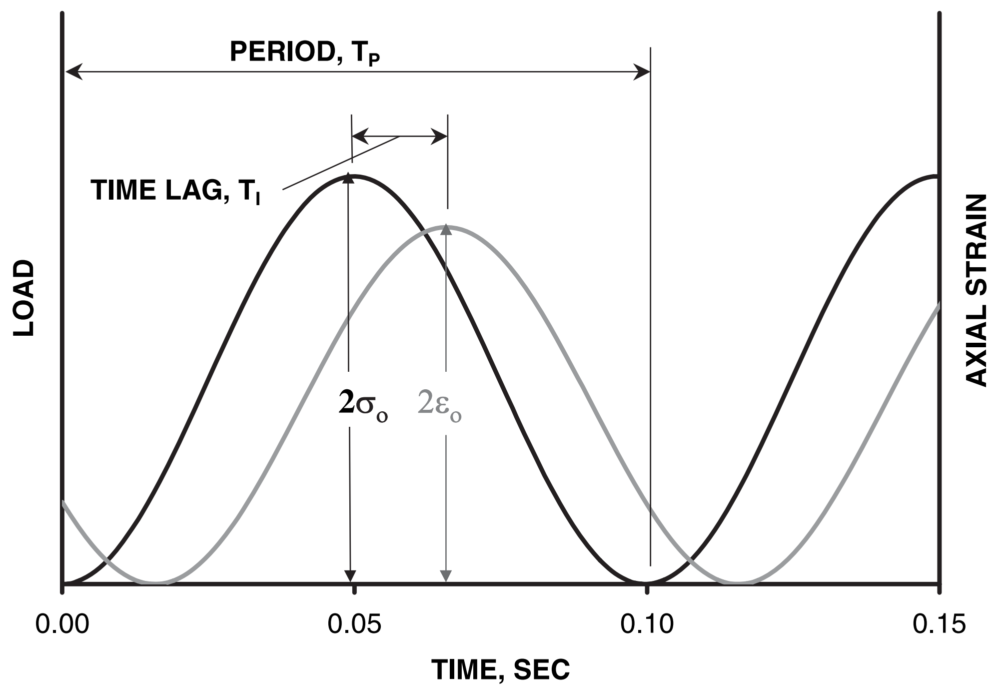


Figure 3. Schematic of Dynamic Modulus Test Data.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

	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

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.

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

4.0 Simple Performance Test System

4.1 The Simple Performance Test System shall be a complete, fully integrated testing system meeting the requirements of these specifications and having the capability to perform the Flow Time, Flow Number, and Dynamic Modulus tests described in Annexes A, B, and C and AASHTO TP62.

4.2 Annex E 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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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 V AC 60 Hz electrical power.

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

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

Where:

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

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

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

6.0 Loading Platens

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

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

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) $\pm$ 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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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
Mass of mounting system and transducer	80 g max
Transducer spring force	1 N max

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

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

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

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

9.7 Alternatives to the standard system described in this section will be considered provided the components meet the range, accuracy, and resolution requirements. Submit data showing the alternative system produces the same modulus and phase angles as the standard system on asphalt concrete specimens tested over the stiffness range of 150 to 10,000 MPa (20,000 to 2,200,000 psi). Annex F describes the minimum testing and analysis required for a non-standard system.

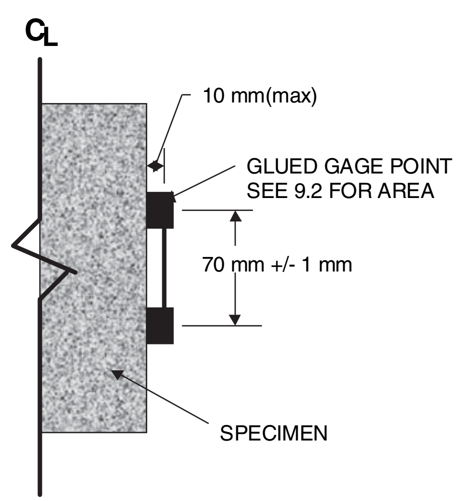


Figure 4. Schematic of Standard Specimen Mounted Deformation Measuring System.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

10.0 Confining Pressure System

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

10.2 The confining pressure cell shall be designed to allow the operator to view the specimen, the specimen mounted deformation measuring system, and the specimen end platens during testing.

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

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

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

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

10.7 A suitable temperature sensor shall be mounted at the mid-height of the specimen in the pressure cell between the specimen and the cell wall. This temperature sensor shall have a range of 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 tests this sensor shall be used to control the temperature in the chamber, and provide a continuous reading of temperature that will be sampled by the data acquisition system during the test.

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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 3 minutes over the complete range of temperatures.

11.5 A suitable temperature sensor shall be mounted in the environmental chamber within 25 mm (1 in) of the specimen at the mid-height of the specimen. This temperature sensor shall have a range of 0 to 60 °C (32 to 140 °F), and be readable and accurate to the nearest 0.25 °C (0.5 °F). This sensor shall be used to control the temperature in the chamber, and provide a continuous reading of temperature that will be sampled by the data acquisition system during the test.

12.0 Computer Control and Data Acquisition

12.1 The Simple Performance Test System shall be controlled from a Personal Computer operating software specifically designed to conduct the Flow Time, Flow Number, and Dynamic Modulus Tests described in Annexes A, B, C, and AASHTO TP62; 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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

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

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

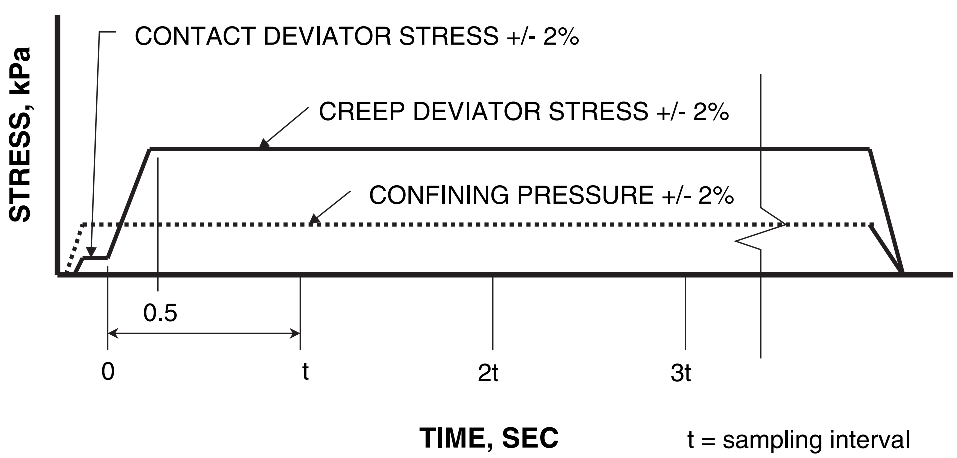


Figure 5. Schematic of Loading and Data Acquisition.

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

1. Project Name
2. Operating Technician
3. Specimen Identification

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

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

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

Response	Tolerance
Deviator stress	+/- 2 percent of target
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 ^{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. Axial strain at the flow time.

5. Average temperature during the test.
6. Average confining stress during the test.
7. Time and corresponding measured deviator stress, measured confining pressure, measured temperature, measured axial strain, and computed rate of change of strain.
8. Warnings
9. Post test remarks.

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

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

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

12.4 Flow Number Test Control and Data Acquisition

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

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

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

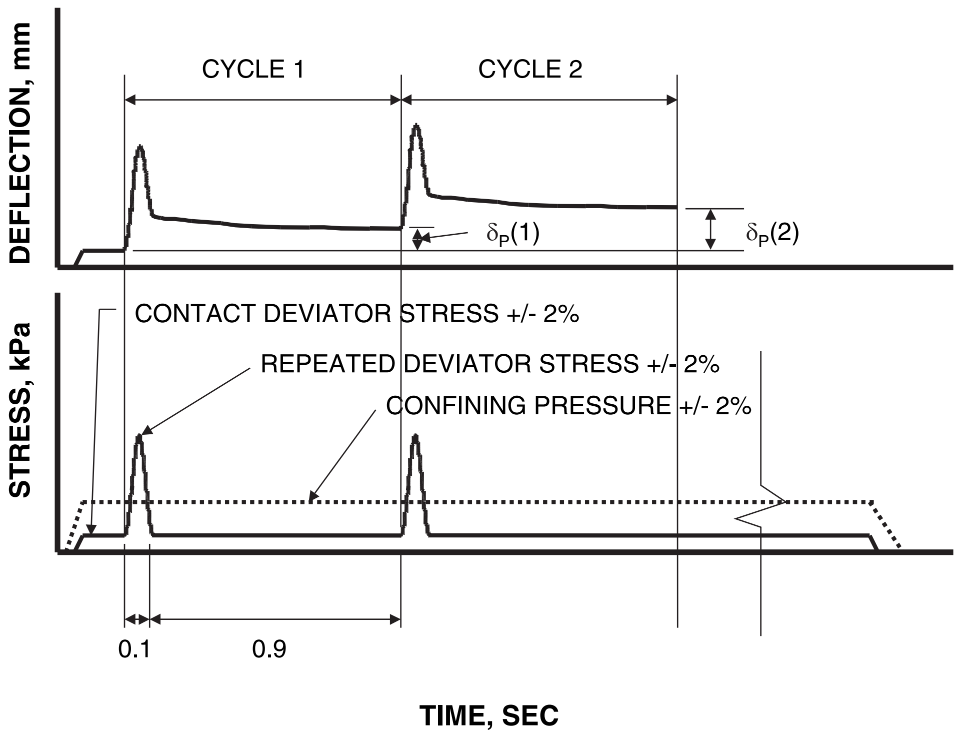


Figure 6. Schematic of Loading and Data Acquisition for Flow Time Test.

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

1. Project Name
2. Operating Technician
3. Specimen Identification
4. File Name
5. Specimen Diameter
6. Specimen Height
7. Target Test Temperature
8. Target Confining Stress

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

9. Target Contact Deviator Stress
10. Target Repeated Deviator Stress
11. Specimen Conditioning Time
12. Sampling Interval
13. Maximum Number of Load Cycles
14. Remarks

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

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

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

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

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

4. Axial strain at the flow number.
5. Average temperature during the test.
6. Average confining stress during the test.
7. Average peak deviator stress.
8. Average contact stress.
9. Maximum standard error of the applied load.
10. Cycle and corresponding measured peak deviator stress, computed load standard error, measured contact stress, measured confining pressure, measured temperature, measured permanent axial strain, and computed rate of change of permanent strain.
11. Warnings
12. Post test remarks.

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

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

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

12.5 Dynamic Modulus Test Control and Data Acquisition

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

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

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

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

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

Response	Tolerance
Confining pressure	+/- 2 percent of target
Temperature	+/- 0.5 ^{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 the 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)

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

- 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.

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

DYNAMIC MODULUS STANDARD REPORT

		Data generated on :	4-Apr-01	**~~Dynamic Modulus, ksi:~~**	**~~45.7~~**
		Data exported on :	4-Apr-01	**~~Phase Angle, Deg.:~~**	**~~30.1~~**
Sample ID:	FHWA D0				
Project:	WO 621	**~~System Configuration :~~**		**~~Data Quality Indicators:~~**	
Test Frequency (Hz):	0.50	**Number Of Movers**	2	**RMS Cmd. Error, %:**	7.9
Specimen Gauge Length (in.):	4.00	**Number Of Channels**	11	**Load Std. Error, %:**	7.2
Specimen Dia. (in.):	4.00			**Disp. Avg. Std. Error, %:**	7.8
Specimen Cross-Sec. Area (in.^2):	12.57	**Points Acquired :**	500	**Disp. Uniformity, %:**	3.4
Test Temperature C:	40.0	**Scan Time :**	20	**Phase Uniformity, Deg.:**	4.5
		Time Between Scans :	40	**Avg. Total Drift, %:**	-4.2

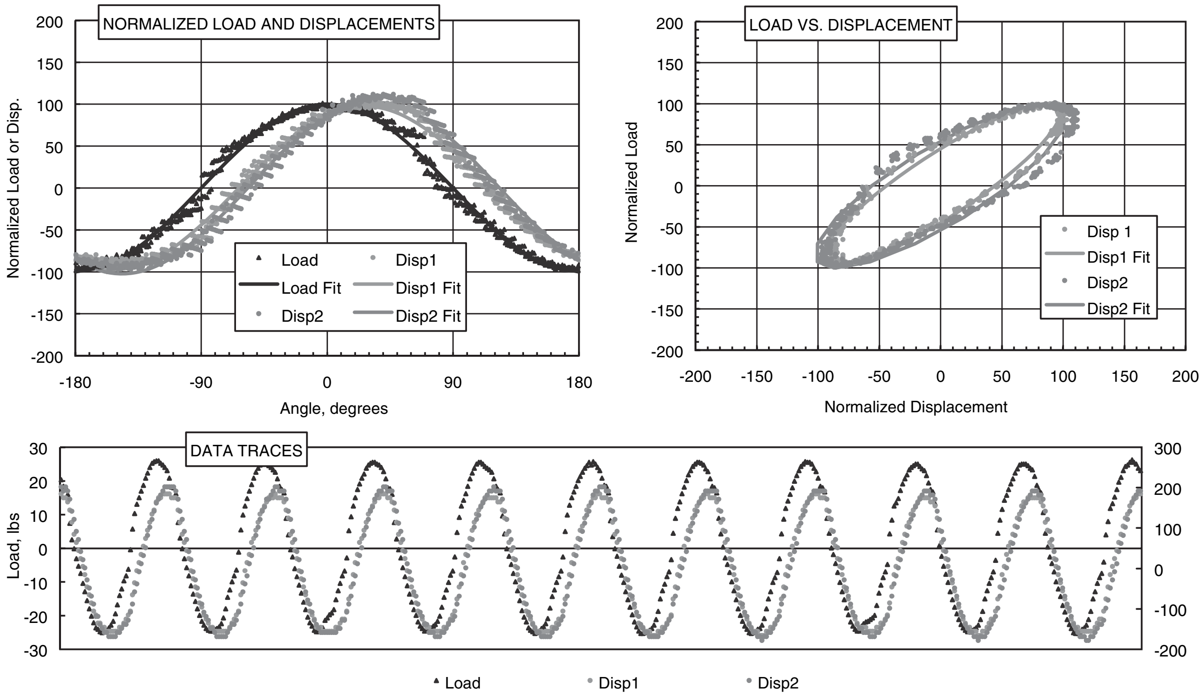


Figure 7. Example Dynamic Modulus Output.

13.0 Computations

13.1 Flow Time Test

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

formula. The rate of change of the strain with respect to time is estimated using the following equation:

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

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

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

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

Where:

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

13.2 Flow Number Test

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

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

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

Where:

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

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

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

Where:

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

13.3 Dynamic Modulus Test

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

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

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

Where:

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

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

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

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

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

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

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

$$\left|Y_j *\right| = \sqrt{A_{j2}^2 + B_{j2}^2} \tag{14}$$

$$\Delta Y_j = \frac{A_{j1}t_N}{\left|Y_j *\right|} \times 100\% \tag{15}$$

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

Where:

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

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

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

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

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

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

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

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

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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

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

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

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

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

Where:

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

14.0 Calibration and Verification of Dynamic Performance

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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 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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Annex A
Simple Performance Test System Flow Time Test

Adapted From
Test Method for Static Creep/Flow Time of Asphalt Concrete Mixtures in Compression

NCHRP Report 465, 2002

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

1 Scope

1.1 This test method covers testing and measurement of the resistance to tertiary flow of cylindrical asphalt concrete specimens in a triaxial state of compressive loading using the Simple Performance Test System.

1.2 In this test, a cylindrical sample of bituminous paving mixture is subjected to a static axial load. Axial strains are recorded throughout the test.

1.3 The test is conducted at a single temperature using specific deviatoric and confining stresses.

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

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

2 Referenced Documents

2.1 AASHTO Standards

PPXX Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System (To be developed).

PPYY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor (To be developed).

2.2 Other

NCHRP 9-29 Equipment Specification for the Simple Performance Test System

3 Definitions

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

4 Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a static axial load. The test can be performed with or without confinement. The applied stress and the resulting axial deformation of the specimen is measured with the Simple Performance

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Test System and used to calculate the flow time. The flow time is the time corresponding to the minimum rate of change of axial strain during a creep test.

5 Significance and Use

5.1 The flow time can be used with the criteria in AASHTO PPXX to judge the acceptability of a mixture to resist permanent deformation.

5.2 The flow time can also be used to compare or rank the permanent deformation resistance of various bituminous paving mixtures.

6 Apparatus

6.1 An approved Simple Performance Test System meeting the requirements of NCHRP 9-29 Equipment Specification for the Simple Performance Test System

6.2 An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 30 to 60 °C (85 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate three test specimens and a dummy specimen with temperature sensor mounted at the center for temperature verification.

6.3 Teflon sheeting, 0.25 mm thick to reduce friction between the specimen and the loading platens.

7 Test Specimens

7.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP YY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor.

7.2 Flow time shall be the average result obtained from three test specimens.

8 Procedure

8.1 Unconfined Tests

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

8.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

8.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

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

8.1.6 Steps 8.1.4 and 8.1.5 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.1.7 Enter the required identification and control information into the Flow Time Software.

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

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

8.1.10 Repeat steps 8.1.4 through 8.1.9 for the remaining test specimens.

8.2 Confined Tests

8.2.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

8.2.2 Encase the dummy specimen in a membrane.

8.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

8.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

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

8.2.7 Steps 8.2.5 and 8.2.6 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.2.8 Enter the required identification and control information into the Flow Time Software.

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

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

8.2.11 Repeat steps 8.2.5 through 8.2.10 for the remaining test specimens.

9 Calculations

9.1 The calculation of the flow time for individual specimens is performed automatically by the Simple Performance Test System software.

9.2 Compute the average and standard deviation of the flow times for the three specimens tested.

10 Report

10.1 Test temperature.

10.2 Deviatoric and confining stress levels.

10.3 Average and standard deviation of flow time for three specimens.

10.4 Attach Simple Performance Test System standard reports for individual specimens.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Annex B
Simple Performance Test System Flow Number Test

Adapted From
Test Method for Repeated Load Testing of Asphalt Concrete Mixtures in Uniaxial Compression

NCHRP Report 465, 2002

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

1. Scope

1.1 This test method covers testing and measurement of the resistance to tertiary flow of cylindrical asphalt concrete specimens in a triaxial state of compressive loading using the Simple Performance Test System.

1.2 This test uses a loading cycle of 1.0 second in duration, consisting of applying 0.1-second haversine load followed by 0.9-second rest period. Permanent axial deformations are recorded throughout the test.

1.3 The test is conducted at a single using specific deviatoric and confining stresses.

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

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

2. Referenced Documents

2.1 AASHTO Standards

PPXX Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System (To be developed).

PPYY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor (To be developed).

2.2 Other

NCHRP 9-29 Equipment Specification for the Simple Performance Test System

3. Definitions

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

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

4. Summary of Method

4.1 A cylindrical sample of bituminous paving mixture is subjected to a haversine axial load. The load is applied for duration of 0.1-second with a rest period of 0.9-second. The rest period has a load equivalent to the seating load. The test can be performed either with or without confinement. Cumulative permanent axial deformations are measured with the Simple Performance Test System and used to calculate the flow number. The flow number is the number of repetitions corresponding to the minimum rate of change of permanent deformation under repeated loading conditions.

5. Significance and Use

5.1 The flow number can be used with the criteria in AASHTO PPXX to judge the acceptability of a mixture to resist permanent deformation.

5.2 The flow number can also be used to compare or rank the permanent deformation resistance of various bituminous paving mixtures.

6. Apparatus

6.1 An approved Simple Performance Test System meeting the requirements of NCHRP 9-29 Equipment Specification for the Simple Performance Test System

6.2 An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 30 to 60 °C (85 to 140 °F) to an accuracy of ± 0.5 °C (1 °F). The chamber shall be large enough to accommodate three test specimens and a dummy specimen with temperature sensor mounted at the center for temperature verification.

6.3 Teflon sheeting, 0.25 mm thick to reduce friction between the specimen and the loading platens.

7. Test Specimens

7.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP YY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor.

7.2 The flow number shall be the average result obtained from three test specimens.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

8. Procedure

8.1 Unconfined Tests

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

8.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

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

8.1.6 Steps 8.1.4 and 8.1.5 including return of the test chamber to the target temperature shall be completed in 3 minutes.

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

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

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

8.1.10 Repeat steps 8.1.4 through 8.1.9 for the remaining test specimens.

8.2 Confined Tests

8.2.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

8.2.2 Encase the dummy specimen in a membrane.

8.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

8.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

8.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

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

8.2.7 Steps 8.2.5 and 8.2.6 including return of the test chamber to the target temperature shall be completed in 3 minutes.

8.2.8 Enter the required identification and control information into the Flow Time Software.

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

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

8.2.11 Repeat steps 8.2.5 through 8.2.10 for the remaining test specimens.

9. Calculations

9.1 The calculation of the flow number for individual specimens is performed automatically by the Simple Performance Test System software.

9.2 Compute the average and standard deviation of the flow numbers for the three specimens tested.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

10. Report

10.1 Test temperature.

10.2 Deviatoric and confining stress levels.

10.3 Average and standard deviation of flow number for three specimens.

10.4 Attach Simple Performance Test System standard reports for individual specimens.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Annex C
Simple Performance Test System Dynamic Modulus Test

Adapted From
Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Permanent Deformation

and

Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Fatigue Cracking

NCHRP Report 465, 2002

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

1. Scope

1.1 This test method covers testing of asphalt concrete mixtures to determine the dynamic modulus and phase angle.

1.2 In the test dynamic modulus and phase angle data are collected at a specified test temperature using various frequencies of loading.

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

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

2. Referenced Documents

2.1 AASHTO Standards

PPXX Standard Practice for Permanent Deformation and Fatigue Evaluation of HMA Using the Simple Performance Test System (To be developed).

PPYY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor (To be developed).

2.2 Other

NCHRP 9-29 Equipment Specification for the Simple Performance Test System

3. Definitions

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

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

4. Summary of Method

4.1 A sinusoidal (haversine) axial compressive stress is applied to a cylindrical specimen of asphalt concrete at a given temperature using a sweep of frequencies. The applied

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

stress and the resulting axial strain response of the specimen at each frequency is measured and used to calculate the dynamic modulus and phase angle for each frequency. The test can be performed either with or without confinement.

5. Significance and Use

5.1 The dynamic modulus can be used with the criteria in AASHTO PPXX to judge the acceptability of a mixture to resist permanent deformation and fatigue cracking.

5.2 The dynamic modulus can also be used to compare or rank the permanent deformation and fatigue resistance of various bituminous paving mixes.

6. Apparatus

6.1 An approved Simple Performance Test System meeting the requirements of NCHRP 9-29 Equipment Specification for the Simple Performance Test System

6.2 An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 20 to 60 °C (68 to 140 °F) to an accuracy of ±0.5 °C (1 °F). The chamber shall be large enough to accommodate three test specimens and a dummy specimen with temperature sensor mounted at the center for temperature verification.

6.3 Teflon sheeting, 0.25 mm thick to reduce friction between the specimen and the loading platens.

7. Test Specimens

7.1 Testing shall be performed on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens fabricated in accordance with AASHTO PP YY Standard Practice for Fabrication of Performance Test Specimens Using the Superpave Gyratory Compactor.

7.2 The dynamic modulus shall be the average result obtained from three test specimens.

8. Test Specimen Instrumentation (Standard Glued Gage Point System)

8.1 If the Simple Performance Test System uses the standard glued gage point system, attach the gage points to the specimen in accordance with the manufacturers instructions.

8.2 Confirm that the gage length is 70 mm ±1 mm measured center to center of the gage points.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

9. Procedure

9.1 Unconfined Tests

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

9.1.2 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

9.1.3 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

9.1.4 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

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

9.1.6 Steps 9.1.4 and 9.1.5 including return of the test chamber to the target temperature shall be completed in 3 minutes.

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

9.1.8 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete and display test data and data quality indicators.

9.1.9 Review the data quality indicators as discussed in Section 10 of this test method. Retest specimens with data quality indicators above the values specified in Section 10.

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

9.1.11 Repeat steps 9.1.4 through 9.1.10 for the remaining test specimens.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

9.2 Confined Tests

9.2.1 Assemble each specimen to be tested with platens and membrane as follows. Place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower o-ring seal. Place the top friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper o-ring seal.

9.2.2 Encase the dummy specimen in a membrane.

9.2.3 Place the specimen and platen assembly in the environmental chamber with the dummy specimen, and monitor the temperature of the dummy specimen to determine when testing can begin.

9.2.4 Turn on the Simple Performance Test System, set the temperature control to the desired testing temperature and allow the testing chamber to equilibrate at the testing temperature for at least one hour.

9.2.5 When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber, remove a test specimen and platen assembly, and quickly place it in the testing chamber.

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

9.2.7 Steps 9.2.5 and 9.2.6 including return of the test chamber to the target temperature shall be completed in 3 minutes.

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

9.2.9 Follow the software prompts to begin the test. The Simple Performance Test System will automatically unload when the test is complete and display test data and data quality indicators.

9.2.10 Review the data quality indicators as discussed in Section 10 of this test method. Retest specimens with data quality indicators above the values specified in Section 10.

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

9.2.12 Repeat steps 9.2.5 through 9.2.11 for the remaining test specimens.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

10. Data Quality Indicators and Calculations

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

10.2 Review the data quality indicators for each test frequency and compare them to the recommended maximum values listed below.

Data Quality Indicator	**Allowable Maximum Value**
Load Standard Error	10 percent
Deformation Standard Error	10 percent
Load Drift	3 percent
Deformation Drift	400 percent
Deformation Uniformity	20 percent
Phase Uniformity	3 degrees

10.3 Review the detailed modulus test report for those frequencies where the data quality indicators exceed the maximum allowable values. Repeat testing of specimens with data quality indicators exceeding the values listed in 10.2.

10.4 Compute the average and standard deviation of the modulus and flow numbers for the three specimens tested.

11. Report

11.1 Test temperature.

11.2 Confining stress level.

11.3 Average and standard deviation of dynamic modulus and phase angle for three specimens.

11.4 Attach Simple Performance Test System standard dynamic modulus summary report.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Annex D
Procedure for Developing a Dynamic Modulus Master Curve for Pavement Structural Design Using The Simple Performance Test System.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

INTRODUCTION

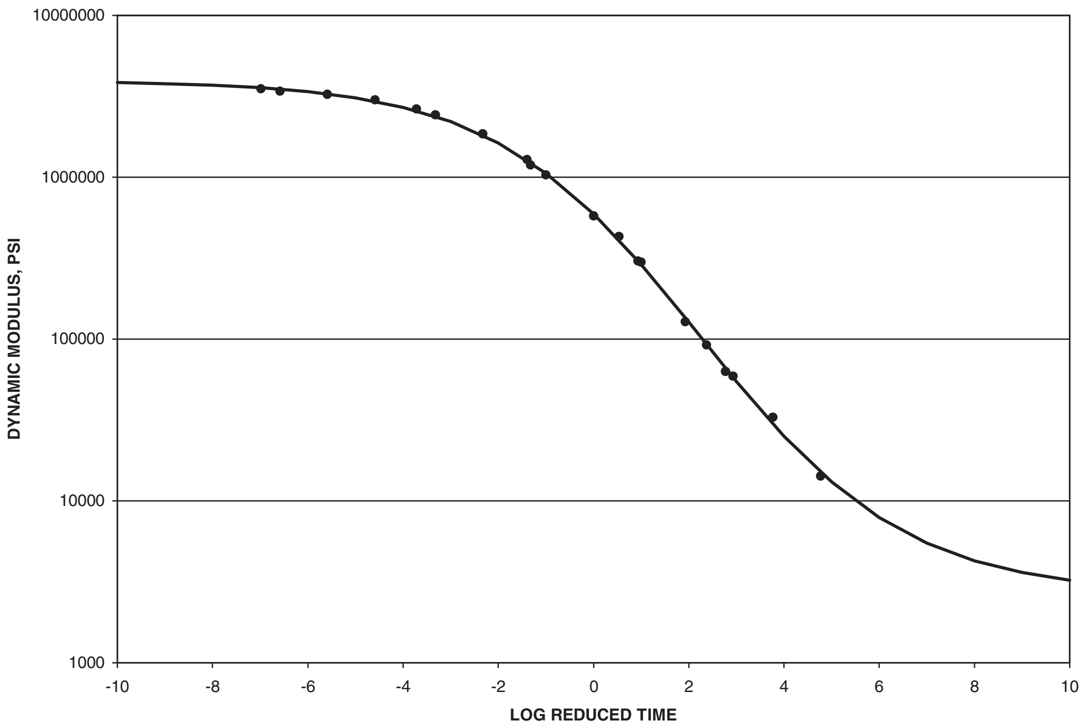
This Annex describes an approach for using the Simple Performance Test system to develop a dynamic modulus master curve for an asphalt concrete mixture. The resulting master curve can be used to compare materials over a wide range of temperatures and loading rates or to generate Level 1 input data required for the 2002 Design Guide.

The approach described here is very similar to that contained in AASHTO Provisional Standard TP62-03, *"Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures,"* except a reduced number of temperatures, an expanded range of frequencies, and an estimate of the limiting maximum modulus are used. The recommended test sequence in AASHTO TP62-03 consists of testing a minimum of 2 replicate specimens at temperatures of –10, 4.4, 21.1, 37.8, and 54.4 °C (14, 40, 70, 100, and 130 °F) at loading frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. This testing provides a database of 60 dynamic modulus measurements from which the parameters of the master curve are determined by numerical optimization. In the approach described here, the Hirsch model *(1)* is used to estimate the limiting maximum modulus of the mixture based on volumetric properties and a limiting binder shear modulus of 1 GPa (145,000 psi). This limiting maximum modulus is then combined with test data from a minimum of 2 replicate specimens tested at temperatures of 4.4, 21.1, and 46.1 °C (40, 70, and 115 °F) at loading frequencies of 10, 1.0, 0.1, and 0.01 Hz. This testing provides a database of 24 measurements from which the parameters of the master curve are determined by numerical optimization.

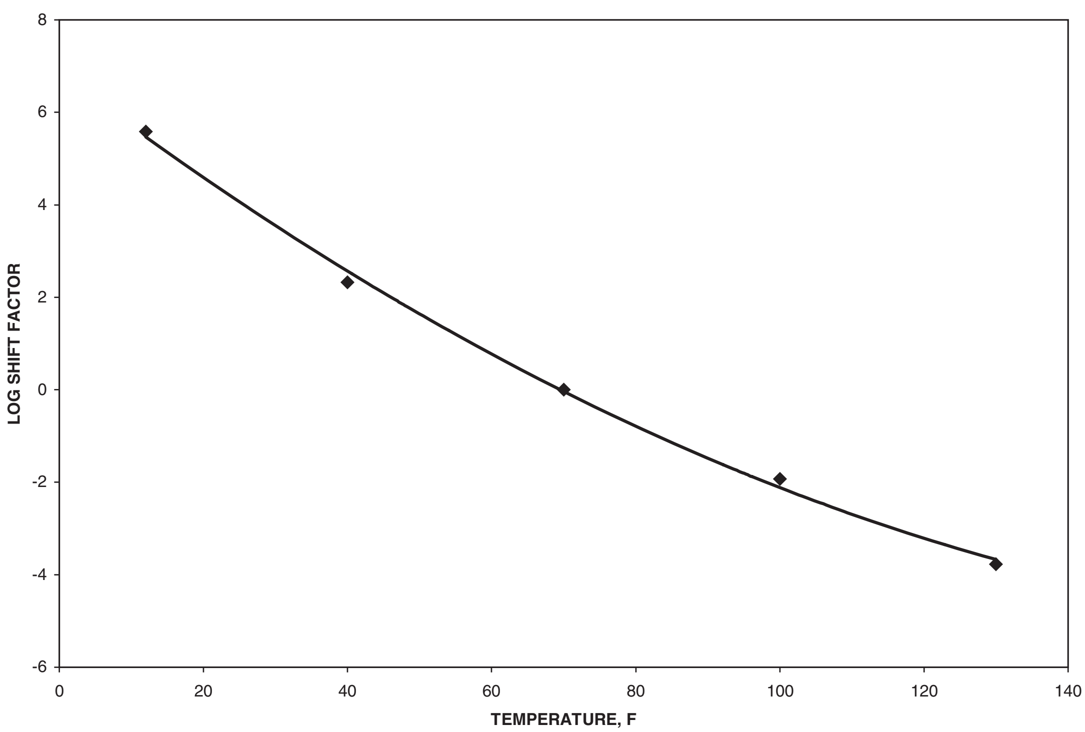
DYNAMIC MODULUS MASTER CURVES

To account for temperature and rate of loading effects on the modulus of asphalt concrete, the 2002 Design Guide constructs a master curve at a reference temperature of 21.1 ^{o}C (70 ^{o}F). Master curves are constructed using the principle of time-temperature superposition. First a standard reference temperature is selected, in this case 21.1 ^{o}C (70 ^{o}F), then data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The master curve of modulus as a function of time formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. Thus, both the master curve and the shift factors are needed for a complete description of the rate and temperature effects. Figure 1 presents an example of a master curve constructed in this manner and the resulting shift factors.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004



a. Master Curve.



b. Shift Factors.

Figure 1. Schematic of Master Curve and Shift Factors.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

In the 2002 Design Guide, the sigmodial function in Equation 1 is used to describe the rate dependency of the modulus master curve.

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

where:
E^* = dynamic modulus
t_r = reduced time
δ = minimum value of E^*
$\delta+\alpha$ = maximum value of E^*
β, γ = parameters describing the shape of the sigmodial function

The fitting parameters δ and α depend on aggregate gradation, binder content, and air void content. The fitting parameters β and γ depend on the characteristics of the asphalt binder and the magnitude of δ and α.

The temperature dependency of the modulus is incorporated in the reduced time parameter, t_r, in Equation 1. Equation 2 defines the reduced time as the actual loading time divided by the time-temperature shift factor, a(T).

$$t_r = \frac{t}{a(T)} \tag{2a}$$

$$\log(t_r) = \log(t) - \log[a(T)] \tag{2b}$$

where:
t_r = reduced time
t = time of loading
a(T) = shift factor as a function of temperature
T = temperature

The shift factors are a function of temperature. In the 2002 Design Guide, the shift factors were expressed as a function of the binder viscosity to allow aging over the life of the pavement to be considered using the Global Aging Model developed by Mirza and Witczak *(2)*. Equation 3 presents the shift factor relationship used in the 2002 Design Guide.

$$\log[a(T)] = c[\log(\eta) - \log(\eta_{70_{RTFOT}})] \tag{3}$$

where:
a(T) = shift factor as a function of temperature and age
η = viscosity at the age and temperature of interest

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

$\eta_{70_{RTFOT}}$ = viscosity at the reference temperature of 70 °F and RTFO aging
c = fitting parameter

For the development of dynamic modulus master curves, it is assumed that short-term oven aging for 4 hours at 135 °C is equivalent to RTFOT aging. For these conditions, the viscosity as a function of temperature can be expressed using the ASTM viscosity-temperature relationship given in Equation 4.

$$\log \log \eta = A + VTS \log T \tag{4}$$

where:

η = viscosity, cP
T = temperature, ° Rankine (°F + 459.67°)
A = regression intercept
VTS = regression slope of viscosity-temperature relationship

Combining Equations 3 and 4 yields the shift factor as a function of temperature relationship used in the 2002 Design Guide for the construction of dynamic modulus master curves from laboratory test data.

$$\log[a(T)] = c\left[10^{A+VTS \log T} - 10^{A+VTS \log(529.67)}\right] \tag{5}$$

where:

a(T) = shift factor as a function of temperature
T = temperature, ° Rankine
A, VTS= viscosity-temperature relationship parameters for RTFOT aging
c = fitting parameter

Substituting Equation 5 into Equation 2b and the result into Equation 1 yields the form of the dynamic modulus master curve relationship used in the 2002 Design Guide for the development of master curves from laboratory test data.

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma\left\{\log(t) - c\left[10^{A+VTS \log T} - 10^{A+VTS \log(529.67)}\right]\right\}}} \tag{6}$$

where:

E* = dynamic modulus
t = loading time
T = temperature, ° Rankine
A, VTS= viscosity-temperature relationship parameters for RTFOT aging
c = fitting parameter

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

δ = minimum value of E*
δ+α = maximum value of E*
β, γ = parameters describing the shape of the sigmodial function

The fitting parameters (α, β, δ, γ, and c) are determined through numerical optimization of Equation 6 using mixture test data collected in accordance with AASHTO TP62-03. Through the numerical optimization, the test data are essentially extrapolated to define the limiting minimum and maximum moduli.

When information concerning the viscosity-temperature relationship for the binder is not available, a master curve can still be constructed and used to compare materials or used in pavement structural design methods other than the 2002 Design Guide. In this case, the shift factors can be described by an Arrhenius function given as Equation 7 *(3).*

$$\log[a(T)] = \frac{\Delta E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{7}$$

where:

a(T) = shift factor as a function of temperature
T = temperature, °K (°C + 273.15°)
T_r = reference temperature, °K
ΔE_a = activation energy, approximately equal to 200,000 J/mol

R =universal gas constant = 8.314 J/°K-mol

Simplifying Equation 7, substituting it into Equation 2b and then substituting the result into Equation 1 yields an alternative form of the dynamic modulus master curve equation that can be used when information on the viscosity-temperature relationship of the binder is not available. Note that the reference temperature for Equation 8 is 21.1 °C.

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma\left\{\log(t) - \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{295.25}\right)\right]\right\}}} \tag{8}$$

Where:

E* = dynamic modulus
t = loading time
T = temperature, °K
ΔE_a = activation energy, J/mol

δ = minimum value of E*
δ+α = maximum value of E*
β, γ = parameters describing the shape of the sigmodial function

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Again, the fitting parameters (α, β, δ, γ, and ΔE_a) are determined through numerical optimization of laboratory test data.

REDUCED TEMPERATURE RANGE

To properly fit the master curves in Equations 6 and 8, test data are needed over a range of temperatures. Particularly troublesome is the collection of dynamic modulus test data at low temperatures to define the upper bound of the sigmoidal function (limiting maximum modulus). Testing over this range of temperatures requires expensive environmental chambers with humidity control, and high load levels. In NCHRP Project 9-29, it was determined that a reasonable estimate of the limiting maximum modulus could be obtained from the Hirsch model *(1)*, and combined with test data over a narrower range of temperatures to develop a dynamic modulus master curve.

Equations 9 and 10 present the Hirsch model, which allows estimation of the modulus of the mixture from binder stiffness data and volumetric properties of the mixture.

$$|E^*|_{mix} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G^*|_{binder}\left(\frac{VFA\ x VMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\dfrac{\left(1-\dfrac{VMA}{100}\right)}{4{,}200{,}000}+\dfrac{VMA}{3VFA|G^*|_{binder}}\right]} \tag{9}$$

where:

$$P_c = \frac{\left(20+\dfrac{VFA\,x\,3|G^*|_{binder}}{VMA}\right)^{0.58}}{650+\left(\dfrac{VFA\,x\,3|G^*|_{binder}}{VMA}\right)^{0.58}} \tag{10}$$

VMA = Voids in mineral aggregates, %
VFA: Voids filled with asphalt, %
$|G^*|_{binder}$ = shear complex modulus of binder, psi

Based on research conducted during the Strategic Highway Research Program (SHRP) by Christensen and Andersen *(4)*, a good engineering estimate of the maximum shear modulus for all binder is approximately 1 GPa or 145,000 psi. Substituting this value into Equations 9 and 10 yields the recommended equation for estimating the limiting maximum modulus of asphalt concrete mixtures from volumetric data.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

$$|E^*|_{max} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+435{,}000\left(\frac{VFA\ xVMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{435{,}000(VFA)}\right]} \tag{11}$$

where

$$P_c = \frac{\left(20+\frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650+\left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \tag{12}$$

$|E^*|_{max}$ = limiting maximum mixture dynamic modulus
VMA = Voids in mineral aggregates, %
VFA = Voids filled with asphalt, %

Figure 2 presents limiting maximum moduli computed using Equation 11 for VMA ranging from 10 to 20 percent, and VFA ranging from 55 to 85 percent. For this wide range of volumetric properties, the limiting maximum modulus varies from about 3,000,000 psi to 3,800,000 psi. These limiting maximum modulus values appear very rational. For conditions with low VMA and high VFA, the limiting maximum modulus approaches the 4,000,000 psi often assumed for Portland cement concrete.

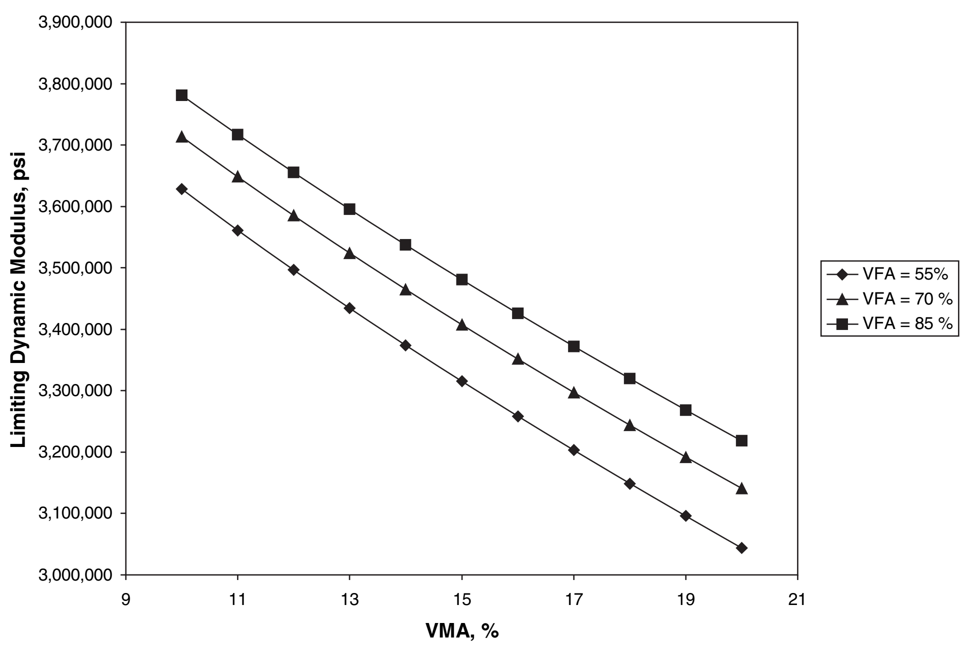


Figure 2. Limiting Maximum Dynamic Modulus Values From the Hirsch Model.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

For a known limiting maximum modulus, the 2002 Design Guide master curve relationship given in Equation 6 reduces to:

$$\log(E^*) = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log(t) - c\left[10^{A+VTS\log T} - 10^{A+VTS\log(529.67)}\right]\right\}}} \qquad (13)$$

where:

E* = dynamic modulus
t = loading time
T = temperature, ° Rankine
A, VTS = viscosity-temperature relationship parameters for RTFOT aging
Max = limiting maximum modulus
δ, β, γ and *c* = fitting parameters

And the alternative master curve relationship given in Equation 8 reduces to:

$$\log(E^*) = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log(t) - \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{295.25}\right)\right]\right\}}} \qquad (14)$$

Where:

E* = dynamic modulus
t = loading time
T = temperature, °K
Max = limiting maximum modulus
δ, β, γ and ΔE_a = fitting parameters

The four unknown fitting parameters are still estimated using numerical optimization of the test data, but since the limiting maximum modulus is known, data at low test temperatures are no longer needed.

MASTERSOLVE WORKBOOK

The computations needed to develop a dynamic modulus master curve are easily performed using the Solver function in Mircosoft EXCEL®. A workbook, called MASTERSOLVE, was developed during NCHRP Project 9-29 for solving Equations 13 and 14. It is available from NCHRP. This section describes the data needed for the solution, and the general flow of computations.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Input Data

The input data that are need to develop a dynamic modulus master curve using the approach described in this Annex are:

1. Average voids in the mineral aggregate (VMA) for the specimens tested.
2. Average voids filled with asphalt (VFA) for the specimens tested.
3. Dynamic modulus and phase angle measured on replicate specimens at temperatures of 4.4, 21.1, and 46.1 °C (40, 70, and 115 °F) at loading frequencies of 10, 1.0, 0.1, and 0.01 Hz. A total of 24 dynamic modulus and phase angle measurements are needed.
4. If shift factors will be developed using the 2002 Design Guide approach, then the coefficients A, and VTS of the viscosity-temperature relationship for the binder are needed. These coefficients should represent the aging condition of the binder in the specimens being tested. Normally this will be RTFOT conditions.

Computations

1. From the average VMA and VFA for the specimens tested compute the limiting maximum modulus using Equations 11 and 12.
2. Compute the average of the dynamic modulus and the average of the phase angle measurements for each of the 12 temperature/frequency combinations.
3. Compute the logarithm of the 12 average dynamic modulus measurements.
4. Compute the time of loading for each of the 12 temperature/frequency combinations as 1/frequency.
5. Use the Solver function in Microsoft EXCEL® to determine the fitting parameters in Equations 13 and/or 14. This is done by setting up a spreadsheet to compute the sum of the squared errors between the logarithm of the average measured dynamic moduli and the value predicted by Equations 13 or 14. The Solver function is used to minimize the sum of the squared errors. The following initial estimates are recommended:

Parameter	2002 Design Guide Equation 13	Arrhenius Shift Factors Equation 14
δ	0.5	0.5
β	-1.0	-1.0
δ	.5	0.5
C	1.2	NA
ΔE_a	NA	1000

6. Generate plots showing: (1) the fitted master curve and the shifted average modulus data as a function of reduced loading time, (2) the shifted average phase angle data as a function of reduced loading time, (3) the shift factors as a function of temperature.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

ANNEX D REFERENCES

1. Christensen, D.W., Pellinen, T.K., Bonaquist, R.F., "Hirsch Model for Estimating the Modulus of Asphalt Concrete," Journal of the Association of Asphalt Paving Technologists, Volume 72, 2003, pp. 97-121.

2. Mirza, M. W. and Witczak, M.W., "Development of a Global Aging System for Short and Long Term Aging of Asphalt Cements," *Journal of the Association of Asphalt Paving Technologists,* Vol. 64, 1995.

3. Pellinen, T. K. "Investigation of the Use of Dynamic Modulus as An Indicator of Hot-Mix Asphalt Performance," Ph.D. Dissertation, Arizona State University, May, 2001.

4. Christensen, D.W., and Anderson, D.A., "Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements," *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Annex E
Specification Compliance Test Methods for the Simple Performance Test System

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Table E1. 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)

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Table E1. 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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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 manufacturer's 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 manufacturer's specifications and repeat the dual applications of pressure as described above to complete verification.

5.0 Temperature Measuring System Verification

5.1 Verification of the temperature measuring system will be performed using a using a NIST traceable reference thermal detector that is readable and accurate to 0.1 ^{o}C.

5.2 A rubber band or O-ring will be used to fasten the reference thermal detector to the system temperature sensor.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

Annex F

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

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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 F-1.

Table F-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.

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

3.0 Dynamic Modulus Testing

3.1 Perform the dynamic modulus testing with the Simple Performance Test System in accordance with Annex C of these specifications. Repeat tests as needed to ensure that the data quality indicators are within their allowable ranges.

3.2 Perform the testing in blocks of three specimens in the order listed in Table F-2. Plan the testing such that all testing in a block will be completed on the same day.

Table F-2. Block Order Testing.

Block	Temperature, °C (°F)	Confinement, kPa (psi)	Specimen Deformation System
1	25 (77)	0	Standard
			Proposed
2	25 (77)	0	Standard
			Proposed
3	25 (77)	0	Standard
			Proposed
4	25 (77)	0	Standard
			Proposed
5	45 (113)	140 (20)	Standard
			Proposed
6	45 (113)	140 (20)	Standard
			Proposed
7	45 (113)	140 (20)	Standard
			Proposed
8	45 (113)	140 (20)	Standard
			Proposed
9	45 (113)	0	Standard
			Proposed
10	45 (113)	0	Standard
			Proposed
11	45 (113)	0	Standard
			Proposed
12	45 (113)	0	Standard
			Proposed

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

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 F-1 and F-2.

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

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

where:

$\bar{y}$ = sample mean
s^2 = sample variance
y_i = measured values

5.0 Statistical Hypothesis Testing

5.1 For each combination of temperature, confining pressure, and frequency of loading test the equality of variances between the standard specimen deformation system and the proposed specimen deformation measuring system using the F-test described below. In the description below, the subscript *s* refers to the standard system and the subscript *p* refers to the proposed system.

Null Hypothesis:

Variance of proposed system equals that of standard system, $\sigma_p^{\ 2} = \sigma_s^{\ 2}$

Alternative Hypothesis:

Variance of proposed system is greater than that of standard system, $\sigma_p^{\ 2} > \sigma_s^{\ 2}$

Test Statistic:

$$F = \frac{s_p^{\ 2}}{s_s^{\ 2}}$$

NCHRP 9-29 Equipment Specification for the Simple Performance Test System
Version 2.0
March 26, 2004

where

s_p^2 = computed sample variance for the proposed system
s_s^2 = computed sample variance for the standard system

Region of Rejection:

For the sample sizes specified, the test statistic must be less than 2.82 to conclude that the variances are equal.

5.2 Summarize the resulting test statistics for dynamic modulus and phase angle.

5.3 If the results conclude the variance is greater for the proposed measuring for any of the combinations of temperature, confinement, and loading frequency tested, then the proposed measuring system is unacceptable.

5.4 For combinations of temperature, confinement, and loading frequency where equality of variances is confirmed by the hypothesis test in Item 5.1, test the equality of means between the standard specimen deformation system and the proposed specimen deformation measuring system using the t-test described below. In the description below, the subscript *s* refers to the standard system and the subscript *p* refers to the proposed system.

Null Hypothesis:

Mean from the proposed system equals that from the standard system, $\mu_p^2 = \mu_s^2$

Alternative Hypothesis:

Mean from the proposed system is not equal to that from the standard system, $\mu_p^2 \neq \mu_s^2$

Test Statistic:

$$t = \frac{\left(\bar{y}_p - \bar{y}_s\right)}{\frac{n}{\sqrt{6}}}$$

where:

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

$\bar{y}_p$ = computed sample mean from the proposed system

$\bar{y}_s$ = computed sample mean from the standard system

s_p^2 = computed sample variance for the proposed system
s_s^2 = computed sample variance for the standard system

Region of Rejection:

For the sample sizes specified, the absolute value of the test statistic must be less than 2.07 to conclude that the means are equal.

5.5 Summarize the resulting test statistics for dynamic modulus and phase angle.

5.6 If the results conclude the means are not equal for any of the combinations of temperature, confinement, and loading frequency tested, then the proposed measuring system is unacceptable.

6.0 Report

6.1 Design data for the mixture used in the evaluation.

6.2 Air void contents for individual specimens and the average and standard deviations of the air void contents for the two subsets.

6.3 Tabular chronological summary of the block testing showing starting date and time and completion date and time for each block.

6.4 Summary tables of dynamic modulus, phase angle, and data quality indicators for each combination of temperature, confining pressure, and loading frequency for the two measuring systems.

6.5 Summary tables of the mean and variance of the dynamic modulus and phase angle for each combination of temperature, confining pressure, and loading frequency for the two measuring systems.

6.6 Summary tables of the hypothesis tests for the variance and mean of the dynamic modulus and phase angle for each combination of temperature, confining pressure, and loading frequency.

6.7 Conclusions concerning the acceptability of the proposed measuring system.

APPENDIX C

Simple Performance Test Specimen Fabrication System Specification

NCHRP 9-29 First Article Equipment Specification for Simple Performance Test Specimen Fabrication Equipment
Version 2.0
June, 29, 2007

Table of Contents

NCHRP 9-29 First Article Equipment Specification for Simple Performance Test Specimen Fabrication Equipment
Version 2.0
June, 29, 2007

1.0 Summary

1.1 This specification describes equipment for preparing 100 mm (4 in) diameter by 150 mm (6 in) high simple performance test specimens from 150 mm (6 in) diameter gyratory specimens.

1.2 The objective of this specification is to encourage manufacturers to develop equipment that speeds the test specimen fabrication process. The goal is to have equipment with the capability to remove nominal 100 mm (4 in) diameter by 150 mm (6 in) high test specimens from 150 mm (6 in) diameter gyratory specimens prepared in existing or future gyratory compactors.

2.0 Definitions

2.1 *Gyratory Specimen.* Refers to 150 mm (6 in) diameter specimens prepared in a gyratory compactor meeting the requirements of AASHTO T312.

2.2 *Simple Performance Test Specimen.* Refers to 100 mm (4 in) diameter by 150 mm (6 in) high specimens for use in the Flow Time, Flow Number, and Dynamic Modulus Tests.

3.0 Simple Performance Test Specimen Fabrication System

3.1 The Simple Performance Test Specimen Fabrication System shall be a complete, fully integrated system with the capability to remove a 100 mm (4 in) diameter by 150 mm (6 in) high simple performance test specimen from a nominal 150 mm (6 in) diameter gyratory specimen.

3.2 The Simple Performance Test Specimen Fabrication System shall be designed so that a skilled technician can prepare a simple performance test specimen from an existing gyratory specimen in 15 minutes or less.

3.3 The Simple Performance Test Specimen Fabrication System shall be designed to handle 150 mm (6 in) diameter gyratory specimens that are from 165 mm to 180 mm (6.5 in to 7.9 in) tall.

3.4 Acceptable cutting fluids are: air and water. If other fluids are proposed, submit data demonstrating that the fluid does not to affect the properties of asphalt.

3.5 When assembled, the Simple Performance Test Specimen Fabrication System shall occupy a foot-print no greater than 1.5 m (5 ft) by 2.4 m (8 ft).

NCHRP 9-29 First Article Equipment Specification for Simple Performance Test Specimen Fabrication Equipment
Version 2.0
June, 29, 2007

3.6 The Simple Performance Test Specimen Fabrication System shall operate on single phase 115 or 230 VAC 60 Hz electrical power.

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

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

4.0 Simple Performance Test Specimen Requirements

4.1 Test specimens shall be monolithic. Specimens formed by stacking or gluing pieces are not acceptable.

4.2 During the fabrication process, the test specimen shall not reach a temperature lower than 0 °C (32 °F)

4.3 Test specimens shall conform to the requirements of Table 1.

5.0 Documentation

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

1. System Introduction.
2. Installation.
3. Specimen Preparation Instructions.
4. Preventative Maintenance.
5. Spare Parts List.
6. Drawings.

6.0 Warranty

6.1 The Specimen Fabrication Equipment shall carry a one year on-site warranty.

NCHRP 9-29 First Article Equipment Specification for Simple Performance Test Specimen Fabrication Equipment
Version 2.0
June, 29, 2007

Table 1. Test Specimen Specification 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

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.

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