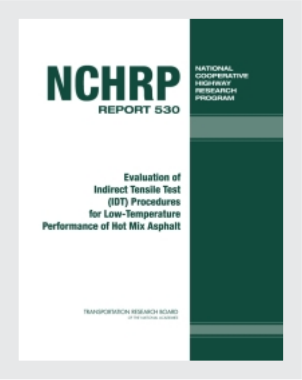

Evaluation of Indirect Tensile Test (IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 530

Evaluation of Indirect Tensile Test (IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt

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Subject Areas
Materials and Construction

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in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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AUTHOR ACKNOWLEDGMENTS

The research documented in this report was performed under NCHRP Project 9-29 by Advanced Asphalt Technologies, LLC (AAT). Ramon Bonaquist, Ph.D., P.E., and Chief Operating Officer for AAT, served as Principal Investigator. Donald W. Christensen, Jr., Ph.D., P.E., and Senior Engineer for Advanced Asphalt Technologies, LLC, was responsible for conducting the work documented in this report. Substantial data gathered with the indirect tensile test device have been summarized and analyzed in this report. These data were submitted by six different laboratories, both public and private, located throughout the United States. AAT sincerely thanks the organizations and individuals for their cooperation. Because several of the participating laboratories requested anonymity, the parties involved unfortunately cannot be individually acknowledged.

FOREWORD

By Edward T. Harrigan
Senior Program Officer
Transportation Research Board

This report presents the findings of a research project to evaluate the use of the indirect tensile creep and strength test procedures in AASHTO Standard Method of Test T322-03 in mixture and structural design methods for hot mix asphalt. The report will be of particular interest to pavement design and materials engineers in state highway agencies, as well as to materials suppliers and paving contractor personnel who are responsible for the design and evaluation of hot mix asphalt mixtures and pavements.

The prevention of the low-temperature cracking (also called thermal cracking) in hot mix asphalt (HMA) pavements is a critical issue for many transportation agencies in the United States and Canada. In the Superpave mix design method developed in the Strategic Highway Research Program (SHRP), this type of distress is addressed through the selection of an appropriate performance grade of asphalt binder and the evaluation of candidate mix designs with the indirect tensile (IDT) creep and strength procedure developed in SHRP Project A-003A by Roque and his co-workers at the Pennsylvania State University.

At the conclusion of SHRP, Roque's IDT procedure was first codified as AASHTO provisional method of test TP9 and then adopted by AASHTO as Standard Method of Test T322-03, *Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*. NCHRP Project 9-19 subsequently identified AASHTO T322 as a suitable *simple performance test* for low-temperature cracking in HMA mix design, and the same procedure was selected in NCHRP Project 1-37A as the *materials characterization test method* for the prediction of low-temperature cracking of flexible pavements in the recently completed Mechanistic-Empirical Pavement Design Guide.

During the 1993-1998 Superpave implementation program, the Federal Highway Administration (FHWA) developed equipment specifications and procured six IDT devices as part of a national pooled fund procurement. This equipment was located at the FHWA's Turner Fairbank Highway Research Center and the five Superpave Regional Centers. The IDT strength test underwent ruggedness testing by the FHWA, the Asphalt Institute, and the Superpave Regional Centers as part of NCHRP Project 90-06. In addition, the IDT was used in the design and analysis of HMA used in WesTrack, MnROAD, FHWA ALF, and many in-service field projects incorporating Superpave-designed HMA. Other private- and public-sector organizations have used the IDT on a continuing basis and have accumulated considerable test data and derived material properties. Work has also been conducted to examine whether TP9 can be performed with simpler, less expensive equipment than the current IDT device. The states, however, have been hesitant to proceed with procurement of this test equipment until such time as the available information was fully analyzed and the test procedure fully evaluated.

Under Phase III of NCHRP Project 9-29, "Simple Performance Tester for Superpave Mix Design," Advanced Asphalt Technologies LLC was assigned the task of evaluating and refining the indirect tensile test (IDT) procedures in AASHTO Standard Method Test T322. In conducting the research, Advanced Asphalt Technologies (1) critically reviewed the procedures and equipment for performing the IDT creep and strength tests; (2) analyzed IDT creep and strength data sets collected by various public and private sector laboratories to determine whether there are significant differences among the data related to the equipment configuration, the details of the test method, or the method of data reduction and analysis; and (3) critically examined the theoretical basis of IDT test and data reduction methods recommended for structural and mix design in Projects 1-37A and 9-19.

Based on the results of this research, the project team suggested several specific changes to AASHTO T322 to reduce its variability and improve the precision and reliability of its results as both a simple performance test in HMA mix design and a materials characterization test for structural design. In particular, further standardization of the IDT creep procedure and equipment is recommended to further improve its precision. The research also found that the equation developed in the SHRP asphalt research program to estimate the HMA coefficient of thermal contraction is not accurate and should be abandoned. A simple, improved procedure for estimating this coefficient was developed that is relatively accurate compared with measured results. Finally, estimates of creep compliance and strength obtained from asphalt binder and mixture volumetric data with the Hirsch model were found to provide good agreement with values measured with AASHTO T322. Such estimates may be useful in situations where time, money, or both are not available to conduct IDT creep and strength tests, or for field quality control purposes.

This final report includes a detailed description of the experimental plan, a discussion of the research results, and two supporting appendixes:

- Appendix A: Review of AASHTO T322 and Recent Proposed Changes
- Appendix B: Equipment Configurations for Creep and Strength Testing of Hot Mix Asphalt Concrete at Low Temperatures

Appendix C: Summary Data for Laboratory Testing Program is available for loan on request from NCHRP.

The research results have been referred to the TRB Mixtures and Aggregate Expert Task Group for its review and possible recommendation to the AASHTO Highway Subcommittee on Materials for adoption of the suggested changes to AASHTO T322 presented in Appendix A.

CONTENTS

EVALUATION OF INDIRECT TENSILE TEST (IDT) PROCEDURES FOR LOW-TEMPERATURE PERFORMANCE OF HOT MIX ASPHALT

SUMMARY

The indirect tensile (IDT) creep and strength tests were developed during the Strategic Highway Research Program (SHRP) to characterize the resistance of hot mix asphalt concrete (HMA) to low-temperature cracking (*1,2*). Currently, the IDT creep and strength tests are considered the most promising for predicting the low-temperature performance of asphalt concrete mixtures. Many contractors and state highway agencies are interested in using these test procedures but feel that additional information is needed on the test device, procedures, and analysis. Therefore, the objective of Phase III of National Cooperative Highway Research Program (NCHRP) Project 9-29, as stated in the expanded scope of work, was to "evaluate and refine the IDT procedures proposed for use as the simple performance test for low-temperature cracking and as the materials characterization test for low-temperature cracking in the pavement design guide developed in NCHRP Project 1-37A."

This report documents work completed in Phase III of NCHRP Project 9-29. The requirements of AASHTO T322, *Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device,* have been reviewed, and a number of relatively minor changes have been suggested. These include the capacity of the loading machine, the range of the environmental chamber, the sensitivity of the load and deformation measurements, and the use of neoprene strips in the IDT loading fixture. Recommended requirements for specimen dimensions and uniformity were also developed based on those prepared for the simple performance test specimens. Guidance on load levels to maintain strains within the allowable limits was also developed. Another important suggestion made in this study is that the temperatures used for low-temperature creep and strength tests should vary according to the stiffness of the mixture. For asphalt concrete mixtures made using PG XX-22 and PG XX-28 binders, the current test temperatures of −20, −10 and 0°C should be retained. For mixtures made using PG XX-16 binders or harder binders, these temperatures should all be increased by 10°C. Similarly, for mixtures made using PG XX-34 binders or softer binders, test temperatures should be decreased by 10°C. Tensile strength tests should always be performed at the middle creep test temperature. This protocol will help ensure good test precision and will also help avoid problems that occur when the maximum relaxation time in the Prony series is exceeded during analysis of creep data.

Anderson and McGennis evaluated the precision of the IDT strength test and reported a standard error for n = 3 replicates of about 7 percent (*3*). A precision study of the IDT creep test was performed as part of Phase III of NCHRP Project 9-29, which

included numerous mixtures from six different laboratories. Evaluation of these data resulted in estimated standard errors for compliance for n = 3 replicates of 8 to 11 percent, expressed as a percentage of the mean. This corresponds to a d2s precision of 22 to 32 percent. The precision for the IDT strength test appears to be acceptable. The precision for the IDT creep procedure, on the other hand, needs to be improved as part of the implementation process. Further standardization of the procedure and equipment should help achieve improvements in precision.

The equation developed during SHRP (*1*) for estimating mixture coefficient of thermal contraction is not accurate and should be abandoned. However, methods for the laboratory measurement of thermal contraction of asphalt concrete mixtures have not been well developed or widely used and are not highly accurate. A simple, improved procedure for estimating the coefficient of thermal contraction has been developed and provides reasonably accurate results.

A laboratory test program was executed in this study to evaluate and compare measurement of creep compliance using the IDT, uniaxial compression, and uniaxial tension tests. An experiment comparing strength measurements was also performed to compare uncorrected IDT strengths, IDT strengths corrected using Roque's procedure as outlined in AASHTO T322, and strengths determined in uniaxial tension. Analysis of the resulting data indicates that asphalt concrete at low temperatures is anisotropic—that is, the properties vary depending upon the axis loaded. The compliance measured using the IDT test was lower than the compliance determined in uniaxial compression, which in turn was lower than that determined in uniaxial tension. It would appear that the modulus of asphalt concrete in the plane perpendicular to compaction is generally higher than that determined in the plane parallel to compaction. Because of this anisotropy, uniaxial creep data cannot be used interchangeably with IDT creep data, and the IDT creep and strength test should be retained for use in characterizing the low-temperature properties of asphalt concrete. It was also found that the uncorrected IDT strength, as determined using the maximum load, is significantly higher than that determined using Roque's procedure, in which the failure load is determined through monitoring specimen deformation. However, the uncorrected IDT strength correlates well with the corrected IDT strength. Because of the danger of damaging transducers during the strength test, it is recommended that the IDT strength be determined by using the maximum load during the test and applying an empirical correction to estimate the corrected IDT strength.

Comparison of measured compliance values with those estimated using the Hirsch model (*4*) showed good agreement, and IDT strength values correlated well with voids filled with asphalt (VFA) values. This suggests that critical temperatures can possibly be easily and accurately estimated from binder test data and mixture volumetric composition. Such a procedure might be useful in situations where time and/or money is not available for IDT creep and strength tests or for quality control purposes. Additional research is suggested to compare critical temperatures estimated in this fashion with those determined using the IDT creep and strength procedure.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Low-temperature cracking, also called thermal cracking, is a serious type of pavement distress that occurs in temperate and sub-Arctic regions throughout North America. This type of pavement failure is the result of tensile stresses caused by sudden temperature drops in combination with embrittlement of the asphalt concrete at low temperatures. It is considered a more common problem in the northern United States and Canada, but has been observed in Texas and Florida. The indirect tensile (IDT) creep and strength tests were developed during the Strategic Highway Research Program (SHRP) to characterize the resistance of hot mix asphalt concrete (HMA) to low-temperature cracking (*1,2*). These methods have been standardized in AASHTO T322, *Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device.* Currently, the IDT creep and strength tests are considered the most promising for predicting the low-temperature performance of asphalt concrete mixtures.

During the mid-1990s, the FHWA procured six IDT test systems for use by the Turner Fairbank Highway Research Center (TFHRC) and five Regional Superpave Centers. These were unusual systems in that they were closed-loop electromechanical systems, rather than the more traditional servo-hydraulic loading systems. All of the users of these systems experienced a range of hardware and software problems, preventing a thorough evaluation of the device and procedure. Currently, there are about a dozen laboratories in the United States performing IDT creep and strength tests on a regular basis. Many contractors and state highway agencies are interested in using these test procedures but feel that additional information is needed on the test device, procedures, and analysis. Therefore, the objective of Phase III of NCHRP Project 9-29, as stated in the expanded scope of work, is to "evaluate and refine the indirect tensile test (IDT) procedures proposed for use as the simple performance test for low-temperature cracking and as the materials characterization test for low-temperature cracking in the pavement design guide developed in NCHRP Project 1-37A."

SCOPE OF STUDY

Given the limited budget, the scope of Phase III of NCHRP Project 9-29 primarily focused on the basic test methods, equipment, and analysis used in the IDT creep and strength tests. The general approach and several critical algorithms used in the computer program developed by Roque and his associates for analyzing IDT data and predicting thermal cracking are included in the scope of this study. However, an in-depth evaluation of this software was not possible given the available resources and was not contemplated in the research problem statement. Based upon the report generated by the NCHRP Project 9-19 team (*5*), this program appears to be functioning well, and an in-depth evaluation is probably not warranted at this time.

RESEARCH APPROACH

The NCHRP elected to have Advanced Asphalt Technologies, LLC (AAT) perform the evaluation and refinement of the IDT creep and strength tests as Phase III of NCHRP Project 9-29. Phase III included eight tasks numbered Task 9 through Task 16:

Task 9. Critically review AASHTO T322 and the changes proposed to the procedures in NCHRP Projects 1-37A and 9-19. Evaluate how these changes may affect the prediction of low-temperature cracking with the measured material properties.

Task 10. Review the results of the ruggedness study conducted under NCHRP Project 90-06. Collect published and unpublished data obtained since 1993 with the various IDT equipment. Evaluate the data to determine whether there are significant differences related to the equipment configuration, the details of the test method, or the method of data reduction and analysis.

Task 11. Prepare a concise white paper discussing how equipment configuration (e.g., screw-type versus servo-hydraulic) might promote or hinder future adoption of the IDT method by the states for HMA mix and pavement structural design.

Task 12. Critically examine the theoretical basis of the IDT test and data reduction methods recommended for structural and mix design in Projects 1-37A and 9-19. Insofar as possible, test their rigor through an independent analysis of test data obtained in Task 10.

Task 13. Submit within 7 months of the initiation of Phase III an interim report presenting the findings of Tasks 9 through 12. Based on these findings, present recommended modifications to AASHTO

T322 or the alternative approaches proposed in Projects 1-37A and 9-19. Propose a laboratory testing plan to verify the soundness of any recommended modifications.

Task 14. Conduct the approved laboratory testing to verify the changes recommended to AASHTO T322 or the alternative procedures from Projects 1-37A and 9-19.

Task 15. Develop an experimental plan for possible future ruggedness and precision/bias studies.

Task 16. Prepare a final report for Phase III that (1) summarizes its findings, (2) documents the Task 15 experimental plan, and (3) presents any recommended modifications to AASHTO T322 or the alternative approaches from Projects 1-37A and 9-19 in AASHTO standard format for review and action by the TRB Superpave Mix and Aggregate Expert Task Group.

An in-depth review of AASHTO T322 and related recent research is included in this report as Appendix A. Early work in Phase III included the collection of IDT creep data from six different laboratories throughout the country. These data were compiled and analyzed statistically; the findings are presented in Chapter 2. Appendix B is the white paper prepared for Task 11, in which various issues concerning IDT test equipment and procedures are discussed. One of the primary recommendations of this white paper was to explore in the laboratory testing part of Phase III the use of uniaxial tests for measuring low-temperature properties of HMA mixtures. Because uniaxial testing is being promoted for mix analysis in NCHRP Project 9-19 and for the construction of dynamic modulus master curves in NCHRP Project 1-37A, its use in low-temperature characterization should maximize equipment use and simplify implementation and training activities. The theory underlying the IDT creep and strength tests is presented and discussed within Chapter 2 of this report. The results of a significant laboratory test program comparing the IDT creep and strength tests to uniaxial test methods (both compression and tension) are also included in Chapter 2. Chapters 3 and 4 are relatively brief, the former being a summary of findings and interpretation of those findings, the later being conclusions and recommendations.

CHAPTER 2

FINDINGS

REVIEW OF AASHTO T322

The discussion below is a summary of the most significant findings presented in Appendix A of this report, which presents a detailed review of AASHTO T322, and recent related work done as part of NCHRP Projects 9-19 and 1-37A. Readers interested in details on these topics should refer to this Appendix. These findings and resulting recommended changes to AASHTO T322 to improve the effectiveness and efficiency of this procedure were forwarded to the task force responsible for recommending revisions to this test method to AASHTO. AASHTO T322 consists of 17 sections:

1. *Scope*
2. *Referenced Documents*
3. *Terminology*
4. *Summary of Method*
5. *Significance and Use*
6. *Apparatus*
7. *Hazards*
8. *Standardization*
9. *Sampling*
10. *Specimen Preparation and Preliminary Determinations*
11. *Tensile Creep/Strength Testing (Thermal Cracking Analysis)*
12. *Tensile Strength Testing (Fatigue Cracking Analysis)*
13. *Calculations*
14. *Report*
15. *Precision and Bias*
16. *Keywords*
17. *References*

Many of these sections are only of nominal significance and have not been addressed as part of this study. Of special significance are Sections *6. Apparatus, 10. Specimen Preparation,* and *11. Tensile Creep/Strength Testing.* The most significant findings of this study on these three critical sections of AASHTO T322 are summarized below.

The specifications for the IDT creep and strength device, as currently given in AASHTO T322, are listed in Table 1. A careful review of these requirements has found several problems with the ranges and sensitivities for the various devices and transducers comprising the IDT test system (see Appendix A). The evaluations have been based upon typical properties of HMA at low temperatures, the fundamental stress-strain relationships for the IDT loading geometry, and typical cost-performance characteristics for loading systems, environmental chambers, and transducers. When appropriate, consistency with suggested requirements for the simple performance test has been considered in evaluating the requirements for the IDT system.

As an example of the nature of the evaluation performed on the requirements summarized in Table 1, consider the specifications for the range for the axial loading device. In *SHRP Report A-357,* the developer of the IDT creep and strength testing procedure presents data for a range of mixtures (*1*). These exhibit a range in compliance values of from about 3×10^{-11} Pa^{-1} to 4×10^{-9} Pa^{-1}. Because the linear range for HMA occurs at strains less than or equal to 0.05 percent, the maximum applied tensile stresses corresponding to these compliance values range from 125 kPa to 17 MPa. Based upon the relationship $\sigma_t = 2P/\pi t D$, the axial loads corresponding to these tensile stresses are 1.5 and 200 kN, respectively, for a specimen 50 mm thick and 150 mm in diameter. However, another consideration is the maximum load that can be applied without a specimen failing. The lowest tensile strength (σ_t) reported in *SHRP A-357* was 1.3 MPa, and the highest was 4.3 MPa. The corresponding load (P) for these tensile strengths can be calculated as $P = \sigma_t \pi t D/2$, where t and D are the specimen thickness and diameter, respectively. The calculated loads based on tensile failure are between 15 and 51 kN for a specimen 50 mm thick. Limiting the load to one-half that required to cause failure and allowing for specimens up to 100 mm in thickness, the anticipated maximum load is then 50 kN. However, to ensure good loading system performance, the capacity of the loading system should be about double the anticipated maximum load, giving a maximum capacity of 100 kN, agreeing nearly exactly with the 98 kN given in AASHTO T322. Evaluation of the displacement rate is more detailed and is presented in Appendix A.

In the previous example, the requirements in AASHTO T322 for the range of the axial loading device appear to be reasonable. However, the sensitivity requirements appear to be too stringent. Consider the worst-case situation, which is for the lowest anticipated load. Because it would be undesirable to approach nonlinearity, in some cases the applied loads might be somewhat less than the estimated minimum load of 1.5 kN, say 1 kN. To calibrate to this load level, ASTM E4 requires a resolution that is 1/100th of the minimum load level or a resolution of 10 N, which is significantly larger (poorer) than the 5-N resolution requirement given in AASHTO T322. Consideration should be given to changing

TABLE 1 AASHTO T322 specifications for IDT apparatus

Component	General Requirements	Range	Sensitivity
Axial loading device	Shall provide a constant load	98 kN maximum load; Displacement rate between 12 and 75 mm/min	5 N minimum
Load measuring device	Electronic load cell	98 kN minimum capacity	5 N minimum
Deformation measuring device(s)	Four linear variable differential transducers (LVDTs)	0.25 mm minimum	0.125 µm minimum
Environmental chamber	Temperature control only; large enough to perform test and condition 3 specimens	-30 to +30 °C	Control to ±0.2 °C
Control and data acquisition system	Shall digitally record load and deformation during test	1 to 20 Hz sampling rate	16-bit A/D board required
Test fixture	As described in ASTM D4123 (diametral resilient modulus testing)	N/A	2 kg maximum frictional resistance

the required resolution for the IDT loading system to 10 kN; this would likely reduce the cost of the equipment required to perform the test.

Various aspects of the equipment specifications, as presented previously in Table 1, were evaluated in detail. The recommended revised specifications for the IDT creep and strength test are given in Table 2.

In many cases, the changes are slight, such as rounding the maximum load to 100 kN rather than 98 kN, or the recommended 0.1 µm sensitivity for the deformation measuring devices compared with the original 0.125 µm sensitivity. The most substantial changes are probably the less stringent requirements for the sensitivity of the axial loading device and load cell (increased to 10 N from 5 N) and the change in the required range of the environmental chamber from −30 to +30°C to −30 to +10°C. Both of these changes should help reduce the cost of the IDT system.

Requirements for specimen preparation in AASHTO T322 are currently vague and should be stated more explicitly to ensure good test data. Table 3 and the accompanying notes list suggested requirements for IDT creep and strength specimens. The values given in this table have largely been based on requirements for specimen uniformity developed during NCHRP Project 9-29 for the simple performance tests (*6*). Maintaining similar requirements for both tests will ensure that technicians are familiar with these standards and that the equipment and techniques needed to produce such specimens are available in most laboratories.

Currently the suggested test temperatures for the creep procedure are 0, −10, and −20°C. Because of the variability in binder grades and the resulting low-temperature properties of asphalt concrete, some specimens are extremely stiff at −20°C, while others may be too compliant at 0°C. The test temperatures used in the IDT creep and strength tests should,

TABLE 2 Proposed revised AASHTO T322 specifications for the IDT apparatus

Component	General Requirements	Range	Sensitivity
Axial loading device	Shall provide a constant load	100 kN maximum load; Maximum displacement rate of at least 12 mm/min	10 N or better
Load measuring device	Electronic load cell	100 kN minimum capacity	10 N or better
Deformation measuring device(s)	Four displacement transducers (LVDTs)	0.1 mm minimum	0.1 µm or better
Environmental chamber	Temperature control only; large enough to perform test and condition 3 specimens	-30 to +10 °C under ambient conditions of 15 to 27 °C	Control to ±0.5 °C
Control and data acquisition system	System shall be operated with the use of a personal computer and shall digitally record load and deformation during test	1 to 20 Hz sampling rate	Consistent with required sensitivity of all system transducers
Test fixture	As described in ASTM D4123 (diametral resilient modulus testing), but with flat neoprene loading strips 12-mm thick by 12-mm wide.	N/A	20 N maximum frictional resistance

TABLE 3 IDT creep and strength specimen requirements

Item	Specification	Remarks
Average diameter	150 to 154 mm	See Note 1
Standard deviation of diameter	1.0 mm	See Note 1
Average thickness	40 to 60 mm	See Note 2
Standard deviation of thickness	1.0 mm	See Note 2
Smoothness	0.3 mm	See Note 3

Table 3 Notes:

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

2. Measure the thickness of the specimen to the nearest 1 mm at eight equally spaced points along the circumference of the specimen, using a pair of calipers or other similar device. Calculate and report the average thickness to the nearest 1 mm. The standard deviation of the specimen thickness shall be less than 1.0 mm. The average thickness shall be used in all material property calculations.

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

therefore, change according to the binder grade used. The relationship between binder stiffness and mixture stiffness is not 1:1; a given change in binder stiffness will produce a somewhat lower change in mixture stiffness. It is suggested that the current test temperatures of 0, −10, and −20°C be maintained for mixtures made using PG XX-22 and PG XX-28 binders. For PG XX-16 and PG XX-10 binders or mixtures that have been severely age-hardened, the recommended test temperatures should be −10, 0, and +10°C. For PG XX-34 binders (or softer), the recommended test temperatures should be −30, −20, and −10°C.

A related problem with the current version of AASHTO T322 is that the test conditions must be determined through a trial-and-error procedure. A load is applied to the specimen; if the resulting strains fall outside the allowable range, the test is aborted, the specimen is allowed to recover for 5 minutes, and the test is then repeated at an adjusted load level. No suggestions are given concerning what the appropriate applied loads should be for different combinations of mixture types and test conditions. Given the suggested revised protocol above, it is possible to provide guidelines for the applied load, as listed in Table 4. The specimen would initially be tested using the initial applied load listed in the second column of Table 4. If the resulting deformations are too small or too large, the test should be aborted, the specimen allowed to recover, and the test repeated using the alternative loads listed in the third column of Table 4.

TABLE 4 Guidelines for applied load in the IDT creep test

Test Temperature	Initial Applied Load (kN)	Other Possible Applied Loads (kN)
Lowest	40	Deformation < 0.01 mm: 80 Deformation > 0.02 mm: 20, 10
Intermediate	10	Deformation < 0.01 mm: 20, 40 Deformation > 0.02 mm: 5, 2
Highest	5	Deformation < 0.01 mm: 10, 20 Deformation > 0.02 mm: 2, 1

In general, most of the recommended modifications to AASHTO T322 are minor and not controversial; therefore, they should be easy to implement. The suggested revisions contained in this report have been forwarded to the task force responsible for recommending revisions to this test method to AASHTO.

EXPERIENCE WITH THE IDT TEST AT THE REGIONAL SUPERPAVE CENTERS

In the late 1990s, IDT test systems were procured by the FHWA for four of the five Regional Superpave Centers. These test systems were to be used for further evaluation of the IDT creep and strength test procedures. The systems were unusual in that they were closed-loop electro-mechanical systems, rather than the much more traditional closed-loop servo-hydraulic systems usually used for IDT tests and other similar procedures. Unfortunately, these test systems were plagued with more or less constant hardware and software problems. These problems were not the results of any inherent flaws in the basic concepts underlying the IDT creep and strength tests, but were the result of typical problems in first-article prototypes, exacerbated by a lack of technical support by the vendor and limited support funds available for performing needed modifications to the IDT systems. This experience has, however, made it unlikely that similar electro-mechanical systems can be effectively implemented for use in IDT testing in the near future.

One aspect of the experience among the Superpave Centers that should be given consideration is their abandonment of using Linear Variable Differential Transformers (LVDTs) during the IDT strength test to determine the exact moment of failure. In a standard IDT strength test, the precise moment of failure, and hence the “true” tensile strength, is difficult to determine, because the specimen fails very gradually and continues to carry substantial load even after large cracks appear. During SHRP, the suggested solution to this problem was to use the horizontal and vertical LVDTs to monitor horizontal and vertical deflections during the strength test. The point of failure is defined as occurring when the difference between the vertical and horizontal deformations reaches a maximum. Unfortunately, keeping LVDTs in place during the strength test often results in damage or destruction to these sensitive and expensive transducers. Engineers within the Superpave Centers agreed that, for practical reasons, the IDT strength test should be done without LVDTs, and the strength based only upon the maximum load. Although the SHRP procedure is more accurate, it appears that it is impractical, and damage to the LVDTs because of this procedure could actually reduce the overall reliability of the IDT creep and strength tests. The relationship between corrected and uncorrected IDT strength were evaluated experimentally in this project, and a relatively accurate empirical equation for estimating the true IDT strength from the uncorrected strength (based on maximum load) was developed. These results, along with other data and analyses constituting the laboratory testing portion of Phase III of NCHRP Project 9-29, are presented later in this chapter.

REFINEMENTS IN THE IDT TEST DURING NCHRP PROJECTS 1-37A AND 9-19

One of the early work elements in the Superpave Support and Performance Models Management Project (FHWA Contract DTFH61-95-C-00100, later NCHRP Project 9-19) was an evaluation of the Superpave low-temperature cracking model. A report on this work element was compiled, which documented numerous problems in the original SHRP thermal cracking model (*7*). A large number of minor problems in the program and its interface with the main SHRP mixture program were documented, along with a number of potentially more serious conceptual problems. One such issue was the use of an equation to estimate the coefficient of thermal contraction, α, of asphalt concrete mixtures, rather than an actual measurement. Research has suggested that the recommended equation for estimating α is not accurate (*8*), but available experimental procedures for measuring α have not been widely used and have not been thoroughly evaluated (*9*). A simple, improved equation for estimating the coefficient of thermal contraction for mixtures has been developed as part of this project and is presented later in this chapter in a section devoted to theoretical considerations of IDT creep and strength testing.

Two other potentially serious problems noted by Janoo and his coauthors (*7*) were the use of a very short, 100-second creep loading time and the characterization of mixture tensile strength using a single measurement at −10°C rather than with a number of measurements over a range of temperatures. However, improvements in the algorithm for generating compliance master curves have made the use of short creep tests more reliable (*5*). Use of only one tensile strength value in the computer program should also be acceptable, because tensile strength is simply one of several inputs used to estimate fracture properties and predict thermal cracking using the calibrated Superpave thermal cracking model.

In summary, the current version of the IDT test and analysis procedure has been substantially improved to address many of the shortcomings found immediately after the conclusion of SHRP. The following changes have been incorporated into the most recent version of the IDT test procedure and Superpave thermal cracking software:

- Simplified formulas have been developed for making correction factors for specimen bulging and non-uniform stress and strain distribution across the specimen;
- The initial portion of data analysis, which involves developing a “trimmed” mean for the response of a given set of specimens, has been enhanced to avoid problems that occurred when a transducer was not responding and also to provide the user an overall indication of the quality of the data being analyzed;
- The procedure used to shift the individual compliance curves to form a master compliance curve has been substantially improved and is more robust and produces reasonable and repeatable master curves even for non-ideal data;
- Most or all of the minor problems (“bugs”) in the original Superpave computer program have been corrected; and
- The entire program has been recalibrated with an expanded data set, which includes the original mixtures and pavements used during SHRP and additional materials and pavements from the Canadian SHRP program.

Potential problems that have not been addressed include a potentially inaccurate estimate of the coefficient of thermal contraction and use of LVDTs during the IDT strength test, which often damages the LVDTs and can result in the collection of faulty data for subsequent creep and strength tests.

PRECISION AND BIAS OF THE IDT TESTER

One of the main objectives of this study was to make a preliminary estimate of the precision of the IDT creep and strength test procedures. Although it had been planned to perform ruggedness testing using the IDT test systems at the Superpave Centers, the many problems with these systems prevented the completion of a thorough ruggedness test program. However, ruggedness testing was performed on the IDT strength test under Contract DTFH61-95-C-00055, as reported by Anderson and McGennis (*3*). The results of this testing are summarized below. As part of Phase III of NCHRP Project 9-29, creep data were collected from six laboratories around the country and summarized and analyzed statistically, as described below, in order to provide estimates of the precision of this procedure.

Precision of the IDT Strength Test

Three laboratories participated in the IDT strength ruggedness study: FHWA’s TFHRC, the Northeast Superpave Center (NESC), and the Asphalt Institute (TAI) (*3*). The objective of ruggedness testing is to evaluate the effect of slight variations in important aspects of test conditions on the test results. An estimate of the precision of the test method is also generally possible. Factors evaluated in the IDT strength ruggedness testing included air voids, preload, temperature, temperature preconditioning, temperature stabilization time, loading rate, and specimen orientation. These tests were conducted at a nominal temperature of –10°C, which is the standard temperature for performing the IDT strength test (*3*).

Anderson and McGennis found that none of the main factors evaluated had a statistically significant effect on the IDT strength test (*3*). However, it should be kept in mind that improvements in the precision of this procedure could result in different conclusions in the future. It was recommended that current tolerances on test temperature (±0.2°C) and requirements for preconditioning time (3 ± 1 hour) be maintained. It was also suggested that specimens be stabilized for 45 minutes prior to testing, unless a given laboratory can document that shorter conditioning times are effective, though specimens should in any case be conditioned for at least 15 minutes prior to testing. Current requirements for loading rate and initial preload appeared to be adequate, as did the tolerance for air void content (*3*). Anderson and McGennis suggested that further studies be conducted to evaluate an air void tolerance of 7.0 ± 1.0 percent, in order to simplify specimen preparation (*3*).

The overall average value of tensile strength for the ruggedness study was 2870 kPa (415 lb/in^2). The pooled standard deviation was 346 kPa (50.1 lb/in^2), which is for a single replicate determination (*3*). Normally, three independent determinations are averaged in an IDT strength test, so statistics should be calculated for $n = 3$. In this case, the standard error would be 200 kPa (29.0 lb/in^2), and the coefficient of variation 7.0 percent. A common and convenient statistic for characterizing the precision of a test method is the d2s precision. The term “d2s” stands for “difference, 2 standard deviations,” and represents the maximum expected difference between two independent measurements, in this case for a single operator within one laboratory. The d2s precision is calculated as $2\sqrt{2} \times SE$, where SE is the standard error based upon an average of several measurements—in this case three measurements. The d2s can be expressed in absolute terms—in units of kPa in this case—or as a percentage of the mean response. For the strength data reported by Anderson and McGennis, the d2s precision is 19.7 percent, expressed as a percentage of the mean (*3*). Considering the generally high variability observed in strength test data, this level of precision is probably acceptable.

Precision Evaluation of the IDT Creep Test

As part of Phase III of NCHRP Project 9-29, numerous laboratories that have IDT creep and strength test systems were contacted and asked to provide data for the purposes of evaluating the precision of IDT creep data. These laboratories were told the results of the study would be anonymous, so detailed information concerning the various laboratories cannot be provided. The nature of the six organizations is summarized briefly in Table 5.

Data were requested for 5 or 6 different mixtures; each laboratory submitted data for 2 to 12 mixtures. No more than 6 mixtures were analyzed from each lab. Most of the laboratories performed tests at –20, –10, and 0°C. Laboratory L3, however, performed tests at temperatures 10 to 20 degrees lower than this, perhaps because the binder grades represented by their mixtures were softer than those normally used, although the resulting compliance data were significantly lower than typical. Most of the laboratories performed three replicate tests at each temperature, except Laboratory L4, which performed four replicates. Extensive information concerning the nature of the mixtures was not provided by the laboratories, though typical data were requested and for the most part were submitted. Table 6 is a summary of the data submitted by the six laboratories. The compliance data submitted by the various laboratories were in a similar range, with the exception of Lab L3, which as mentioned previously, performed their tests at significantly lower temperatures than normal.

The replicates referred to in Table 6 were individual tests on the same mixture, which are normally averaged when reporting the final results of the IDT creep compliance test. In other words, this data set does not include full “true” replication, in which the same mixture was tested repeatedly, in each case using three replicate measurements. However, the three individual measurements comprising a normal IDT creep test contain perfectly useful statistical information and can be treated as replicates for the purposes of evaluating the precision of the IDT creep test. In this study, the three (or in

TABLE 5 Description of laboratories participating in the precision study

Laboratory Code	Type of Organization	Type of Test System
L1	University	Servo-hydraulic
L2	Commercial Engineering, Research, and Testing	Servo-hydraulic
L3	Commercial Engineering, Research, and Testing	Servo-hydraulic
L4	Material Supplier	Servo-hydraulic
L5	Material Supplier	Servo-hydraulic
L6	Superpave Center	Electro-mechanical

TABLE 6 Summary of data submitted for compliance precision study

Lab. Code	No. of Mixes	No. of Temp.	No. of Reps.	Total No. of Tests	Minimum Compliance (1/GPa)	Maximum Compliance (1/GPa)
L1	4	3	3	33	0.031	0.583
L2	4	3	3	36	0.030	0.511
L3	6	3	3	54	0.027	0.188
L4	6	3	4	96	0.032	0.543
L5	2	3	3	18	0.053	0.875
L6	4	3	3	36	0.046	0.737
All labs	**26**	**3**	**3-4**	**273**	**0.027**	**0.875**

one case four) individual measurements on each mix were analyzed separately to provide independent replicate determinations. These were then used to estimate an average value and a standard deviation for each mixture for a given laboratory. These values were then averaged over all mixtures for a given laboratory. For standard deviation, the average was calculated as the square root of the average variance, which is the correct way of calculating an average or pooled standard deviation. Statistics were calculated for compliance, m-value (log-log slope of creep compliance), and Poisson's ratio (ν).

Because a normal IDT creep test consists of an average of three measurements, the standard deviation and coefficient of variation calculated as described above (for a single measurement) overestimate the variability in the standard procedure. In order to estimate the standard deviation for the complete procedure (including full replication), the standard deviation for an average containing three replicates must be calculated—this is simply the standard deviation divided by the square root of 3. This is referred to in this report as the standard error (SE). Finally, the d2s precision was calculated for each laboratory and temperature.

Figures 1 through 4 graphically represent d2s precision estimates for compliance, m-value, Poisson's ratio, and critical temperature (respectively) for the six laboratories involved in this study. For compliance (Figure 1) d2s precision is given as a percentage, while for m-value (Figure 2), Poisson's ratio (Figure 3), and critical temperature (Figure 4), it is in absolute terms. Critical temperature is the temperature at which the calculated thermal stress equals the tensile strength; it represents the expected cracking temperature during a single extreme low-temperature event (*10*). This value was estimated using typical values for tensile strength (3.0 MPa) and coefficient of thermal expansion (1.1×10^{-5} m/m/°C), so that the variability was from compliance measurements only.

The variability in compliance, in general, appears to increase with temperature and is generally in the range of about 10 to 30 percent, though it is somewhat higher for Lab L5 and Lab L6. Because data for only two mixtures were submitted for Lab L5, the variability estimates are not completely reliable. The higher variability for Lab L6 is probably due to the electro-mechanical test system used there, which, as discussed previously, was one of the prototypes procured for the Superpave Centers that exhibited many software and hardware problems. The average d2s precision for all laboratories was 22, 28, and 32 percent at the lowest temperature, the middle temperature, and the highest temperature, respectively. Excluding data from Lab L6 would probably reduce these values to about 20 to 30 percent, which is somewhat high for single-operator precision values. If it is assumed that

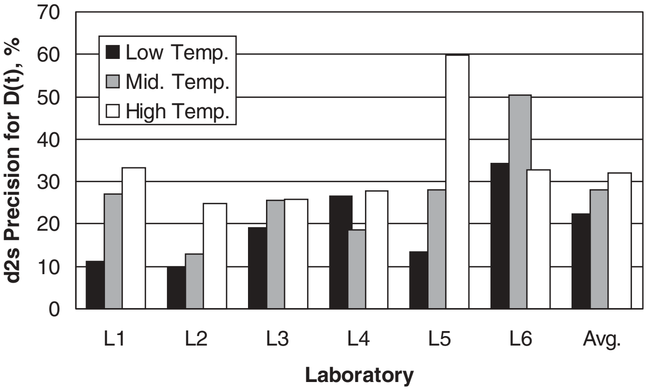


Figure 1. D2S precision for compliance for six laboratories.

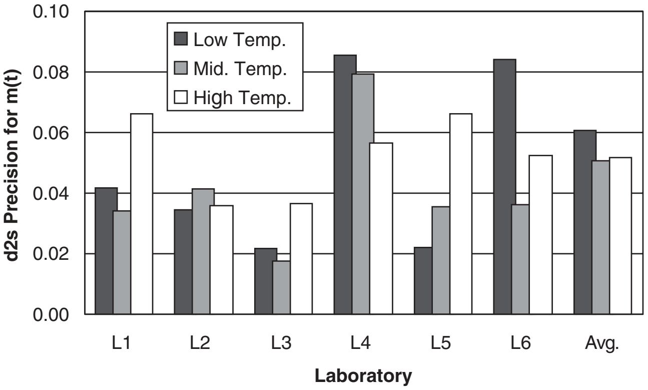


Figure 2. D2S precision for m(t) for six laboratories.

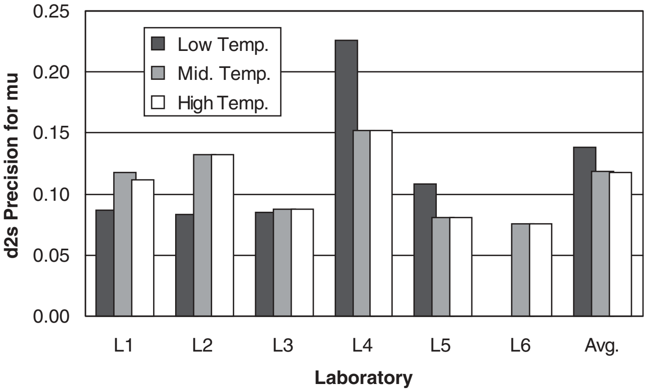
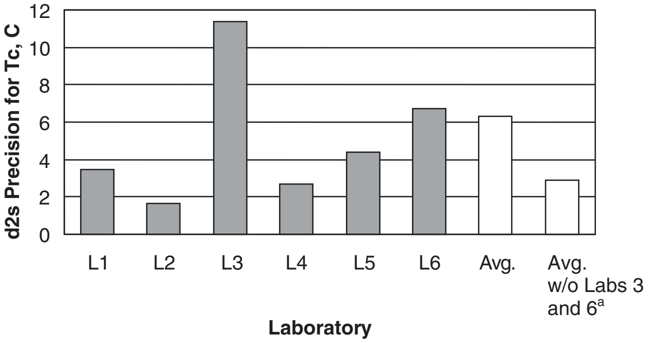


Figure 3. D2S precision for Poisson's ratio for six laboratories.



[a] The reasons for excluding the results from Labs 3 and 6 from the average are given in the text.

Figure 4. D2S precision for critical temperature for six laboratories.

interlaboratory d2s values are roughly twice single-operator values, the interlaboratory precision for compliance would be 40 to 60 percent, which is clearly too high. However, improvements in test equipment and procedures can probably substantially improve the precision of this test.

Similar trends are observed in d2s precision for m-value and Poisson's ratio. The variability for Poisson's ratio seems to be particularly high, given that the average values for ν were from 0.35 to 0.40. The poor precision for the determination of Poisson's ratio and the fact that this property is in general not considered critical in determining resistance to low-temperature cracking, indicate that measurement of ν is not necessary for low-temperature characterization of asphalt concrete. It is of course a necessary part of the IDT procedure.

The d2s precision values for critical temperature (Figure 4) range from slightly less than 2°C for Lab L2 to almost 12°C for Lab L3. However, the compliance data for Lab L3 was determined at very low temperatures, which is probably the reason for the extreme variability in critical temperatures. This emphasizes the importance of performing compliance measurements at appropriate temperatures. As discussed previously, the compliance measurements for Lab L6 were done using an electro-mechanical test system and should also not be considered representative of the data quality possible with a good servo-hydraulic system. Eliminating these two laboratories, the average d2s precision for critical temperature was 2.9°C, equivalent to half a binder grade. Again, this is probably somewhat high considering that this is a single-operator value, but it should be possible to improve this value by further standardization of the low-temperature test equipment and procedure.

Summary of Findings on Precision and Bias

A summary of the various estimated statistics on the IDT creep and strength tests is presented in Table 7. These statistics are based upon a test consisting of the average of three replicates. Because the statistics were calculated based upon replicate measurements conducted within each laboratory, the results correspond approximately to single-operator conditions; between-laboratory variability would be larger. The statistics on strength are based upon the data reported by Anderson and McGennis, as discussed previously (*3*). The statistics for IDT creep data are based upon data submitted by six different laboratories, as described previously. The precision estimates for critical temperature were calculated without the data from Labs L3 and L6, because of the anomalously high variability in this statistic for these laboratories.

The precision for the IDT strength test appears to be acceptable. The precision for the IDT compliance procedure, on the other hand, needs to be improved as part of the implementation process. Ruggedness testing for this procedure is the next logical step in the development of this procedure. This testing should identify items in the procedure and equipment that substantially affect the test precision.

THEORY OF IDT TESTING AND ANALYSIS

There are a number of theoretical considerations in the evaluation of both the IDT and uniaxial creep and strength tests. These include the following issues:

- Linearity,
- Homogeneity,
- Anisotropy,
- Poisson's ratio,
- Coefficient of thermal contraction, and
- Estimation of relaxation modulus from creep compliance.

These issues impact the test methods and analysis in a variety of ways. They are discussed in detail in the following sections.

TABLE 7 Summary of statistics on IDT creep and strength tests (n=3 replicates)

Property	Statistics	Lowest Temp.	Middle Temp.	Highest Temp.
Strength	Average, kPa	N/A	2870	N/A
	Std. Error, kPa		200	
	C. V., %		7.0	
	d2s, %		19.7	
Compliance	Average, 1/GPa	0.0463	0.0986	0.2809
	Std. Error, 1/GPa	0.0042	0.0115	0.0413
	C. V., %	7.9	9.9	11.3
	d2s, %	22.3	28.0	32.0
$m(t) = \frac{d \log D}{d \log t}$	Average	0.143	0.238	0.355
	Std. Error	0.021	0.018	0.018
	d2s	0.061	0.051	0.052
Poisson's Ratio	Average	0.350	0.376	0.376
	Std. Error	0.049	0.042	0.042
	d2s	0.139	0.118	0.118
Critical Temp.	Average, °C	-26.3		
	Std. Error, °C	1.0		
	d2s, °C	2.9		

Linearity

The issue of linearity is of great practical importance. Intuitively, asphalt concrete at low temperatures is expected to behave in a linear manner through loading approaching the point of failure, because of the high stiffness of asphalt concrete under these conditions and the very low strains. It is, however, important to verify that the loads used in the IDT test are appropriate—as high as possible, to ensure large deflections and good repeatability, while still remaining in the linear viscoelastic region. AASHTO T322 calls for a maximum strain of 500×10^{-6} mm/mm, or 0.05 percent. This value is consistent with work performed by Mehta and Christensen (*11*), who reported that deviations from linearity began to occur at the same strain level of 0.05 percent. This aspect of AASHTO T322 probably does not need revision.

Homogeneity

Homogeneity is the degree to which the properties of a material are the same at any given point. Most mechanical analyses, including those used to estimate mechanical properties from both the IDT and uniaxial creep and strength tests, assume that a material is homogenous—that is, the properties are the same at any given location within the object considered. However, asphalt concrete is clearly not truly homogenous, because it is composed of three distinct phases—asphalt binder, aggregate, and air. The question is, therefore, whether significant errors are involved in the assumption of homogeneity in the analysis of IDT and uniaxial tests and in the analysis of thermal cracking in general. In general, the larger a specimen is compared to any nonuniformity it contains, the more accurate the assumption of homogeneity. For this reason, homogeneity is probably a very good assumption when analyzing an entire, intact paving system. However, for test specimens of relatively small size, homogeneity might not be even approximately obtained.

Weissman and associates presented a detailed analysis of the effects of specimen dimension on the results of permanent deformation tests (*12*). They discussed the concept of the representative volume element (RVE), which in simple terms can be thought of as the minimum acceptable specimen dimension for a given test and material in order to ensure that the assumption of homogeneity is met. Meeting RVE requirements is an important contribution to test precision. Weissman and his coauthors suggested an RVE of 125 mm for an asphalt concrete mixture containing 19-mm nominal maximum size aggregate. In order to ensure that end effects were insignificant, this would mean that a uniaxial creep test would require a specimen about 350 mm high by 125 mm in diameter (*12*). However, this analysis dealt with permanent deformation tests, where the modulus of the aggregate is much greater than that of the surrounding mastic, a situation that greatly increases RVE size. For low-temperature tests, the RVE should be significantly smaller. Furthermore, because of the strip loading used in the IDT test and the correction factors developed for this test during SHRP that should account for the triaxial loading conditions, end effects should not be a concern for this test. On the other hand, the typical 50-mm specimen thickness for the IDT is very small, as is the LVDT gage length of 37.5 mm. Without a detailed finite element analysis (which was beyond the scope of this study), it cannot be concluded with certainty whether RVE requirements have been met for either the IDT or uniaxial creep and strength tests at low temperature.

One indication of whether the specimen size for the IDT and uniaxial tests is adequate is the precision of these methods compared to what is possible for similar tests where specimen homogeneity is not an issue. For the IDT precision study described previously, the single-test coefficient of variation (C.V.) ranged from 14 to 20 percent. In the experiment phase of this project, presented later in this chapter, the single test C.V. for the IDT creep test was found to be 16 percent, which is in excellent agreement with the results of the interlaboratory precision study. Mehta and Christensen reported C.V. values of 9 to 17 percent for relaxation tests performed using the IDT geometry (*11*). Pellinen reported in detail on the precision of uniaxial dynamic modulus measurements using cylinders 100 mm in diameter by 150 mm high; her analysis broke the variability of the data into within- and between-specimen components (*13*). She reported overall C.V. values for a standard specimen with two LVDTs to be 15 to 21 percent for 12.5-mm mixtures and 17 to 24 percent for 19-mm mixtures (*13*). As a comparison, Christensen and Anderson reported C.V. values for complex modulus of asphalt binders—a very homogenous material compared to asphalt concrete—measured using a dynamic shear rheometer to range from 10 to 17 percent (*14*). Because of the complexity of preparing asphalt concrete specimens for testing, a somewhat higher level of variability should be expected compared to data on asphalt binders. Therefore, it would appear that typical precision levels for both the IDT and uniaxial modulus tests are consistent with a reasonable degree of homogeneity. Further improvements in test precision would provide additional confidence that specimen homogeneity is not an issue with these procedures.

Anisotropy

Isotropic behavior is generally assumed when analyzing test data or performing stress and strain analyses. That is, it is assumed that the mechanical properties of the material in question are independent of direction and sense. Because of the manner in which asphalt concrete specimens and pavements are compacted, it is quite possible that asphalt concrete is anisotropic, that its properties vary depending upon the direction of loading. Support for anisotropic behavior is seen in the relationships between uniaxial and shear moduli values reported by several researchers (*4, 15*). For an isotropic, linear elastic material, the uniaxial modulus $|E^*|$ should be $2(1 + \nu)\ |G^*|$, where ν is Poisson's ratio, typically ranging from about 0.3 to 0.5 for asphalt concrete and $|G^*|$ is the shear modulus. Although the behavior of asphalt concrete under the conditions in question is linear viscoelastic rather than linear elastic, this relationship should apply quite well. However, $|E^*|$ values are normally much higher compared to $|G^*|$ than predicted by this relationship, indicating that there is substantial anisotropy in the behavior of asphalt concrete mixtures (*4*). It appears that because of preferential orientation of aggregate particles during the shearing that occurs with compaction, the shear stiffness of mixtures perpendicular to the plane of compaction is relatively low compared to the uniaxial compressive stiffness in the direction of compaction.

The results of the laboratory testing performed as part of this project (described later in this chapter) indicate that the low-temperature creep compliance of asphalt concrete mixtures does in fact exhibit anisotropy. The creep compliance measured in the diametral plane using the IDT test is less than that measured along the length of the specimen (uniaxially) in compression, which in turn is less than the compliance measured in uniaxial tension. The effect of this anisotropy on the results of IDT and uniaxial stiffness tests is, however, not clear. On one hand, the IDT test has an advantage compared to the uniaxial test because the IDT procedure primarily measures creep compliance in the horizontal plane, which is most important in thermal cracking. On the other hand, the analysis of the IDT test is based upon an assumption of isotropic behavior, and so the analysis is probably not completely accurate, because it appears that the properties in tension and compression are not identical. However, because the tensile strains in the IDT test are quite low, the difference in the tension and compression compliance values is probably small, resulting in a small effect on the IDT data analysis. In view of the apparent anisotropy in asphalt concrete mixtures, the IDT test geometry is probably the most effective of the available methods for determining low-temperature creep compliance.

Poisson's Ratio

Another issue in the IDT test procedure is whether it is truly necessary to determine Poisson's ratio when characterizing the mechanical behavior of HMA at low temperature. Poisson's ratio represents the ratio of lateral to axial deformation under uniaxial loading. It is theoretically necessary to know Poisson's ratio when performing stress analyses in two or three dimensions. However, in performing simple, one-dimensional stress analyses, such as those used in the Superpave thermal cracking analysis, Poisson's ratio is not used. Furthermore, for most materials, Poisson's ratio falls between about 0.2 and 0.5. For asphalt concrete, Huang states that values typically fall in a narrower range, from 0.3 to 0.4 (*16*). Huang goes on to state, "Because Poisson's ratio has a relatively small effect on pavement responses, it is customary to assume a reasonable value for use in design, rather than to determine it from actual tests" (*16*). It appears as though determination of Poisson's ratio is not critical to the prediction of low-temperature cracking, again suggesting that perhaps uniaxial creep tests could provide the needed data more simply and more directly than the IDT creep test. However, it should be kept in mind that in order to properly analyze IDT creep data, it is essential to determine strains in both the vertical and horizontal directions, so that calculation of Poisson's ratio is an inherent part of the IDT procedure.

Coefficient of Thermal Contraction

The thermal stress developed when a pavement cools is directly proportional to the coefficient of thermal contraction. An equation was developed during SHRP for estimating the coefficient of thermal contraction, which is based upon mixture composition and the coefficient of thermal contraction values for the binder and aggregate (*1*):

$$\alpha_{mix} = \frac{\alpha_{AC} VMA + \alpha_{Agg}(100 - VMA)}{300} \qquad (1)$$

where

α_{mix} = linear coefficient of thermal contraction for mixture, m/m/C;
α_{AC} = volumetric coefficient of thermal contraction for asphalt binder, $m^3/m^3/C$;
α_{Agg} = volumetric coefficient of thermal contraction for aggregate, $m^3/m^3/C$; and
VMA = voids in mineral aggregate.

As detailed by Kwanda and Stoffels, the SHRP equation is not accurate (*8*). Values of α_{mix} measured by Kwanda and Stoffels and as calculated using the SHRP equation are plotted in Figure 5. Another problem with the SHRP approach is that the coefficient of thermal contraction of the aggregate must be known. The values estimated during SHRP were made using α_{Agg} values estimated based upon typical values for the aggregates used in each mixture. In most cases, this information will

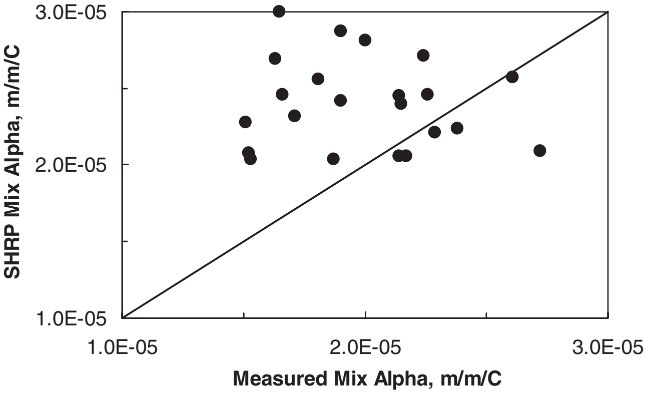


Figure 5. Coefficient of thermal contraction values for SHRP mixtures, as measured by Kwanda and Stoffels (8) and as predicted using the SHRP equation.

not be readily available to engineers and technicians performing mixture design and analysis. Although laboratory procedures for measuring the coefficient of thermal contraction of asphalt concrete mixtures do exist, these methods have not been widely used and are of unknown precision (*9*). An improved, simpler approach is needed for estimating α_{mix} for use in analyzing low-temperature IDT and/or uniaxial creep and strength test data.

In examining the thermal contraction data on the SHRP mixtures for this project, it was found that the mixture coefficient of thermal contraction as predicted using the SHRP equation is largely independent of α_{Agg}. This is because the coefficient of thermal contraction for binders—typically around 1.15×10^{-4} m/m/°C (linear) at temperatures above the glass transition—is much, much larger than the typical value for construction aggregates, about 7×10^{-6} m/m/°C. Furthermore, it was found that mixture coefficient of thermal contraction was much more strongly related to binder volume rather than VMA, as assumed in the SHRP equation. Therefore, a more appropriate equation for estimating the coefficient of thermal contraction for asphalt concrete mixtures would be:

$$\alpha_{mix} = \frac{\alpha_{AC} Vbe + 7 \times 10^{-6}(100 - VMA)}{100} \tag{2}$$

Where *Vbe* is the volume percentage of asphalt binder in a mixture, and the coefficient of thermal contraction for the binder is a linear value, in m/m/°C. Equation 2 can be rearranged to give α_{AC} in terms of the mixture composition and coefficient of thermal contraction:

$$\alpha_{AC} = \frac{\alpha_{mix} 100 - 7 \times 10^{-6}(100 - VMA)}{Vbe} \tag{3}$$

Using Equation 3, the SHRP mixture composition data provided by Lytton and his associates (*1*), and the mixture coefficient of thermal contraction values measured by Kwanda and Stoffels (*8*), α_{AC} values were estimated for the SHRP mixtures. Because coefficient of thermal contraction values for binders are largely a function of the glass transition temperature of the binder, there should be an approximate relationship between binder stiffness at low temperature and this estimated value of α_{AC}. However, the binder data on the SHRP mixtures were very limited and based on measurements on extracted binders that are probably not highly reliable. Also, low-temperature binder data might not always be available when analyzing data on asphalt concrete mixtures at low temperature. Therefore, it was felt that mixture stiffness data would provide a more practical means of estimating α_{AC}. Mixture creep compliance is a function of binder stiffness, aggregate modulus, and mixture composition, and so is not a good choice for relating to binder coefficient of thermal contraction. Mixture m-value (d [log (*D*)]/d [log(*t*)]), where *D* is the creep compliance, is a much better choice for correlation to α_{AC}, because this should be largely independent of aggregate properties and mixture composition. Figure 6 is a plot of α_{AC} values calculated using Equation 3 as a function of mixture m-values. There is a definite relationship, though it is only weak to moderate in strength ($R^2 = 42$ %). However, it should be kept in mind that the measurement of the coefficient of thermal contraction of the mix is difficult and somewhat variable. The standard deviation for α_{mix} for the data reported by Kwanda and Stoffels (*8*) was 1.5×10^{-6} m/m/°C, corresponding to a standard error (n = 2) of 1.1×10^{-6} m/m/°C and a d2s precision of 3.0×10^{-6} m/m/°C. For the average α_{mix} value of 2.0×10^{-5} m/m/°C, this last value corresponds to a precision of 15 percent as a percentage of the mean response. Also note in Figure 6 that the calculated values of α_{AC} are relatively large, typical for temperatures above T_g. It can be concluded that it is generally not necessary to account for the decrease in α_{AC} that occurs at and below T_g.

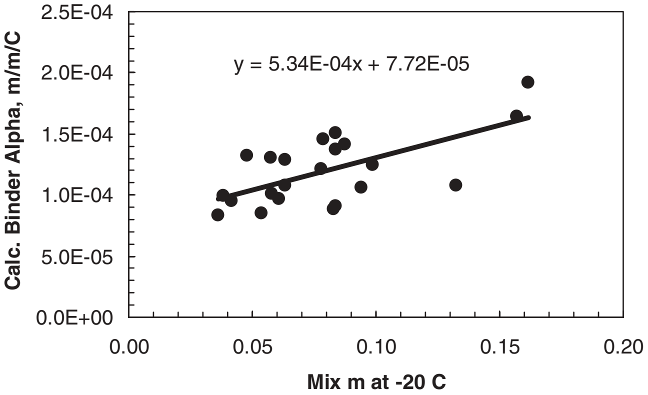


Figure 6. Calculated binder coefficient of thermal contraction as a function of mixture m-value at −20°C for SHRP mixtures ($R^2 = 42\%$).

Using the relationship shown in Figure 6, α_{AC} values were estimated for the SHRP mixtures and then used along with *Vbe* and VMA values to predict α_{mix} values, using Equation 2. These calculations can be combined into one equation for estimating the coefficient of thermal contraction of asphalt concrete mixtures:

$$\alpha_{mix} = \frac{(5.3 \times 10^{-4} m + 7.7 \times 10^{-5}) Vbe + 7 \times 10^{-6}(100 - VMA)}{100} \tag{4}$$

Where *m* is the log-log slope of the mixture creep compliance with respect to time (t), from = 5 to 100 seconds at the lowest test temperature, normally −20°C. The resulting values are compared to those measured by Kwanda and Stoffels (*8*) in Figure 7. Although the predictions are not highly accurate, they are substantially better than those made using the SHRP equation (Figure 5). Furthermore, compared with the d2s confidence limits for measured α_{mix} (included in Figure 7 as horizontal error bars), the accuracy of the predictions is probably as good as can be expected and appears to be comparable in accuracy to values determined experimentally. It is suggested that Equation 4 be used to estimate α_{mix} values when analyzing low-temperature creep and strength data on

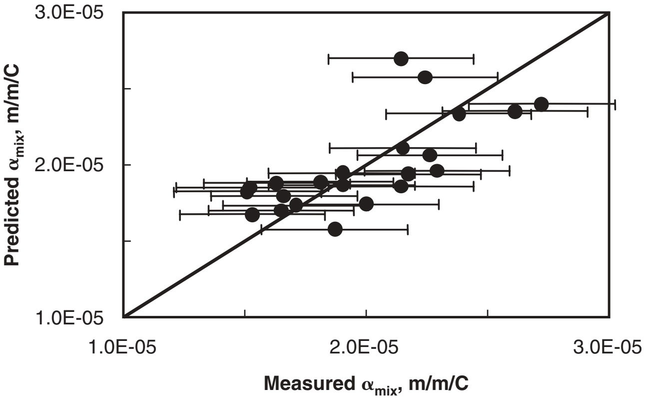


Figure 7. Mixture coefficient of thermal contraction values as measured by Kwanda and Stoffels (8) (with d2s precision limits for measured values) and as predicted by Equation 4.

asphalt concrete mixtures, rather than either using the SHRP equation (Equation 1) to estimate values or determining values experimentally.

Estimation of Relaxation Modulus from Creep Compliance

Another potential problem in the analysis of low-temperature creep data is the estimation of relaxation modulus from creep compliance. This is an essential step in the calculation of thermal stress in a pavement using either IDT or uniaxial creep data. In the approach developed by Roque and his associates during and after SHRP (*1,5*), a master curve of creep compliance is developed from creep data at three temperatures, normally –20, –10 and 0°C. Then, an exponential, or Prony, series is fit to these data:

$$D(t_r) = D_0 + \sum_{i=1}^{N} D_i\left(1 - e^{-tr/\tau i}\right) + {t_r}/{\eta} \tag{5}$$

where

$D(t_r)$ = creep compliance at reduced time t_r,
D_0 = glassy compliance at $t_r = 0$,
D_i = compliance for Prony series element *i,*
τ_i = relaxation time for Prony series element *i,* and
η = viscosity as $t_r \rightarrow \infty$.

The relaxation modulus is related to the creep compliance through the Laplace transform:

$$L[D(t)]L[E(t)] = s^2 \tag{6}$$

where

$L[D(t)]$ = the Laplace transform of the creep compliance,
$L[E(t)]$ = the Laplace transform of the relaxation modulus, and
s = the transform parameter.

An exponential series for the relaxation modulus can be calculated once the Prony series parameters for the creep compliance are known:

$$E(t_r) = \sum_{i=1}^{N+1} E_i e^{-\tau i/t_r} \tag{7}$$

where

$E(t_r)$ = relaxation modulus at reduced time t_r
E_i = modulus for Prony series element *i*
τ_i = relaxation time for Prony series element *i*

Both Equation 5 and Equation 7 represent mechanical analogues for describing linear viscoelastic behavior. Equation 5 represents a generalized Maxwell model, whereas Equation 7 represents a generalized Kelvin model.

The procedure described above was used to calculate relaxation modulus using data for six different mixtures, as submitted by Lab L4 of the IDT creep precision study described previously. In fitting the Prony series to the creep compliance data, five evenly spaced relaxation times were assumed, covering a time range slightly larger than that for the entire master curve. Then the compliance values for each element were determined using simultaneous equations, resulting in exact agreement between the measured and fitted Prony-series compliance values at each of the selected relaxation times. The Prony series parameters for the relaxation modulus were calculated using the collocation method described by Christensen (*17*); a detailed description of this method is beyond the scope of this report, but it also relies on simultaneous equations to determine the series parameters. An example of the Prony series fit to the creep compliance is shown in Figure 8, which is for mixture 1 from Lab L4 of the precision study. Note that the compliance values predicted by the Prony series approach diverge dramatically from the power law fit to the master curve at a reduced time of about 1×10^6 seconds. This represents the end of the experimentally determined master curve and the longest relaxation time for the Prony series. Figure 9 shows the corresponding predicted relaxation modulus; the creep modulus, 1/D(t), which is a rough approximation to the relaxation modulus; and an estimate of the relaxation modulus based upon Christensen's method for approximate inversion of the Laplace transform (*10,17*). As with the creep compliance, the relaxation modulus values predicted using the Prony series approach diverge dramatically from other estimates at long reduced times. Some irregularities in the Prony series values are also evident as waviness in the master curve at long reduced times, which is due to the discrete nature of the Prony series. If a very large number of elements are used at closely spaced relaxation times, these irregularities become insignificant. It would appear from this and other comparisons that Christensen's approximate method is somewhat more accurate and reliable than the Prony series method, although the differences are small except at long reduced times.

The six mixtures submitted by Lab L4 in the precision study were analyzed as described above. Furthermore, each analysis was performed using the full set of creep data (–20, –10, and 0°C data), using data at –20 and –10°C only, and using data at –20°C only. This was done to evaluate the effect of mixture stiffness on the Prony series error, because the error

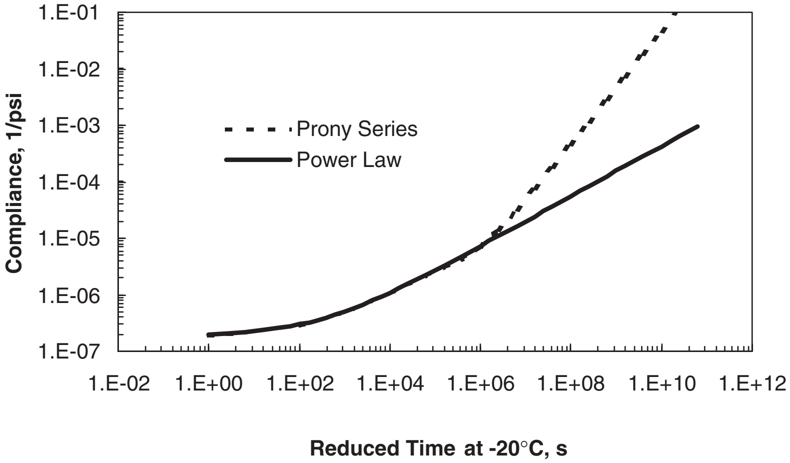


Figure 8. Creep compliance for Mixture 1 from Lab L4 of the precision study: Power law and Prony series fits to the master creep curve.

is likely to become more severe as the mixture becomes stiffer. The results shown above were typical, and the analysis confirmed that the extent of this error became larger as the asphalt concrete stiffness increased. To quantify the magnitude of this error, Christensen's version of the SHRP analysis method was used to estimate a critical cracking temperature (*10*). This method is essentially identical to the SHRP method, but Christensen's (*17*) approximate method for estimating relaxation modulus from creep compliance is used rather than the Prony series approach, and the calculation stops at estimating the critical cracking temperature, T_c, defined as that at which the thermal stress in the pavement reaches the tensile strength. In this case, a typical mixture coefficient of thermal expansion of 1.1×10^{-5} m/m/°C was assumed for all mixtures. Similarly, a typical tensile strength of 3.0 MPa was also assumed. However, to estimate the potential error in the Prony series approach, three additional estimates of T_c were made using relaxation modulus values estimated using the Prony series approach, with full data, data to −10°C, and with −20°C data only. The results of this analysis are summarized in Figure 10. Note that the critical cracking temperatures estimated using the Prony series approach are always lower than those calculated using Christensen's (*17*) approximate method for estimating the relaxation modulus. Furthermore, the error increases as the data used in the analysis become stiffer. The errors however are generally small—only a few degrees—though for the −20°C data, the errors often exceed 3°C.

This error can be corrected in several ways. The number of relaxation times used in the Prony series could be increased (say doubled) and the time covered by the Prony series also increased. Another approach would be to use an approximate method for estimating the relaxation modulus, which,

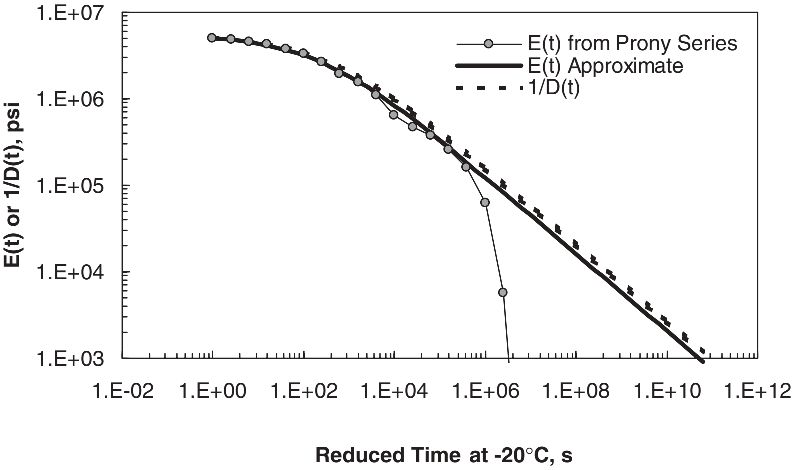


Figure 9. Relaxation modulus for mixture 1 from Lab L4 of the precision study: Values estimated using Prony series approach, Christensen's approximate method, and the inverse of the creep compliance.

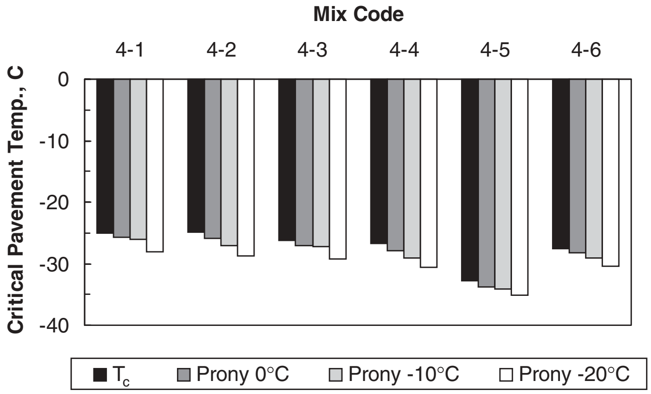


Figure 10. Errors in critical cracking temperature resulting from using Prony series approach to estimate relaxation modulus.

although not as theoretically elegant, produces more robust estimates over a wide range of conditions. The third approach is the simplest and most direct: adjust IDT (or uniaxial) creep test temperatures to avoid collecting exceedingly stiff compliance data. Based upon this analysis and general experience with low-temperature creep data, the following protocol is suggested:

- For mixtures made using PG XX-22 and PG XX-28 binders, creep tests should be performed at –20, –10 and 0°C; tensile strength should be determined at –10°C.
- For mixtures made using PG XX-34 binders (or softer), creep tests should be performed at –30, –20 and –10°C; strength tests should be performed at –20°C.
- For mixtures made using PG XX-16 binders (or harder), or severely aged mixtures, creep tests should be performed at –10, 0, and +10°C; strength tests should be performed at 0°C.

This approach should ensure that the compliance data collected will not be prone to excessive errors when the maximum relaxation time for the Prony series is exceeded. This will have the added benefit of producing more uniform data, which should help improve the precision of the test. This protocol is also consistent with that presented earlier, based on more practical considerations.

Summary and Findings on Theory of Testing and Analysis

Under the loads normally used in the IDT creep test and likely to be used for uniaxial creep testing, asphalt concrete behaves essentially as a linear viscoelastic material. Data at this time suggest that IDT specimens are large enough to provide for a reasonable degree of homogeneity for most asphalt concrete mixtures, though additional research needs to be done in this area.

Poisson's ratio does not need to be known for an analysis of thermal stresses in asphalt concrete pavement, so there is no need to determine it as part of a uniaxial creep test. It is, however, an essential part of the IDT creep test.

The SHRP equation for estimating the coefficient of thermal expansion of asphalt concrete mixtures is not accurate. A simple and reasonably accurate alternative method has been developed that uses the volumetric composition of the mixture and the mixture m-value (log-log creep compliance slope with respect to time) to estimate the coefficient of thermal contraction of the mixture. This approach appears to be similar in accuracy to the laboratory measurement of the coefficient of thermal contraction.

The Prony series method of calculating relaxation modulus from creep compliance, in general, works acceptably well, but can result in significant errors for stiff mixtures when the maximum relaxation time for the series is exceeded during the analysis. To avoid this problem, test temperatures should be varied according to the binder grade used in producing a mixture. The current test temperatures should continue to be used for PG XX-22 and PG XX-28 binders. For mixtures made using softer binders, all test temperatures should be lowered by 10°C; for mixtures made using harder binders or heavily aged binders, all test temperatures should be raised by 10°C.

COMPARISON OF COMPLIANCE VALUES AS DETERMINED USING UNIAXIAL TENSION, UNIAXIAL COMPRESSION, AND THE IDT TEST

An experimental test program was designed and executed to answer several important questions related to the determination of the low-temperature creep compliance of asphalt concrete mixtures:

- Is the low-temperature creep compliance of asphalt concrete similar in tension and compression?
- Does the IDT creep test provide creep values similar to those determined in uniaxial tension or compression?
- If the creep compliance values as determined in uniaxial tension, uniaxial compression, and with the IDT creep test are not similar, what is the nature of the relationship among these data?
- How does the precision of test data compare for compliance determined using uniaxial tension, uniaxial compression, or the IDT test?

This section of this report discusses the design, execution, results, and findings of this test program.

Materials, Methods, and Experiment Design

Table 8 lists the four aggregate types and gradations used in the laboratory testing performed as part of Phase III of NCHRP Project 9-29. Nominal maximum aggregate size ranged from 9.5 mm to 25 mm, and the mineralogy was

TABLE 8 Aggregate gradations

	Aggregate Type:			
Sieve Size *mm*	9.5-mm VA Limestone	12.5-mm MD Diabase	19-mm VA Granite	25-mm PA Gravel
	Percent Passing by Weight:			
37.5	100	100	100	100
25.0	100	100	100	97
19.0	100	100	96	86
12.5	100	97	76	63
9.5	97	75	54	46
4.75	63	38	33	35
2.36	42.0	29.3	24.0	25.0
1.18	26.7	22.7	18.8	14.0
0.600	17.2	18.5	15.0	9.0
0.300	11.2	11.9	10.8	5.0
0.150	7.9	7.2	6.1	4.0
0.075	6.3	5.6	3.2	3.9

TABLE 9 Binder grades and bending beam rheometer test data

	Binder Grade			
Temperature	PG 58-28	PG 64-22	PG 76-16	PG 76-22
°C	*Stiffness (MPa)/m-value (PAV Residue):*			
-6			78/0.321	
-12		214/0.359	158/0.285	179/0.349
-18	216/0.373	507/0.275		
-24	548/0.278			

distinctly different for each aggregate type. The four binders used in the study are given in Table 9. The grades included were PG 58-28, PG 64-22, PG 76-16, and PG 76-22. The first three of these asphalt binders were unmodified; the PG 76-22 was an SBS modified binder.

A total of 16 mixtures were designed with these materials—each of four aggregate types with each of four binder types. All were designed according to Superpave procedures, with an N_{design} of 100 gyrations. The resulting design volumetric composition of the mixtures is given in Table 10 (the design air void level was in all cases 4 percent by volume). The resulting mixtures covered a wide range of VMA—12.6 to 17.6 percent by volume—and a similarly wide range of VFA—68 to 77 percent by volume.

The experiment consisted of measuring both the creep compliance and tensile strength of the mixtures at low temperature, using various procedures. The creep compliance was measured by indirect tensile, uniaxial tension, and uniaxial compression. The IDT creep compliance tests were performed following procedures outlined in AASHTO T322. Specimens having a diameter of 150 mm and a thickness of 50 mm were sawn from standard Superpave gyratory specimens. The specimens for uniaxial tension and uniaxial compression tests were 100 mm in diameter and 150 mm high and were cored and sawn from high (165-mm) gyratory specimens. The procedure used in the uniaxial tests followed as much as possible the same protocol as described in AASHTO T322 for IDT tests, except where the different geometry made changes necessary. The LVDTs used in the IDT creep tests were as described in AASHTO T322—two transducers on each face, one vertical and one horizontal, all with a gage length of 37.5 mm. For the uniaxial tests, two LVDTs were mounted in diametrally opposite locations at the specimen midheight with a gage length of 100 mm. For the uniaxial tension test, the ends of the specimen were fastened to the loading platens using epoxy cement. For the compression tests, rubber loading pads were used between the specimen ends and platens to distribute the load and avoid stress concentrations. All creep tests were 100 seconds in duration and were performed at three temperatures for each mixture. Most of the specimens were tested at −20, −10 and 0°C. Specimens made with the PG 76-16 binder were however tested at −10, 0 and 10°C, because of the hardness of the binder used in specimens (as recommended previously).

Two types of strength tests were performed: IDT strength, per AASHTO T322, and uniaxial tension. The tests were performed at the middle creep temperature, usually −10°C, except that the specimens with the PG 76-16 binder were tested at 0°C. The IDT strength tests were instrumented so that the exact procedure described in AASHTO T322 could be used to determine the point of failure. In analyzing the data, this procedure was used along with the more direct approach of simply using the maximum load to determine the IDT strength. Hereafter, these are referred to as the corrected IDT strength

TABLE 10 Volumetric properties of mixtures

		Aggregate Type:			
Binder	Property	VA Limestone	MD Diabase	VA Granite	PA Gravel
PG 58-28	*AC, Wt. %*	6.2	4.75	4.4	4.4
	VMA, Vol. %	17.3	13.7	14.3	12.6
	VFA, Vol. %	76.9	70.7	72.1	68.2
PG 64-22	*AC, Wt. %*	6.2	4.75	4.4	4.4
	VMA, Vol. %	17.3	13.5	14.2	12.6
	VFA, Vol. %	76.9	70.5	71.7	68.3
PG 76-16	*AC, Wt. %*	6.2	4.75	4.4	4.4
	VMA, Vol. %	17.6	13.7	15.0	12.8
	VFA, Vol. %	77.2	70.8	73.3	68.8
PG 76-22	*AC, Wt. %*	6.2	4.75	4.4	4.4
	VMA, Vol. %	17.0	13.5	14.4	12.7
	VFA, Vol. %	76.5	70.3	72.1	68.6

and the uncorrected IDT strength. The IDT strength tests were performed using a loading rate of 12.5 mm per minute. The uniaxial tension strength tests were performed at a loading rate of 3.75 mm/min, which provides a strain rate roughly equivalent to that in the standard IDT strength test.

The experiment designs for both creep and strength can be considered full factorials. For the creep experiment, there are five factors—test type, aggregate type, binder type, temperature, and loading time—at 4, 4, 3, and 2 levels, respectively (loading times analyzed were 10 and 100 seconds). For the strength experiment, there are only three factors—test/analysis type, aggregate type, and binder type—at 3, 4, and 4 levels, respectively. As described in the following section, a variety of graphical and statistical methods were used in analyzing the data. The primary problem in both experiments involved comparing test data produced on the same set of materials using different methods of testing. Many of the comparisons were done using regression analysis, often with log-log transformations. A more rigorous comparison of compliance test data was done by treating compliance values as paired measurements. For both sets of tests, estimates were made of test variability, presented as both standard deviation and coefficient of variation.

Results of Low-Temperature Creep Compliance Experiment

The most straightforward comparison of data involves graphical methods and basic regression analysis. In Figure 11, the compliance as measured in uniaxial compression is compared to that measured in uniaxial tension. As might be expected, the compliance in tension is usually higher than that measured in compression. The difference between these two measurements is smaller at low temperatures/low compliance values and increases at higher temperatures/compliance values. At high compliance values, the value in tension is often two or more times the value as determined in compression. There is no obvious trend in terms of aggregate—the relationship between the two tests appears to be similar for the four different aggregates used.

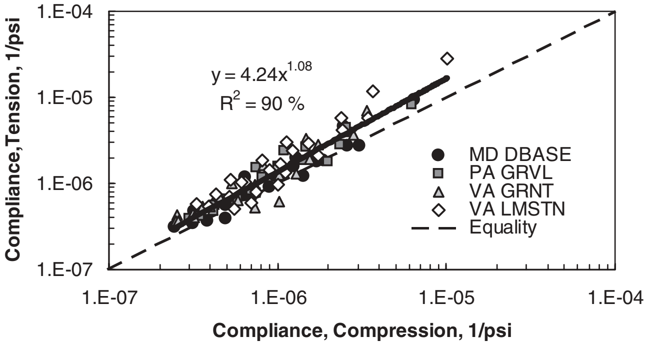


Figure 11. Comparison of compliance as measured in uniaxial compression and as measured in uniaxial tension.

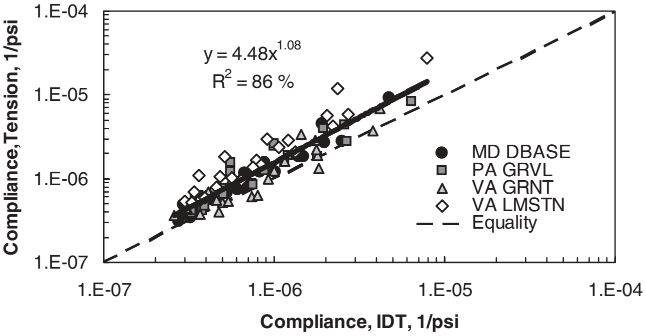


Figure 12. Comparison of compliance as measured in uniaxial tension and as measured using IDT test.

In Figure 12, the compliance values measured in uniaxial tension are compared to those determined using the IDT procedure. The compliance values in tension again appear to be significantly higher, exhibiting a very similar relationship to that between compliance in uniaxial tension and compression. However, in this case it appears that the nature of the relationship varies slightly among the different aggregates used. The difference in compliance values appears largest for the Virginia limestone mixtures, whereas the difference for the Virginia granite mixtures appears to be negligible. This suggests that the compliance as measured using the IDT can be affected by the aggregate used; it is possible, for example, that because of the high stresses at the point of loading that some aggregate particles are being crushed, resulting in substantial redistribution of stresses. It is also possible that the anisotropy is in fact caused by preferential orientation of asymmetric aggregate particles and that the degree of such orientation varies depending upon the specific aggregate used in a mixture.

Based upon Figures 11 and 12, it should be expected that the compliance as measured in uniaxial compression and as measured using the IDT procedure will compare closely. This is confirmed in Figure 13, where these values are plotted against one another. Note that this relationship appears to vary depending on aggregate type, with the softer aggregates exhibiting somewhat lower compliance values in the IDT test compared to the harder aggregates (the Maryland aggregate is a relatively

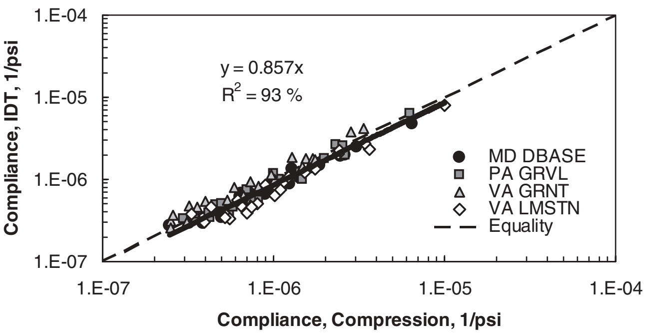


Figure 13. Comparison of compliance as measured in uniaxial compression and as measured using IDT test.

hard diabase). To confirm this, Figure 14 is shown, which is identical to Figure 13, but only includes the hard aggregates (Virginia granite and Maryland diabase). Although the regression line is slightly closer to equality, and the R^2 value is actually lower, the relationship appears to be more uniform and indicative of a better relationship between these test data. Because of the possibility of crushing aggregate and the resulting non-linear behavior, caution should be used in applying the IDT test to mixtures made using soft, friable aggregates.

Two findings stand out in the graphical comparison of compliance values: (1) compliance values in tension and compression are not equal, as assumed in the analysis of the IDT test; and (2) compliance values as determined using the IDT procedure tend to agree very well with those determined in uniaxial compression but not with values determined using uniaxial tension. In interpreting these findings, it must be remembered that the axes in which compliance is determined in these three tests are not the same—the uniaxial tests evaluate compliance along the length (or height) of the gyratory specimen, whereas the IDT evaluates compliance along the diameter of the specimen. Furthermore, the air void distribution in typical gyratory specimens is not uniform, but tends to be higher near the center of the specimen. Because the strain measurements in the IDT test are made near the center of the specimen, the effective air void content for the IDT tests is lower than that for the uniaxial tests. Therefore, there are two possible sources for the higher compliance values determined in the IDT test compared to uniaxial tension: anisotropy and differences in air void content. It is possible that the orientation of aggregate particles during compaction causes anisotropy in laboratory compacted specimens, so that the compliance along the specimen diameter—as determined with the IDT test—is lower than as determined in uniaxial tests. The somewhat lower effective air void content in the IDT specimens is also expected to produce lower compliance values. However, an analysis of creep modulus values as predicted using the Hirsch model (*4*) indicates that differences in air void levels probably only account for a few percent of the observed differences. Because of the apparent presence of substantial anisotropy in asphalt concrete specimens, the IDT creep test should be retained as the preferred procedure for characterizing the low-temperature stiffness of asphalt concrete mixtures.

A more rigorous comparison of data generated by the three low-temperature test methods is given in Tables 11 through 16, which summarize the result of statistical pair-wise comparisons for creep compliance, master curve parameters, and critical cracking temperature. Table 11 compares the compliance measured in uniaxial compression and uniaxial tension. This table includes comparisons at loading times of 10 and

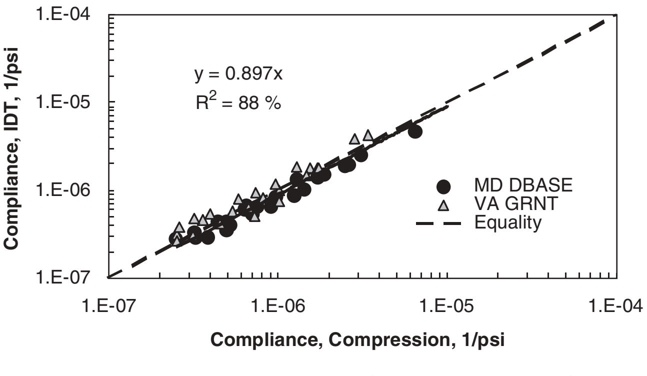


Figure 14. Comparison of compliance as measured in uniaxial compression and as measured using IDT test, hard aggregates only.

TABLE 11 Statistical test for equality of compliance measured in uniaxial compression and as measured in uniaxial tension

Parameter	*D*(Tens.)– *D*(Comp.) *1/psi*	*D*(Tens.)– *D*(Comp.) *%*	Test Stat. |*t**|	Sig. Diff.?
Temp. 1, 10 s	1.08E-07	19.3	2.228	YES
Temp. 1, 100 s	1.01E-07	9.9	1.295	NO
Temp. 2, 10 s	3.76E-07	30.6	2.559	YES
Temp. 2, 100 s	5.29E-07	23.4	2.126	NO
Temp. 3, 10 s	1.26E-06	34.5	2.175	YES
Temp. 3, 100 s	2.16E-06	23.4	1.773	NO

TABLE 12 Statistical test for equality of master curve parameters and critical temperatures from uniaxial compression data and uniaxial tension data

Parameter	Diff.: Tens. – Comp.	Test Stat. |*t**|	Sig. Diff.?
Log (D_0)	0.093	1.574	NO
Log (D_1)	0.260	2.125	NO
M	-0.094	3.345	YES
d log $a(T)$/d T	-0.038	3.584	YES

TABLE 13 Statistical test for equality of compliance measured in uniaxial tension and as measured using the IDT procedure

Parameter	*D*(IDT) – *D*(Tens.) *1/psi*	*D*(IDT)– *D*(Tens.) *%*	Test Stat. |*t**|	Sig. Diff.?
Temp. 1, 10 s	-1.69E-07	-50.0	2.787	YES
Temp. 1, 100 s	-1.98E-07	-45.6	2.053	NO
Temp. 2, 10 s	-4.58E-07	-74.9	2.677	YES
Temp. 2, 100 s	-5.98E-07	-51.7	2.188	YES
Temp. 3, 10 s	-1.54E-06	-102.4	2.260	YES
Temp. 3, 100 s	-2.42E-06	-55.4	1.766	NO

TABLE 14 Statistical test for equality of master curve parameters and critical temperatures from uniaxial tension data and IDT data

Parameter	Diff.: IDT – Tens.	Test Stat. |*t**|	Sig. Diff.?
Log (D_0)	-0.201	2.117	NO
Log (D_1)	-0.308	2.345	YES
M	0.123	3.417	YES
d log $a(T)$/d T	0.046	3.597	YES

TABLE 15 Statistical test for equality of compliance measured in uniaxial compression and as measured using the IDT procedure

Parameter	*D*(IDT)–*D*(Comp.) *1/psi*	*D*(IDT)–*D*(Comp.) *%*	Test Stat. |*t**|	Sig. Diff.?
Temp. 1, 10 s	-6.10E-08	-16.5	1.973	NO
Temp. 1, 100 s	-9.71E-08	-21.2	2.200	YES
Temp. 2, 10 s	-8.21E-08	-14.6	2.130	NO
Temp. 2, 100 s	-6.90E-08	-8.2	1.284	NO
Temp. 3, 10 s	-2.85E-07	-20.6	2.394	YES
Temp. 3, 100 s	-2.66E-07	-8.3	1.205	NO

TABLE 16 Statistical test for equality of master curve parameters and critical temperatures from uniaxial compression data and IDT data

Parameter	Diff.: IDT – Comp.	Test Stat. |*t**|	Sig. Diff.?
Log (D_0)	-0.108	1.434	NO
Log (D_1)	-0.047	0.627	NO
M	0.029	1.436	NO
d log *a*(*T*)/d *T*	0.008	2.140	YES

100 seconds at all three test temperatures. The paired observation test is constructed as follows (*18*):

$$H_0 : Y_1 = Y_2$$

$$H_a : Y_1 \neq Y_2$$

$$\text{If } |t^*| \leq t(1-\alpha/2; n-1) \text{ conclude } H_0;$$

$$\text{otherwise, conclude } H_a$$

$$t^* = (Y_1 - Y_2)/s(Y_1 - Y_2)$$

Where Y_1 and Y_2 are the two quantities being compared, for example, compliance at the lowest temperature and 100 seconds as determined using compression (Y_1) and tension (Y_2); and s is the pooled standard deviation. From the results summarized in Table 11, it appears that the difference between compliance measurements made in compression and tension is greater at short loading times than at long loading times, although the compliance as determined in tension is always greater than that determined in compression. Table 12 shows that several of the master curve parameters exhibit significant differences. The master curve parameters included in Table 12 (and Tables 14 and 16) are D_0, the glassy compliance; D_1, the location parameter; *M,* the limiting log-log slope of the compliance function; and the shift constant, d log $a(T)$/d(T) (the slope of the log of the shift factor with respect to temperature).

Tables 13 and 14 are the corresponding summary comparisons of compliance as measured in uniaxial tension and as determined using the IDT procedure. In this case, the differences appear even larger, with most compliance values and most master curve parameters showing statistically significant differences for the two procedures. Note that the differences in compliance values range from about 45 percent to over 100 percent, with the compliance in tension always much larger than that determined using the IDT test.

The final set of statistical comparisons is given in Tables 15 and 16. In examining the compliance values, the difference between compliance values determined in uniaxial compression and using the IDT test is statistically significant in two of six cases. The compliance values determined in compression range from about 8 to 20 percent higher than those determined using the IDT test. The only master curve parameter for which the difference is statistically significant is the shift constant. In general, the compliance values determined using the IDT test and those determined using uniaxial compression compare favorably, but they are not entirely interchangeable.

The statistical analysis presented above agrees with the graphical comparison presented earlier and confirms that the observed differences in compliance values determined using the three procedures are statistically significant. As discussed, the IDT creep compliance values are the lowest, followed by the values determined in compression. The compliance values determined in tension are the highest. As discussed earlier, the relatively low compliance values determined using the IDT test are probably the result of anisotropy and not, primarily, differences in air void, air void distribution, or both.

An important consideration in evaluating the three low-temperature compliance tests is the variability in the resulting data. To provide better estimates of variances, the data from all mixtures were combined into two sets having reasonably similar compliance values. The lower compliance set included data from all mixtures for temperature 1 at 100 seconds and temperature 2 at 10 seconds. The higher compliance set included data from all mixtures for temperature 2 at 100 seconds and temperature 3 at 10 seconds. By combining the data in this way, 30 degrees of freedom were achieved in the variance estimates. The resulting variances are shown in Table 17.

By calculating variance ratios for each pair of data, an F-statistic was constructed and compared to a critical value of $F(1 - \alpha/2, n_1 - 1, n_2 - 1) = F(0.975, 30, 30) = 2.07$ (*18*). At a significance level of 0.05, only the difference between the variances for the IDT test and the compression for the lower compliance set is statistically significant. In general, it appears that the three test procedures produce data with similar variability. The pooled C.V. for the compliance values were 10 percent for uniaxial tension, 16 percent for uniaxial compression, and IDT for n = 1 replicate. For n = 2 replicates, the C.V. values were 7 percent for uniaxial tension and 11 percent for uniaxial compression and IDT. The C.V. dropped further for n = 3 replicates to 6 percent for uniaxial tension and 9 percent for uniaxial compression and IDT.

TABLE 17 Estimated variances for compliance measurements

Test	Lower Compliance Temp. 1, 100 s & Temp. 2, 10 s	Higher Compliance Temp. 2, 100 s & Temp. 3, 10 s
Tension	7.53E-15	8.74E-14
Compression	1.52E-14	8.16E-14
IDT	6.95E-15	6.67E-14

Comparison of Strength Test Procedures

An important aspect of the IDT creep and strength test procedure is the specific procedure required to perform the IDT strength test. As currently written, the IDT strength test in AASHTO T322 requires deformation to be monitored using vertical and horizontal LVDTs mounted on the specimen. The load for calculating strength is determined from the point at which the vertical minus horizontal deformation is a maximum. Unfortunately, this procedure often results in damaged or destroyed transducers. As a result, many laboratories now run the IDT strength test without LVDTs and simply use the maximum load to calculate the strength. One of the main objectives of the experimental plan was to evaluate the differences among the uncorrected IDT strength determined from the maximum load, the corrected IDT strength determined from the maximum difference in the vertical and horizontal deformations, and the strength as measured in direct tension. Figure 15 shows the relationship between uncorrected and corrected IDT strengths. The relationship is reasonably good, with an R^2 value of 74 percent.

An important, related question is whether or not the correct strength actually provides tensile strength values similar to those measured in direct tension. Figure 16 illustrates the relationship between uncorrected IDT strength and the direct tension strength. Figure 17 is the corresponding plot for corrected IDT strength and strength in the direct tension test.

It is clear that the procedure in AASHTO T322 does in fact provide a better estimate of the tensile strength measured in direct tension than using the maximum load in the IDT test to calculate strength. However, the relationship is still not very strong, with an R^2 value of 49 percent. It should be remembered that asphalt concrete stiffness is anisotropic and that strength might also be so. Therefore, differences in IDT and uniaxial tensile strength are not necessarily indicative of inaccuracies in either test procedure. Although the AASHTO T322 procedure does appear to be reasonable, it is suggested, because of practical problems with this approach, that tensile strength be estimated from uncorrected IDT strength using the equation given in Figure 15 ($R^2 = 74\ \%$):

$$\textit{Tensile Strength} = (0.78 \times \textit{IDT Strength}) + 38 \qquad (8)$$

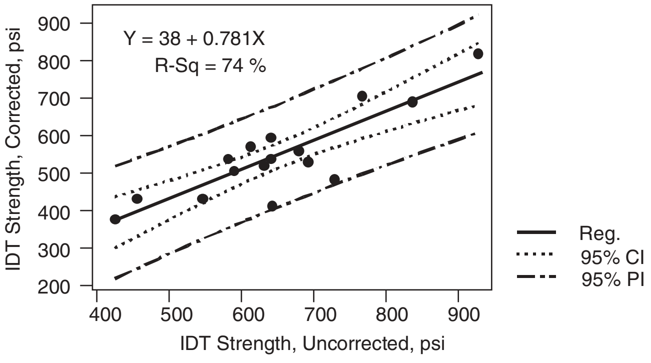


Figure 15. Regression line with 95-percent confidence and prediction intervals for relationship between uncorrected and corrected IDT strength.

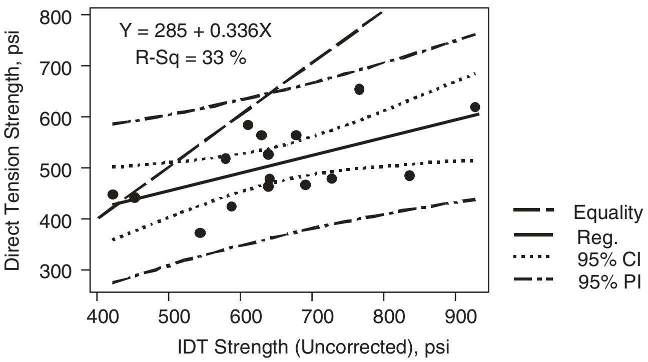


Figure 16. Regression line with 95-percent confidence and prediction intervals for relationship between uncorrected IDT strength and direct tension strength.

This approach should provide good estimates of actual tensile strength without risking damage or destruction of expensive instrumentation during the IDT strength test.

A simple, alternative approach to estimating tensile strength is to develop a regression equation based on mixture volumetric composition. Such a method might be useful, for instance, in quality control applications. The best such model found for the data generated in this project is shown in Figure 18, which is a plot of direct tension strength as a function of VFA. This relationship is better than that between IDT strength and tensile strength and similar in strength to that between corrected IDT strength and tensile strength. However, in examining this figure it was noticed that several of the outlying points were for mixtures made using a modified binder (PG 76-22).

A multiple regression model was developed which allowed for a different slope for mixtures with unmodified and modified binders by using an indicator variable for binder type and including in the model the interaction term for indicator variable by VFA. The results of this regression model are summarized in Table 18. It was found that if both a different intercept and slope were allowed for the modified binder, neither term was significant. A different slope was allowed in this case because it was believed to be a more reason-

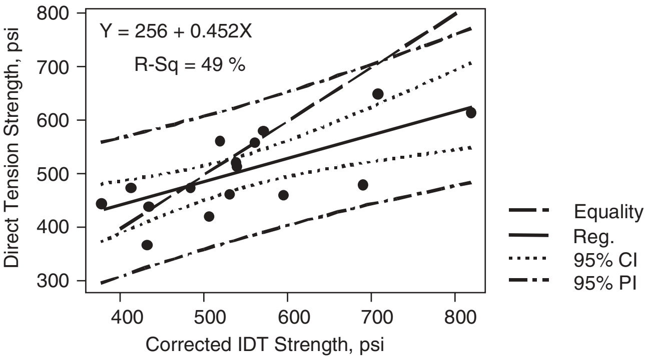


Figure 17. Regression line with 95-percent confidence and prediction intervals for relationship between corrected IDT strength and direct tension strength.

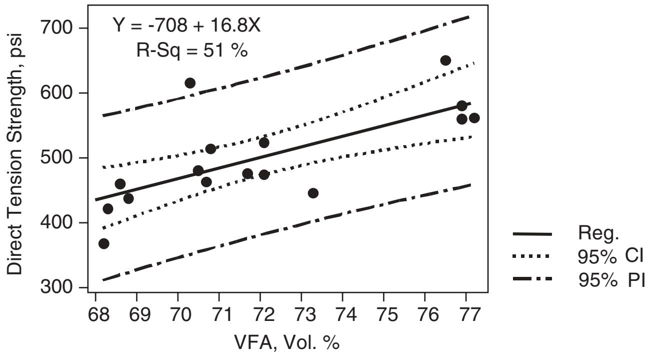


Figure 18. Regression line with 95-percent confidence and prediction intervals for relationship between VFA and direct tension strength.

able assumption. Based upon the results given in Table 18, the regression equation for strength of mixtures using nonmodified binders is:

$$Strength = -739 + 16.9\ VFA \tag{9}$$

For mixtures made using modified binders, the equation becomes

$$Strength = -739 + 18.1\ VFA \tag{10}$$

As seen in Figure 19, this approach greatly improved the quality of the model. In this plot, modified VFA is simply VFA for mixtures with unmodified binders and 1.08 × VFA for mixtures made using modified binders—this adjustment accounts for the difference in slopes for the two cases. Additional research is needed to expand the data set underlying this model, especially with regard to additional modified binders. However, it is potentially a very useful method for estimating tensile strength when measurements are impossible or impractical.

Based on this analysis, the procedure included in AASHTO T322 for determining the true point of failure in the IDT strength test produces significantly better estimates of the true tensile strength than simply using the maximum load developed during the test. However, the AASHTO T322 procedure is not highly accurate and can damage the LVDTs used to monitor deformation during the test. It is therefore recommended that the standard procedure for determining IDT strength should be to determine the maximum load, calculate the uncorrected IDT strength, and then correct it using Equation 8. For some applications, such as quality control testing,

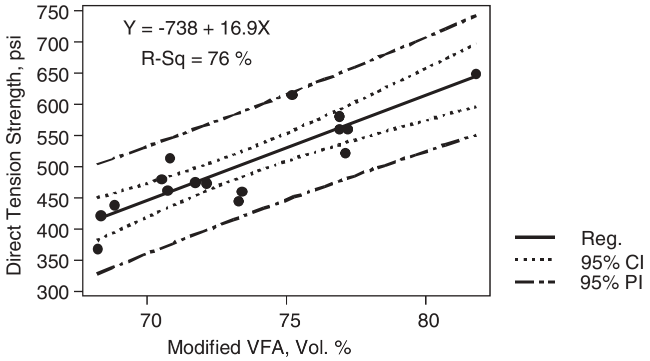


Figure 19. Regression line with 95-percent confidence and prediction intervals for relationship between VFA (modified to account for effect of modified binder) and direct tension strength.

strengths estimated from VFA, using Equations 9 and 10 (or improved versions of these relationships) are probably adequate. Additional research should be performed to better define the relationship between mixture volumetrics, binder type, and tensile strength.

Effect of Test Procedure on Estimated Cracking Temperature

From the previous analyses and discussions, it is clear that there are differences in both creep compliance and strength, depending upon the specific test procedure used. Ultimately, the most important aspect of these differences is their effect on estimated critical cracking temperature. To evaluate the effect of the test procedure on critical cracking temperature, a thermo-viscoelastic analysis was performed using the three different data sets, following Christensen's version (*10*) of Roque and Hiltunen's procedure (*5*). To limit the effect of differences in tensile strength, the direct tension tensile strength was used for each analysis. The results of these analyses are shown in Figures 20 through 22.

In Figure 20, critical cracking temperature from compliance in uniaxial tension is compared to critical temperature determined using compliance data in uniaxial compression. Included in this plot (and the following two) are two standard deviation confidence intervals for the difference between two observations. The agreement in this case is reasonable, except for two points (both Virginia limestone mixes), which show much lower cracking temperatures using tension data than those determined using compression data. The corre-

TABLE 18 Results of regression model for direct tension strength with VFA and binder type as predictors

Predictor	Coefficient	Standard Deviation	t-value	Significance Level
Constant	-739.0	228.8	-3.23	0.007
VFA	16.939	3.171	5.34	0.000
Ind. Varb × VFA	1.1794	0.317	3.72	0.003
R^2 = 76.3 %; R^2 (adjusted for degrees of freedom) = 72.7 %				

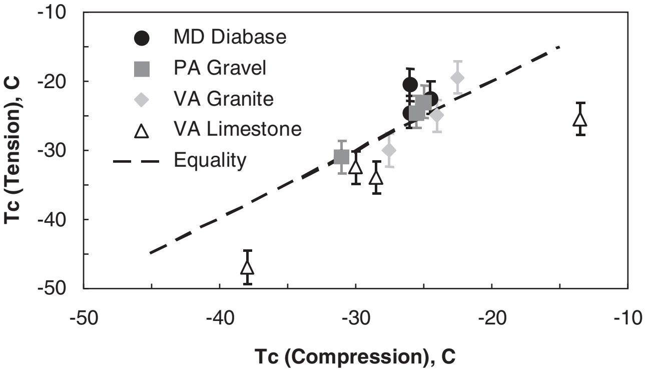


Figure 20. Comparison of critical temperature determined from creep compliance in uniaxial tension and creep compliance in uniaxial compression ($R^2 = 55\%$).

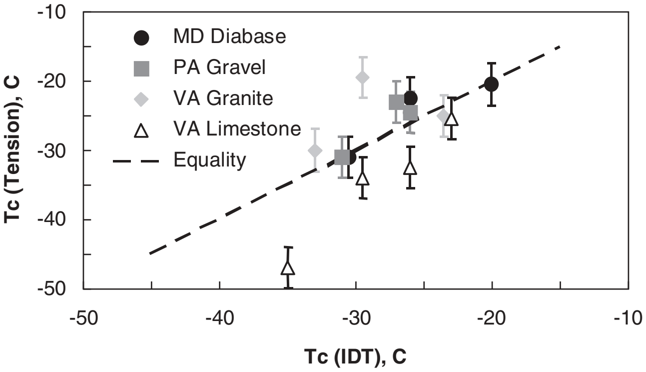


Figure 21. Comparison of critical temperature determined from creep compliance in uniaxial tension and creep compliance from IDT test ($R^2 = 42\%$).

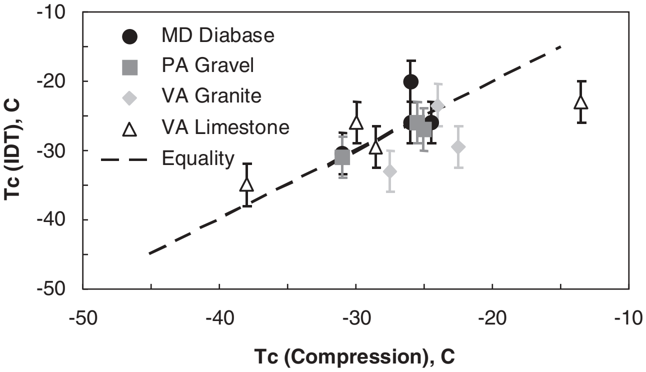


Figure 22. Comparison of cracking temperature determined from IDT test and creep compliance in uniaxial compression ($R^2 = 42\%$).

sponding figure in which critical temperatures were determined using uniaxial tension compliance data and IDT compliance data is shown in Figure 21. In this case, the agreement is poor—there does not appear to be a useful relationship between the results of these analyses. The comparison of critical temperatures determined from IDT compliance data and uniaxial compression compliance data is shown in Figure 22. Again, the relationship is relatively weak.

It is somewhat puzzling that the overall differences in compliance values for the three procedures do not seem to affect the critical cracking temperatures. For example, because the compliance in uniaxial tension is in general significantly higher than that determined from the IDT test, it would be expected that the critical cracking temperatures determined using uniaxial tension compliance data would, in general, be lower than those determined from IDT data. However, this is not the case, as seen in the previous plots. Apparently, differences in the shapes of the master curves and in the temperature dependence as determined using these procedures tend to offset the trends in differences in compliance. The overall result is that all three methods produce critical cracking temperatures in the same temperature range. However, the relationships between critical temperatures are poor. This confirms that uniaxial compliance test data cannot be used as a substitute for IDT compliance data.

Summary and Findings on Comparison of Low-Temperature Creep Compliance Tests and Strength Tests

Based upon the results of low-temperature compliance and strength tests performed on 16 different mixtures using several different test procedures, a number of important findings are apparent. Perhaps most importantly, asphalt concrete specimens prepared using a gyratory compactor are anisotropic—the compliance determined across the diameter is different from that measured along the length of the cylinder. In general, it appears that the IDT creep compliance is slightly less than the uniaxial compliance in compression and substantially less than the uniaxial compliance determined in tension. Although laboratory compaction using the gyratory device does not exactly replicate field compaction, it seems likely that similar anisotropy exists in pavements. Therefore, caution must be used when comparing compliance or modulus values for asphalt concrete determined using different test geometries and using the resulting values in pavement design. Because of this anisotropy, it is recommended at this time that the IDT creep test be retained as the standard method for measuring low-temperature creep compliance of asphalt concrete. There does not seem to be a similar degree of anisotropy in strength test data. Tensile strengths determined in direct tension are similar to those determined using the corrected IDT strength test procedure in AASHTO T322. Furthermore, it appears that corrected IDT strength can be estimated fairly well from uncorrected IDT strength using Equation 8. Therefore, the overall recommendation from the experimental portion of this study is that the IDT creep and strength test be retained for use in estimating the thermal cracking resistance of asphalt concrete but that IDT strengths obtained from the maximum load should be empirically adjusted to provide more realistic estimates of the actual tensile strengths of mixtures.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

GENERAL RECOMMENDATIONS FOR LOW-TEMPERATURE CREEP AND STRENGTH TESTING OF ASPHALT CONCRETE

The IDT geometry was originally selected during SHRP for use in low-temperature characterization of asphalt concrete mixtures primarily because the specimen preparation methods available at that time did not include ways of making specimens suited for uniaxial measurement of creep compliance, relaxation modulus, or strength. The simple performance tests developed as part of NCHRP Project 9-19 and the dynamic modulus master curve characterization methods for structural design recommended in NCHRP Project 1-37A require specimens 100 mm in diameter and 150 mm high to be used in uniaxial testing. Therefore, this obstacle to uniaxial testing no longer exists. Uniaxial testing would also potentially allow the use of relaxation modulus tests, rather than creep tests, which would eliminate the need to calculate the relaxation modulus from the creep compliance. However, relaxation tests have not been widely performed on asphalt concrete mixtures; and, for practical purposes, the creep test should probably be retained regardless of test geometry. A review of the equipment required to perform dynamic modulus master curve testing indicated that, with only minor modifications, it could be used to perform low-temperature uniaxial creep tests. This would have several advantages:

- Cost savings on purchase of test equipment;
- Cost savings on purchase of specimen preparation equipment and test accessories;
- Cost savings on training engineers and technicians to prepare specimens and perform tests;
- Greater reliability of data due to greater experience with a single test geometry and test device; and
- Greater flexibility in scheduling testing, if more than one device is needed in a lab.

For these reasons, significant effort was expended in the laboratory testing of Phase III of NCHRP Project 9-29 to evaluate uniaxial tensile creep testing as the standard low-temperature test for asphalt concrete.

Unfortunately, the laboratory testing and analysis indicated that compliance values determined in uniaxial tension were significantly higher than those determined using the IDT test. Furthermore, the correlation between the two sets of data was not extremely strong. In fact, the compliance values determined using the IDT appear to agree more closely with compliance values determined in uniaxial compression. Because of the extensive work done on the IDT test and analysis—especially the calibration of the Superpave thermal cracking model to field studies—it is recommended at this time that the IDT creep and strength test be retained as the primary method of evaluating the low-temperature properties of asphalt concrete mixtures.

Compliance Measurements

Although determining compliance in uniaxial compression is potentially simpler, quicker, and more economical than using the IDT test, these procedures do not provide interchangeable data. The compliance determined using the IDT test is generally somewhat lower than that determined in uniaxial compression and much lower than that determined in uniaxial tension. This is most likely the result of anisotropy in asphalt concrete specimens prepared using the gyratory compactor. The compliance in the diametral plane appears to be significantly lower than that in perpendicular planes (e.g., along the length of the specimen). Although the gyratory compactor may not always replicate the conditions of field compaction, it seems likely that similar anisotropy exists in situ and that the IDT creep and strength test is probably the best approach to providing estimates of the properties of asphalt concrete in place. Uniaxial compression is suitable for determining creep compliance for research purposes, but it must be realized that the resulting data may not accurately reflect in situ properties or the results of the IDT or other procedures. In general, pavement engineers and researchers should recognize the anisotropic nature of asphalt concrete and make certain that the properties they are using for specification and design purposes are determined using appropriate and uniform methods.

Strength Measurements

The IDT strength procedure as currently described in AASHTO T322 involves using LVDTs to determine the true point of failure and associated tensile strength. This procedure often results in damaged or destroyed LVDTs and is not practical. Phase III of Project 9-29 found that a reasonably good relationship exists between uncorrected IDT strength and IDT strength determined using the more accurate, instrumented procedure of AASHTO T322. It is recommended that the IDT strength test be performed without LVDTs and that the uncorrected strength determined using the maximum load then be adjusted to estimate the corrected IDT strength using the empirical relationship presented in this report as Equation 8.

Proposed Changes to AASHTO T322

The requirements of AASHTO T322 have been reviewed, and a number of relatively minor changes have been recommended. Specific changes in transducer specifications and most other requirements included in this procedure were presented previously in Table 2. Recommended requirements for specimen dimensions and uniformity were listed in Table 3. A revised loading protocol is given in Table 4.

Another important recommendation made in this study is that the temperatures used for low-temperature creep and strength tests should vary according to the stiffness of the mixture. For asphalt concrete mixtures made using PG XX-22 and PG XX-28 binders, the current test temperatures of −20, −10 and 0°C should be retained. For mixtures made using PG XX-16 binders or harder, these temperatures should all be increased by 10°C. Similarly, for mixtures made using PG XX-34 binders or softer, test temperatures should be decreased by 10°C. Highly aged mixtures should also be tested at the higher test temperatures. Tensile strength tests should always be performed at the middle creep test temperature. This protocol will help ensure good test precision and will also help avoid problems that occur when the maximum relaxation time in the Prony series is exceeded during analysis of creep data.

Precision of the IDT Creep And Strength Tests

Anderson and McGennis (*3*) evaluated the precision of the IDT strength test and reported a standard error for n = 3 replicates of about 7 percent. A precision study of the IDT creep tests was performed as part of NCHRP Project 9-29 Phase III, which included numerous mixtures from six different laboratories. Evaluation of these data resulted in estimated standard errors for compliance for n = 3 replicates of 8 to 11 percent expressed as a percentage of the mean (coefficient of variation, or C.V.). This corresponds to a d2s precision of 22 to 32 percent. The laboratory testing executed in this project gave nearly identical results, with an estimated C.V. of 9 percent. The precision for the IDT strength test appears to be acceptable. The precision for the IDT compliance procedure, on the other hand, needs to be improved as part of the implementation process. Further standardization of the procedure and equipment should help achieve improvements in precision.

COEFFICIENT OF THERMAL CONTRACTION

The equation developed during SHRP for estimating mixture coefficient of thermal contraction is not accurate and should be abandoned. Methods for the laboratory measurement of thermal contraction of asphalt concrete mixtures have not been well developed or widely used and are not highly accurate. A simple improved procedure for estimating the coefficient of thermal contraction was developed in this project and provides reasonably accurate results.

ESTIMATING CREEP COMPLIANCE AND STRENGTH VALUES

NCHRP Project 1-37A recommended a three-level hierarchical system for determining inputs for flexible pavement design and analysis. For thermal cracking, IDT creep and strength measurements in accordance with AASHTO T322 are needed for the most reliable, Level 1 determination. Level 2 uses reduced IDT testing at a single temperature; Level 3 is based on typical compliance and strength values for mixtures. In Project 1-37A, predicted thermal cracking based on Level 3 input data did not correlate well with measured thermal cracking for 36 Long Term Pavement Performance (LTPP) sections used to calibrate the Level 3 analysis.

Work performed during Phase III of NCHRP Project 9-29 suggests that better Level 2 and 3 thermal cracking input data might be obtained by determining compliance values using the Hirsch model (*4*) and estimating tensile strength from VFA using Equations 8 and 9. In evaluating the effects of differences in air void content on creep compliance, compliance estimates were made for the mixtures tested in this study using the Hirsch model; binder compliance values were estimated from bending beam rheometer (BBR) test data. Mixtures made with the modified asphalt (PG 76-22) were not included in this analysis, because only one set of BBR data was available, rather than the two needed to develop reasonable creep stiffness estimates over a range of temperatures and loading times. BBR data were empirically adjusted from the Pressure Aging Vessel (PAV) to the Rolling Thin Film Oven Test (RFOT) condition, based upon typical test data as reported by Christensen and Anderson in their study of the SHRP asphalt binders (*14*). The resulting estimated compliance values were in excellent agreement with those measured with the IDT test, as shown in Figure 23. This figure demon-

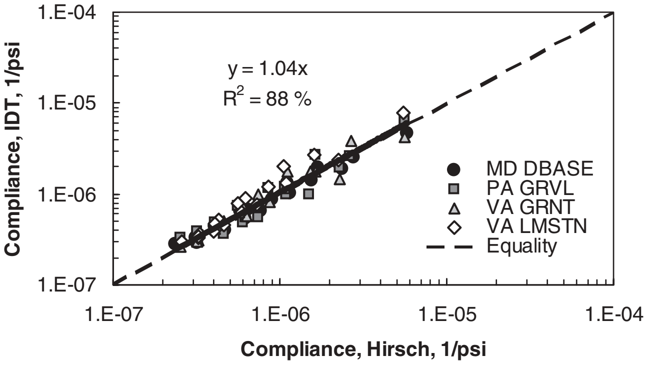


Figure 23. Compliance values as estimated using the Hirsch model and as measured using the IDT test.

strates the feasibility of using estimated compliance values to evaluate the low-temperature properties of asphalt concrete. Additional effort is needed to determine if critical cracking temperatures estimated in this way agree reasonably well with those determined using the IDT creep and strength test. If positive results are obtained, the approach should be further developed and documented for possible use in future revisions of the pavement design guide developed in NCHRP Project 1-37A.

IMPLEMENTATION

Based on the findings from Phase III of NCHRP Project 9-29, additional efforts to implement AASHTO T322 and the compliance and strength predictive equations developed in Project 9-29 are warranted. Initial plans for these future implementation efforts are presented in this section.

AASHTO T322

Three activities associated with AASHTO T322 should be considered. The first involves the incorporation of the changes recommended in Tables 2, 3, and 4 into AASHTO T322. These recommendations as well as Appendix A, which documents them in detail, have already been forwarded to the task force responsible for recommending revisions to this test method to AASHTO.

The next logical step in the implementation of AASHTO T322 is the completion of ruggedness testing for the creep testing procedure in AASHTO T322. As outlined below, this is a substantial effort requiring a significant commitment of equipment and resources. Unfortunately, the IDT equipment originally purchased for the Superpave Centers cannot be used in the ruggedness testing because of its documented poor performance and the lack of technical support for the equipment. The ruggedness testing should be performed using properly calibrated servo-hydraulic equipment meeting the revised AASHTO T322 requirements. There are two options for gaining access to such equipment. The first is to procure second generation IDT devices specifically for the ruggedness testing. The second is to contract with laboratories who currently have the equipment meeting the requirements.

Guidance on the statistical design of a ruggedness testing program is presented in ASTM C 1067 “Standard Practice for Conducting a Ruggedness Screening Program for Test Methods for Construction Materials.” The standard design tests seven factors that are anticipated to significantly affect the results at two levels. Eight measurements are made using predetermined combinations of the seven factors, and the entire experiment is replicated within a given laboratory. This results in a total of 16 measurements within each laboratory. Ruggedness testing of the creep procedure in AASHTO T322 is complicated somewhat by the trimmed mean analysis approach used in this procedure. In the trimmed mean approach, data from two sides of three specimens are needed to develop a single creep compliance curve. Thus, complete replication of the creep testing procedure at a specific temperature requires the collection and analysis of data from three specimens. Table 19 presents one possible scenario for the factors and levels to be used in ruggedness testing for the AASHTO T322 creep procedure. The factors included in Table 19 are based in the research team’s experience with AASHTO T322 and may require modification as additional data on factors affecting IDT creep tests are published by other researchers and practitioners.

In addition to the factors and their levels, the ruggedness testing should be conducted over a range of compliances and include mixtures with a range of nominal maximum aggregate sizes. Table 20 presents possible mixture combinations and testing temperatures that may be included in the ruggedness testing. This design includes four mixture/temperature combinations.

Ruggedness testing involves a significant level of effort from the participating laboratories. For the design outline above, each participating laboratory would perform 192 creep tests. Assuming that four laboratories participate in the AASHTO T322 creep procedure ruggedness testing experiment and that all specimens are fabricated at a single location, the specimen fabrication laboratory will prepare 384 test specimens. Rules of thumb for estimating levels of effort are 1.5 hours for each creep test and 2.5 hours per test specimen for fabrication. Thus a ruggedness testing experiment involving 4 laboratories, 2 mixtures, and 2 temperatures will require approximately 2,112 person-hours of testing effort. An additional 400 hours professional time should be budgeted for initial planning, coordination, data compilation, data analysis, and reporting.

The third implementation item associated with AASHTO T322 is future research to better characterize the relationship between uncorrected IDT strength and corrected IDT strength as determined using the procedure given in AASHTO T322. This will provide an improved equation for estimating the corrected IDT strength from the uncorrected strength calculated using the maximum load. An additional 16 mixtures combined with the 16 mixtures tested in this project should

TABLE 19 Example ruggedness testing factors for AASHTO T322 creep testing

Factor	Low Level	High Level
Equilibrium temperature	X – 1 °C	X + 1 °C
Strain level	< 0.025	< 0.05
Specimen air voids	5 %	8 %
Specimen thickness	40 mm	60 mm
Loading strips	With neoprene	Without neoprene
Load application	First load	Second load
End parallelism	< 1.0 °	< 2.0 °

TABLE 20 Example mixture and temperature combinations for AASHTO T322 creep procedure ruggedness testing

Number	Mixture Type	Binder	Temperature, °C
1	Coarse 9.5 mm	PG 76-16	10 and –10 C
2	Fine 25 mm	PG 58-28	0 and –20

provide a very robust data set for the development of an improved predictive model. The data collected in this effort can also be used for the development of improved empirical models for estimating tensile strength from volumetric properties as discussed below. The level of effort for this testing is estimated to be approximately 300 person-hours of testing effort and 160 person-hours of professional effort.

Compliance and Strength Predictive Methods

In addition to work associated with AASHTO T322, future research is needed to further develop and evaluate procedures for estimating resistance to low-temperature cracking using binder test data and mixture composition through application of the Hirsch model to determine mixture creep compliance and application of empirical methods to estimate strength. Such approaches would be very useful for general mixture selection, mixture design guidance, quality control applications, and as possible replacements for the current Level 2 and 3 thermal cracking data input for the pavement design guide developed in NCHRP Project 1-37A. The major effort for estimating creep compliance is the development of methods to predict the binder master curve from limited AASHTO M320 test data. Approximately 240 person-hours of professional effort should be budgeted for this task. The 16 additional mixtures described above when combined with the 16 tested in this project should provide a very robust data set for comparing estimated and measured creep compliance and for developing an improved model for estimating tensile strength from mixture volumetric properties. Approximately 220 person-hours of testing effort should be included for conducting creep tests prior to the strength testing described in the preceding section. Finally, approximately 240 person-hours of professional effort should be budgeted for analyzing this data and the strength data and preparing a report documenting the work.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Based upon the literature review, review of AASHTO T322, and the results of a substantial laboratory testing program performed during Phase III of NCHRP Project 9-29, the following conclusions and recommendations are made:

- The IDT creep and strength test should be retained as the standard method for determining the creep compliance and tensile strength of asphalt concrete mixtures at low temperatures.
- Asphalt concrete specimens compacted in the laboratory exhibit substantial anisotropy in their creep compliance at low temperatures. The compliance measured across the diameter of the specimen is greater than that measured in both compression and tension along the length of the specimen. This anisotropy does not appear to be caused by differences in air void content or air void distribution, but is probably the result of preferential aggregate particle orientation that occurs during compaction. This anisotropy is the primary reason for preferring the IDT creep and strength tests over other procedures.
- Pavement engineers and researchers should be careful when using compliance and modulus values for asphalt concrete in pavement design and analysis, because these and related properties are potentially anisotropic and their values will depend upon the direction and sense of the applied stress with respect to the orientation relative to the compaction process.
- The IDT strength test should be performed without LVDTs. The uncorrected IDT strength should be calculated based on maximum load, and the corrected or "true" strength estimated using the empirical equation developed in this project.
- Test temperatures for the IDT creep and strength test should be linked to binder grade: −20, −10, and 0°C for PG XX-28 and PG XX-22 binders; −10, 0, and +10°C for PG XX-16 and harder; and −30, −20, and −10°C for PG XX-34 binder and softer. Reasonable adjustments should be made for testing field cores, which may exhibit substantial age hardening.
- A number of relatively minor revisions listed in this report should be made to AASHTO T322. These have been forwarded to the task force responsible for recommending revisions to this test method to AASHTO.
- The coefficient of variation of creep compliance values measured using the IDT test was found to range from about 8 to 11 percent for tests performed at a number of different laboratories using several different test systems. This variability is probably somewhat high for a standard test method, but improved test procedures and equipment will help to reduce this to an acceptable level. The precision of the IDT strength test is probably acceptable in its current form.
- Ruggedness testing for the AASHTO T322 creep test procedure is the next logical step in the implementation of this procedure. An initial ruggedness testing plan and estimated level of effort are provided in this report.
- Additional research is suggested in two areas. Further testing and analysis is needed to refine the relationship between uncorrected IDT strength and the actual strength as determined using the procedure currently given in AASHTO T322 (using LVDTs to determine the point of failure). Research should also be undertaken to evaluate the accuracy of critical cracking temperatures determined using the Hirsch model to estimate creep compliance values and empirical methods for determining approximate tensile strength. Such a procedure would be useful for general mixture selection, mixture design guidance, quality control applications, and as a possible replacement for the current Level 2 and 3 thermal cracking data input for the pavement design guide developed in NCHRP Project 1-37A.

REFERENCES

1. Lytton, R. L., J. Uzan, E. G. Fernando, R. Roque, D. Hiltunen, and S. Stoffels, "Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixtures," *Report SHRP-A-357,* Washington D.C.: Strategic Highway Research Program, National Research Council, 1993.
2. Buttlar, W. G., and R. Roque, "Development and Evaluation of the Strategic Highway Research Program Measurement and Analysis System for Indirect Tensile Testing at Low Temperature," *Transportation Research Record No. 1454: Asphalt Concrete Mixture Design and Performance,* Washington, D.C.: National Academy Press, 1994, pp. 163–171.
3. Anderson, R. M., and R. B. McGennis, "Ruggedness Evaluation of AASHTO TP7 and TP9, Phase I: Simple Shear Test at Constant Height (TP7) Indirect Tensile Strength Test (TP9)," *Report FHWA HIPT (Task J),* The Federal Highway Administration, Washington, D.C., November 1998, 41 pp.
4. Christensen, D. W., T. K. Pellinen, and R. F. Bonaquist, "Hirsch Model for Estimating the Modulus of Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists,* Volume 72, 2003, pp. 97–121.
5. Witczak, M. W., R. Roque, D. R. Hiltunen, and W. G. Buttlar, "Modification and Re-Calibration of Superpave Thermal Cracking Model," NCHRP 9-19 Project Report, Arizona State University Department of Civil and Environmental Engineering, Tempe, Arizona, December 2000.
6. Bonaquist, R. F., D. W. Christensen, W. Stump, *NCHRP Report 513: Simple Performance Tester for Superpave Mix Design: First Article Development and Evaluation,* Transportation Research Board of the National Academies, Washington, D.C., 2003, 54 pp.
7. Janoo, V., T. Pellinen, D. Christensen, and H. Von Quintus, "Evaluation of the Low-Temperature Cracking Model in Superpave," Draft Report to the Federal Highway Administration, Contract DTFH61-95-C-00100, undated (ca. 1997).
8. Kwanda, F. D., and S. Stoffels, "Determination of the Coefficient of Thermal Contraction of Asphalt Concrete Using the Resistance Strain Gage Technique," *Journal of the Association of Asphalt Paving Technologists,* Vol. 65, 1996, pp. 73–92.
9. Mehta, Y., S. Stoffels, and D. W. Christensen, "Determination of Coefficient of Thermal Contraction of Asphalt Concrete Using Indirect Tensile Test Hardware," *Journal of the Association of Asphalt Paving Technologists,* Vol. 68, 1999, pp. 349–367.
10. Christensen, D. W., "Analysis of Creep Data for Indirect Tension Test on Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists,* Vol. 67, 1998, pp. 458–492.
11. Mehta, Y. A., and D. W. Christensen, "Determination of the Linear Viscoelastic Limits of Asphalt Concrete at Low and Intermediate Temperatures," *Journal of the Association of Asphalt Paving Technologists,* Vol. 69, 2000, pp. 281–312.
12. Weissman, S. L., J. L. Sackman, J. Harvey, and F. Long, "Selection of Laboratory Test Specimen Dimension for Permanent Deformation of Asphalt Concrete Pavements," submitted for presentation at 1999 TRB Annual Meeting.
13. Pellinen, T. K., *Investigation of the Use of Dynamic Modulus as an Indicator of Hot-Mix Asphalt Performance,* A Dissertation Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy, Arizona State University, May 2001.
14. Christensen, D. W., and D. A. Anderson, "Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalts," *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992, pp. 67–98.
15. Tabyebali, A. A., J. A. Deacon, and C. L. Monismith, "Development and Evaluation of Surrogate Fatigue Models for SHRP A-003A Abridged Mix Design Procedure," *Journal of the Association of Asphalt Paving Technologists,* Vol. 64, 1995, pp. 340–364.
16. Huang, Y. H., *Pavement Analysis and Design,* Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1993, p. 366.
17. Christensen, R. M., *Theory of Viscoelasticity: An Introduction,* New York: Academy Press, 1982, 364 pp.
18. Neter, J., Wasserman, W., and Kutner, M. H., *Applied Linear Statistical Models,* 2nd Ed. Homewood, IL. Richard D. Irwin, Inc., 1985, 1,127 pp.

APPENDIX A

REVIEW OF AASHTO T322 AND RECENT PROPOSED CHANGES

INTRODUCTION

The primary purpose of this appendix is to summarize the procedures for performing the indirect tension (IDT) creep and strength test and the methods for analyzing the subsequent data, as described in AASHTO T322, *Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device.* This appendix also includes recent suggested modifications to this standard, which have occurred during the course of NCHRP Projects 1-37A and 9-19. This information is critical to understanding the current form of the IDT test system and changes likely to occur over the next few years.

This appendix includes a summary of AASHTO T322, a section on modifications to AASHTO T322 recommended during NCHRP Projects 1-37A and 9-19, a section on related research, a section discussing the results of this review and presenting various findings, a section presenting conclusions and recommendations, and a list of references. This appendix is intended to provide detailed background information supporting the findings, conclusions, and recommendations presented in the body of the NCHRP 9-29 Phase III final report. However, an attempt has also been made to make this suitable as a stand-alone document.

AASHTO T322

AASHTO T322 consists of 17 sections:

1. *Scope*
2. *Referenced Documents*
3. *Terminology*
4. *Summary of Method*
5. *Significance and Use*
6. *Apparatus*
7. *Hazards*
8. *Standardization*
9. *Sampling*
10. *Specimen Preparation and Preliminary Determinations*
11. *Tensile Creep/Strength Testing (Thermal Cracking Analysis)*
12. *Tensile Strength Testing (Fatigue Cracking Analysis)*
13. *Calculations*
14. *Report*
15. *Precision and Bias*
16. *Keywords*
17. *References*

Many of these sections are only of nominal significance and will not be discussed here, including sections 1, 2, 3, 5, 7, 15, 16, and 17. The sections below address the most significant parts of the specification in sequence.

AASHTO T322 Sections

Section 4. Summary of Method

The Summary of Method in Section 4 presents a good introductory description of the test procedure:

> 4.1 This standard describes two procedures. For one procedure, the tensile creep and tensile strength are determined on the same specimen for thermal cracking analyses, and for the other procedure the tensile strength is determined separately for fatigue cracking analyses.
>
> 4.2 The tensile creep is determined by applying a static load of fixed magnitude along the diametral axis of a specimen. The horizontal and vertical deformations measured near the center of the specimen are used to calculate a tensile creep compliance as a function of time. Loads are selected to keep horizontal strains in the linear viscoelastic range (typically below a horizontal strain of 500×10^{-6} mm/mm) during the creep test. By measuring both horizontal and vertical deformations in regions where the stresses are relatively constant and away from the localized non-linear effects induced by the steel loading strips, Poisson's ratio can be more accurately determined. Creep compliance is sensitive to Poisson's ratio measurements.
>
> 4.3 The tensile strength is determined immediately after determining the tensile creep or separately by applying a constant rate of vertical deformation (or ram movement) to failure.

The most important features of this test system are the indirect tensile test geometry, the use of both compliance and strength tests, the assumption of linear viscoelastic behavior, and the determination of not only creep compliance but also of Poisson's ratio during the IDT creep test.

One of the most important issues concerning the IDT creep and strength test is that of test geometry. The IDT geometry was originally selected for use in low-temperature characterization of asphalt concrete mixtures during the Strategic Highway Research Program (SHRP) primarily because the specimen preparation methods available at that time did not include ways of making specimens suited for uniaxial measurement of creep compliance, relaxation modulus, or strength. The simple performance tests developed as part of NCHRP Project 9-19 and the characterization methods developed for use in conjunction with the pavement design guide developed in NCHRP Project 1-37A require 100-mm diameter by 150-mm high specimens to be used in uniaxial testing. Therefore, this obstacle to uniaxial testing at low temperature no longer exists. This would also potentially allow the use of relaxation modulus tests, rather than creep tests, which would eliminate the need to calculate the relaxation modulus from the creep compliance. However, relaxation tests have not been widely performed on asphalt concrete mixtures; and, for practical purposes, the creep test should probably be retained regardless of test geometry. Phase III of NCHRP Project 9-29 included an evaluation of the possible use of uniaxial creep testing as the standard low-temperature test for asphalt concrete. Because the uniaxial test can produce compliance data in the same exact format as the IDT test, there would be no need for major changes in the Superpave thermal cracking program.

Examination of the equipment requirements for the dynamic modulus master curve equipment as developed earlier in NCHRP Project 9-29 indicates that this equipment should have both the load capacity and transducer resolution for properly performing the creep test on asphalt concrete at low temperatures; this evaluation is described in detail in Appendix B of this report and summarized in Chapter 2 of the body of the report. The maximum load capacity of 22.5 kN (5 kips) is, however, too low for performing uniaxial tensile strength tests, which would require a maximum load of 70 kN (16 kips) to ensure that all or almost all mixtures could be tested to failure. Therefore, it is suggested that mixture tensile strength normally be determined using either the IDT or uniaxial tensile strength tests on a high-capacity static test machine separate from the dynamic modulus master curve device. However, it should also be possible to perform both creep and strength tests on a single, high-performance servo-hydraulic system, as long as all equipment requirements are met. Such a system would, however, likely be somewhat more expensive than the standard dynamic modulus master curve system. A new, draft test procedure should be written for performing uniaxial creep tests, based upon AASHTO T322 and the specifications developed for the simple performance tests and related procedures as part of NCHRP Project 9-29.

The issue of linearity is of great practical importance. Intuitively, it should be expected that asphalt concrete at low temperatures should behave in a linear manner through loading approaching the point of failure because of the high stiffness of asphalt concrete under these conditions and the very low strains. It is, however, important to verify that the loads used in the IDT test are appropriate—as high as possible, to ensure large deflections and good repeatability, while still remaining in the linear viscoelastic region. AASHTO T322 calls for a maximum strain of 500×10^{-6} mm/mm, or 0.05 percent. This value is consistent with work performed by Mehta and Christensen (*A1*), who reported that deviations from linearity began to occur at the same strain level of 0.05 percent. This aspect of AASHTO T322 probably does not need revision.

The final general issue in the IDT test procedure is whether it is truly necessary to determine Poisson's ratio when characterizing the mechanical behavior of HMA at low temperature. Poisson's ratio represents the ratio of lateral to axial deformation under uniaxial loading. It is theoretically necessary to know Poisson's ratio when performing stress analyses in two or three dimensions. However, in performing simple, one-dimensional stress analyses, such as those used in the Superpave thermal cracking analysis, Poisson's ratio is not needed. Furthermore, for most materials, Poisson's ratio falls between about 0.2 and 0.5. For asphalt concrete, Huang (*A2*) states that values typically fall in a narrower range, from 0.3 to 0.4. Huang goes on to state "Because Poisson's ratio has a relatively small effect on pavement responses, it is customary to assume a reasonable value for use in design, rather than to determine it from actual tests." (*A2*) It appears as though determination of Poisson's ratio is not critical to the prediction of low-temperature cracking, again suggesting that perhaps uniaxial creep tests could provide the needed data more simply and more directly than the IDT creep test.

Section 6. Apparatus

There are six main components to the IDT test system:

- Axial loading device,
- Load measuring device,
- Deformation measuring device(s),
- Environmental chamber,
- Control and data acquisition system, and
- Specimen loading frame (test fixture).

This section of AASHTO T322 provides specifications for each of these subsystems, which are summarized in Table A-1 below. The term "test fixture" is used here rather than "loading frame" to describe the device that holds the IDT specimen in place and transfers the load from the testing device to the specimen, as loading frame is an ambiguous term that could be confused with the loading system. In order to evaluate these specifications, it is necessary to examine the possible range of responses for HMA at low temperature and also to understand what ranges and sensitivities are possible and practical for the systems in question. The following paragraphs address these issues.

In *SHRP Report A-357,* the developers of the IDT creep and strength testing procedure present data for a range of mixtures (*A3*). These show a typical range in compliance values of about 3×10^{-11} Pa^{-1} to 4×10^{-9} Pa^{-1}. Because the linear range for HMA occurs at strains less than or equal to 0.05 percent, the maximum applied tensile stresses corresponding to these compliance values range from 125 kPa to 17 MPa. Based upon the relationship $\sigma_t = 2P/\pi tD$, the axial loads corresponding to these tensile stresses are 1.5 and 200 kN, respectively, for a specimen 50 mm thick and 150 mm in diameter. However, another consideration is the maximum load that can be applied without failing a specimen. The lowest tensile strength, σ_t, reported in *SHRP A-357* (*A3*) was 1.3 MPa; the highest was 4.3 MPa. The corresponding load, *P,* for these tensile strengths can be calculated as $P = \sigma_t \pi tD/2$, where *t* and *D* are the specimen thickness and diameter, respectively. The calculated loads based on tensile failure are between 15 and 51 kN for a 50-mm-thick specimen. Limiting the load to one-half that required to cause failure and allowing for specimens up to 100 mm in thickness, the anticipated maximum load is then

TABLE A-1 AASHTO T322 specifications for IDT apparatus

Component	General Requirements	Range	Sensitivity
Axial loading device	Shall provide a constant load	98 kN maximum load; Displacement rate between 12 and 75 mm/min	5 N minimum
Load measuring device	Electronic load cell	98 kN minimum capacity	5 N minimum
Deformation measuring device(s)	Four linear variable differential transducers (LVDTs)	0.25 mm minimum	0.125 µm minimum
Environmental chamber	Temperature control only; large enough to perform test and condition 3 specimens	-30 to +30 °C	Control to ±0.2 °C
Control and data acquisition system	Shall digitally record load and deformation during test	1 to 20 Hz sampling rate	16-bit A/D board required
Test fixture	As described in ASTM D4123 (diametral resilient modulus testing)	N/A	2 kg maximum frictional resistance

50 kN. However, to ensure good loading system performance, the capacity of the loading system should be about double the anticipated maximum load, giving a maximum capacity of 100 kN, agreeing nearly exactly with the 98 kN given in AASHTO T322.

In evaluating the required sensitivity of the loading system, the worst-case situation is for the lowest anticipated load. Because it would be undesirable to approach nonlinearity, in some cases the applied loads might be somewhat less than the estimated minimum load of 1.5 kN, say 1 kN. To calibrate to this load level, ASTM E4 requires a resolution that is 1/100th of the minimum load level or a resolution of 10 N, which is significantly larger (poorer) than the 5 N resolution requirement given in AASHTO T322. Consideration should be given to changing the required resolution for the IDT loading system to 10 kN; this would likely reduce the cost of the equipment required to perform the test.

Addressing the requirements for the required displacement rate is more complicated. Because linearity requires a maximum strain of 0.05 percent, this represents the maximum horizontal strain during the IDT creep test. In a creep test, the load is applied very quickly during the initial part of the test, typically within a period of not more than one second. The condition requiring the highest loading rate is for very stiff materials at low temperature, because in this case the behavior is nearly elastic and most of the specimen deformation will occur during the initial application of the load. Therefore, in order to calculate the vertical deformation, an applied load of 98 kN and a specimen compliance of 3×10^{-11} Pa^{-1} can be assumed. Two useful equations relating load, Poisson's ratio, and horizontal and vertical deformations are given in ASTM D 4123, *Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures:*

$$E = P(\nu + 0.27)/t\Delta H \tag{A-1}$$

$$\nu = 3.59\,\Delta H/\Delta V - 0.27 \tag{A-2}$$

where

E = modulus, MPa (inverse of the creep compliance D);
P = applied load, N;
ν = Poisson's ratio;
t = specimen thickness, mm;
ΔH = total horizontal deformation, mm; and
ΔV = total vertical deformation, mm.

Because these equations are based upon conditions of plane stress, which is a simplification of the actual three-dimensional state of stress during an IDT test, they should be considered approximate. However, they should be accurate enough for the purposes of estimating the required loading rates and transducer sensitivities. Rearranging Equation A-1, replacing ΔH with $\Delta V/5.38$ (from Equation A-2 for $\nu = 0.40$):

$$\Delta V = 5.38\, P(\nu + 0.27)/Et \tag{A-3}$$

Assuming a Poisson's ratio of 0.4, for the given conditions of $P = 50$ kN and $D = 3 \times 10^{-11}$ Pa^{-1}, the maximum expected vertical deformation for the IDT creep test is 0.10 mm. If this is to be applied during a maximum ramp time of one second, the maximum expected displacement rate is then 0.10 mm/s, or 6 mm/min. However, to ensure that the system has adequate reserve capacity for good control of the loading rate, a higher maximum displacement rate is desirable, say 12 mm/min. This corresponds exactly with the lowest displacement rate given in AASHTO T322. It is not clear why a range is specified for the displacement rate; there is no reason to arbitrarily limit the maximum displacement rate for the IDT system. It is recommended that the required displacement rate for IDT test systems be given as at least 12 mm/min.

Evaluation of the requirements for the IDT load cell follow directly from the previous discussion. The maximum applied load is 50 kN, and the load cell should have a maximum capacity substantially higher than the maximum expected load to avoid overloading and potentially damaging the transducer. Therefore, the load cell should have a maximum capacity of at least 100 kN. The sensitivity of the load cell should at least match the sensitivity of the loading system, determined to be 10 N rather than the 5 N listed in AASHTO T322.

The first issue concerning specimen deformation measurement that should be addressed is the type of transducer to be used. Currently, AASHTO T322 requires the use of LVDTs. Although LVDTs are widely used in this type of test, there are other types of transducers that have been used with this system with success, including strain-gage–based clip-on gages. The specification should not specify the type of transducer to be used, only the required level of performance in terms of gage length, range, and sensitivity.

The maximum deflection to be measured during an IDT creep test will occur in the vertical direction. Based upon equations given in *SHRP Report A-357* (*A3*), the vertical strain measured during an IDT test can be nearly twice the horizontal strain, which is limited to 0.05 percent. Therefore, the maximum expected deflection during a typical test would be 0.001 × 38 mm, or 0.04 mm. This range would however be extremely difficult to work with in setting up and executing a test. Current requirements in AASHTO T322 are for a minimum LVDT range of 0.25 mm; commercially available IDT equipment used at Advanced Asphalt Technologies, LLC, uses displacement transducers with an overall range of 2.5 mm, which include a software window of 0.25 mm that is enabled after initial specimen set up. This is an effective system that should be considered in the next generation of HMA low-temperature testing equipment.

Evaluation of the required sensitivity of the deformation transducers for the IDT is straightforward. Only the case of horizontal deflections needs to be addressed, because these will always be significantly smaller than vertical deflections and so represent the critical situation. Linearity constraints, as discussed previously, limit horizontal strains during the IDT creep to 0.05 percent. However, it is impossible to determine test conditions a priori so that strains are always close to this limit; therefore, a realistic strain at the end of the test would be 0.025 percent. Also, it must be kept in mind that this is the strain at the end of a typical IDT creep test; the strain at the start of collection of data can be as much as five times less than this, or 0.005 percent (50 parts per million). Given the standard gage length of 38 mm, this represents a minimum expected deflection of 1.9 μm. To maintain a reasonable resolution under this worst-case situation of about 5 percent, would require a transducer sensitivity of 0.1 μm (4 μin.).

The current specifications for the temperature chamber in AASHTO T322 require a range of −30 to +30°C, with a control sensitivity of ±0.2°C. Examining typical IDT creep data, a temperature control sensitivity of ±0.2°C translates to a maximum potential error in creep compliance of about 3 percent. This appears reasonable; however, a temperature chamber with this level of control sensitivity would be prohibitively expensive. A more realistic requirement for sensitivity would be the one already established for the simple performance tests, ±0.5°C. This could lead to maximum potential compliance errors of about 8 percent, though the error in most cases would be smaller because of the cyclic nature of temperature control systems and the relatively large thermal mass of the IDT specimens. Furthermore, as with the requirements for the temperature chamber to be used with the simple performance tests, ambient conditions should be given under which the specification should be met—15 to 27°C. There is no need to require the IDT chamber to have a range extending to 30°C; this means that the system must have a substantial heating system in order to control temperatures at ambient temperatures and above, increasing the complexity and cost of the chamber. The required temperature range for the chamber should be narrowed to −30 to 10°C under the given ambient conditions.

The requirements for system control and data acquisition are largely acceptable but could be slightly improved. The use of a personal computer in the control and data acquisition system should be explicitly required. On the other hand, the required sensitivity of the data acquisition system could be more effectively stated to be consistent with the required sensitivity of the various transducers. The manner in which this is achieved should be left to the equipment supplier.

The test fixture is specified to meet the requirements of ASTM D4123, which is a standard test method for diametral resilient modulus testing. It is suggested that a separate, smaller frame be used to help meet the requirements of this specification. A maximum frictional resistance of 2 kg is also specified in AASHTO T322. If the minimum applied load is 1 kN, as discussed previously, the maximum frictional resistance should be no more than about 2 percent of this, or 20 N. This is in very close agreement to the 2 kg frictional resistance in the current specification. However, as frictional resistance is a force, AASHTO T322 should be revised to specify the maximum frictional resistance in Newtons rather than kilograms. A simple procedure should be given for evaluating the frictional resistance of the test fixture. ASTM D4123 requires stainless steel loading strips one-half inch wide, with a curvature matching that of the IDT specimen. Generally, load applications to materials such as asphalt concrete must include some provisions for distributing the load evenly over the test specimen and avoiding stress concentrations and eccentricities. These issues are not addressed by the current requirements of ASTM D4123. The curvature of the loading strips, though nominally addressing the geometry of the specimen, may in fact cause more problems than it solves, because this could increase stress concentrations and eccentric loading unless the curvature and alignment of the specimen exactly match that of the loading strips. A more conventional approach would be to use flat, neoprene loading strips, one-half inch thick by one-half inch wide. These strips would be compliant enough to assume the shape of the IDT specimen regardless of irregularities and would greatly reduce the potential for stress concentrations and eccentricities.

A summary of the suggested revised specifications for the IDT apparatus to be used in conjunction with AASHTO T322 is given in Table A-2. Many of the changes are slight, for example, giving the maximum range of the loading device and load cell as 100 kN rather than the “soft” metric value of 98 kN. The sensitivity of the loading device and load

TABLE A-2 Proposed revised AASHTO T322 specifications for the IDT apparatus

Component	General Requirements	Range	Sensitivity
Axial loading device	Shall provide a constant load	100 kN maximum load; Maximum displacement rate of at least 12 mm/min	10 N or better
Load measuring device	Electronic load cell	100 kN minimum capacity	10 N or better
Deformation measuring device(s)	Four displacement transducers (LVDTs)	0.1 mm minimum	0.1 µm or better
Environmental chamber	Temperature control only; large enough to perform test and condition 3 specimens	–30 to +10 °C under ambient conditions of 15 to 27 °C	Control to ±0.5 °C
Control and data acquisition system	System shall be operated with the use of a personal computer and shall digitally record load and deformation during test	1 to 20 Hz sampling rate	Consistent with required sensitivity of all system transducers
Test fixture	As described in ASTM D4123 (diametral resilient modulus testing), but with flat neoprene loading strips 12-mm thick by 12-mm wide.	N/A	20 N maximum frictional resistance

cell is decreased, while the sensitivity of the deformation measuring devices has been increased. The suggested use of flat neoprene loading strips—rather than curved, stainless steel strips—should be evaluated in the laboratory testing portion of Phase III of NCHRP 9-29.

8. Standardization

The requirements for calibration and verification of the IDT test system in the current version of AASHTO T322 are somewhat vague. AASHTO T322 includes the following requirements:

- The testing system shall be calibrated prior to initial use and at least once a year thereafter.
- The temperature control in the environmental chamber and all transducers used in the IDT system shall be verified (no frequency given).
- If the results of any verification are not satisfactory, appropriate actions shall be taken to correct the response of the transducer(s) in question.

Accurate execution of the IDT creep test requires that all transducers in the test system be calibrated and operating properly. The calibration requirements should be more detailed, referring to appropriate ASTM standards (ASTM E4 for load and ASTM D 6027 for deflection and specimen deformation). The verification procedure and required hardware for verification should also be more detailed. IDT systems should include a proving ring for load verification and a verification system for checking the transducers, such as a calibration block with a very sensitive micrometer. A standard specimen, 10 mm thick by 150 mm in diameter, made of 6061 T6 aluminum alloy, should also be supplied with the IDT system. Such a specimen would provide an effective stiffness similar to that of a typical asphalt concrete specimen at –30 to –20°C and would exhibit stable properties with $E = 69$ GPa and $\nu = 0.33$. Furthermore, the thinness of the specimen should produce conditions approaching that of plane stress, simplifying the analysis and providing additional certainty in the results of the verification. A full system calibration frequency of once every year is probably adequate. A confidence check using the aluminum standard should be performed every time the system is used. Verification of the load cell and LVDTs should be required when the confidence check fails, at least once per month when the system is being used, and prior to beginning tests if the system has not been used for more than 30 days.

9. Sampling

This section probably needs little or no revision. Currently, specimen preparation according to either AASHTO T312 (Superpave gyratory compactor) or AASHTO PP3 (rolling wheel compactor) is permitted. Consideration should be given to requiring gyratory compaction only, in order to reduce variability and promote reproducibility in IDT creep and strength tests. The current specification states that if cores from roadways are to be tested, they should be taken following procedures given in ASTM D5361.

10. Specimen Preparation and Preliminary Determinations

Requirements for specimen diameter and thickness are not critical to the results of the IDT creep and strength test; however, some revisions in this section of AASHTO T322 are needed. One critical point is the smoothness and parallelism of the specimen faces; currently, AASHTO T322 only states that the specimen sides should be "smooth" and "parallel." The specimen requirements given in Table A-3 are partly based upon those developed for the First Article Equipment Specifications for the Simple Performance Test System developed earlier during NCHRP Project 9-29 and should help ensure good test results with the IDT creep and strength procedure (*A4*). The required specimen diameter in Table A-3 has been given as 150 to 154 mm, rather than the 150 ± 9 mm given in AASHTO T322, to maintain consistency with the requirements of the simple performance test. The specimen thickness requirement has also been changed slightly, given as 40 to 60 mm, rather than as 38 to 50 mm as in AASHTO T322. This change is suggested to provide a "hard" metric specification and also to allow some margin for error in producing 50-mm-thick specimens, which are considered standard for the IDT test. Specimen parallelism is specified through the use of the standard deviation of the thickness, which is limited to less than 1.0 mm, which corresponds to a 2s limit of about 1.2 degrees, similar to the 1 degree requirement for the simple performance test.

Another requirement of this section is to determine the bulk specific gravity of the specimen following AASHTO T166, with the caveat that high-absorption specimens should be tested using an impermeable plastic film rather than a paraffin coating as specified in AASHTO T166. This requirement is necessary to ensure that the surfaces are clean so that the LVDT gage points can be properly glued to the specimen. There is also a statement here that if direct immersion is used to determine the bulk specific gravity, the specimen must then be dried to a constant weight prior to fastening of the LVDT gage points. In the interest of ensuring consistent bulk specific gravity measurements and also to ensure rapid and consistent specimen preparation, it is suggested that this part of AASHTO T322 be revised to require that all bulk specific gravity measurements be made using impermeable plastic rather than the saturated surface-dry method or the paraffin coating technique.

11. Tensile Creep/Strength Testing (Thermal Cracking Analysis)

Several changes are needed within this section of AASHTO T322. First, the suggested test temperatures for the creep procedure are 0, −10, and −20°C. Because of the variability in binder grades and the resulting low-temperature properties of asphalt concrete, some specimens are extremely stiff at −20°C, while others may be too compliant at 0°C. The test temperatures used in the IDT creep and strength test should, therefore, change according to the binder grade used. The relationship between binder stiffness and mixture stiffness is not 1:1; a given change in binder stiffness will produce a somewhat lower change in mixture stiffness. Therefore, it is not necessary or advisable to link IDT test temperatures directly to low-temperature binder grade. It is suggested that the current test temperatures of 0, −10, and −20°C be maintained for mixtures made using PG XX-28 and PG XX-22 binders. For PG XX-16 and XX-10 binders, or mixtures that have been severely age-hardened, the recommended test temperatures should be −10, 0, and +10°C. For PG XX-34 binders (or softer), the recommended test temperatures should be −30, −20, and −10°C.

A practical problem with the current version of AASHTO T322 is that the test conditions are to be determined using a trial-and-error procedure. A load is applied to the specimen and, if the resulting strains fall outside the allowable range, the test is aborted, the specimen is allowed to recover for 5 minutes, and the test is then repeated at an adjusted load level. No suggestions are given concerning what the appropriate applied loads should be for different combinations of mixture types and test conditions. Given the suggested revised protocol recommended above, Table A-4 presents guidelines for the applied load.

These guidelines are based upon typical ranges for asphalt concrete modulus under the conditions likely under the proposed protocol. The maximum allowed deformation corresponds to the maximum allowable horizontal strain for

TABLE A-3 IDT creep and strength specimen requirements

Item	Specification	Remarks
Average diameter	150 to 154 mm	See Note 1
Standard deviation of diameter	1.0 mm	See Note 1
Average thickness	40 to 60 mm	See Note 2
Standard deviation of thickness	1.0 mm	See Note 2
Smoothness	0.3 mm	See Note 3

Table A-3 Notes:

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

2. Measure the thickness of the specimen to the nearest 1 mm at 8 equally spaced points along the circumference of the specimen, using a pair of calipers or other similar device. Calculate and report the average thickness to the nearest 1 mm. The standard deviation of the specimen thickness shall be less than 1.0 mm. The average thickness shall be used in all material property calculations.

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

TABLE A-4 Guidelines for applied load in the IDT creep test

Test Temperature	Initial Applied Load (kN)	Other Possible Applied Loads (kN)
Lowest	40	Deformation < 0.01 mm: 80 Deformation > 0.02 mm: 20, 10
Intermediate	10	Deformation < 0.01 mm: 20, 40 Deformation > 0.02 mm: 5, 2
Highest	5	Deformation < 0.01 mm: 10, 20 Deformation > 0.02 mm: 2, 1

linearity, 0.05 percent, rounded up from 0.019 to 0.02 mm. The lower limit represents one-half this value, which is necessary to ensure adequate resolution of the deformation data during the test. In the final version of the IDT software, it might be possible to provide a utility that estimates the specimen compliance from the binder grade (or bending beam rheometer test data) and mixture composition and uses this information to calculate the initial load for the test. Additional software controls could be designed to monitor the progress of the test and make adjustments to the applied load as needed.

Another important issue in executing the IDT creep and strength test is the temperature and rate for IDT strength testing. In the original conception of the IDT procedure and in the current version of AASHTO T322, the strength test was to be performed at the same three temperatures as the creep test—typically, −20, −10, and 0°C. However, partly because of the irregular relationship between temperature and tensile strength and probably to make the entire test procedure more efficient, most laboratories perform the strength test at −10°C only. The specified loading rate in AASHTO T322 for the strength test is 12.5 mm/min. The assumption in this approach to testing is that the IDT strength test should be performed quickly, to eliminate time dependency from the result. However, because the strength of HMA, like modulus or compliance, is time and temperature dependent, an effort should be made to make the time and temperature conditions for the IDT strength test at least approximately representative of what occurs in the field during low-temperature cracking events.

The analysis of a suitable loading rate for the IDT strength test can only be done in an approximate manner, but should help obtain reasonable test conditions. Examination of thermal stress development curves shows that at cooling rates of 5°C/hr, most of the tensile stress in the mixture is generated during the last two hours of cooling. This representative loading time agrees with the 2-hour effective loading time used in most limiting stiffness approaches to controlling thermal cracking (*A5*). However, it is suggested that the IDT strength test be performed at the middle creep test temperature, which is 12 to 18°C higher than the minimum binder grading temperature. Considering that the actual cracking temperature should generally be several degrees below the grading temperature, the IDT strength test would normally be performed at about 15 to 21°C above the anticipated cracking temperature. Typically, shift factors for asphalt binders at low temperature vary −0.2 log shift factors per °C (*A6*). Therefore, the failure time for an IDT strength test roughly equivalent to the 2-hour failure time during a thermal cracking event would be $7200 \text{ s} / [10^{(-0.2)(-18)}] = 1.8 \text{ s}$. A typical failure strength for asphalt concrete at low temperature would be 3 MPa (*A3, A5, A7*). Because for diametral loading, $\sigma_x = 2\,P/\pi t D$, the corresponding vertical load for a typical IDT strength would be 35 kN. Using a typical low-temperature asphalt concrete modulus value of 14 GPa, a Poisson's ratio of 0.4, and a specimen thickness of 50 mm, Equation A-3 can be used to estimate the vertical displacement at failure for a typical IDT strength test as 0.18 mm. Because the estimated equivalent failure time was found to be 1.8 sec, the loading rate for the IDT strength test should be 0.1 mm/sec. The IDT strength test should, therefore, be performed at a vertical displacement rate of approximately 0.1 mm/sec or 6 mm/min, which is somewhat slower than the 12.5 mm/min currently specified in AASHTO T322. Considering the approximate nature of this analysis and the fact that the Superpave thermal cracking model has been calibrated using strength data collected at 12.5 mm/min, no change to the strength test loading rate in AASHTO T322 is recommended.

The specimen conditioning time given in AASHTO T322 is 3 hours ±1 hour. Three hours is probably an acceptable time for temperature equilibration, but the range of ±1 hour is probably too large given the potential for possible physical hardening of the specimen at low temperatures. It is suggested that this range be reduced to ±0.5 hours. AASHTO T322 should also include an alternate approach using a dummy specimen with an embedded temperature sensor, which could be used to provide additional assurance of proper specimen equilibration. If the dummy specimen is used, the test should be completed within 1 hour of reaching equilibration. Some mention should be made here of the possibility for steric hardening under continued storage at low temperatures, so engineers and technicians have some understanding of the reason for this limitation and the possible consequences if it is ignored. This section of AASHTO T322 also states that the test should not begin until the chamber is within ±0.2°C of the target temperature. As discussed previously, this requirement is too stringent; the allowable temperature range should be increased to ±0.5°C.

12. Tensile Strength Testing (Fatigue Cracking Analysis)

Tensile strength is not required information for the fatigue analysis to be used in the pavement design guide developed in NCHRP Project 1-37A. Therefore, there is no longer a need for this section in AASHTO T322.

13. Calculations

This section of AASHTO T322 describes in detail the procedure for organizing data and calculating creep compliance and Poisson's ratio. The procedure for data collection is not explained; the specification should provide information concerning the standard structure for data files, including times at which data should be collected, and what properties should be reported and in what format. A key issue in this section of AASHTO T322 is the data trimming process, in which arrays of data are collected representing six cases: two sides for each of three specimens. The highest and lowest values are somewhat arbitrarily discarded, and the remaining four arrays are used to estimate average values. This procedure was apparently needed because of the high variability in IDT data during early versions of the test. There are several problems with this approach. As the hardware and procedures used in this procedure have been improved, the quality of the data has also improved, to the point where the data trimming might in most cases represent an unnecessary discarding of otherwise useful and perfectly accurate data. On the other hand, it is conceivable that in some cases perhaps only one or as many as three data arrays might be faulty. An alternate approach is suggested to ensure that the quality of IDT creep data is acceptable:

- Data for each test should be analyzed as the test is run, to ensure that they are of good quality. The IDT software should automatically verify that load and deformation data are reasonable and produce sensible results. If not, the operator should be informed that the test data generated were of poor quality, and the test should be repeated. If an additional test fails, the specimen should be discarded and only two specimens used in the analysis.
- Upon completion of the test and analysis of the data, the creep compliance, m-values, and Poisson's ratio values for each specimen should be compiled, and the average and standard deviation reported for the complete set of tests. The software should notify the operator if the values appear unusual or otherwise of poor quality.

Analyzing the data in this way would ensure that if an individual test is suspect, it is repeated immediately rather than waiting until all tests are completed to evaluate the data and realizing that there were one or more suspect test results. Furthermore, analyzing the replicate specimens separately and reporting statistics on these data allows the technician and/or engineer to evaluate the overall quality of the data and the repeatability of the results. This is particularly important in situations where the IDT procedure is being used to compare two different mixtures. For example, without appropriate test statistics, it would be very difficult to evaluate if a difference of 20 percent in the creep compliance of two such mixtures represents a statistically significant difference.

The details of the calculations presented in AASHTO T322 have been modified somewhat over the past 6 years and so will not be discussed in this appendix. This section of the specification needs to be edited to ensure that it represents the latest version of the calculation procedure as developed during NCHRP Project 9-19 (*A8*).

14. Report

This section of AASHTO T322 is straightforward but does need some revision. Because the reporting of creep compliance is relatively complicated, the standard format for such a report should be given here, including the times at which test results are to be reported and the properties to be included in the report. This section should also include information concerning the standard format for input into the pavement design guide developed in NCHRP Project 1-37A for analyzing thermal cracking. There are references to the Superpave software in this section of the specification that should be deleted.

15. Precision and Bias

This section currently contains no information. Although some limited information is now available, it probably is not extensive enough to include in a precision and bias statement. Perhaps a note could be included here giving preliminary estimates of the precision of the IDT creep and strength tests.

AASHTO T322 Summary

There are a number of important issues concerning AASHTO T322. The most fundamental issue is whether the low-temperature creep compliance of asphalt concrete should be determined using the IDT geometry or whether a uniaxial creep test should be used. This is especially pertinent as the simple performance tests being developed as part of NCHRP Project 9-19 are uniaxial tests, and, as a result, in a few years, equipment for preparing specimens and performing uniaxial creep tests should be commercially available at a reasonable cost. Using the same test geometry for both the simple performance tests and the low-temperature creep compliance test would simplify implementation activities and potentially reduce the cost of equipment and training for laboratories wishing to have the capability of performing both procedures.

Various other relatively minor issues have been identified in the review of AASHTO T322. Some of the existing requirements for the loading system, environmental chamber, and load and deformation transducers should be revised; suggested changes were presented previously in Table A-2. Existing requirements for IDT specimen dimensions are largely subjective. Specific requirements for specimen dimensions and uniformity were given in Table A-3 and were based upon requirements developed for use in conjunction with the simple performance test. The current test protocol involves testing at three temperatures (−20, −10, and 0°C) regardless of the binder grade used. This sometimes results in marginal data for one of the temperatures, where the compliance of the specimen was either too high or too low to be of value in the analysis. A more efficient system would be to link the creep compliance test temperatures to the low-temperature binder grade used in making the asphalt concrete. This would ensure that the creep data would almost always be in the desired range. Statistical analyses should be provided in calculating compliance data, so that the technician or engineer running the test can immediately evaluate the quality of the data and repeat the test if needed.

In general, most of the required modifications in AASHTO T322 are minor, other than the fundamental issue of whether the IDT test is the most efficient method for determining the creep compliance of asphalt concrete mixtures at low temperatures. That issue can be best addressed through experimental testing to compare creep compliance data at low temperatures determined using both procedures. Provided that the results of such testing suggest that the IDT test be retained, the suggested modifications in AASHTO T322 could be easily made and should not be controversial. If the laboratory testing supports the use of uniaxial compression in low-temperature creep tests, then a new standard would have to be developed, although much of it could be borrowed from AASHTO T322 and from existing proposed standards for the simple performance tests.

RECENT RELATED CHANGES TO THE IDT TEST PROCEDURE, EQUIPMENT, AND ANALYSIS

The IDT creep and strength procedure was developed during SHRP, which took place 10 to 15 years ago. Since the conclusion of SHRP, there have been numerous substantial changes in the test procedure, equipment, and analysis methods used in performing the IDT creep and strength test and interpreting the resulting data. The following subsections of the report discuss the various changes that have occurred, organized more or less chronologically: post-SHRP developments, IDT research at the Superpave Regional Centers, and modifications during NCHRP Projects 1-37A and 9-19.

Post-SHRP Developments in the IDT Procedure

The modifications in the IDT test and analysis procedure in the first several years following completion of SHRP primarily involved improvements in the methods used to calculate creep compliance and Poisson's ratio from load and deflection data. During SHRP, finite element analyses performed on the IDT test geometry indicated that the simple, plane stress analysis typically used in the past to analyze the results of the test can produce substantial errors. These errors result from two sources: horizontal and vertical bulging of the specimen and nonuniform strains across the vertical and horizontal diameter. Correction factors were developed for use in a cumbersome, iterative calculation of creep compliance and Poisson's ratio (*A3*). Within 2 years of the completion of SHRP, a simplified procedure was developed for accounting for nonideal conditions during the IDT test (*A7*). An empirical set of equations was developed based upon the results of the finite element analysis, which avoided the iterative procedure in calculating compliance and Poisson's ratio.

A second area of modification occurred in the manner in which calculated creep compliance data are used to generate a master curve, providing creep compliance data at a selected reference temperature (−20°C in this case) over a wide range of loading times. In producing such master curves, use is made of time-temperature superposition, which essentially involves shifting log compliance-log time functions determined at several temperatures along the log time axis until a single function is created. Often this procedure is done visually, which leads to substantial differences in results generated by different engineers; and it also requires substantial overlap among the compliance curves for best results. During SHRP, creep tests were performed for 1,000 seconds, which generally produced good overlap of data. Details of the procedure used to develop compliance master curves were not provided in the final SHRP reports, but later publications provided such information. Also, at the conclusion of SHRP, it was decided that the length of the IDT creep test should be reduced from 1,000 to 100 seconds to shorten the test time required to complete the test. This unfortunately meant that the compliance curves determined at the three test temperatures often provided little or no overlap for developing the master compliance curve. This required development of new algorithms for extrapolating the master curve and shifting the resulting data.

IDT Research at the Superpave Regional Centers

A third area of research, unfortunately of limited scope, occurred under the auspices of the Regional Superpave Centers established by the FHWA in 1995–96. There were five such regional centers throughout the country: the Northeast Superpave Center, located at the Pennsylvania Transportation Institute of the Pennsylvania State University; the Southeast Superpave Center, located at the National Center for Asphalt Technology at Auburn University; The Northcentral Superpave Center, associated with the Indiana Department of Transportation and Purdue University; the Southcentral Superpave Center at the University of Texas; and the West Coast Superpave Center, which was divided between the University of California at Berkeley and the University of Nevada at Reno. All of the Superpave Centers, except for the West Coast Center, were given IDT creep and strength test systems designed and manufactured by Instron Corporation. These systems were unique in that they were closed-loop electromechanical ("screw") test machines; most closed-loop test systems are servo-hydraulic. It was believed that these systems would potentially be less expensive to purchase and operate, and also easier and safer to operate, especially in a state highway or contractor's laboratory that might lack experienced test engineers.

Unfortunately, these systems were plagued with a wide range of hardware and software problems and a lack of customer support. There were frequent problems with malfunctioning LVDTs used to measure IDT deformation and with the conditioners used in conjunction with these transducers. Part of this problem was related to the practice of keeping LVDTs mounted on the specimens during strength tests, which frequently damaged the LVDTs. Sometimes the LVDT was damaged enough to be completely nonfunctional, but often times it was only slightly damaged, so that it was not clear that the LVDT was not functioning properly. Another source of problems was the placement of some of the LVDT conditioning circuits inside the environmental chamber, which subjected these electronics to frost and moisture. The manufacturer explained that the nature of the bid documents required them to design the system in a less than ideal manner and indicated that, given more flexibility in their choice of transducer type, they could have produced a significantly more reliable system.

The software supplied with these systems was inflexible and difficult to operate and frequently crashed. The latter problem was possibly caused by insufficient memory in the computer systems supplied with these test systems. Some engineers at the Superpave Centers complained that the ramp times required to reach specified loads for the creep tests were too long, though experience at the Northeast Center was that this was a software limitation and not a limitation of the capability of the electromechanical system.

Because of the numerous problems encountered by the various Superpave Centers in operating these systems, only one—the Northeast Center—performed IDT tests on a regular basis using this equipment; recently, the Northcentral Center also began using their system. The quality of the data produced at the Northeast Center was, however, marginal, and testing was continued only in an effort to gain experience with this system. The Northeast Center did publish one research paper on analysis of the IDT creep test, which was essentially a detailed explanation of a simplified version of Roque and Hiltunen's analysis (*A3*), suitable for use in estimating thermal cracking temperatures using IDT creep and strength data (*A9*).

In general, it appears that most of the problems encountered in the IDT systems used within the Superpave Centers could have been corrected, given an adequate investment of time and money by the manufacturer and/or the Superpave Centers. Many of the problems were relatively minor ones dealing with the LVDTs and conditioners or were related to the software and were not fundamental problems with the test system. Unfortunately, this experience has probably created a situation in which it would be politically inadvisable to continue to promote electromechanical systems for use in IDT creep and strength testing. The likely market for this test is probably too small to motivate any equipment manufacturer to provide significant custom engineering design and support for the IDT test system. The most practical approach for pavement engineers is, therefore, to use off-the-shelf test systems to perform the test, with a minimum of specially machined accessories. One potentially effective approach, for example, would be to encourage suppliers of the frequency-sweep equipment to be used in characterizing mixtures for the pavement design guide developed in NCHRP 1-37A to include as an option the necessary capacity, hardware, and software for performing the IDT creep test, perhaps in combination with uniaxial tensile strength. It is even possible that uniaxial creep tests would provide data equivalent to that provided by the IDT procedure, which would mean that the same specimens could be used throughout the testing needed for flexible pavement design work. This is an issue that should be addressed in the laboratory testing to be done as part of Phase III of NCHRP Project 9-29.

One aspect of the experience among the Superpave Centers that should be given consideration is their abandonment of using LVDTs during the IDT strength test to determine the exact moment of failure. In a standard IDT strength test, the precise moment of failure, and hence the "true" tensile strength, is difficult to determine, because the specimen fails very gradually and continues to carry substantial load even after large cracks appear. During SHRP, the suggested solution to this problem was to use the horizontal and vertical LVDTs to monitor horizontal and vertical deflections during the strength test. The point of failure is defined as occurring when the difference between the vertical and horizontal deformations reaches a maximum. This is the procedure included in AASHTO T322. Unfortunately, as explained previously, keeping LVDTs in place during the strength test often results in damage or destruction to these sensitive and expensive transducers. Engineers within the Superpave Centers agreed that for practical reasons, the IDT strength test should be done without LVDTs and the strength based only upon the maximum load. Although the AASHTO T322 procedure is probably more accurate, it appears that it is impractical, and damage to the LVDTs as a result of this procedure could actually reduce the overall reliability of the IDT creep and strength tests. In any case, the IDT strength test is only an approximation of the "true" tensile strength, and there is no reason to suspect that the refinement included in AASHTO T322 provides a more accurate result. For example, it is quite possible that IDT tensile strengths are in general lower than uniaxial tensile strengths. Because the AASHTO T322 "correction" actually results in lower IDT strengths, this would actually increase the error inherent in the test. The relationship between IDT strength and uniaxial tensile strength should be evaluated experimentally by testing a range of mixtures using both procedures. If necessary, empirical relationships can be developed among apparent IDT strength, the "corrected" strength as used in the Superpave thermal cracking program, and uniaxial tensile strength. Because the Superpave thermal cracking program was designed to use "corrected" IDT strength as input, care must be taken to provide test data equivalent to that produced using this procedure.

Modification of the IDT Procedure During NCHRP Projects 1-37A and 9-19

One of the early work elements in the Superpave Support and Performance Models Management Project (FHWA Contract DTFH61-95-C-00100, later NCHRP Project 9-19) was an evaluation of the Superpave low-temperature cracking model. A report on this work element was compiled that documented numerous problems in the original SHRP thermal cracking model (*A10*). Most of these problems were in the computer program used to analyze the data and predict thermal cracking and have been addressed in recent modifications of the program. However, some suggestions made in this report were not incorporated into later versions of the Superpave thermal cracking model.

One important issue raised in the report by Janoo and colleagues was the determination of the coefficient of thermal contraction, α (*A10*). The value of α has an extremely strong effect on the cracking temperature of asphalt concrete, and an accurate value for this parameter is essential to developing accurate predictions for low-temperature cracking. It is probably of equal importance to obtaining accurate measurements of compliance and strength. In the original SHRP procedure, α was to be estimated based upon mixture composition (*A3*). The accuracy of this procedure, however, was never verified. Kwanda and Stoffels actually measured the coefficient of thermal contraction of the mixtures used in developing the SHRP low-temperature cracking test procedures and models and found very poor correlation between the predicted and measured values of α (*A11*). Mehta et al. later presented a procedure based upon Kwanda and Stoffel's, in which α was measured using the instrumentation used in the IDT creep test (*A12*). However, the accuracy of this procedure has not been fully evaluated. Also, Janoo and associates (*A10*) pointed out that the coefficient of thermal contraction of asphalt cement binders and asphalt concretes is not constant, but varies with temperature. Typically, α is relatively constant at high temperatures, but begins to reduce as temperature is lowered, reaching a value at lower temperatures which is substantially lower than that at high temperatures (*A10*). However, assuming a binder α-value typical for temperatures above the glass transition is a conservative approach. Furthermore, mixture α-values measured by Kwanda and Stoffels (*A11*) suggest that in the temperature range of –20 to 0°C this assumption appears to be reasonable, as discussed in Chapter 2 of this report.

The change in the coefficient of thermal contraction of mixtures with temperature is due entirely to the properties of the binder, as the value of α for aggregates is constant and independent of temperature. Furthermore, it should be kept in mind that the value of α for asphalt binders is much greater than for aggregates, and as a result, the coefficient of thermal contraction for mixtures is mostly a function of the binder properties. Thus, if the value of α for mixtures is to be estimated, a typical value for α for the aggregate can probably be assumed, and what is then critical is assuming the correct relationship between α and temperature for the selected binder. Using these assumptions, a simple and reasonably accurate equation for estimating the coefficient of thermal contraction for mixtures has been developed as part of Phase III of NCHRP Project 9-29 and is presented at the end of Chapter 2 of this report.

Another important suggestion made by Janoo and his coauthors (*A10*) was to increase the time of the creep test to 1,000 seconds, rather than 100, to simplify the procedure used in developing the master curve, and also to improve the reliability of the results. Recent improvements in the algorithms used to develop master curves from IDT creep data have probably addressed this problem. Although Janoo and associates indicated that the procedure used to estimate relaxation modulus from creep compliance seemed to work well, they suggested that perhaps a better approach would be to measure relaxation modulus directly, using a constant rate of strain test. However, recent research in which constant rate of strain tests were performed on asphalt concrete has clearly shown that the strain rate in these tests is difficult to control, and the results are, therefore, difficult to analyze and interpret. At this time, as the general approach and analysis method appear to work well, there is no reason to consider this suggestion further.

A final serious, pertinent issue raised by Janoo and his associates (*A10*) was the inadequate incorporation of tensile strength in the model. Although the original intent in SHRP was to use tensile strength data at –20, –10, and 0°C, this apparently proved impractical. Later versions of the Superpave low-temperature cracking model used only tensile strength at –10°C. As pointed out in the report by Janoo and colleagues, the tensile strength of asphalt concrete increases with decreasing temperature, up to a certain point, after which the tensile strength begins to decrease slowly (*A10*). Although this would appear to create a significant problem in the Superpave thermal cracking model, the tensile strength data are in fact used only to estimate the fracture parameter, A, from an empirical equation. Because this equation was developed based upon –10°C IDT strength data, altering the data used as input would result in substantial errors in the procedure. Because the thermal cracking model has been calibrated based upon IDT strength data at –10°C, this approach should continue to be used.

Partly in response to the report by Janoo and colleagues, Witczak et al. (*A8*) made a considerable effort to refine the thermal cracking program. The simple errors identified in the program were corrected. Minor refinements were made in the data reduction module. For example, the calculation of compliance is based upon using "trimmed" means of deflections, which for the IDT test generally means averaging the data from four transducers after discarding the lowest and highest transducer outputs. This procedure originally did not properly handle LVDTs that were erroneously providing no output; improvements in the data reduction procedure handled this situation appropriately and apparently provide the operator with some indication of overall data quality, though the nature of this information is not yet clear. Equations for making corrections for bulging and for nonuniform distribution of stress and strain across the IDT specimen were empirically simplified into forms that allowed direct calculation of the factors, rather than iterative calculations as initially required (*A8*).

Significant improvements were made in the procedure used in developing master compliance curves from IDT creep data during NCHRP Project 9-19 (*A8*). In developing a master curve, compliance data at several temperatures is shifted with respect to the time (horizontal) axis to form a single curve representing creep compliance as a function of time. In analyzing IDT data, the reference temperature is usually −20°C. To form the IDT master curve, the creep data at −10 and 0°C are shifted to form a unified curve with the data at −20°C. This shifting is equivalent to dividing the actual loading times for a given test by a constant called the shift factor, a(T). Figure A-1 is a sketch showing graphically the construction of a master compliance curve from IDT data.

Although the construction of a master curve is not difficult, producing master curves in a standardized manner can be difficult, especially if the data are noisy or otherwise nonideal. Often, experienced engineers will develop master curves graphically, using a trial-and-error procedure involving substantial judgment. In order to make use of a master curve within a computer program, this process must be implemented through a series of algorithms, which apply logic and mathematics rather than judgment and experience to automatically generate a master curve. It is essential that such a procedure be robust and repeatable. That is, such an algorithm should, from a similar set of data, produce a comparable master curve, even with a substantial amount of variation in the data. Another problem in generating master curves is that, ideally, the compliance curves at each temperature should overlap slightly in order to produce the most accurate master curve. However, the current IDT creep testing protocol does not always produce compliance curves with such overlap. An effective automated procedure must, therefore, also address this shortcoming.

The initial algorithms used in generating master curves from IDT creep data were not always effective, resulting in substantial errors in the shift factors, which in turn produced errors in the calculation of thermal stresses and the resulting cracking. Buttlar and Roque addressed this problem in the development of a computer program called MASTER, which was designed to reliably generate master curves from IDT creep data even when substantial noise was present or when the data did not overlap. The details of the algorithms used in this program are described in detail in a NCHRP Project 9-19 report (*A8*). In summary, MASTER functions by considering a full range of ideal and nonideal situations, evaluating an IDT data set to determine what potential problems are present, and then implementing an effective algorithm for shifting the creep curves to generate a master compliance curve. The NCHRP Project 9-19 report also includes the results of an evaluation of MASTER. This program appears to work effectively in reliably producing effective creep curves. The only potential problem at this point appears to be with the shift factors. In MASTER, shift factors are determined individually for each set of temperatures; there is no assumed function (exponential, Arrhenius, etc.) used to fit shift factors as a function of temperature. For very stiff mixtures, because of the very small slope in the creep compliance data, shift factors at the lowest temperatures can become unreliable. Although it is not fully explained in recent NCHRP Project 9-19 reports, it appears that in order to evaluate shift factors at temperatures other than those used in IDT testing, a polynomial is fit to the calculated shift factors and is then used to interpolate or extrapolate shift factors at other temperatures. This procedure can potentially produce substantial errors, though such errors should be infrequent and should only occur with poor-quality data.

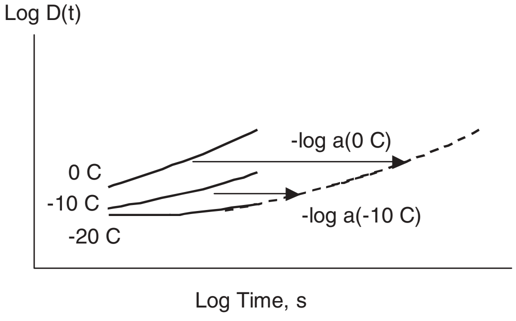


Figure A-1. Schematic of master curve construction from IDT data.

This potential shortcoming in MASTER could be avoided by two changes: (1) linking the IDT test temperature to the low-temperature binder grade used, so that excessively low compliance values are avoided, and (2) using a linear fit to the log a(T)-temperature data. Using IDT test temperatures related to the binder grade would also tend to produce much better quality data in general, as this protocol would tend to result in compliance data in the ideal range for the test system. It would also simplify the test procedure, as the response of different mixtures would tend to be similar regardless of the binder used, so that it will be easier for the technician performing the test to establish appropriate stress levels.

Summary of Recent Changes in the IDT Procedure

The current version of the IDT test and analysis procedure have been substantially improved and have addressed many of the shortcomings found immediately after the conclusion of SHRP. The following changes have been incorporated into the most recent version of the IDT test procedure and Superpave thermal cracking software (*A8*):

- Simplified formulas have been developed for making correction factors for specimen bulging and non-uniform stress and strain distribution across the specimen;
- The initial portion of data analysis, which involves developing a "trimmed" mean for the response of a given set of specimens, has been enhanced to avoid problems that occurred when a transducer was not responding and also to provide the user an overall indication of the quality of the data being analyzed;
- The procedure used to shift the individual compliance curves to form a master compliance curve has been substantially improved and is more robust and produces reasonable and repeatable master curves even for nonideal data;

- Most or all of the minor problems ("bugs") in the original SHRP computer program have been corrected; and
- The entire program has been recalibrated with an expanded data set, which includes the original mixtures and pavements used during SHRP and additional materials and pavements from the Canadian SHRP program.

Potential problems that have not been addressed include potentially inadequate characterization of the coefficient of thermal contraction and use of LVDTs during the IDT strength test, which often results in damage to the LVDTs, which can then result in the collection of faulty data for subsequent creep and strength tests.

DISCUSSION AND FINDINGS

The review of the original IDT strength and creep test and data analysis methods and subsequent modifications and related research indicate that the current procedure and analysis are much improved over the original SHRP version and should in most cases provide reliable results. A number of minor changes in AASHTO T322 have been suggested to improve the specifications for the IDT equipment and procedure. Many of the problems pointed out in the report by Janoo and colleagues (*A10*) have either been effectively addressed or are no longer pertinent. One issue that requires additional attention is the characterization of the coefficient of thermal contraction. Although Witczak and his associates apparently believe that the equation for estimating α is reasonably accurate (*A8*), research by Kwanda and Stoffels suggests otherwise (*A11*). A simple and reasonably accurate equation for estimating the coefficient of thermal contraction for asphalt concrete mixtures has been developed as part of Phase III of NCHRP Project 9-29 and is presented in Chapter 2 of this report.

More reliable data and more consistent results from subsequent analysis of these data can probably be obtained by using an IDT testing protocol in which the test temperatures are linked to the low-temperature binder grade used in the asphalt concrete. This would ensure that the compliance values for a given mixture would be either within or close to an ideal range for measurement and subsequent analysis. In order to simplify implementation, it is suggested that the basic test protocol of testing at −20, −10, and 0°C be maintained for PG XX-22 and PG XX-28 binders. For PG XX-16 binders (and harder), the test temperatures should be −10, 0, and +10°C. For PG XX-34 binders (and softer), the test temperatures should be −30, −20, and −10°C. Furthermore, it is suggested that for severely aged mixtures (either from pavement cores or from an accelerated laboratory aging procedure), the test temperatures be increased by 10°C. Tensile strength tests should be performed at the middle test temperature, usually −10°C.

For some mixtures, use of the Prony series to characterize the creep compliance of asphalt concrete mixtures can potentially cause problems in that the Prony series predicts rapidly increasing compliance when extended to longer reduced times than those for which the model was fitted. This problem is analyzed in detail in Chapter 2 of this report. It is most likely to occur for unusually stiff mixtures, and so using the adjustable test temperature protocol described previously would help to reduce or eliminate this problem. If necessary, the Superpave thermal cracking program should be modified to provide a power-law extrapolation of the compliance data to reduced times well beyond those used to fit the master curve, to ensure that this problem does not occur.

The use of the LVDTs to determine the precise moment of failure in the IDT strength test must be abandoned; it results in damage to the LVDTs that can then create severe problems in data quality in subsequent IDT creep and strength tests. Empirical relationships should be established between IDT strengths determined in AASHTO T322 and (a) those based upon maximum load during the IDT test and (b) those determined using a direct tension test with a 100-mm diameter by 150-mm high specimen, as will be used in the proposed Superpave simple performance tests. This will simplify the IDT test and allow engineers to use a test procedure consistent with what will probably become standard test procedures and geometries in the future.

Because the barriers that existed during SHRP to developing procedures for uniaxial tests at low temperatures no longer exist and because such uniaxial tests will become standard procedures in the near future, it is suggested that uniaxial creep and strength become the standard test method for low-temperature characterization of asphalt concrete mixtures. However, the IDT procedure as currently used should be retained for use on field cores. Laboratory testing should be performed to evaluate the relationship between data produced using uniaxial and IDT procedures and to develop empirical corrections if necessary.

CONCLUSIONS AND RECOMMENDATIONS

Based upon a review of AASHTO T322, and related papers and reports documenting changes in the IDT creep and strength test procedures and analysis, the following conclusions and recommendations are made:

- A number of minor changes in AASHTO T322 have been suggested and should be made in the next version of the standard.
- The proposed specification for the dynamic modulus master curve test equipment, as developed during NCHRP 9-29, should be revised to include optional requirements for equipment intended to perform not only the dynamic modulus test but also uniaxial creep tests and IDT creep tests at low temperature.
- Mixture tensile strength at low temperatures should be determined using either the current IDT procedure or uniaxial tensile strength. Normally, these tests should be performed on a large, static test system separate from the dynamic modulus master curve/low-temperature creep system. However, all tests could be performed on a single high-performance system if desired.

- A draft specification should be developed for uniaxial creep and strength testing at low temperatures, based upon AASHTO T322 and the specifications for the dynamic modulus master curve test equipment as developed as part of NCHRP Project 9-29.
- The relationship between uniaxial compliance and IDT compliance at low temperature should be experimentally evaluated, and empirical equations developed for estimating IDT compliance from uniaxial compliance should be developed if needed.
- Empirical relationships between the SHRP "corrected" IDT strength, the uncorrected IDT strength, and uniaxial tensile strength should be developed so that strength tests can be performed using the IDT geometry without attaching LVDTs or using a uniaxial test geometry.
- An improved procedure for either calculating or measuring the coefficient of thermal contraction of asphalt concrete mixtures has been developed and is presented in Chapter 2 of this report.
- Test temperatures for low-temperature creep tests should vary according to the binder grade. PG XX-22 and PG XX-28 binders should be tested at −20, −10, and 0°C; PG XX-16 binders should be tested at −10, 0, and +10°C; PG XX-34 binders should be tested at −30, −20, and −10°C. Test temperatures for severely aged mixtures should be increased 10°C above these temperatures. Tensile strength tests should be performed at the middle creep test temperature.

APPENDIX A REFERENCES

A1. Mehta, Y. A., and D. W. Christensen, "Determination of the Linear Viscoelastic Limits of Asphalt Concrete at Low and Intermediate Temperatures," *Journal of the Association of Asphalt Paving Technologists,* Vol. 69, 2000, pp. 281-312.

A2. Huang, Y. H., *Pavement Analysis and Design,* Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1993, p. 366.

A3. Lytton, R. L., J. Uzan, E. G. Fernando, R. Roque, D. Hiltunen, S. Stoffels, "Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixtures," *Report SHRP-A-357,* Washington D.C.: Strategic Highway Research Program, National Research Council, 1993.

A4. Bonaquist, R. F., D. W. Christensen, and W. Stump, "Simple Performance Tester for Superpave Mix Design: First Article Development and Evaluation," *NCHRP Report 513,* Transportation Research Board, National Research Council, Washington, D.C., 2003, 54 pp.

A5. Anderson, D. A., D. W. Christensen, R. Dongre, M. G. Sharma, J. Runt, and P. Jordhal, *Asphalt Behavior at Low Service Temperature,* Report FHWA-RD-88-078, Final Report to the FHWA, Springfield, VA: National Technical Information Service, March 1990, 337 pp.

A6. Christensen, D. W., and D. A. Anderson, "Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalts," *Journal of the Association of Asphalt Paving Technologists,* Vol. 61, 1992, pp. 67–98.

A7. Buttlar, W. G., and R. Roque, "Development and Evaluation of the Strategic Highway Research Program Measurement and Analysis System for Indirect Tensile Testing at Low Temperature," *Transportation Research Record No. 1454: Asphalt Concrete Mixture Design and Performance,* Washington, D.C.: National Academy Press, 1994, pp. 163–171.

A8. Witczak, M. W., R. Roque, D. R. Hiltunen, and W. G. Buttlar, "Modification and Re-Calibration of Superpave Thermal Cracking Model," *NCHRP 9-19 Project Report,* Arizona State University Department of Civil And Environmental Engineering, Tempe, Arizona, December 2000.

A9. Christensen, D. W., "Analysis of Creep Data for Indirect Tension Test on Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists,* Vol. 67, 1998, pp. 458–492.

A10. Janoo, V., T. Pellinen, D. Christensen, H. Von Quintus, "Evaluation of the Low-Temperature Cracking Model in Superpave," *Draft Report to the Federal Highway Administration,* Contract DTFH61-95-C-00100, undated (ca. 1997).

A11. Kwanda, F. D., and S. Stoffels, "Determination of the Coefficient of Thermal Contraction of Asphalt Concrete Using the Resistance Strain Gage Technique," *Journal of the Association of Asphalt Paving Technologists,* Vol. 65, 1996, pp. 73–92.

A12. Mehta, Y., S. Stoffels, and D. W. Christensen, "Determination of Coefficient of Thermal Contraction of Asphalt Concrete Using Indirect Tensile Test Hardware," *Journal of the Association of Asphalt Paving Technologists,* Vol. 68, 1999, pp. 349–367.

APPENDIX B

EQUIPMENT CONFIGURATIONS FOR CREEP AND STRENGTH TESTING OF HOT MIX ASPHALT CONCRETE AT LOW TEMPERATURES

INTRODUCTION

The purpose of this appendix is to present a detailed review of equipment requirements for low-temperature creep and strength testing of asphalt concrete mixtures. During the Strategic Highway Research Program (SHRP), procedures were developed for characterizing the mechanical behavior of asphalt concrete at low temperature and using the resulting data in a rational analysis to provide reasonably accurate predictions of thermal cracking. The test procedures developed were the indirect tension (IDT) creep and strength tests summarized in AASHTO T322. Since the conclusion of SHRP, these procedures and the required equipment have not been fully evaluated, refined, and implemented. Implementation activities were attempted through the FHWA Regional Superpave Centers, but were unsuccessful, largely due to problems associated with the specific IDT test system purchased for use by the Superpave Centers. In the meantime, development of new uniaxial test methods for use in the Superpave simple performance tests and in characterizing asphalt concrete mixtures as required by the pavement design guide developed in NCHRP Project 1-37A have provided engineers with an attractive alternative to the IDT creep and strength procedure. This appendix focuses on an evaluation of the possible use of the dynamic modulus test equipment to perform both the IDT and uniaxial creep and strength tests at low temperature.

Following this introduction, a substantial background section is presented, in which the essentials of low-temperature cracking are presented, along with a discussion of the development of the Superpave IDT creep and strength test procedures and the more recently developed simple performance and dynamic modulus tests. This is followed by a detailed review of the equipment requirements for both procedures. Specific recommendations for revising the IDT creep and strength equipment requirements are summarized. The dynamic modulus test equipment—the version required for master curve development for structural pavement design—was reviewed to determine the changes needed for performing low-temperature creep and strength tests. It was concluded that this version of the dynamic modulus test equipment should require only slight modifications to perform low-temperature creep and strength tests, in either a uniaxial or diametral geometry.

The NCHRP Project 9-29 Phase III Interim report included the recommendation that the low-temperature creep and strength testing required for the Superpave thermal cracking model should primarily be performed using uniaxial testing performed on the dynamic modulus master curve equipment as required in the pavement design guide developed in NCHRP Project 1-37A. However, as is made clear throughout this report, the presence of anisotropy in the creep compliance of asphalt concrete mixtures measured at low temperatures strongly suggests that the IDT test should be retained as the standard procedure, though some relatively minor revisions are needed in this method. The reader should keep this in mind while reading this appendix and the comparison of the IDT and uniaxial test geometries.

BACKGROUND

In order to fully appreciate the various issues surrounding appropriate equipment for performing low-temperature creep and strength tests on asphalt concrete, it is essential to understand the basics of low-temperature cracking. It is also useful to know the history of the development of the IDT creep and strength tests. Furthermore, recent development of uniaxial test procedures and equipment for use in the Superpave simple performance tests and in the dynamic modulus test needed for asphalt concrete characterization in the pavement design guide developed in NCHRP Project 1-37A make a uniaxial creep and strength test at low temperatures a possible alternative to the IDT procedure. In the sections below, information is presented to provide the reader with background needed to understand these and other important issues surrounding low-temperature testing of asphalt concrete mixtures.

Low-Temperature Cracking

Low-temperature cracking, also referred to as thermal cracking, occurs in flexible pavements during rapid temperature drops in the winter months in temperate and sub-Arctic regions. Like most materials, the volume of asphalt concrete changes with changes in temperature—when it cools down, it contracts, and when it warms up, it expands. In an actual pavement, the asphalt concrete is prevented from moving, because there are normally no joints in flexible pavement systems. Therefore, when an asphalt concrete pavement is rapidly cooled, it develops substantial tensile stresses. This situation is worsened by the temperature-dependent nature of asphalt concrete; not only does it contract upon cooling, but its modulus increases, and its strain capacity decreases. Therefore, when an asphalt concrete pavement is subjected to rapid cooling at low temperatures, it becomes more brittle while at the same time developing substantial thermal stresses in tension. This combination of conditions is the primary cause of thermal cracking in asphalt concrete pavements.

In severe low-temperature events, cracking can be catastrophic, occurring explosively and resulting in the immediate development of transverse cracks. These cracks are typically spaced at 3 to 10 meters and usually run from one-half to completely across the pavement. Although crack-widths are often initially quite small, thermal cracks will gradually widen, allowing water and dirt to enter the crack. After several years, thermal cracks can lead to serious pavement distress. Thermal cracking can also occur through a fatigue mechanism. In this case, individual low-temperature events are not severe enough to create stresses in excess of the tensile strength of the pavement but are high enough so that accumulated damage over months or years will eventually cause transverse cracks to develop. Figure B-1 is a photograph of typical low-temperature cracking.

The primary factor contributing to low-temperature cracking is the use of asphalt binders that are too stiff for a given climate. Recent experience suggests that the Superpave performance grading of binders, when properly applied, has greatly reduced the potential for thermal cracking in asphalt concrete pavements. However, other factors besides binder grade will affect the low-temperature properties of an asphalt concrete mixture, including binder content, air void content, aggregate gradation and type, pavement thickness, type and thickness of the pavement subbase, and the type of the underlying subgrade. In order to obtain the most reliable evaluation of the resistance of an asphalt concrete mixture to low-temperature cracking, a rational procedure for testing and analysis of the mixture is needed that takes into account most of these factors.

The SHRP IDT Creep and Strength Tests

During SHRP, low-temperature cracking was identified as one of the major forms of distress in asphalt concrete pavements. A concerted effort was made to develop an effective mechanics-based approach to evaluate the resistance of asphalt concrete mixtures to this form of damage; the IDT creep and strength tests were the result (*B1*). In these tests, a thin, circular specimen of asphalt concrete is loaded across its diameter to determine its mechanical properties at low temperatures. A typical specimen is 50-mm thick and 150-mm in diameter and is prepared by sawing a thin section out of a standard specimen prepared using a gyratory compactor. Pavement cores can also be used to make specimens for this procedure. In the creep test, constant stress loading is used to determine the compliance of the mixture at −20, −10, and 0°C, usually over a period of 100 seconds. In the strength test, the specimen is loaded at a constant rate of 12.5 mm/min (0.5 in/min) until the specimen fails in tension. This test is usually performed at −10°C. The IDT test geometry was selected, rather than a simpler uniaxial test, because at the time laboratory specimens for testing asphalt concrete mixtures were generally 100-mm in diameter and no more than 100-mm high, and usually shorter. Preparing an appropriate specimen for uniaxial testing from this type of compacted sample would be difficult or impossible (*B1*). Furthermore, the general procedures and equipment for performing uniaxial tests on asphalt concrete were not well developed, whereas the IDT test geometry had been widely used in a number of procedures. An additional advantage of the IDT geometry is that thin field cores can be easily tested. The SHRP research team therefore decided to use the IDT geometry for the SHRP thermal-cracking tests (*B1*). Figure B-2 is a sketch of an instrumented IDT test specimen (*B2*).

The Superpave thermal cracking computer model is quite complex, and a detailed description is beyond the scope of this appendix. It will only be briefly summarized here; the interested reader should refer to Witczak et al. (*B3*), a recent report providing up-to-date, detailed information on this computer program. There are several steps in the analysis of data gathered using the IDT creep and strength test: data evaluation and averaging; compliance calculation; master curve construction; calculation of relaxation modulus; stress calculation; and cracking prediction. In the Superpave thermal cracking computer program, these steps are implemented through a number of subroutines that model various aspects of the problem, such as environmental effects, pavement response, and pavement distress. A special procedure is used in the strength test to determine the exact moment of failure. This involves monitoring the specimen deflection during testing and defining the moment of failure as the point at which the difference between the vertical and horizontal deformations reaches a peak. Calculation of compliance using the IDT system is somewhat complicated by the three-dimensional state of stress that exists

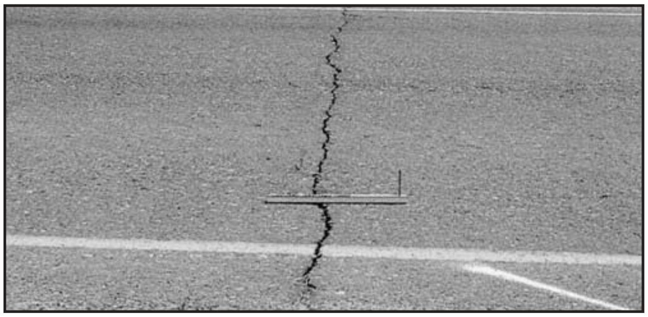


Figure B-1. Typical low-temperature cracking in an asphalt concrete pavement.

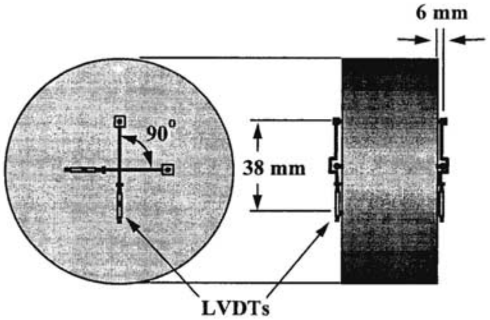


Figure B-2. Sketch of an instrumented IDT test specimen.
SOURCE: The Asphalt Institute (B3).

during diametral loading. In the Superpave IDT creep and strength tests, the distribution of stress and strain within the IDT specimen is modeled through a series of semi-empirical equations based upon the results of three-dimensional finite element analyses. This approach provides more accurate results than the simpler and more widely used approach of applying a simple plane stress analysis to the IDT loading geometry.

Soon after the conclusion of SHRP, numerous problems were identified in many of the tests and computer programs developed during SHRP, including the IDT test and thermal cracking program. These problems were well documented in a report by Janoo and his associates (*B4*). Over the next several years, Witczak et al. made a substantial effort to improve the test and the associated analyses and computer program. As documented in the report published by this group (*B3*), the IDT creep and strength test and the Superpave thermal cracking program now appear to be reasonably reliable and accurate.

Problems with Electromechanical IDT Systems Used at the Regional Superpave Centers

In 1996, the Federal Highway Administration established five Regional Superpave Centers, to assist with the implementation of the Superpave technology. The Superpave Centers generally represented cooperative ventures between the hosting state highway department and a state-run or state-related research university. Most of the Superpave Centers were given IDT creep and strength test systems designed and manufactured by Instron Corporation. These systems were unique in that they were closed-loop electromechanical ("screw") test machines; most closed-loop test systems are servo-hydraulic. It was believed that these systems would potentially be less expensive to purchase and operate and also easier and safer to operate, especially in a state highway or contractor's laboratory that might lack experienced test engineers.

Unfortunately, these systems were plagued with a wide range of hardware and software problems and a lack of customer support. There were frequent problems with malfunctioning of the LVDTs used to measure IDT deformation and the conditioners used in conjunction with these transducers. Part of this problem was related to the practice of keeping LVDTs mounted on the specimens during strength tests, which frequently damaged the LVDTs, sometimes enough so that the LVDT was completely nonfunctional, but often times only slightly, so that it was not clear that the LVDT was damaged and not functioning properly. For this reason, a procedure is needed to estimate the "corrected" IDT strength from that determined without use of LVDTs. Another source of problems was the placement of some of the LVDT conditioning circuits inside the environmental chamber, which subjected these electronics to frost and moisture. The manufacturer (Instron Corporation) explained that the nature of the bid documents required them to design the system in a less than ideal manner and indicated that given more flexibility in their choice of transducer type, they could have produced a significantly more reliable system.

The software supplied with these systems was inflexible and difficult to operate, and frequently crashed. The latter problem was probably caused by insufficient memory in the computer systems supplied with these test systems. Some engineers at the Superpave Centers complained that the ramp times required to reach specified loads for the creep tests were too long, though experience at the Northeast Center was that this was a software problem and not due to limitations in the capability of the electromechanical loading system.

Because of the numerous problems encountered by the various Superpave Centers in operating these systems, only one—The Northeast Center—performed IDT tests on a regular basis using this equipment; recently, the Northcentral Superpave Center also began using their system. The quality of the data produced at the Northeast Center was, however, marginal and testing was continued mostly in an effort to gain experience with this system. The Northeast Center did publish one research paper on analysis of the IDT creep test (*B5*), which was essentially a detailed explanation of a simplified version of Roque and Hiltunen's analysis (*B1*), suitable for use in estimating thermal cracking temperatures using IDT creep and strength data. Although ruggedness testing with the IDT systems was planned, because of the frequent and serious problems with the Instron IDT system, significant progress was never made on this task.

The frustrating experience within the Superpave Centers with the Instron IDT system has probably created a situation in which it would be inadvisable to continue to promote electromechanical systems for use in IDT creep and strength testing. The likely market size for this test is probably perceived as too small to motivate any equipment manufacturer to provide significant custom engineering, design, and support for the IDT test system. The most practical approach for pavement engineers is, therefore, to use off-the-shelf test systems to perform the test, with a minimum of specially machined accessories. For this reason, suppliers of the frequency-sweep equipment to be used in characterizing mixtures for the pavement design guide developed in NCHRP Project 1-37A should be encouraged to include as an option the necessary capacity, hardware, and software for performing low-temperature creep and strength tests using the IDT procedure.

Although it has some practical advantages, uniaxial testing does not provide data equivalent to that produced with the IDT test. The IDT strength test should however be performed without LVDTs, and the apparent strength calculated using the maximum load. The "true" IDT strength should then be adjusted using the empirical relationship given in the body of this report as Equation 8.

NCHRP Projects 1-37A and 9-19

During the past 5 years, much effort has been made at improving the standard test procedures and analysis methods used to design asphalt concrete mixtures and pavements. This effort has progressed on several fronts. In NCHRP

Project 9-19 work has continued on developing and refining test methods and models for use in a comprehensive and accurate version of Superpave. A similar effort has been made under NCHRP Project 1-37A in selecting test methods and procedures for pavement structural design; but, in this case, a more conservative approach has been used in order to ensure that the resulting procedures are highly robust and reliable and suitable for use by practicing engineers. A third related effort has been in the development of simple performance tests for use in conjunction with Superpave volumetric mix design, performed under NCHRP Project 9-19.

There has been significant articulation among these efforts, so that there is consistency among many of the proposed test procedures. At this time, the specific procedure to be used for the simple performance tests has not been finalized, but the test geometry has been; a 150-mm-high by 100-mm-diameter specimen will be used, which is to be prepared by coring and sawing a 170-mm-high by 150-mm-diameter gyratory specimen. All candidate simple performance tests involve uniaxial testing. This same geometry is also to be used in the dynamic modulus test to be used in the mixture characterization needed for the pavement design guide developed in NCHRP Project 1-37A. Furthermore, many of the tests being performed in developing advanced models for eventual incorporation into the comprehensive Superpave pavement modeling system also involve this same test geometry. Figure B-3 is a schematic of an instrumented specimen for dynamic modulus testing, using the same uniaxial geometry as proposed for the various candidate simple performance tests (*B6*).

Equipment specifications for the simple performance tests and the dynamic modulus master curve test were developed during NCHRP Project 9-19 and refined during NCHRP Project 9-29. First article devices have been manufactured and evaluated. It is likely that within several years, many laboratories will have the capability of performing the simple performance tests and the dynamic modulus test as required by the pavement design guide developed in NCHRP Project 1-37A. An initial review of the specifications for the dynamic modulus master curve test device (presented later in this appendix) has indicated that with only slight modifications, it could be used to perform low-temperature creep and strength tests for use in the Superpave thermal cracking model. Many private and public laboratories would be well-served by having the ability to perform not only the simple performance tests and the dynamic modulus master curve procedure using a single piece of equipment but also the low-temperature creep and strength test. This would have many advantages:

- Cost savings on purchase of test equipment;
- Cost savings on purchase of specimen preparation equipment and test accessories;

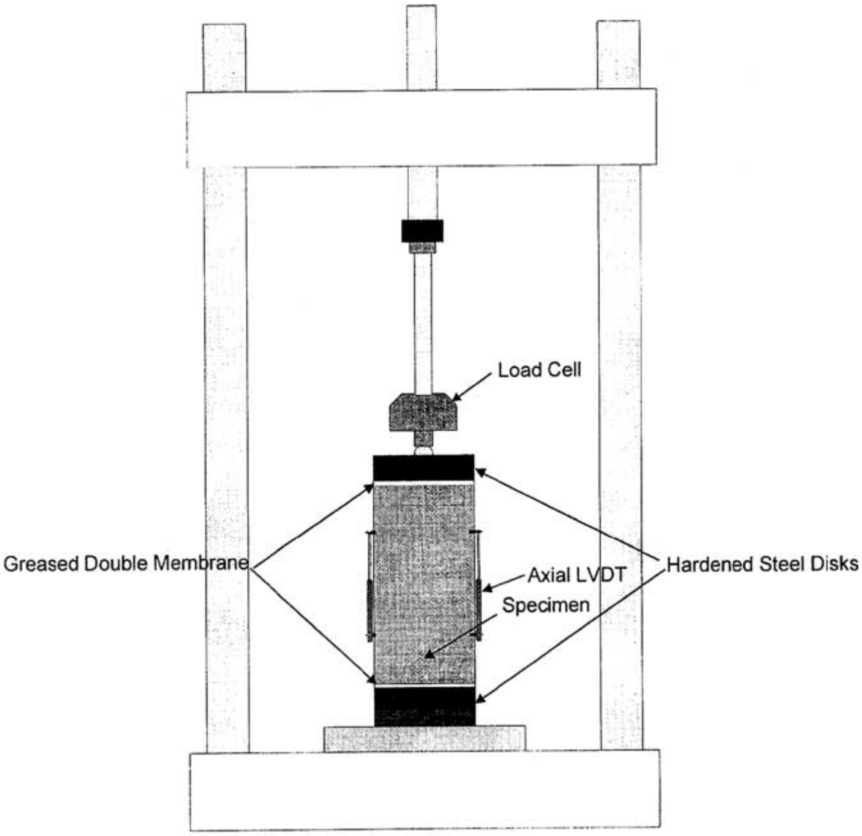


Figure B-3. Schematic of dynamic modulus test.
SOURCE: Witczak et al. (*B6*).

- Cost savings on training engineers and technicians to prepare specimens and perform tests;
- Greater reliability of data due to greater experience with a single test geometry and test device; and
- Greater flexibility in scheduling testing, if more than one device is needed in a lab.

The decision during SHRP to use the IDT test geometry rather than a uniaxial test was made mostly because the equipment and procedures for preparing and testing uniaxial specimens did not exist at that time (*B1*). Although this situation has changed with the ongoing development and implementation of uniaxial tests as part of NCHRP Project 9-29 and related efforts, the IDT should be retained as the standard method for low-temperature characterization of asphalt concrete because IDT tests and uniaxial tests simply do not provide equivalent results. In the following section of this appendix, recommended improvements for the IDT creep and strength test are summarized. Current draft specifications for the dynamic modulus master curve test equipment are presented and evaluated with respect to performing both uniaxial and diametral tests at low temperature; suggestions are also made concerning the use of the dynamic modulus master curve test equipment for determining creep compliance at low temperatures.

REVIEW OF IDT CREEP AND STRENGTH EQUIPMENT

The procedure and equipment for performing IDT creep and strength tests are described in detail in AASHTO T322, Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device. This standard is reviewed in detailed in Appendix A of this report. A summary of the suggested revised specifications for the IDT apparatus to be used in conjunction with AASHTO T322 is given in Table B-1; the interested reader should refer to Appendix A for the details of the evaluation. The changes proposed in Table B-1 are not substantial and should not be difficult to implement.

USE OF DYNAMIC MODULUS MASTER CURVE TEST EQUIPMENT FOR LOW-TEMPERATURE CREEP AND STRENGTH TESTING

A similar approach to the analysis presented in Appendix A for the IDT creep and strength test is presented below for uniaxial testing of asphalt concrete at low temperatures. Table B-2 is a summary of the requirements for a testing system to perform the dynamic modulus master curve testing required for the pavement design guide developed in NCHRP Project 1-37A. The sections that follow present an analysis of modifications required to use this equipment for IDT creep and strength tests at low temperature.

The temperature requirements for the dynamic modulus master curve test system should be expanded for low-temperature testing from −10 to −30°C. The specified accuracy of ±0.5°C is adequate.

The load capacity for the dynamic modulus master curve test system is given as 22.5 kN (5.0 kips) in dynamic mode. This capacity is adequate for low-temperature creep testing, as it would allow the application of creep stresses up 2.8 MPa (410 lb/in^2). Considering that the tensile strength of asphalt concrete at low temperature ranges from about 1.3 to 4.3 MPa (190 to 630 lb/in^2), this should be more than adequate for creep testing. However, the load capacity must be increased for tensile strength testing. Doubling the typical maximum tensile strength of 4.3 MPa (630 lb/in^2) and rounding, the required load capacity of the system would be 70 kN (16 kips). Although this represents a tripling of the load capacity, this additional capacity is for static loading, which is a less stringent condition than for dynamic loading. If possible, equipment

TABLE B-1 Proposed revised AASHTO T322 specifications for the IDT apparatus

Component	General Requirements	Range	Resolution
Axial loading device	Shall provide a constant load	100 kN maximum load; Maximum displacement rate of at least 12 mm/min	10 N or better
Load measuring device	Electronic load cell	100 kN minimum capacity	10 N or better
Deformation measuring device(s)	Four displacement transducers (LVDTs or equivalent)	0.1 mm minimum	0.1 µm or better
Environmental chamber	Temperature control only; large enough to perform test and condition 3 specimens	–30 to +10 °C under ambient conditions of 15 to 27 °C	Control accuracy to ±0.5 °C
Control and data acquisition system	System shall be operated with the use of a personal computer and shall digitally record load and deformation during test	1 to 20 Hz sampling rate	Consistent with required resolution of all system transducers
Test fixture	As described in ASTM D4123 (diametral resilient modulus testing), but with flat neoprene loading strips 12-mm thick by 12-mm wide.	N/A	20 N maximum frictional resistance

TABLE B-2 Summary of requirements for dynamic modulus test equipment

Item	Requirements for Dynamic Modulus Test Equipment for Generating Master Curves for Structural Design
ENVIRONMENTAL CHAMBER	
Temperature range	−10 to 60 °C
Control accuracy	To within ±0.5 °C of specified temperature
LOADING SYSTEM	
Dynamic load	22.5 kN (5.0 kips)
Contact load	5 % of test load
Static load and peak dynamic load accuracy	±2 % of specified value
Dynamic load accuracy	Maximum standard error of 5 %
Loading rate	0.01 to 25 Hz
LOAD MEASUREMENT SYSTEM	
Range	Equal to or greater than stall force of loading system actuator
Accuracy	±1 % maximum for loads ranging from 2 to 100 % of the machine, when verified in accordance with ASTM E4
Resolution	Shall comply with requirements of ASTM E4
AXIAL STRAIN TRANSDUCER	
Gage length	70 mm nominal
Range	1 mm minimum
Resolution	Equal to or better than 0.0002 mm (7.8 micro-inch)
Error	0.0025 mm (0.0001 in) maximum when verified according to ASTM D 6027
Miscellaneous	Shall be designed for rapid specimen installation and testing
MISCELLANEOUS REQUIREMENTS	
Confining pressure	No
Computer control and data acquisition	Controlled from personal computer and capable of running dynamic modulus test and analyzing resulting data as specified

design for low-temperature IDT creep testing should also have the capability of performing the IDT strength test. However, if this is not practical, the strength test could be performed on a separate, stand-alone system design specifically for high-capacity static testing.

The requirements for contact load and static load accuracy appear to be acceptable. Determining the required loading rate requires some analysis. As noted in Appendix A for the IDT test, the most extreme requirements for loading rate occur at low temperatures, where the asphalt concrete is behaving elastically and therefore will deform very quickly. Assuming a compliance of 3×10^{-11} Pa^{-1} (2×10^{-7} in^2/lb) and an applied stress of 2.2 MPa (320 lb/in^2), the resulting strain would be 6.6×10^{-5}, which for a 150-mm-high uniaxial specimen would translate to a deflection of 0.010 mm. Assuming that the maximum load should be reached in one second, this would translate to a loading rate of 0.6 mm/min; allowing for adequate reserve capacity in the system, the required loading rate would be 1.2 mm/min (0.047 in/min). This rate is quite slow and should be well within the capability of the dynamic modulus test equipment. This required loading rate is ten times lower than the 12 mm/min (0.47 in/min) rate required for IDT testing and demonstrates the greater efficiency of uniaxial loading as compared with diametral loading.

The gage length and range for the axial strain transducers appear to be appropriate. As with the IDT test discussed in Appendix A, determination of the required transducer resolution should be based upon a maximum strain of about 0.025 percent and a strain during the initial stages of the creep test of about one-fifth this value, or 0.005 percent. For the gage length of 70 mm, this translates to a deformation of 0.0035 mm, or 3.5 μm. For a maximum error of about 5 percent, the required resolution would then be 0.2 μm (7 μin). This requirement is precisely the same as that established for the dynamic modulus test and therefore need not be changed. The requirements for error should also be appropriate for low-temperature testing. The need for a system that can be rapidly attached and zeroed during testing also remains the same. The requirements for the axial strain transducers for low-temperature creep testing are identical to those already established for the dynamic modulus master curve test.

The miscellaneous requirements for the test system are equally applicable to the low-temperature creep and strength tests. Therefore, to adapt the dynamic modulus master curve test system to low-temperature creep and strength testing, either in a uniaxial or diametral mode, only two changes are needed: (1) the maximum static capacity of the system must be 100 kN (22 kips) and (2) the system must be capable of loading at a rate of at least 12 mm/min.

Although the increased static capacity required for low-temperature creep and strength testing is substantial, it greatly increases the flexibility and capability of the dynamic modulus master curve test system. Also, as mentioned, because it is static capacity, rather than dynamic, the increased cost should not be large. The accessories required for low-temperature IDT tests should be included in the low-temperature creep and strength system option.

CONCLUSIONS AND RECOMMENDATIONS

A thorough review of the low-temperature creep and strength test procedures and equipment was performed and has been presented in Appendix A for the IDT test and this appendix for uniaxial tests. Based upon this review, the following conclusions and recommendations are made:

- Several minor refinements in the IDT equipment specification are needed; revised equipment requirements are discussed in detail in Appendix A of this report and are summarized in Table B-1 of this appendix.
- The dynamic modulus master curve test equipment needed for HMA characterization in the pavement design guide developed in NCHRP 1-37A is capable of properly performing low-temperature uniaxial creep tests with only minor modification.
- A significant increase in static loading capacity is need in the dynamic modulus master curve test system in order to perform IDT strength tests at low temperature. If necessary, strength tests could be performed on a separate system designed specifically for high-capacity static testing.
- A combined dynamic modulus/low-temperature IDT creep and strength test system should be recommended by NCHRP and FHWA

APPENDIX B REFERENCES

B1. Lytton, R. L., J. Uzan, E. G. Fernando, R. Roque, D. Hiltunen, S. Stoffels, "Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixtures," *Report SHRP-A-357,* Washington D.C.: Strategic Highway Research Program, National Research Council, 1993.

B2. The Asphalt Institute, *Superpave Asphalt Mixture Analysis, Course Notebook,* National Asphalt Training Center II, Washington, DC: Federal Highway Administration, Office of Technology Applications, May, 1996.

B3. Witczak, M. W., R. Roque, D. R. Hiltunen, and W. G. Buttlar, "Modification and Re-Calibration of Superpave Thermal Cracking Model," *NCHRP 9-19 Project Report,* Arizona State University Department of Civil And Environmental Engineering, Tempe, Arizona, December 2000.

B4. Janoo, V., T. Pellinen, D. Christensen, H. Von Quintus, "Evaluation of the Low-Temperature Cracking Model in Superpave," *Draft Report to the Federal Highway Administration,* Contract DTFH61-95-C-00100, undated (ca. 1997).

B5. Christensen, D. W., "Analysis of Creep Data for Indirect Tension Test on Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists,* Vol. 67, 1998, pp. 458–492.

B6. Witczak, M. W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Von Quintus, H., "Simple Performance Test for Superpave Mix Design," *NCHRP Report 465,* Transportation Research Board, Washington, D.C., 2002.

APPENDIX C

SUMMARY DATA

A disk containing summary data files for NCHRP Project 9-29 is available for loan upon request to NCHRP, Transportation Research Board.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation