NCHRP

REPORT 444

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

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

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FOREWORD

By Staff
Transportation Research Board

This report presents recommended changes to AASHTO Standard Method of Test T283, “Resistance of Compacted Bituminous Mixture to Moisture Induced Damage,” to enhance T283’s compatibility with Superpave® volumetric mix design. It will be of particular interest to materials engineers in state highway agencies and contractor personnel responsible for the design of hot-mix asphalt (HMA) according to the current Superpave or older Marshall and Hveem methods.

Moisture damage in HMA pavements gained national attention in the late 1970s, and its reported occurrence continues to grow. Moisture damage contributes to a variety of distresses, including rutting, raveling, and cracking, that significantly diminish the performance and service life of HMA pavements.

During 1987 through 1993, the Strategic Highway Research Program (SHRP) carried out several major research projects to identify the root causes of moisture damage and to develop better methods for predicting moisture damage in the mix design process. At the end of the program, however, the conclusion was reached that only minor progress had been made in understanding the mechanism (or mechanisms). Moreover, an objective assessment of the experimental results suggested that none of the laboratory procedures developed under SHRP provided a more accurate prediction of moisture damage than did the existing AASHTO Standard Method of Test T283. Consequently, AASHTO T283 was incorporated in Superpave volumetric mix design to determine HMA moisture damage susceptibility.

AASHTO T283 is derived from research carried out by Lottman in NCHRP Project 4-08(03)[1] and refined by Tunnicliff and Root in NCHRP Project 10-17.[2] The procedure and suggested failure criteria are based on the moisture-induced behavior of 4-in.-diameter specimens compacted to an air-voids content of 7 ± 1 percent with a Marshall or Hveem compaction device. Thus, the use of 150-mm-diameter specimens compacted with the Superpave gyratory compactor raised questions of whether the results would be comparable with those obtained on the smaller diameter specimens.

Under NCHRP Project 9-13, “Evaluation of Water Sensitivity Tests,” the University of Nevada at Reno was assigned the task of evaluating whether conducting AASHTO T283 with specimens prepared according to Superpave volumetric mix design (AASHTO MP2 and PP28) yields results comparable with those obtained with Marshall- and Hveem-compacted specimens. The research team conducted a comprehensive laboratory testing program to statistically compare the tensile strengths and resilient moduli of 150-mm gyratory-compacted specimens measured before and after conditioning

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[1] *NCHRP Report 192: Predicting Moisture-Induced Damage to Asphaltic Concrete* and *NCHRP Report 246: Predicting Moisture-Induced Damage to Asphaltic Concrete–Field Evaluation*.

[2] *NCHRP Report 274: Use of Antistripping Additives in Asphaltic Concrete Mixtures–Laboratory Phase* and *NCHRP Report 373: Use of Antistripping Additives in Asphaltic Concrete Mixtures–Field Evaluation.*

in accordance with AASHTO T283 to the same properties measured on Marshall, Hveem, and 100-mm gyratory-compacted specimens. Specimens were prepared to duplicate Superpave-designed mixes from Alabama, Colorado, Maryland, Nevada, and Texas that had reported resistance to moisture damage ranging from good to poor.

The report includes a general discussion of the entire research effort, a summary of relevant results from the laboratory test program, and conclusions and significant findings. Of particular interest is that no statistically significant differences were found between the tensile strengths and resilient moduli (or their wet-to-dry ratios) of 150-mm-diameter, Superpave gyratory-compacted specimens and 4-in.-diameter, Marshall-compacted specimens. In general, however, the larger gyratory-compacted specimens did yield significantly different results from 4-in.-diameter, Hveem-compacted specimens. The report also discusses the effect on the test results of variations in loose and compacted mix aging, specimen conditioning methods, and saturation levels. An appendix presents the recommended changes to AASHTO T283 to accommodate its use in Superpave volumetric mix design.

The two-part final report (Volume I, *Tensile Strength Experiments*, and Volume II, *Resilient Modulus Experiments*) is supported by five detailed technical work reports.[3] This published report includes Volume I and the recommended changes to AASHTO T283; Volume I along with Volume II and the five supporting reports are also planned for future publication in the CRP CD-ROM *Bituminous Materials Research Series*.

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[3] (1) Comparison of Gyratory, Marshall and Hveem Compacted Mixtures–Tensile Strength; (2) Effect of Performing Resilient Modulus Tests Prior to Tensile Strength Determinations During Water Sensitivity Testing; (3) Comparison of Water Sensitivity Results on Samples Prepared with the Superpave Gyratory Compactor and Marshall Impact Compactor–Tensile Strength; (4) Comparison of Gyratory, Marshall and Hveem Compacted Mixtures–Resilient Modulus; and (5) Comparison of Water Sensitivity Test Results on Samples Prepared with Superpave Gyratory Compactor and Marshall Impact Compactor–Resilient Modulus.

CONTENTS

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 9-13, "Evaluation of Water Sensitivity Tests," by the Pavements and Materials Program, Civil Engineering Department, University of Nevada. Jon A. Epps, Professor of Civil Engineering, and Peter E. Sebaaly, Professor of Civil Engineering, the University of Nevada, are co-principal investigators on the project and the principal authors of the report. The other authors are Jorge Penaranda, Graduate Research Assistant, Michele R. Maher, Graduate Research Assistant, and Martin B. McCann, Graduate Research Assistant, the University of Nevada; and Adam J. Hand, Assistant Professor of Civil Engineering, Purdue University. Dr. Hand was responsible for earlier portions of the project, which were performed at the University of Nevada.

The authors wish to acknowledge the contributions of Tim E. Steele, Maria V. Ardila-Coulson, and Lisa A. Cody, of the Civil Engineering Department, University of Nevada. Mr. Steele, Senior Development Technician, was responsible for the equipment maintenance and the purchasing associated with the project. Ms. Ardila-Coulson, Director, Transportation Technology Transfer Center, performed the accounting, office supervision, and general project coordination. Ms. Cody, Program Assistant, Transportation Technology Transfer Center, prepared the report.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

General Observations

In the late 1970s and early 1980s, a significant number of pavements in the United States began to experience distress associated with moisture sensitivity of hot-mix asphalt (HMA) materials. Premature rutting, raveling, and wear were observed on many pavements. The causes of this sudden increase in pavement distress because of water sensitivity have not been conclusively identified. Practitioners and researchers suggest that changes in asphalt binders, decreases in asphalt binder content to satisfy rutting associated with increases in traffic (i.e., traffic volume, traffic weight, and tire pressure), changes in aggregate quality, increased widespread use of selected design features (e.g., open-graded friction courses, chip seals, and fabric interlayers), and poor quality control were primarily responsible for increased water sensitivity problems.

Regardless of the cause of this moisture-related premature distress, methods are needed to identify HMA behavior in the presence of moisture. Test methods and pavement performance prediction tools need to be developed that couple the effects of moisture on the properties of HMA mixtures with performance prediction to estimate the behavior of the mixture in resisting rutting, fatigue, and thermal cracking when it is subjected to moisture under different traffic levels in various climates.

Current State of the Practice

Methods are presently not available to couple the effects of moisture on material properties with pavement performance prediction. Most public agencies use tests on loose or compacted HMA to determine the water sensitivity of the paving material. These test results cannot be used directly to rationally predict performance. Only limited correlations have been established between water sensitivity test results and observed performance of pavements that contain the tested HMA.

The water sensitivity test methods listed below are national standards and are used by public agencies (AASHTO [*1*] and ASTM [*2*]):

- AASHTO T283, “Resistance of Compacted Bituminous Mixture to Moisture Induced Damage”;
- ASTM D4867, “Effect of Moisture on Asphalt Concrete Paving Mixtures”;
- AASHTO T165/ASTM D1075, “Effect of Water on Compressive Strength of Compacted Bituminous Mixtures”; and
- ASTM D3625, “Effect of Water on Bituminous-Coated Aggregate Using Boiling Water.”

Other laboratory test methods are used by public agencies but are not national standards. These test methods include Marshall samples subjected to immersion, Hveem samples subjected to moisture vapor, and a pedestal freeze-thaw test. The Strategic Highway Research Program (SHRP) identified a method of test that is presently designated as AASHTO Provisional Standard (TP34), “Moisture Sensitivity Characteristics of Compacted Bituminous Mixtures Subjected to Hot and Cold Climate Conditions.” This method of test is based on AASHTO T283.

The present Superpave® methodology does not couple the water sensitivity of the HMA paving mixture with climate and traffic to allow for pavement performance prediction for a particular paving project. The Superpave methodology uses AASHTO T283 to evaluate the susceptibility of HMA to moisture. The moisture sensitivity test is performed on a laboratory-mixed, 150-mm-diameter, gyratory compacted sample as part of the mixture design process. The sample is prepared at the design asphalt content and at the design gradation as defined by the job mix formula (JMF) for the project.

AASHTO T283 AND SUPERPAVE

AASHTO T283 is based on research performed by R. P. Lottman under NCHRP Project 4-08(03) (*3*,*4*) and subsequent research performed by D. G. Tunnicliff and R. E. Root under NCHRP Project 10-17 (*5*,*6*). The AASHTO method indicates that it is suitable for testing samples prepared as part of the mixture design process (i.e., laboratory-mixed–laboratory-compacted), as part of the plant control process (i.e., field-mixed–laboratory-compacted) and for cores taken from the roadway (i.e., field-mixed–field-compacted). Laboratory-compacted samples can be prepared by the Marshall, Hveem, or Superpave gyratory method.

The AASHTO procedure ages the mixed, loose HMA for 16 hr at 60 °C. After compaction to an air-void content of 7 percent ±1 percent, the samples are extruded from the compaction mold and allowed to age from 72 to 96 hr (3 to 4 days) at room temperature. The samples are then placed under water, and a vacuum is used to saturate the samples to a level between 55 and 80 percent. A freeze cycle (16 hr at −18 °C) and a thaw-soak cycle (24 hr at 60 °C) are used to condition the sample prior to indirect tension testing at 25 °C (Table 1; tables are grouped at the end of each chapter).

The Superpave volumetric mixture design method uses the SHRP gyratory compactor to prepare 150-mm-diameter by about 115-mm samples (according to the Superpave procedures, samples are to be compacted to 95 mm in height at 7 percent ±1 percent air voids for AASHTO T283 testing). The Superpave sample preparation method conditions the mixed, loose HMA sample for 4 hr at 135 °C (the 4 hr may be reduced to 2 hr for testing volumetric, gyratory compaction properties only). The compacted mixture is aged at room temperature for 0 to 24 hr. Thus, the differences between the AASHTO T283 sample preparation method and the Superpave gyratory sample preparation method include the time and temperature of aging and the size of the sample (diameter and height).

SHRP recommended the use of AASHTO T283 to evaluate the water sensitivity of HMA within the Superpave volumetric mixture design system. This recommendation was made by the SHRP asphalt research team with little testing to establish retained tensile strength ratio correlations among sample preparation methods (i.e., sample conditioning, method of compaction, and size of samples). This deficiency in the research was recognized by three groups: the SHRP asphalt research team, an NCHRP research project that defined needed Superpave-related research, and the FHWA Asphalt Mixture Technical Working Group. NCHRP Project 9-13, "Evaluation of Water Sensitivity Tests," was developed to address some of the identified research needs relative to the use of AASHTO T283 with the Superpave volumetric design method.

PROJECT OBJECTIVES

The objectives of this research project are "to evaluate AASHTO T283 and to recommend changes to make it compatible with the Superpave system."

RESEARCH APPROACH

General Considerations

The response variables of indirect tensile strength at 25 °C and resilient modulus at 25 °C will be measured before and after conditioning of the HMA samples. The independent variables of importance that were considered for inclusion in the study are given below. This listing is largely based on the summary of AASHTO T283, ASTM D4867, and the Superpave test methods summarized in Table 1. The independent variables are

1. Compaction method
   a. Superpave gyratory compactor
   b. Marshall impact compactor
   c. Hveem kneading compactor
2. Sample diameter and height
   a. Superpave gyratory compactor: 150-mm diameter by 95 mm
   b. Superpave gyratory compactor: 100-mm diameter by 62 mm
   c. Marshall impact compactor: 100-mm diameter by 62 mm
   d. Hveem kneading compactor: 100-mm diameter by 62 mm
3. Aging method on loose HMA
   a. AASHTO T283: 16 hr at 60 °C
   b. Superpave: 2 hr at 135 °C
   c. Superpave: 4 hr at 135 °C
   d. No aging
4. Aging method on compacted HMA
   a. ASTM D4867: 0–24 hr at room temperature
   b. AASHTO T283: 72–96 hr at room temperature
5. Degree of saturation
   a. 55 percent
   b. 75 percent
   c. 90 percent
6. Type of aggregate
   a. Alabama/Georgia limestone of moderate-to-low water sensitivity
   b. Colorado alluvial of high water sensitivity
   c. Texas limestone of high water sensitivity
   d. Nevada alluvial of moderate-to-high water sensitivity
   e. Maryland limestone of high water sensitivity
7. Freeze-thaw cycles
   a. None
   b. One
8. Type of antistrip additive
   a. None
   b. Liquid antistrip
   c. Dry hydrated lime on wet aggregate
9. HMA mixing
   a. Laboratory
   b. Field (plant)

Partial factorial experimental designs were developed (as defined below) to determine the effect of many of these independent variables on indirect tensile strength and resilient modulus.

Compaction Method and Sample Size

The Superpave gyratory and Marshall impact compaction methods were selected for study because they are currently in widespread use or will be in widespread use in the future. Sample diameter and heights are those currently used by most public agencies. The gyratory sample size of 150-mm diameter by 95 mm is required in the Superpave volumetric design procedure. Superpave gyratory compaction equipment has the capability of compacting 100-mm-diameter samples. The Hveem method of compaction was not to be included in the study at the request of the project panel. A small graduate study project was included, however, and a limited number of Hveem compacted samples were evaluated. The Superpave gyratory compactor is not widely used.

Aging on Loose and Compacted HMA

The aging methods selected for loose HMA are those used by AASHTO T283 (16 hr at 60 °C) and Superpave (4 hr at 135 °C). Research has indicated that the 4-hr Superpave aging can be reduced to 2 hr and not influence the results of the volumetric design procedure. If aging is not required for sample preparation, the time required to perform the water sensitivity test can be reduced. ASTM D4867 does not require loose mix aging. Loose sample aging of 0 hr, 16 hr at 60 °C, 2 hr at 135 °C, and 4 hr at 135 °C are included in the test program.

AASHTO T283 requires a compacted mixture aging period of from 72 to 96 hr (3 to 4 days) at room temperature. ASTM D4867 indicates that the aging period of from 0 to 24 hr at room temperature is appropriate prior to the start of the test. Compacted sample aging periods of from 0 to 4 hr at 135 °C and from 88 to 96 hr at room temperature are included in the test program.

Saturation

The degree of saturation influences water sensitivity test results. AASHTO T283 and ASTM D4867 indicate that the degree of saturation should be between 55 and 80 percent. Some state DOTs and the original Lottman procedure used higher saturation percentages. Saturation levels of 55, 75, and 90 percent are included in the test program.

Aggregate Type

Five aggregates were selected to span the range of water sensitivity observed in the field. Aggregates from Alabama, Colorado, Maryland, Nevada, and Texas have been selected. The aggregates from Colorado, Maryland, and Nevada were reported by state representatives to be water-sensitive. The aggregates from Alabama and Texas have low-to-moderate water sensitivity (Table 2).

The aggregates were selected from ongoing projects that are Superpave volumetric mixture design projects. Asphalt binders from these projects were sampled. The mix designs used for these field projects are those used by the state DOTs with limited verification on this research project (three asphalt binder contents were combined with field-constructed gradation at the JMF).

Freeze-Thaw Cycles

Some public agencies use one freeze-thaw cycle (AASHTO T283) and others do not use a freeze-thaw cycle (ASTM D4867). A significant difference in test results can occur with certain types of aggregates because of the inclusion or absence of a freeze-thaw cycle. Samples conditioned with and without a freeze-thaw cycle are included in the study.

Antistrip Agent

A wide variety of antistrip agents are evaluated by AASHTO T283 and ASTM D4867. At the request of the project panel, an antistrip research task was not included in the study.

Mixing

The AASHTO T283 test is intended for use as a mixture design test (i.e., laboratory-mixed–laboratory-compacted) and as a field control test (i.e., field-mixed–laboratory-compacted, field-mixed–field-compacted, or core). At the request of the project panel, only laboratory-mixed–laboratory-compacted samples were evaluated in this study.

Materials and Mixtures

Asphalt binders and aggregates were selected from Superpave volumetric mixture design projects in the states of Alabama, Colorado, Maryland, Nevada, and Texas. The Alabama, Colorado, Maryland, and Texas projects were constructed during the 1997 construction season. The Nevada project was constructed in 1995 with one of the mixtures used on the WesTrack project. Table 2 contains general information about the projects' locations, contractors, design traffic volumes, asphalt binders, and aggregates. More detailed information on the asphalt binders, aggregates, and mixture designs can be found in Appendix A.

Research Plan

Four main tasks constituted the research plan for this study:

1. Evaluation of the Impact of Conducting the Resilient Modulus Test Prior to the Tensile Strength Test,

2. Comparison of Four Compaction Methods,
3. Comparison of Two Compaction Methods (Complete Factorial), and
4. Comparison of Two Compaction Methods (Partial Factorial).

Task 1 investigated the influence of the resilient modulus test on tensile test results (using three aggregate sources). Task 2 determined the effect of four sample compaction methods and sample size on water sensitivity testing for fixed conditions of aging and conditioning (using five aggregate sources). Task 3 investigated the influence of two compaction methods on water sensitivity testing for variable conditions of aging and conditioning (using one aggregate source). Tasks 1, 2, and 3 performed "complete" factorial experiments for the selected variables. Using a "partial" factorial experimental plan, Task 4 further investigated the influence of two compaction methods on water sensitivity testing for variable curing/aging and conditioning (using five aggregate sources).

The results of Tasks 1, 2, and 3 are contained in interim reports for this project (*7–9*). The experimental plan and testing sequence for all four of these tasks is described below.

Task 1:Evaluation of the Impact of Conducting the Resilient Modulus Test Prior to the Tensile Strength Test

Resilient modulus was selected as one of the response variables because it is believed to be more sensitive to changes in asphalt binder properties and a mixture's sensitivity to damage by water than is tensile strength. In addition, resilient modulus can be used as a measure of the load distribution capability of a pavement material (i.e., elastic modulus in layered elastic models to calculate stress, strain, and deflection in pavement layers).

Most public agencies presently use tensile strength as the response variable when performing water sensitivity tests. Resilient modulus, which is employed by only a few state agencies, typically is used by public agencies for information and not for acceptance in the mix design or field quality control/quality assurance (QC/QA) process.

The test program for Tasks 1 and 2 is described in Table 3, in which the program is identified as test sequence "M." The flow diagram for sample testing for "M" is shown in Figure 1. An 18-sample test program was used. Asphalt binders and aggregates from Alabama, Colorado, and Nevada were used in this task. Both 150-mm-diameter Superpave gyratory and 100-mm-diameter Marshall impact compactors were used for sample preparation. The following four fixed curing/aging and sample conditioning methods were used:

1. Loose mix aging of a 4-hr duration at 135 °C,
2. Compacted mix aging of a 96-hr duration at room temperature,
3. Saturation level of 75 percent, and
4. With and without a freeze-thaw cycle after partial saturation. The air void content was targeted to be between 6 and 8 percent.

Task 2: Comparison of Four Compaction Methods

One of the main issues to be resolved by this research program is the effect of compaction method on the results of AASHTO T283. AASHTO T283 indicates that laboratory compaction can be performed by one of three methods: Marshall impact hammer (100-mm diameter by 62 mm), Hveem kneading (100-mm diameter by 62 mm), or Superpave gyratory (100-mm diameter by 62 mm). At present, the AASHTO T283 method of test does not allow the use of the recently developed Superpave gyratory compactor for sample preparation. AASHTO Provisional Standard TP34 indicates that the Superpave gyratory compactor can be used to mold 150-mm-diameter by 95-mm samples for use in AASHTO T283. As stated previously, the SHRP asphalt research team made this recommendation on sample compaction and size for the AASHTO Provisional Standard with little testing to establish retained tensile strength ratio correlations among sample preparation methods.

A limited test program was therefore established to allow for comparison of compaction methods and sample size. This test program is described in Table 3, in which it is identified as test sequences "M," "S," and "A." Test sequence "M" allows for comparisons of 150-mm-diameter Superpave gyratory and 100-mm-diameter Marshall impact compacted samples. Test sequence "S" allows for comparisons of 100-mm-diameter Superpave gyratory samples with other compaction methods. Test sequence "A" allows for comparisons of 100-mm-diameter Hveem kneading compacted samples with other compaction methods. The Hveem portion of this study was performed by graduate students at the University of Nevada and was not a part of the budget of this study as requested by the project panel.

Task 2 allows for comparisons among 100-mm-diameter by 62-mm samples compacted with the Superpave gyratory, Marshall impact, and Hveem kneading compactors. In addition, the test results obtained on 100-mm-diameter by 62-mm samples can be compared with the test results obtained on 150-mm-diameter by 95-mm Superpave gyratory compacted samples.

The flow diagram for sample testing is shown in Figure 2. A nine-sample test program was used. Asphalt binders and aggregates from Alabama, Colorado, Maryland, Nevada, and Texas were used in this task. The following five fixed curing/aging and sample conditioning methods were used:

1. Loose mix aging of a 4-hr duration at 135 °C,
2. Compacted mix aging of a 96-hr duration at room temperature,

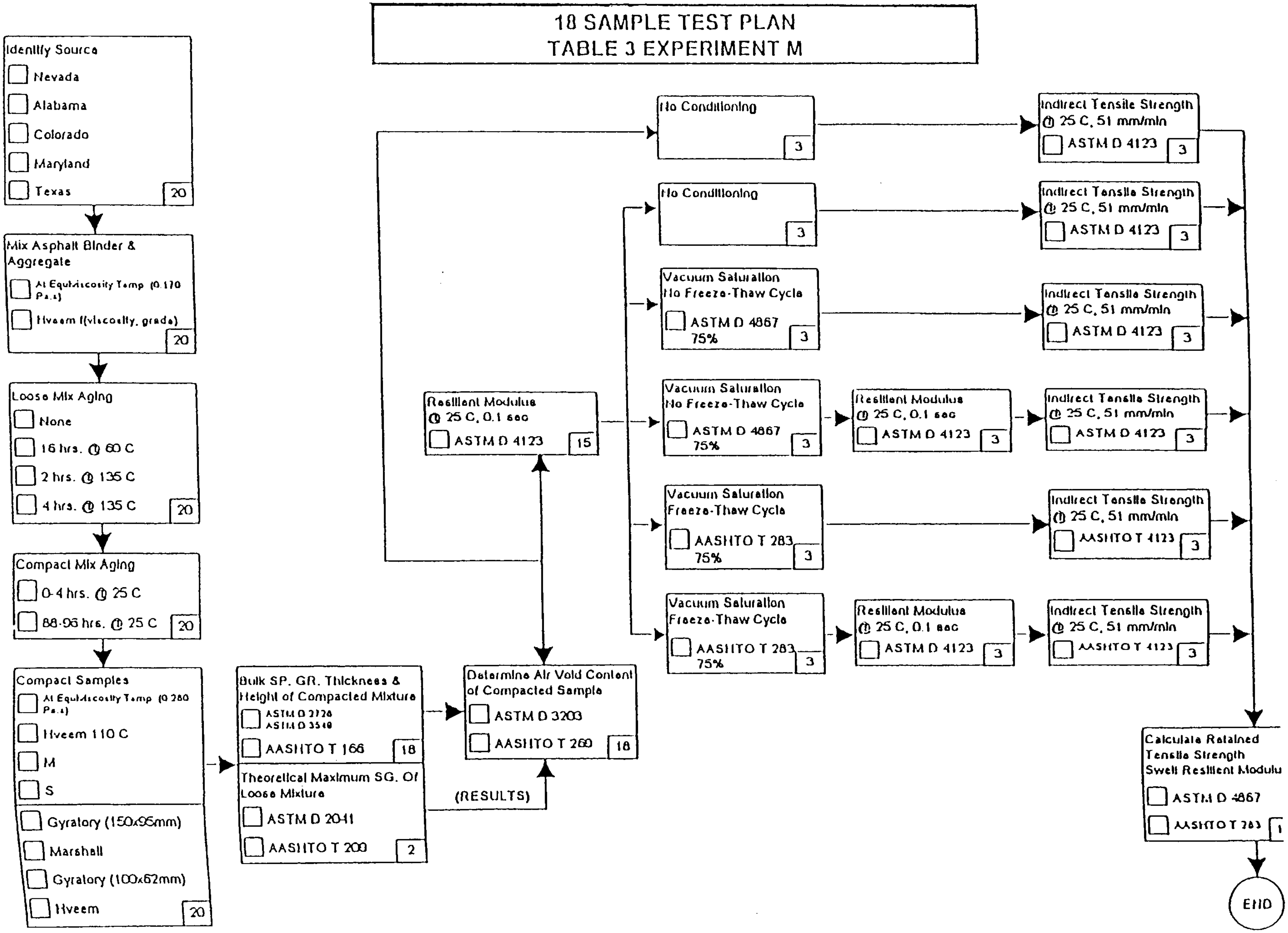

Figure 1. Test programs for M (18 samples).

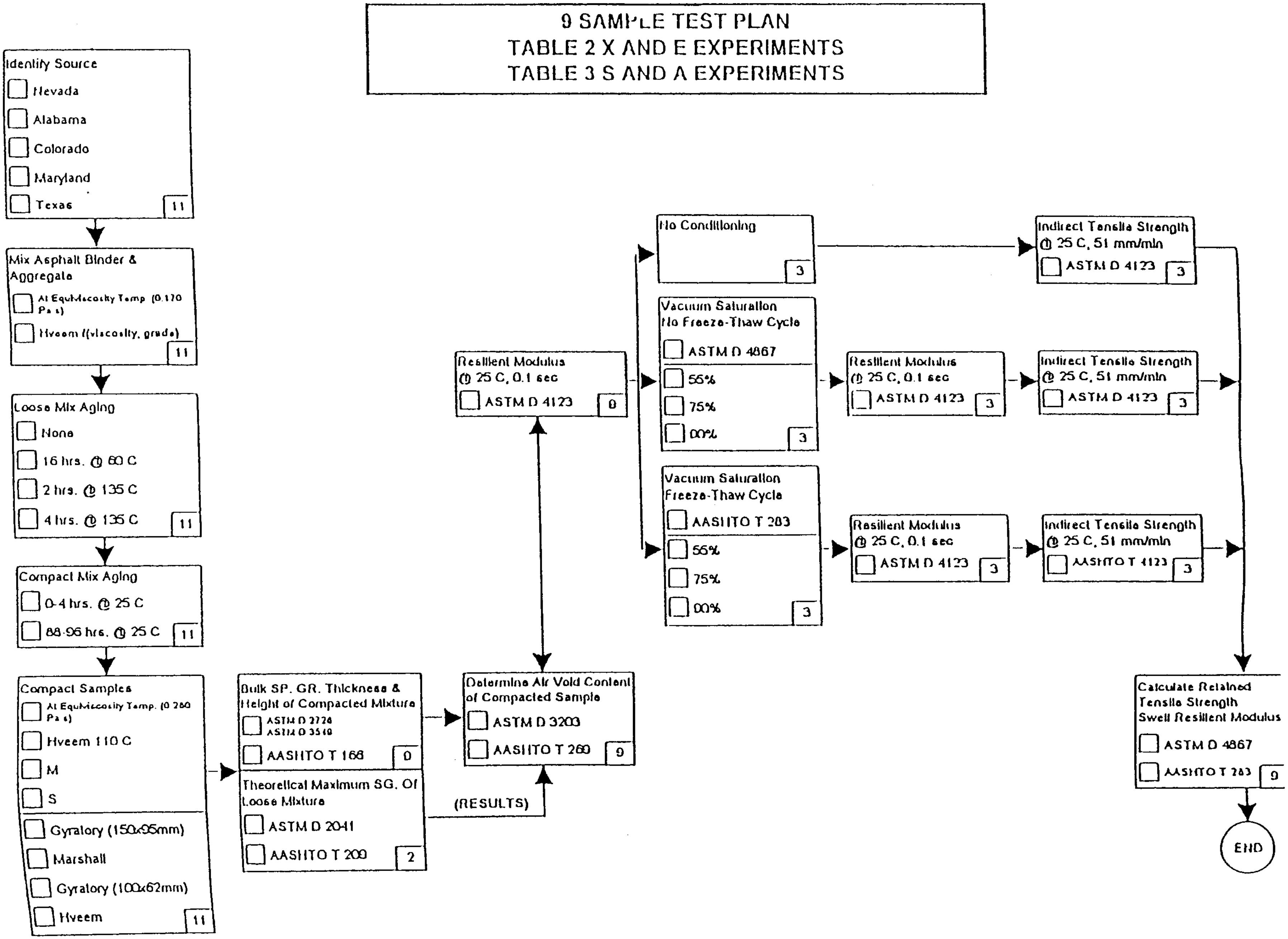

Figure 2. Test programs for X, E, S, and A (9 samples).

3. Saturation level of 75 percent, and
4. With and without a freeze-thaw cycle after partial saturation. The air void content was targeted to be between 6 and 8 percent.

Task 3: Comparison of Two Compaction Methods (Complete Factorial)

Task 2 compared test results obtained on samples compacted by four methods but using fixed curing/aging and sample conditioning methods. Task 3 compared test results obtained on 150-mm-diameter by 95-mm Superpave gyratory compacted samples with 100-mm-diameter by 62-mm Marshall impact compacted samples subjected to a range of curing/aging and conditioning. The following four curing/aging and sample conditioning ranges were used:

1. Loose mix aging
   a. None
   b. 16 hr at 60 °C
   c. 2 hr at 135 °C
   d. 4 hr at 135 °C
2. Compacted mix aging
   a. 0 hr
   b. 96 hr at room temperature
3. Saturation level
   a. 55 percent
   b. 75 percent
   c. 90 percent
4. With and without freeze-thaw cycle after partial saturation. The air void content was targeted to be between 6 and 8 percent.

A complete factorial experimental plan was used for this task to define as precisely as possible the influence of aging and conditioning on the test results. Only two compaction methods and one aggregate were selected to reduce the number of samples to a manageable number. Marshall impact compaction was selected because it is currently the most commonly used method for the preparation of AASHTO T283 laboratory-compacted samples. The 150-mm-diameter Superpave gyratory compaction method was selected because the Superpave volumetric mixture design method is scheduled to replace the currently used Marshall and Hveem procedures.

Table 4 describes the experimental plan. Only the Nevada mixture was used for this portion of the study. A nine-sample test program (Figure 2) was used in this task.

Task 4: Comparison of Two Compaction Methods (Partial Factorial)

Task 3 performed a complete factorial experimental plan on a single mixture subjected to a variety of curing/aging and conditioning methods with samples prepared by two compaction methods. Task 4 compared test results obtained on 150-mm-diameter by 95-mm Superpave gyratory compacted and 100-mm-diameter by 62-mm Marshall impact compacted samples subjected to a range of curing/aging and conditioning. The curing/aging and conditioning were identical to those used in Task 3 of the project and described above.

A partial factorial experimental plan described in Table 4 was used to allow for the inclusion of five mixtures (Alabama, Colorado, Maryland, Nevada, and Texas). The "X" designation in the table identifies the partial factorial experimental plan developed by the project statistician. The "E" designation indicates the additions made by the project engineer to allow for a complete factorial on a portion of the study (Nevada mixture). Figures 2 and 3 describe the nine- and six-sample test sequences used for this task.

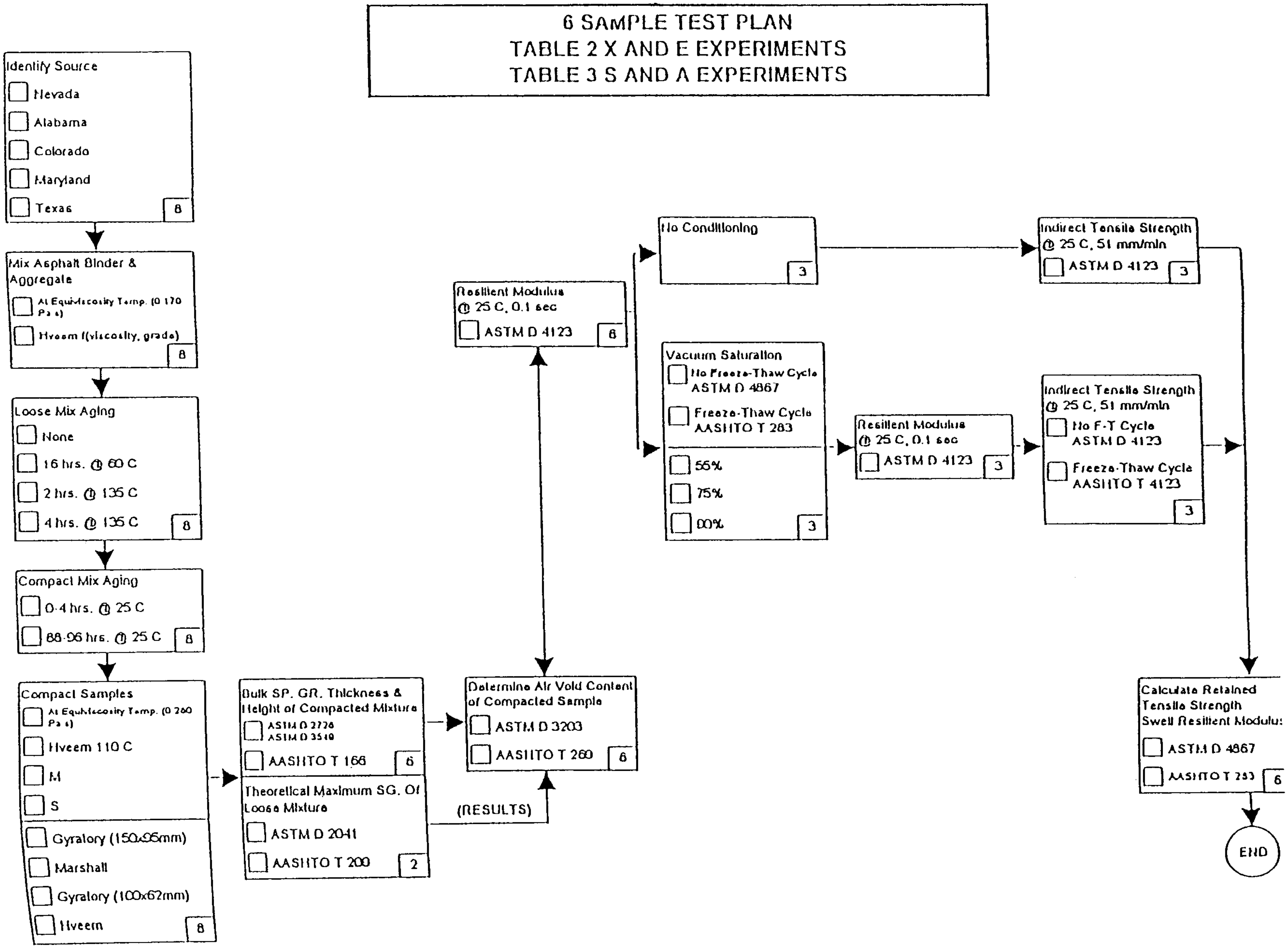

Figure 3. *Test programs for X, E (6 samples).*

TABLE 1 Water Sensitivity Tests Comparison

Test Parameter	ASTM D4867	AASHTO T283	Superpave
Specimen Size	62 mm x 100 mm	62 mm x 100 mm	95 mm x 150 mm
Mixing Temperature	Depends on Compaction Method (1)	Depends on Compaction Method (1)	Equiviscous (0.170 Pa•s)
Loose Mix Curing	None	Cool at Room Temp. 2 hrs. Cure at 60°C - 16 hrs.	135°C - 4 hrs.
Compaction Temperature	Depends on Compaction Method (1) (1-2 hrs. in oven)	135°C (2 hrs. in oven)	Equiviscous (0.280 Pa•s)
Compacted Mixture Curing	0-24 hrs. @ Room Temp. Before Start of Testing	72 to 96 hrs. @ Room Temp. Before Start of Testing	Same as AASHTO T283
Air Void Content of Compacted Specimen, %	6-8	6-8	Same as AASHTO T283
Sample Grouping	Average Air Voids of Two sets of Samples About Same	Average Air voids of Two Sets of Samples About Same	Same as AASHTO T283
Saturation	•55 - 80% •About 20 in. Hg for 5 min. •Calculations Different than AASHTO T283	•55-80% •10-26 in. Hg for 5-10 min. •Calculation Different than ASTM D4867	Same as AASHTO T283
Swell Determination	yes	no	Same as AASHTO T283
Freeze	-18 + 2°C for min. 15 hrs. (Optional by Note)	-18 + 3°C for min. 16 hrs. Remove by Note	Same As AASHTO T283
Water Soak	60 + 1.0°C for 24 hrs.	60 + 0.1°C for 24 + 1 hr.	Same As AASHTO T283
Strength Property	Indirect Tensile at 25 + 1°C with Loading Rate of 51 mm per min.	Indirect Tensile at 25 + 1°C	Same As AASHTO T283
Precision and Bias	yes	no	no

Note: (1) Use mixing temperature as specified by:
Marshall compaction (ASTM D1559, AASHTO T245)
Kneading compaction (ASTM D1561, AASHTO T247)
Compression (ASTM D1074) U.S. Army Corps of Engineers (ASTM D3387)

TABLE 2 General Project Information

State	**Project Information**		**Contractor**	**Traffic Volume, 20 year ESAL, Million**	**Asphalt Binder Grade**	**Antistrip Used During Construction**	**Gradation**	**Aggregate Type**	
	Number	*Highway*						Coarse	Fine
Alabama	IM-STPAAF-65-3 (141) Blount County	IH 65	Whitaker Contracting Corporation	10-30	PG 64-22 (AC-30)*	None	25.5 mm Coarse	Limestone	Limestone
Colorado	IR (CX) 025-1 (122)	IH 25	Corn Construction	5	PG 58-28**	1% Hydrated Lime	19.0 mm Fine	Alluvial (partially crushed)	Alluvial (partially crushed)
Maryland	SHA 73.0-39	Rt 40	Keystone	10-30	PG 64-28	None	12.5 mm Coarse	Limestone	Limestone
Nevada	WesTrack Lyon County	Test Track	Granite Construction	3-10	PG 64-22	1.5% Hydrated Lime	19.0 mm Fine	Alluvial (partially crushed)	Alluvial (partially crushed)
Texas	NH 97 (428) CSJ-44-3-38 Clay County	US 82	Duininck Brothers	3-10	PG 70-22	None	12.5 mm Coarse	Limestone	Limestone

Notes: * PG 67-22
** PG 58-28 used in laboratory study; PG 64-28 from Koch used for construction

TABLE 3 Engineering-Based Special Studies—Tasks 1 and 2

Compaction		Gyratory (150 x 95 mm)				Gyratory (100 x 62 mm)				Marshall (100 x 62 mm)				Hveem (100 x 62 mm)			
% Saturation		75				75				75				75			
Freeze/Thaw		Yes		No		Yes		No		Yes		No		Yes		No	
Compacted Mix Aging		Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Aggregate	Loose Mix Aging																
Source 1 Nevada (N)	None																
	16 h/60°C																
	2 h/135°C																
	4 h/135°C	E,M		X,M		S		S		E,M		X,M		A		A	
Source 2 Alabama (A)	None																
	16 h/60°C																
	2 h/135°C																
	4 h/135°C	S,M		X,M		S		S		S,M		S,M		A		A	
Source 3 Colorado (C)	None																
	16 h/60°C																
	2 h/135°C																
	4 h/135°C	S,M		X,M		S		S		S,M		S,M		A		A	
Source 4 Maryland (M)	None																
	16 h/60°C																
	2 h/135°C																
	4 h/135°C	X		S		S		S		X		S		A		A	
Source 5 Texas (T)	None																
	16 h/60°C																
	2 h/135°C																
	4 h/135°C	S		S		S		S		S		S		A		A	

Notes: X—Statistical-based experiment (from Table 1)
E—Additional testing for engineering-based experiment (from Table 2)
S—Speciality study (100-mm-diameter Superpave gyratory sample)
M—Speciality study (influence of resilient modulus on tensile strength)
A—Speciality study (100-mm-diameter Hveem impact sample)

TABLE 4 Statistical- and Engineering-Based Experimental Plan—Task 2

Compaction		Gyratory (150 x 95 mm)												Marshall (100 x 62 mm)											
% Saturation		55				75				90				55				75				90			
Freeze/Thaw		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
Compacted Mix Aging		Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Aggregate	Loose Mix Aging																								
Source 1 Nevada (N)	None	E	X	X	E	X	X	X	X	X	E	E	X	E	E	E	E	E	E	E	E	E	E	E	X
	16 h/60°C	E	X	X	E	X	X	E	X	X	E	X	X	E	E	E	E	E	X	E	E	E	E	E	E
	2 h/135°C	X	X	X	X	X	E	E	X	E	X	X	E	E	E	X	E	X	E	E	E	E	E	E	E
	4 h/135°C	X	E	E	X	E	X	X	E	X	X	X	X	E	E	X	E	E	E	E	E	E	X	E	E
Source 2 Alabama (A)	None	X	X		X	X		X	X		X	X		X							X				
	16 h/60°C	X		X	X		X	X		X	X		X				X								
	2 h/135°C		X	X		X	X	X	X	X			X								X				
	4 h/135°C		X	X		X			X	X	X	X	X									X			
Source 3 Colorado (C)	None	X			X		X	X		X	X	X	X							X					
	16 h/60°C	X	X		X	X		X	X		X	X		X											
	2 h/135°C	X		X	X	X	X		X		X	X											X		
	4 h/135°C		X	X		X	X	X	X	X			X				X								
Source 4 Maryland (M)	None	X	X	X		X			X		X	X			X										
	16 h/60°C		X	X	X	X	X	X		X		X												X	
	2 h/135°C	X			X		X	X		X	X	X	X		X									X	
	4 h/135°C	X	X		X	X		X	X		X	X						X			X				
Source 5 Texas (T)	None	X			X	X	X		X	X		X						X							
	16 h/60°C	X	X	X		X		X		X	X	X	X			X						X			
	2 h/135°C		X	X	X	X	X	X		X	X		X	X						X					
	4 h/135°C	X		X	X		X		X		X	X													X

Notes: X—Statistical-based experiment (from Table 1)
E—Additional testing for engineering-based experiment (from Table 2)

CHAPTER 2

FINDINGS

INTRODUCTION

For convenience in the presentation of test results, a number of codes and abbreviations are used in the test and in tables and figures of the report. These codes are summarized below:

- Aggregate Source
  - AL: Alabama
  - CO: Colorado
  - MD: Maryland
  - NV: Nevada
  - TX: Texas
- Compaction Method
  - G150: 150-mm-diameter Superpave gyratory compactor sample
  - G100: 100-mm-diameter Superpave gyratory compactor sample
  - M100: 102-mm-diameter Marshall impact compactor sample
  - H100: 102-mm-diameter Hveem kneading compactor sample
- Conditioning of Samples
  - Dry: No conditioning with water or freeze-thaw cycle
  - No F-T: Partial water saturation, no freeze-thaw cycle
  - F-T: Partial water saturation with freeze-thaw cycle
- Resilient Modulus
  - MR

TEST RESULTS

As stated previously, four main tasks constitute the test program for this research project. These tasks are

1. Evaluation of the Impact of Conducting the Resilient Modulus Test Prior to the Tensile Strength Test,
2. Comparison of Four Compaction Methods,
3. Comparison of Two Compaction Methods (Complete Factorial), and
4. Comparison of Two Compaction Methods (Partial Factorial).

The tensile strength and tensile strength ratio test results are contained in interim reports for this project (*7–9*) and are summarized below.

Tables 5 and 6 contain the tensile strength and the tensile strength ratios for Task 1, Evaluation of the Impact of Conducting the Resilient Modulus Test Prior to the Tensile Strength Test. The second interim report (*8*) contains a detailed analysis of the data obtained in this portion of the study. The information will be summarized below and in Chapter 3.

Table 7 contains the tensile strength and the tensile strength ratio information for Task 2, Comparison of Four Compaction Methods. The first interim report (*7*) contains a detailed analysis of the data obtained in this portion of the study. The information will be summarized in Chapter 3.

Tables 8 and 9 contain the tensile strength and the tensile strength ratios for Task 3, Comparison of Two Compaction Methods (Complete Factorial). The third interim report (*9*) contains a detailed analysis of the data obtained in this portion of the study. The information will be summarized in Chapter 3.

Table 10 contains the tensile strength and the tensile strength ratio for Task 4, Comparison of Two Compaction Methods (Partial Factorial). The data in Table 10 will be summarized in Chapter 3.

TABLE 5 Tensile Strength Test Results for 18-Sample Test Sequence—Task 1

AGGREGATE SOURCE	COMPACTION METHOD	SAMPLE CONDITIONING	RESILIENT MODULUS CODE	TENSILE STRENGTH, psi			MEAN	STANDARD DEVIATION	NO. OF SAMPLES	COEFFICIENT OF VARIATION
				SAMPLE NUMBER						
				1	2	3				
ALABAMA	GYRATORY 150 mm	DRY	NO MR	88.8	81.4	73.6	81.3	7.60	3	9.35
			MR	90.2	69.0	87.6	82.3	11.56	3	14.06
		NO F - T	NO MR	50.0	45.4	43.9	46.4	3.18	3	6.85
			MR	61.7	40.5	45.1	49.1	11.15	3	22.71
		F - T	NO MR	62.0	47.0	79.9	63.0	16.47	3	26.16
			MR	49.1	51.1	46.4	48.9	2.36	3	4.83
	MARSHALL 100 mm	DRY	NO MR	93.7	92.4	83.9	90.0	5.32	3	5.91
			MR	92.0	95.7	115.3	101.0	12.52	3	12.40
		NO F - T	NO MR	73.2	68.8	98.1	80.0	15.80	3	19.74
			MR	98.0	77.0	89.4	88.1	10.56	3	11.98
		F - T	NO MR	58.4	55.8	66.1	60.1	5.36	3	8.91
			MR	96.1	99.2	118.2	104.5	11.97	3	11.45
COLORADO	GYRATORY 150 mm	DRY	NO MR	62.8	76.3	86.5	75.2	11.89	3	15.81
			MR	76.9	62.5	77.3	72.2	8.43	3	11.67
		NO F - T	NO MR	48.2	52.2	43.8	48.1	4.20	3	8.74
			MR	55.3	38.7	41.2	45.1	8.95	3	19.86
		F - T	NO MR	49.2	57.4	48.0	51.5	5.12	3	9.93
			MR	37.4	50.1	47.7	45.1	6.75	3	14.97
	MARSHALL 100 mm	DRY	NO MR	143.0	111.1	115.1	123.1	17.38	3	14.12
			MR	78.9	82.1	83.6	81.5	2.40	3	2.94
		NO F - T	NO MR	64.0	45.5	29.2	46.2	17.41	3	37.66
			MR	37.3	59.5	48.3	48.4	11.10	3	22.95
		F - T	NO MR	30.3	28.3	23.5	27.4	3.49	3	12.77
			MR	34.2	51.2	45.5	43.6	8.65	3	19.83

(*continued on next page*)

TABLE 5 (*Continued*)

AGGREGATE SOURCE	COMPACTION METHOD	SAMPLE CONDITIONING	RESILIENT MODULUS CODE	TENSILE STRENGTH, psi			MEAN	STANDARD DEVIATION	NO. OF SAMPLES	COEFFICIENT OF VARIATION
				SAMPLE NUMBER						
				1	2	3				
NEVADA	GYRATORY 150 mm	DRY	NO MR	206.5	169.0	-	187.8	26.52	3	14.12
			MR	207.5	216.2	202.6	208.8	6.89	3	3.30
		NO F - T	NO MR	173.5	173.6	149.9	165.7	13.65	3	8.24
			MR	175.5	145.0	139.5	153.3	19.39	3	12.65
		F - T	NO MR	135.8	128.1	156.6	140.2	14.74	3	10.52
			MR	158.6	153.4	165.9	159.3	6.28	3	3.94
	MARSHALL 100 mm	DRY	NO MR	269.0	264.0	286.0	273.0	11.53	3	4.22
			MR	270.4	266.2	320.3	285.6	30.10	3	10.54
		NO F - T	NO MR	110.6	117.4	153.8	127.3	23.23	3	18.25
			MR	182.8	157.9	168.5	169.7	12.50	3	7.36
		F - T	NO MR	88.0	74.6	63.8	75.5	12.12	3	16.06
			MR	137.5	74.8	87.6	100.0	33.13	3	33.14

TABLE 6 Tensile Strength Ratio for 18-Sample Test Sequence—Task 1

AGGREGATE SOURCE	COMPACTION METHOD	SAMPLE CONDITIONING	RESILIENT MODULUS CODE	TENSILE STRENGTH RATIO	
				DRY NO MR AS DENOMINATOR	DRY MR AS DENOMINATOR
ALABAMA	GYRATORY 150 mm	DRY	NO MR	N/A	N/A
			MR	1.01	N/A
		NO F - T	NO MR	0.57	0.56
			MR	0.60	0.60
		F - T	NO MR	0.77	0.77
			MR	0.60	0.59
	MARSHALL 100 mm	DRY	NO MR	N/A	N/A
			MR	1.12	N/A
		NO F - T	NO MR	0.89	0.79
			MR	0.98	0.87
		F - T	NO MR	0.67	0.60
			MR	1.16	1.03
COLORADO	GYRATORY 150 mm	DRY	NO MR	N/A	N/A
			MR	0.96	N/A
		NO F - T	NO MR	0.64	0.67
			MR	0.60	0.62
		F - T	NO MR	0.69	0.71
			MR	0.60	0.62
	MARSHALL 100 mm	DRY	NO MR	N/A	N/A
			MR	0.66	N/A
		NO F - T	NO MR	0.38	0.57
			MR	0.39	0.59
		F - T	NO MR	0.22	0.34
			MR	0.35	0.54
NEVADA	GYRATORY 150 mm	DRY	NO MR	N/A	N/A
			MR	1.11	N/A
		NO F - T	NO MR	0.88	0.79
			MR	0.82	0.73
		F - T	NO MR	0.75	0.67
			MR	0.85	0.76
	MARSHALL 100 mm	DRY	NO MR	N/A	N/A
			MR	1.05	N/A
		NO F - T	NO MR	0.47	0.45
			MR	0.62	0.59
		F - T	NO MR	0.28	0.26
			MR	0.37	0.35

TABLE 7 Tensile Strength Test Results—Task 2

Aggregate Source	Compaction Method	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
			Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
			1	2	3					
Alabama	G 150	Dry	90.2	69.0	87.6	82.3	11.6	3	14.1	
		No F-T	61.7	40.5	45.1	49.1	11.2	3	22.7	0.60
		F-T	49.1	51.1	46.4	48.9	2.4	3	4.8	0.59
	G 100	Dry	110.9	120.8	122.6	118.1	6.3	3	5.3	
		No F-T	29.8	38.3	33.0	33.7	4.3	3	12.7	0.29
		F-T	47.5	52.3	48.3	49.4	2.6	3	5.2	0.42
	M 100	Dry	92.0	95.7	115.3	101.0	12.5	3	12.4	
		No F-T	98.0	77.0	89.4	88.1	10.6	3	12.0	0.87
		F-T	96.1	99.2	118.2	104.5	12.0	3	11.5	1.03
	H 100	Dry	124.8	117.0	141.7	127.8	12.6	3	9.9	
		No F-T	40.1	49.9	42.0	44.0	5.2	3	11.8	0.34
		F-T	40.0	39.0	55.7	44.9	9.4	3	20.9	0.35
Colorado	G 150	Dry	76.9	62.5	77.3	72.2	8.4	3	11.7	
		No F-T	55.3	38.7	41.2	45.1	9.0	3	19.9	0.62
		F-T	37.4	50.1	47.7	45.1	6.7	3	15.0	0.62
	G 100	Dry	163.2	121.2	132.2	138.9	21.8	3	15.7	
		No F-T	48.9	46.5	51.3	48.9	2.4	3	4.9	0.35
		F-T	34.2	27.3	36.5	32.7	4.8	3	14.7	0.24
	M 100	Dry	78.9	82.1	83.6	81.5	2.4	3	2.9	
		No F-T	37.3	59.5	48.3	48.4	11.1	3	23.0	0.59
		F-T	34.2	51.2	45.5	43.6	8.7	3	19.8	0.54
	H 100	Dry	135.6	125.9	112.0	124.5	11.9	3	9.5	
		No F-T	31.6	43.0	41.8	38.8	6.3	3	16.1	0.31
		F-T	35.1	30.6	20.5	28.7	7.5	3	26.0	0.23
Maryland	G 150	Dry	70.1	76.0	75.0	73.7	3.2	3	4.3	
		No F-T	60.9	74.2	59.8	65.0	8.0	3	12.3	0.88
		F-T	86.6	78.8	89.0	84.8	5.3	3	6.3	1.15
	G 100	Dry	111.3	115.1	113.2	113.2	1.9	3	1.7	
		No F-T	53.9	59.6	62.2	58.6	4.2	3	7.2	0.52
		F-T	97.8	96.2	95.7	96.6	1.1	3	1.1	0.85
	M 100	Dry	76.8	76.9	71.8	75.2	2.9	3	3.9	
		No F-T	62.2	63.2	60.8	62.1	1.2	3	1.9	0.83
		F-T	56.2	64.4	61.4	60.7	4.1	3	6.8	0.81
	H 100	Dry	111.3	101.1	113.2	108.5	6.5	3	6.0	
		No F-T	74.3	74.0	77.0	75.1	1.7	3	2.2	0.69
		F-T	71.6	67.9	64.0	67.8	3.8	3	5.6	0.63

(*continued on next page*)

TABLE 7 (*Continued*)

Aggregate Source	Compaction Method	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
			Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
			1	2	3					
Nevada	G 150	Dry	207.5	216.2	202.6	208.8	6.9	3	3.3	
		No F-T	175.5	145.0	139.5	153.3	19.4	3	12.6	0.73
		F-T	158.6	153.4	165.9	159.3	6.3	3	3.9	0.76
	G 100	Dry	276.8	285.8	299.6	287.4	11.5	3	4.0	
		No F-T	91.4	90.4	113.8	98.5	13.2	3	13.4	0.34
		F-T	92.5	93.2	92.6	92.8	0.4	3	0.4	0.32
	M 100	Dry	270.4	266.2	320.3	285.6	30.1	3	10.5	
		No F-T	182.8	157.9	168.5	169.7	12.5	3	7.4	0.59
		F-T	137.5	74.8	87.6	100.0	33.1	3	33.1	0.35
	H 100	Dry	210.7	233.1	245.4	229.7	17.6	3	7.7	
		No F-T	61.2	62.4	51.8	58.5	5.8	3	9.9	0.25
		F-T	64.1	65.8	48.4	59.4	9.6	3	16.1	0.26
Texas	G 150	Dry	177.1	176.6	165.8	173.2	6.4	3	3.7	
		No F-T	105.2	110.6	110.1	108.6	3.0	3	2.7	0.63
		F-T	121.3	121.7		121.5	0.3	2	0.2	0.70
	G 100	Dry	186.7	164.8	165.0	172.2	12.6	3	7.3	
		No F-T	88.3	107.3		97.8	13.4	2	13.7	0.57
		F-T	76.0	86.6	75.7	79.4	6.2	3	7.8	0.46
	M 100	Dry	129.3	117.1	110.7	119.0	9.4	3	7.9	
		No F-T	71.5	84.6	78.4	78.2	6.6	3	8.4	0.66
		F-T	79.9	64.5	80.7	75.0	9.1	3	12.2	0.63
	H 100	Dry	185.0	182.8	183.8	183.9	1.1	3	0.6	
		No F-T	73.7	73.2	76.0	74.3	1.5	3	2.0	0.40
		F-T	44.3	42.6	42.3	43.1	1.1	3	2.5	0.23

TABLE 8 Tensile Strength Test Results for Superpave Gyratory Compacted Samples—Complete Factorial—Task 3

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
16h/60C	55	0 h	Dry	220.9	207.4	230.7	219.7	11.7	3	5.3	
			No F-T	81.4	98.4	84.6	88.1	9.0	3	10.3	0.40
			F-T	169.6	172.5	153.5	165.2	10.2	3	6.2	0.75
		96 h	Dry	146.9	147.2	135.5	143.2	6.7	3	4.7	
			No F-T	81.6	115.9	114.3	103.9	19.4	3	18.6	0.73
			F-T	85.1	88.5	100.5	91.4	8.1	3	8.9	0.64
	75	0 h	Dry	220.9	207.4	230.7	219.7	11.7	3	5.3	
			No F-T	66.2	77.8	77.9	74.0	6.7	3	9.1	0.34
			F-T	141.4	145.1	151.9	146.1	5.3	3	3.6	0.67
		96 h	Dry	146.9	147.2	135.5	143.2	6.7	3	4.7	
			No F-T	81.3	80.0	83.4	81.6	1.7	3	2.1	0.57
			F-T	105.3	88.8	107.1	100.4	10.1	3	10.0	0.70
	90	0 h	Dry	220.9	207.4	230.7	219.7	11.7	3	5.3	
			No F-T	80.8	63.7	66.5	70.3	9.2	3	13.0	0.32
			F-T	145.8	145.4	154.5	148.6	5.1	3	3.5	0.68
		96 h	Dry	146.9	147.2	135.5	143.2	6.7	3	4.7	
			No F-T	66.3	78.2	92.4	79.0	13.1	3	16.5	0.55
			F-T	54.3	68.0	73.2	65.2	9.8	3	15.0	0.46
16 h/60C	55	0 h	Dry	276.5	272.1	271.1	273.2	2.9	3	1.1	
			No F-T	141.1	135.8	158.0	145.0	11.6	3	8.0	0.53
			F-T	166.6	153.1	176.7	165.5	11.8	3	7.2	0.61
		96 h	Dry	256.2	270.5	226.9	251.2	22.2	3	8.8	
			No F-T		122.1	122.6	122.4	0.4	2	0.3	0.49
			F-T	85.0	88.6	88.5	87.4	2.1	3	2.3	0.35
	75	0 h	Dry	276.5	272.1	271.1	273.2	2.9	3	1.1	
			No F-T	146.2	135.3	178.5	153.3	22.5	3	14.7	0.56
			F-T	117.7	145.6	173.1	145.5	27.7	3	19.0	0.53
		96 h	Dry	256.2	270.5	226.9	251.2	22.2	3	8.8	
			No F-T	160.3	132.8	137.8	143.6	14.6	3	10.2	0.57
			F-T	85.1	78.2	105.6	89.6	14.3	3	15.9	0.36
	90	0 h	Dry	276.5	272.1	271.1	273.2	2.9	3	1.1	
			No F-T	129.4	146.2	98.5	124.7	24.2	3	19.4	0.46
			F-T	145.5	132.9	110.6	129.7	17.7	3	13.6	0.47
		96 h	Dry	256.2	270.5	226.9	251.2	22.2	3	8.8	
			No	115.7	08.9	114.0	112.9	3.5	3	3.1	0.45
			F-T	88.3	71.3	80.9	80.2	8.5	3	10.6	0.32

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TABLE 8 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
2 h/135C	55	0 h	Dry	277.4	239.3	247.8	254.8	20.0	3	7.8	
			No F-T	110.9	103.8	107.2	107.3	3.6	3	3.3	0.42
			F-T		132.4	60.0	96.2	51.2	2	53.2	0.38
		96 h	Dry	211.2	239.8	224.1	225.0	14.3	3	6.4	
			No F-T	201.7	207.0	208.8	205.8	3.7	3	1.8	0.91
			F-T	100.4	107.3	148.4	118.7	26.0	3	21.9	0.53
	75	0 h	Dry	277.4	239.3	247.8	254.8	20.0	3	7.8	
			No F-T	105.8	108.6	107.2	107.2	1.4	3	1.3	0.42
			F-T	126.1	161.2	130.9	139.4	19.0	3	13.7	0.55
		96 h	Dry	211.2	239.8	224.1	225.0	14.3	3	6.4	
			No F-T	209.1	178.9	208.3	198.8	17.2	3	8.7	0.88
			F-T	98.5	94.8		96.7	2.6	2	2.7	0.43
	90	0 h	Dry	277.4	239.3	247.8	254.8	20.0	3	7.8	
			No F-T	99.7	95.8	9.7	95.4	4.5	3	4.7	0.37
			F-T	144.6	155.7	160.6	153.6	8.2	3	5.3	0.60
		96 h	Dry	211.2	239.8	224.1	225.0	14.3	3	6.4	
			No F-T	172.2		178.1	175.5	3.7	3	2.1	0.78
			F-T	82.9	102.7	92.1	92.6	9.9	3	10.7	0.41
4 h/135C	55	0 h	Dry	220.8	270.5	248.3	246.5	24.9	3	10.1	
			No F-T	148.3	153.8	127.7	143.3	13.8	3	9.6	0.58
			F-T	143.8	156.5	161.0	153.8	8.9	3	5.8	0.62
		96 h	Dry	223.8	225.5	218.0	222.4	3.9	3	1.8	
			No F-T	150.1	171.1	154.9	158.7	11.0	3	6.9	0.71
			F-T	174.7	164.6	157.5	165.6	8.6	3	5.2	0.74
	75	0 h	Dry	220.8	270.5	248.3	246.5	24.9	3	10.1	
			No F-T	139.7	97.1	124.3	120.4	21.6	3	17.9	0.49
			F-T	117.3	120.7	105.6	114.5	7.9	3	6.9	0.46
		96 h	Dry	223.8	225.5	218.0	222.4	3.9	3	1.8	
			No F-T	175.5	145.0	139.5	153.3	19.4	3	12.6	0.69
			F-T	158.6	153.4	165.9	159.3	6.3	3	3.9	0.72
	90	0 h	Dry	220.8	270.5	248.3	246.5	24.9	3	10.1	
			No F-T	124.5	145.1	139.0	136.2	10.6	3	7.8	0.55
			F-T	88.7	121.4	108.4	106.2	16.5	3	15.5	0.43
		96 h	Dry	223.8	225.5	218.0	222.4	3.9	3	1.8	
			No F-T	167.6	170.2	165.6	167.8	2.3	3	1.4	0.75
			F-T	117.7	107.4	114.0	113.0	5.2	3	4.6	0.51

TABLE 9 Tensile Strength Test Results for Marshall Impact Compacted Samples—Task 3

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
None	55	0 h	Dry	171.1	180.6	166.5	172.7	7.2	3	4.2	
			No F-T	85.4	93.1	86.1	88.2	4.3	3	4.8	0.51
			F-T	58.9	57.6	56.4	57.6	1.3	3	2.2	0.33
		96 h	Dry	212.2	221.8	200.0	211.3	10.9	3	5.2	
			No F-T	121.9	92.4		107.2	20.9	2	19.5	0.51
			F-T	84.6	65.7	75.2	75.2	9.5	3	12.6	0.36
	75	0 h	Dry	171.1	180.6	166.5	172.7	7.2	3	4.2	
			No F-T	123.0	128.1	92.1	114.4	19.5	3	17.0	0.66
			F-T	106.1	123.7	118.1	116.0	9.0	3	7.8	0.67
		96 h	Dry	212.2	221.8	200.0	211.3	10.9	3	5.2	
			No F-T	213.9	210.3	186.5	203.6	14.9	3	7.3	0.96
			F-T	106.9	84.3	117.7	103.0	17.0	3	16.6	0.49
	90	0 h	Dry	171.1	180.6	166.5	172.7	7.2	3	4.2	
			No F-T	93.0	101.8	91.1	95.3	5.7	3	6.0	0.55
			F-T	106.7	86.4	107.9	100.3	12.1	3	12.0	0.58
		96 h	Dry	212.2	221.8	200.0	211.3	10.9	3	5.2	
			No F-T	145.8	211.1		178.5	46.2	2	25.9	0.84
			F-T	79.5	97.1	99.1	91.9	10.8	3	11.7	0.43
16 h/60C	55	0 h	Dry	263.3	241.1	287.3	263.9	23.1	3	8.8	
			No F-T	163.4	183.0	197.1	181.2	16.9	3	9.3	0.69
			F-T	112.6	128.5	122.7	121.3	8.0	3	6.6	0.46
		96 h	Dry	234.7	245.8	248.5	243.0	7.3	3	3.0	
			No F-T	140.1	156.7	137.2	144.7	10.5	3	7.3	0.60
			F-T	101.7	81.7	97.1	93.5	10.5	3	11.2	0.38
	75	0 h	Dry	263.3	241.1	287.3	263.9	23.1	3	8.8	
			No F-T	188.0	174.0	172.6	178.2	8.5	3	4.8	0.68
			F-T	73.9	71.1	75.4	73.5	2.2	3	3.0	0.28
		96 h	Dry	234.7	245.8	248.5	243.0	7.3	3	3.0	
			No F-T	192.2	129.2	150.2	157.2	32.1	3	20.4	0.65
			F-T	72.2	76.8	84.8	77.9	6.4	3	8.2	0.32
	90	0 h	Dry	263.3	241.1	287.3	263.9	23.1	3	8.8	
			No F-T	218.5	171.8	190.5	193.6	23.5	3	12.1	0.73
			F-T	97.1	133.4		115.3	25.7	2	22.3	0.44
		96 h	Dry	234.7	245.8	248.5	243.0	7.3	3	3.0	
			No F-T	127.2	131.2	151.3	136.6	12.9	3	9.5	0.56
			F-T	76.1	76.5	92.7	81.8	9.5	3	11.6	0.34

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TABLE 9 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
2 h/135C	55	0 h	Dry	218.9	234.5	190.9	214.8	22.1	3	10.3	
			No F-T	136.4	139.9	124.5	133.6	8.1	3	6.0	0.62
			F-T		116.4	131.8	124.1	10.9	2	8.8	0.58
		96 h	Dry	158.6	161.5	137.9	152.7	12.9	3	8.4	
			No F-T	114.5	138.5	143.3	132.1	15.4	3	11.7	0.87
			F-T	130.1	110.4	107.1	115.9	12.4	3	10.7	0.76
	75	0 h	Dry	218.9	234.5	190.9	214.8	22.1	3	10.3	
			No F-T	128.0	131.6	144.2	134.6	8.5	3	6.3	0.63
			F-T	101.8	99.8	102.3	101.3	1.3	3	1.3	0.47
		96 h	Dry	158.6	161.5	137.9	152.7	12.9	3	8.4	
			No F-T	144.3	154.4	166.4	155.0	11.1	3	7.1	1.02
			F-T	136.4	118.6	138.1	131.0	10.8	3	8.2	0.86
	90	0 h	Dry	218.9	234.5	190.9	214.8	22.1	3	10.3	
			No F-T	106.7	86.4	107.9	100.3	12.1	3	12.0	0.47
			F-T	80.1	98.8	123.0	100.6	21.5	3	21.4	0.47
		96 h	Dry	158.6	161.5	137.9	152.7	12.9	3	8.4	
			No F-T	140.1	143.1	102.7	128.6	22.5	3	17.5	0.84
			F-T	106.7	119.3	135.9	120.6	14.6	3	12.1	0.79
4 h/135C	55	0 h	Dry	201.6	211.4	234.1	215.7	16.7	3	7.7	
			No F-T	125.4	113.3	158.1	132.3	23.2	3	17.5	0.61
			F-T	160.8	150.7	142.9	151.5	9.0	3	5.9	0.70
		96 h	Dry	264.9	244.8	270.9	260.2	13.7	3	5.3	
			No F-T	146.0	175.8	166.8	162.9	15.3	3	9.4	0.63
			F-T	172.9	151.1	117.6	147.2	27.9	3	18.9	0.57
	75	0 h	Dry	201.6	211.4	234.1	215.7	16.7	3	7.7	
			No F-T		131.4	120.3	125.9	7.8	2	6.2	0.58
			F-T	136.2	123.2	149.5	136.3	13.2	3	9.6	0.63
		96 h	Dry	264.9	244.8	270.9	260.2	13.7	3	5.3	
			No F-T	182.8	157.9	168.5	169.7	12.5	3	7.4	0.65
			F-T		74.8	87.6	81.2	9.1	2	11.1	0.31
	90	0 h	Dry	201.6	211.4	234.1	215.7	16.7	3	7.7	
			No F-T	192.4	227.8	200.3	206.8	18.6	3	9.0	0.96
			F-T	121.2	124.2		122.7	2.1	2	1.7	0.57
		96 h	Dry	264.9	244.8	270.9	260.2	13.7	3	5.3	
			No F-T	119.5	117.6	112.8	116.6	3.5	3	3.0	0.45
			F-T	110.8	87.3	113.1	103.7	14.3	3	13.8	0.40

TABLE 10 Tensile Strength for Alabama, Colorado, Maryland, and Texas Superpave Gyratory and Marshall Impact Compacted Samples, Partial Factorial Experiment—Task 4

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi Sample Number 1	2	3	Statistics (Tensile Strength) Mean	Standard Deviation	N Samples	Coefficient of Variation	Tensile Strength Ratio
None	55	0 h	Dry	96.3	97.1	122.5	105.3	14.9	3	14.1	
			No F-T	54.3	43.6	46.9	48.3	5.5	3	11.4	0.46
			F-T								
		96 h	Dry	111.0	81.6	96.2	96.3	14.7	3	15.3	
			No F-T								
			F-T	63.3	63.1	79.1	68.5	9.2	3	13.4	0.71
	75	0 h	Dry	96.3	97.1	122.5	105.3	14.9	3	14.1	
			No F-T	58.4	52.8	61.8					
			F-T	FAILED	FAILED	FAILED					
		96 h	Dry	111.0	81.6	96.2	96.3	14.7	3	15.3	
			No F-T	FAILED	FAILED	FAILED					
			F-T	59.5	63.8	72.2					
	90	0 h	Dry	96.3	97.1	122.5	105.3	14.9	3	14.1	
			No F-T								
			F-T	55.6	FAILED	FAILED	55.6	N/A	1	N/A	0.53
		96 h	Dry	111.0	81.6	96.2	96.3	14.7	3	15.3	
			No F-T	52.1	51.9	54.9					
			F-T	FAILED	FAILED	FAILED					
16 h / 60°C	55	0 h	Dry	83.0	75.5	78.2	78.9	3.8	3	4.8	
			No F-T	FAILED	36.1	44.1	40.1	5.7	2	14.1	0.51
			F-T								
		96 h	Dry	56.7	60.4	56.6	57.9	2.2	3	3.7	
			No F-T	77.2	49.6	72.3	66.4	14.7	3	22.2	1.15
			F-T	59.4	57.8	73.6	63.6	8.7	3	13.7	1.10
	75	0 h	Dry	83.0	75.5	78.2	78.9	3.8	3	4.8	
			No F-T								
			F-T	42.5	FAILED	FAILED	42.5	N/A	1	N/A	0.54
		96 h	Dry	56.7	60.4	56.6	57.9	2.2	3	3.7	
			No F-T	60.6	60.5	65.2	62.1	2.7	3	4.3	1.07
			F-T								
	90	0 h	Dry	83.0	75.5	78.2	78.9	3.8	3	4.8	
			No F-T	45.6	49.8	FAILED	47.7	3.0	2	6.2	0.60
			F-T	45.6	49.7	FAILED	47.7	2.9	2	6.1	0.60
		96 h	Dry	56.7	60.4	56.6	57.9	2.2	3	3.7	
			No F-T								
			F-T	42.8	48.1	48.5	46.5	3.2	3	6.8	0.80

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
2 h / 135°C	55	0 h	Dry	77.9	63.7	76.3	72.6	7.8	3	10.7	
			No F-T								
			F-T	FAILED	FAILED	58.7	58.7	N/A	1	N/A	0.81
		96 h	Dry	77.9	63.7	76.3	72.6	7.8	3	10.7	
			No F-T	62.5	62.8	57.1	60.8	3.2	3	5.3	0.84
			F-T								
	75	0 h	Dry	77.9	63.7	76.3	72.6	7.8	3	10.7	
			No F-T	FAILED	42.5	FAILED	42.5	N/A	1	N/A	0.59
			F-T	FAILED	61.3	FAILED	61.3	N/A	1	N/A	0.84
		96 h	Dry	77.9	63.7	76.3	72.6	7.8	3	10.7	
			No F-T	55.6	66.4	59.2	60.4	5.5	3	9.1	0.83
			F-T	68.3	57.9	NA	63.1	7.4	2	11.7	0.87
	90	0 h	Dry	77.9	63.7	76.3	72.6	7.8	3	10.7	
			No F-T	FAILED	FAILED	FAILED					
			F-T								
		96 h	Dry	77.9	63.7	76.3	72.6	7.8	3	10.7	
			No F-T								
			F-T	47.3	45.2	42.2	44.9	2.6	3	5.7	0.62
4 h / 135°C	55	0 h	Dry	117.3	97.5	105.8	106.9	9.9	3	9.3	
			No F-T								
			F-T	56.8	56.2	51.9	55.0	2.7	3	4.9	0.51
		96 h	Dry	70.2	69.0	87.6	75.6	10.4	3	13.8	
			No F-T	55.9	40.2	48.8	48.3	7.9	3	16.3	0.64
			F-T								
	75	0 h	Dry	117.3	97.5	105.8	106.9	9.9	3	9.3	
			No F-T	FAILED	FAILED	47.9	47.9	N/A	1	N/A	0.45
			F-T								
		96 h	Dry	70.2	69.0	87.6	75.6	10.4	3	13.8	
			No F-T	55.6	66.4	59.2	60.4	5.5	3	9.1	0.80
			F-T	68.3	57.9	FAILED	63.1	7.4	2	11.7	0.83
	90	0 h	Dry	117.3	97.5	105.8	106.9	9.9	3	9.3	
			No F-T	54.9	FAILED	61.5	58.2	4.7	2	8.0	0.54
			F-T	55.5	46.2	FAILED	50.9	6.6	2	12.9	0.48
		96 h	Dry	70.2	69.0	87.6	75.6	10.4	3	13.8	
			No F-T	51.4	45.8	39.3	45.5	6.1	3	13.3	0.60
			F-T	FAILED	FAILED	FAILED					

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
None	75	0 h	Dry	167.1	137.1	125.5	143.2	21.5	3	15.0	
			No F-T	110.2	75.6	109.1	98.3	19.7	3	20.0	0.69
			F-T								
		96 h	Dry								
			No F-T								
			F-T								
2 h / 135°C	75	0 h	Dry	105.4	97.1	88.1	96.9	8.7	3	8.9	
			No F-T	84.4	53.4	71.4	69.7	15.6	3	22.3	0.72
			F-T								
		96 h	Dry								
			No F-T								
			F-T								
4 h / 135°C	90	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	93.7	92.4	89.9	92.0	1.9	3	2.1	
			No F-T								
			F-T	110.1	100.2	86.8	99.0	11.7	3	11.8	1.08
None	55	0 h	Dry	69.2	63.6	52.4	61.7	8.6	3	13.9	
			No F-T	43.2	40.9	41.4	41.8	1.2	3	2.9	0.68
			F-T								
		96 h	Dry	65.4	73.3	58.9	65.9	7.2	3	10.9	
			No F-T								
			F-T	65.2	63.2	49.1	59.2	8.8	3	14.8	0.90
	75	0 h	Dry	69.2	63.6	52.4	61.7	8.6	3	13.9	
			No F-T								
			F-T	26.4	40.9	27.4	31.6	8.1	3	25.7	0.51
		96 h	Dry	65.4	73.3	58.9	65.9	7.2	3	10.9	
			No F-T	52.5	48.4	47.6	49.5	2.6	3	5.3	0.75
			F-T								
	90	0 h	Dry	69.2	63.6	52.4	61.7	8.6	3	13.9	
			No F-T	16.7	28.2	27.6	24.2	6.5	3	26.8	0.39
			F-T	39.4	38.0	35.1	37.5	2.2	3	5.8	0.61
		96 h	Dry	65.4	73.3	58.9	65.9	7.2	3	10.9	
			No F-T	43.2	40.9	41.4	41.8	1.2	3	2.9	0.64
			F-T	19.3	30.4	22.0	23.9	5.8	3	24.2	0.36

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
16 h / 60°C	55	0 h	Dry	100.1	88.1	93.5	93.9	6.0	3	6.4	
			No F-T	37.0	45.5	61.6	48.0	12.5	3	26.0	0.51
			F-T	65.6	73.0	67.6	68.7	3.8	3	5.6	0.73
		96 h	Dry	95.9	FAILED	106.0	101.0	7.1	2	7.1	
			No F-T								
			F-T	72.8	79.1	66.3	72.7	6.4	3	8.8	0.72
	75	0 h	Dry	100.1	88.1	93.5	93.9	6.0	3	6.4	
			No F-T	35.2	44.7	41.7	40.5	4.9	3	12.0	0.43
			F-T								
		96 h	Dry	95.9	FAILED	106.0	101.0	7.1	2	7.1	
			No F-T	47.7	FAILED	55.6	51.7	5.6	2	10.8	0.51
			F-T	48.8	39.9	39.9	42.9	5.1	3	12.0	0.42
	90	0 h	Dry	100.1	88.1	93.5	93.9	6.0	3	6.4	
			No F-T								
			F-T	64.0	57.8	58.3	60.0	3.4	3	5.7	0.64
		96 h	Dry	95.9	FAILED	106.0	101.0	7.1	2	7.1	
			No F-T	39.6	47.9	51.6	46.4	6.1	3	13.3	0.46
			F-T								
2 h / 135°C	55	0 h	Dry	101.1	89.1	93.7	94.6	6.1	3	6.4	
			No F-T	57.6	54.6	61.0	57.7	3.2	3	5.5	0.61
			F-T								
		96 h	Dry	99.9	89.9	98.2	96.0	5.4	3	5.6	
			No F-T	70.7	64.7	63.4	66.3	3.9	3	5.9	0.69
			F-T	69.8	68.7	54.1	64.2	8.8	3	13.7	0.67
	75	0 h	Dry	101.1	89.1	93.7	94.6	6.1	3	6.4	
			No F-T	43.9	44.3	50.9	46.4	3.9	3	8.5	0.49
			F-T	82.3	67.5	54.8	68.2	13.8	3	20.2	0.72
		96 h	Dry	99.9	89.9	98.2	96.0	5.4	3	5.6	
			No F-T								
			F-T	79.1	62.7	70.9	70.9	8.2	3	11.6	0.74
	90	0 h	Dry	101.1	89.1	93.7	94.6	6.1	3	6.4	
			No F-T								
			F-T	57.5	69.5	59.1	62.0	6.5	3	10.5	0.66
		96 h	Dry	99.9	89.9	98.2	96.0	5.4	3	5.6	
			No F-T	49.0	49.7	49.0	49.2	0.4	3	0.8	0.51
			F-T								

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
4 h / 135°C	55	0 h	Dry	FAILED	112.6	96.8	104.7	11.2	2	10.7	
			No F-T								
			F-T	65.8	58.5	FAILED	62.2	5.2	2	8.3	0.59
		96 h	Dry	76.9	62.5	77.3	72.2	8.4	3	11.7	
			No F-T	58.5	68.9	73.1	66.8	7.5	3	11.2	0.93
			F-T								
	75	0 h	Dry	FAILED	112.6	96.8	104.7	11.2	2	10.7	
			No F-T	54.7	70.0	38.0	54.2	16.0	3	29.5	0.52
			F-T	65.8	58.5	65.0	63.1	4.0	3	6.3	0.60
		96 h	Dry	76.9	62.5	77.3	72.2	8.4	3	11.7	
			No F-T	55.3	38.7	41.2	45.1	9.0	3	19.9	0.62
			F-T	49.4	50.1	47.7	49.1	1.2	3	2.5	0.68
	90	0 h	Dry	FAILED	112.6	96.8	104.7	11.2	2	10.7	
			No F-T	47.0	FAILED	33.9	40.5	9.3	2	22.9	0.39
			F-T								
		96 h	Dry	76.9	62.5	77.3	72.2	8.4	3	11.7	
			No F-T								
			F-T	55.2	48.4	35.8	46.5	9.8	3	21.2	0.64
None	75	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	142.3	153.6	136.2	144.0	8.8	3	6.1	
			No F-T	90.1	74.7	73.3	79.4	9.3	3	11.7	0.55
			F-T								
16 h / 60°C	55	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	86.3	87.2	67.3	80.3	11.2	3	14.0	
			No F-T								
			F-T	66.3	76.2	84.5	75.7	9.1	3	12.0	0.94
2 h / 135°C	75	0 h	Dry	101.5	98.7	100.3	100.2	1.4	3	1.4	
			No F-T								
			F-T	44.8	72.3	42.3	53.1	16.6	3	31.3	0.53
		96 h	Dry								
			No F-T								
			F-T								
4 h / 135°C	55	0 h	Dry	72.5	88.6	85.3	82.1	8.5	3	10.4	
			No F-T	FAILED	FAILED	43.8	43.8	N/A	1	N/A	0.53
			F-T								
		96 h	Dry								
			No F-T								
			F-T								

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
None	55	0 h	Dry	114.9	119.2	121.7	118.6	3.4	3	2.9	
			No F-T								
			F-T	122.7	142.9	120.9	128.8	12.2	3	9.5	1.09
		96 h	Dry	131.3	126.8	117.5	125.2	7.0	3	5.6	
			No F-T	78.3	84.2	81.0	81.2	3.0	3	3.6	0.65
			F-T	63.5	56.1	74.3	64.6	9.2	3	14.2	0.52
	75	0 h	Dry	114.9	119.2	121.7	118.6	3.4	3	2.9	
			No F-T	101.6	98.2	111.8	103.9	7.1	3	6.8	0.88
			F-T								
		96 h	Dry	131.3	126.8	117.5	125.2	7.0	3	5.6	
			No F-T								
			F-T	123.8	124.7	119.1	122.5	3.0	3	2.5	0.98
	90	0 h	Dry	114.9	119.2	121.7	118.6	3.4	3	2.9	
			No F-T								
			F-T	54.7	63.9	68.1	62.2	6.9	3	11.0	0.52
		96 h	Dry	131.3	126.8	117.5	125.2	7.0	3	5.6	
			No F-T	103.2	115.1	99.9	106.1	8.0	3	7.5	0.85
			F-T								
16 h / 60°C	55	0 h	Dry	114.9	119.2	121.7	118.6	3.4	3	2.9	
			No F-T	92.7	93.2	101.1	95.7	4.7	3	4.9	0.81
			F-T	116.3	138.7	139.0	131.3	13.0	3	9.9	1.11
		96 h	Dry	111.4	111.8	106.4	109.9	3.0	3	2.7	
			No F-T	103.7	101.0	108.6	104.4	3.9	3	3.7	0.95
			F-T								
	75	0 h	Dry	114.9	119.2	121.7	118.6	3.4	3	2.9	
			No F-T								
			F-T	118.3	122.0	122.2	120.8	2.2	3	1.8	1.02
		96 h	Dry	111.4	111.8	106.4	109.9	3.0	3	2.7	
			No F-T	90.4	106.1	106.1	100.9	9.1	3	9.0	0.92
			F-T	77.3	84.4	95.1	85.6	9.0	3	10.5	0.78
	90	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	111.4	111.8	106.4	109.9	3.0	3	2.7	
			No F-T	101.0	103.6	118.1	107.6	9.2	3	8.6	0.98
			F-T	102.3	120.5	98.9	107.2	11.6	3	10.8	0.98

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
2 h / 135°C	55	0 h	Dry	68.9	66.0	FAILED	67.5	2.1	2	3.0	
			No F-T	79.2	70.6	76.2	75.3	4.4	3	5.8	1.12
			F-T								
		96 h	Dry	113.7	115.7	100.0	109.8	8.5	3	7.8	
			No F-T								
			F-T	99.2	96.5	103.7	99.8	3.6	3	3.6	0.91
	75	0 h	Dry	68.9	66.0	FAILED	67.5	2.1	2	3.0	
			No F-T								
			F-T	118.4	120.1	124.8	121.1	3.3	3	2.7	1.80
		96 h	Dry	113.7	115.7	100.0	109.8	8.5	3	7.8	
			No F-T	103.8	110.0	98.9	104.2	5.6	3	5.3	0.95
			F-T								
	90	0 h	Dry	68.9	66.0	FAILED	67.5	2.1	2	3.0	
			No F-T	104.8	109.0	103.1	105.6	3.0	3	2.9	1.57
			F-T	91.5	93.0	99.1	94.5	4.0	3	4.3	1.40
		96 h	Dry	113.7	115.7	100.0	109.8	8.5	3	7.8	
			No F-T	100.0	102.7	94.3	99.0	4.3	3	4.3	0.90
			F-T	100.6	104.7	111.1	105.5	5.3	3	5.0	0.96
4 h / 135°C	55	0 h	Dry	89.0	86.0	105.1	93.4	10.3	3	11.0	
			No F-T	91.0	96.1	99.2	95.4	4.1	3	4.3	1.02
			F-T	88.2	87.7	87.7	87.9	0.3	3	0.3	0.94
		96 h	Dry	70.1	76.0	75.0	73.7	3.2	3	4.3	
			No F-T								
			F-T	82.9	88.2	77.5	82.9	5.4	3	6.5	1.12
	75	0 h	Dry	89.0	86.0	105.1	93.4	10.3	3	11.0	
			No F-T	121.3	133.5	128.7	127.8	6.1	3	4.8	1.54
			F-T								
		96 h	Dry	70.1	76.0	75.0	73.7	3.2	3	4.3	
			No F-T	60.9	74.2	59.8	65.0	8.0	3	12.3	0.88
			F-T	86.6	78.8	89.0	84.8	5.3	3	6.3	1.15
	90	0 h	Dry	89.0	86.0	105.1	93.4	10.3	3	11.0	
			No F-T								
			F-T	84.9	80.9	89.6	85.1	4.4	3	5.1	0.91
		96 h	Dry	70.1	76.0	75.0	73.7	3.2	3	4.3	
			No F-T	63.3	63.6	61.0	62.6	1.4	3	2.3	0.85
			F-T								

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
None	55	0 h	Dry	91.7	85.4	86.5	87.9	3.4	3	3.8	
			No F-T								
			F-T	95.1	85.9	95.1	92.0	5.3	3	5.8	1.05
		96 h	Dry								
			No F-T								
			F-T								
2 h / 135°C	90	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	59.4	71.5	70.9	67.3	6.8	3	10.1	
			No F-T	84.6	84.7	82.3	83.9	1.4	3	1.6	1.25
			F-T								
2 h / 135°C	90	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	99.5	97.9	103.3	100.2	2.8	3	2.8	
			No F-T	81.1	82.8	84.9	82.9	1.9	3	2.3	0.83
			F-T								
4 h / 135°C	75	0 h	Dry	85.8	86.5	73.5	81.9	7.3	3	8.9	
			No F-T	81.4	78.0	81.8	80.4	2.1	3	2.6	0.98
			F-T								
		96 h	Dry	202.8	210.2	207.0	206.7	3.7	3	1.8	
			No F-T								
			F-T	100.1	115.4	97.5	104.3	9.7	3	9.3	0.50
None	55	0 h	Dry	134.3	113.6	123.9	123.9	10.4	3	8.4	
			No F-T	73.6	81.1	81.2	78.6	4.4	3	5.5	0.63
			F-T								
		96 h	Dry	76.9	71.5	85.2	77.9	6.9	3	8.9	
			No F-T								
			F-T	89.8	94.1	81.9	88.6	6.2	3	7.0	1.14
	75	0 h	Dry	134.3	113.6	123.9	123.9	10.4	3	8.4	
			No F-T	57.5	55.6	56.6	56.6	1.0	3	1.7	0.46
			F-T	57.7	49.3	77.1	61.4	14.3	3	23.2	0.50
		96 h	Dry	76.9	71.5	85.2	77.9	6.9	3	8.9	
			No F-T								
			F-T	109.5	133.9	117.9	120.4	12.4	3	10.3	1.55
	90	0 h	Dry	134.3	113.6	123.9	123.9	10.4	3	8.4	
			No F-T								
			F-T								
		96 h	Dry	76.9	71.5	85.2	77.9	6.9	3	8.9	
			No F-T	74.7	77.7	76.7	76.4	1.5	3	2.0	0.98
			F-T	66.2	54.2	87.8	69.4	17.0	3	24.5	0.89

(*continued on next page*)

TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
16 h / 60°C	55	0 h	Dry	183.5	208.2	215.5	202.4	16.8	3	8.3	
			No F-T								
			F-T	102.5	110.3	114.0	108.9	5.9	3	5.4	0.54
		96 h	Dry	104.8	112.1	126.1	114.3	10.8	3	9.5	
			No F-T	103.6	101.2	107.4	104.1	3.1	3	3.0	0.91
			F-T	65.5	65.6	70.7	67.3	3.0	3	4.4	0.59
	75	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	104.8	112.1	126.1	114.3	10.8	3	9.5	
			No F-T	93.9	87.7	83.6	88.4	5.2	3	5.9	0.77
			F-T	99.0	84.2	94.4	92.5	7.6	3	8.2	0.81
	90	0 h	Dry	183.5	208.2	215.5	202.4	16.8	3	8.3	
			No F-T	88.4	92.7	96.7	92.6	4.2	3	4.5	0.46
			F-T	91.0	89.6	88.8	89.8	1.1	3	1.2	0.44
		96 h	Dry	104.8	112.1	126.1	114.3	10.8	3	9.5	
			No F-T	81.2	67.6	81.3	76.7	7.9	3	10.3	0.67
			F-T	92.5	88.0	92.4	91.0	2.6	3	2.8	0.80
2 h / 135°C	55	0 h	Dry	111.5	110.4	102.1	108.0	5.1	3	4.8	
			No F-T	54.2	54.6	54.4	54.4	0.2	3	0.4	0.50
			F-T	99.7	91.5	88.2	93.1	5.9	3	6.4	0.86
		96 h	Dry	184.4	171.2	171.4	175.7	7.6	3	4.3	
			No F-T	54.4	54.8	51.9	53.7	1.6	3	2.9	0.31
			F-T								
	75	0 h	Dry	111.5	110.4	102.1	108.0	5.1	3	4.8	
			No F-T								
			F-T	124.0	133.0	FAILED	128.5	6.4	2	5.0	1.19
		96 h	Dry	184.4	171.2	171.4	175.7	7.6	3	4.3	
			No F-T	110.8	111.1	107.8	109.9	1.8	3	1.7	0.63
			F-T	88.0	86.8	94.4	89.7	4.1	3	4.6	0.51
	90	0 h	Dry	111.5	110.4	102.1	108.0	5.1	3	4.8	
			No F-T	115.2	120.9	124.5	120.2	4.7	3	3.9	1.11
			F-T	82.4	85.5	92.4	86.8	5.1	3	5.9	0.80
		96 h	Dry	184.4	171.2	171.4	175.7	7.6	3	4.3	
			No F-T								
			F-T	92.5	88.0	92.4	91.0	2.6	3	2.8	0.52

(*continued on next page*)

TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
4 h / 135°C	55	0 h	Dry	134.5	145.4	FAILED	140.0	7.7	2	5.5	
			No F-T	120.4	132.2	107.7	120.1	12.3	3	10.2	0.86
			F-T								
		96 h	Dry	177.1	176.6	165.8	173.2	6.4	3	3.7	
			No F-T	123.1	122.0	107.7	117.6	8.6	3	7.3	0.68
			F-T	99.7	91.5	88.2	93.1	5.9	3	6.4	0.54
	75	0 h	Dry	134.5	145.4	FAILED	140.0	7.7	2	5.5	
			No F-T	113.9	154.5	127.0	131.8	20.7	3	15.7	0.94
			F-T	117.6	115.8	96.0	109.8	12.0	3	10.9	0.78
		96 h	Dry								
			No F-T								
			F-T								
	90	0 h	Dry	134.5	145.4	FAILED	140.0	7.7	2	5.5	
			No F-T								
			F-T	81.8	78.3	84.8	81.6	3.3	3	4.0	0.58
		96 h	Dry	177.1	176.6	165.8	173.2	6.4	3	3.7	
			No F-T	121.0	104.9	116.9	114.3	8.4	3	7.3	0.66
			F-T								

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TABLE 10 (*Continued*)

Loose Mix Aging	Saturation Level	Compacted Mix Aging	Sample Conditioning	Tensile Strength, Psi			Statistics (Tensile Strength)				Tensile Strength Ratio
				Sample Number			Mean	Standard Deviation	N Samples	Coefficient of Variation	
				1	2	3					
None	75	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	65.6	66.3	52.1	61.3	8.0	3	13.0	
			No F-T								
			F-T	73.2	74.5	76.8	74.8	1.8	3	2.4	1.22
16 h / 60°C	55	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	209.6	215.2	221.6	215.5	6.0	3	2.8	
			No F-T	89.4	99.1	103.2	97.2	7.1	3	7.3	0.45
			F-T								
16 h / 60°C	90	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	209.6	215.2	221.6	215.5	6.0	3	2.8	
			No F-T								
			F-T	FAILED	50.3	50.0	50.2	0.2	2	0.4	0.23
2 h / 135°C	75	0 h	Dry								
			No F-T								
			F-T								
		96 h	Dry	0.0	0.0	0.0	0.0	0.0	3	#DIV/0!	
			No F-T	101.1	109.1	111.4	107.2	5.4	3	5.0	#DIV/0!
			F-T								
4 h / 135°C	90	0 h	Dry	140.1	136.2	139.8	138.7	2.2	3	1.6	
			No F-T	131.0	132.7	119.0	127.6	7.5	3	5.9	0.92
			F-T								
		96 h	Dry								
			No F-T								
			F-T								

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

INTRODUCTION

The objectives of this study are (a) to evaluate AASHTO T283, "Resistance of Compacted Bituminous Mixture to Moisture Induced Damage," and (b) to recommend changes to make it compatible with the Superpave system. One of the central issues of the study is to determine the influence of the compaction method and size of sample on the results of the AASHTO T283 method of test. Comparisons have been made among the 150-mm-diameter Superpave gyratory (G150) compacted samples, 100-mm-diameter Superpave gyratory (G100) compacted samples, 100-mm-diameter Marshall impact (M100) compacted samples, and 100-mm-diameter Hveem kneading (H100) compacted samples. The G150 compacted samples are 95 mm in height, and all 100-mm-diameter samples are 62 mm in height; thus, the height-to-diameter ratio of all samples is the same.

Results from the four main tasks performed in the laboratory are used to define the influence of compaction method and sample size on the tensile strength and tensile strength ratio of samples subjected to no conditioning and conditioning (no freeze-thaw and freeze-thaw). In some of the laboratory tasks, the loose mix and compacted mix aging/curing conditions were fixed. In other laboratory tasks, the loose mix and compacted mix aging/curing conditions were varied, as described previously.

The influence of compaction method and sample size on tensile strength and tensile strength ratio will be discussed under the following topics in this chapter:

- Dry tensile strength,
- No freeze-thaw tensile strength,
- Freeze-thaw tensile strength,
- Dry versus no freeze-thaw tensile strength,
- Dry versus freeze-thaw tensile strength,
- No freeze-thaw versus freeze-thaw tensile strength,
- Level of saturation,
- Tensile strength ratio,
- Water sensitivity,
- Variability and compaction method, and
- Variability and mixture source.

Results from three interim reports (*7–9*) and additional statistical analysis on the complete and partial factorial tasks conducted in this study are summarized below. All the statistical analyses presented in this report were conducted at a level of significance of 5 percent (0.05) unless specified otherwise.

DRY TENSILE STRENGTH

Selection of Resilient Modulus as a Response Variable

Both resilient modulus and tensile strength were measured on all samples in this research project. As previously stated, resilient modulus was selected as one of the response variables in this study because resilient modulus is believed to be more sensitive to changes in asphalt binder properties and a mixture's sensitivity to damage by water than is tensile strength. In addition, resilient modulus can be used as a measure of the load distribution capability of a pavement material.

Most public agencies presently use tensile strength as the response variable when performing the AASHTO T283 water sensitivity test and do not perform the resilient modulus test. Thus the public agencies do not perform a resilient modulus test prior to tensile strength testing in AASHTO T283. The test sequence used for the majority of NCHRP Project 9-13 included resilient modulus testing prior to tensile strength determination. Thus, it was necessary to define the effect of performing resilient modulus testing prior to tensile strength determination.

An 18-sample test program was utilized to determine the effect of performing resilient modulus testing prior to tensile strength determination. Results of this test program are contained in the second interim report (*8*) for this project and are summarized below.

A statistical comparison of tensile strengths of samples subjected to resilient modulus testing and not subjected to resilient modulus testing is shown in Tables 11 and 12 for samples compacted with the 150-mm-diameter Superpave gyratory compactor and the 100-mm-diameter Marshall impact compactor, respectively. A statistical difference of tensile strength does not exist among sample groups subjected to and not subjected to resilient modulus testing prior to tensile strength determination. This observation was valid for those groups of samples not conditioned (dry) and those sample groups conditioned (no F-T and F-T).

A nonstatistical analysis indicates that 16 of the 18 data set comparisons of tensile strength ratio obtained in this study are not significantly influenced by resilient modulus testing prior to the determination of tensile strength. These observations on tensile strength and tensile strength ratio are based on observations made with Alabama, Colorado, and Nevada aggregates and binders and loose mix aged for 4 hr at 135 °C and compacted mix aged for 96 hr at room temperature.

Comparison of Four Compaction Methods

This task of the project provided information that illustrates the effect of compaction method and sample size on the dry tensile strengths (Tables 13–19). The variables included in this task are mixture source (Alabama, Colorado, Maryland, Nevada, and Texas) and conditioning (dry, no freeze-thaw, and freeze-thaw). The aging of the samples was fixed (loose mix aging 4 hr at 135 °C and compacted mix aging at 96 hr at room temperature).

Tables 13–15 show statistical comparisons of samples prepared with the G150 compactor with samples prepared with the G100 compactor, M100 compactor, and H100 compactor, respectively. Table 16 shows the statistical comparison of the G150 compacted samples with all the 100-mm-diameter samples. Tables 17 and 18 show the comparison of the G100 compacted samples with the M100 compacted and H100 compacted samples, respectively. This information is summarized below.

G150 Samples versus G100 Samples

Table 13 indicates that the dry tensile strengths of samples compacted by the G100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 4 of 5 possible comparisons. In 1 of 5 comparisons, the dry tensile strengths were statistically the same.

G150 Samples versus M100 Samples

Table 14 indicates that the dry tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 1 of 5 possible comparisons. In 3 of 5 comparisons, the dry tensile strengths were statistically the same; in 1 of 5 comparisons, the M100 compacted samples had a lower dry tensile strength than the companion G150 compacted samples.

G150 Samples versus H100 Samples

Table 15 indicates that the dry tensile strengths of samples compacted by the H100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 2 of 5 possible comparisons. In 3 of 5 comparisons, the dry tensile strengths were statistically the same.

G150 Samples versus All 100-mm-Diameter Samples

Table 16 indicates that the dry tensile strengths of samples compacted by methods that produced 100-mm-diameter samples (Superpave gyratory, Marshall impact, and Hveem kneading) were statistically larger than those of the samples compacted by the G150 compactor for 7 of 15 possible comparisons. In 7 of 15 comparisons, the dry tensile strengths were statistically the same; for 1 of 15 comparisons, the 100-mm-diameter compacted samples had a lower dry tensile strength than the companion G150 compacted samples.

G100 Samples versus M100 Samples

Table 17 indicates that the dry tensile strengths of samples compacted by the M100 compactor were statistically the same as those of the G100 compactor for 2 of 5 possible comparisons. In 3 of 5 comparisons, the M100 samples had a lower dry tensile strength than the companion G100 compacted samples.

G100 Samples versus H100 Samples

Table 18 indicates that the dry tensile strengths of samples compacted by the H100 compactor were statistically the same as those of the G100 compactor for 4 of 5 possible comparisons. In 1 of 5 comparisons, the H100 samples had a lower dry tensile strength than the companion G100 compacted samples.

H100 Samples versus M100 Samples

Table 19 indicates that the dry tensile strength of samples compacted by the M100 compactor were statistically larger than those of samples compacted with the H100 compactor in 1 of 5 possible comparisons. In 2 of 5 comparisons, the dry tensile strengths were statistically the same; in 2 of 5 comparisons, the M100 compacted samples had a lower dry tensile strength than the companion H100 compacted samples.

Comparison of Two Compaction Methods (Complete Factorial)

This task of the project provided information that illustrates the effect of compaction method and sample size on the dry tensile strengths (Tables 20–22). The variables included in this portion of the study were compaction method (G150 and

M100); loose mix aging (none, 16 hr at 60 °C, 2 hr at 135 °C, and 4 hr at 135 °C); compacted mix aging (none and 96 hr at room temperature); and conditioning (dry, no freeze-thaw, and freeze-thaw). A single mixture source was used (Nevada).

Tables 20–22 show the statistical comparisons from this portion of the study. This information is summarized below.

G150 Samples versus M100 Samples

Table 20 indicates that the dry tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 3 of the 24 possible comparisons. In 18 of 24 comparisons, the tensile strengths were statistically the same; in 3 of 24 comparisons, the M100 compacted samples had a lower dry tensile strength than the companion G150 compacted samples.

Loose Mix and Compacted Mix Aging

Tables 21 and 22 show the influence of loose mix aging and compacted mix aging on the dry tensile strength. Loose mix aging (Table 21) increases (to a statistically significant degree) the dry tensile strength in 4 of 12 possible comparisons. In 8 of 12 comparisons, the dry tensile strengths are statistically the same. For 3 of the 4 data groups that illustrated an increase in dry tensile strengths with loose mix aging, 3 were associated with 96 hr of compacted mix curing at room temperature of G150 compacted samples.

Compacted mix aging (Table 22) does not significantly affect the dry tensile strength. In 7 of 8 possible comparisons, the dry tensile strengths of samples subjected to two levels of compacted mix aging were statistically the same. In 1 of 8 comparisons, compacted mix aging decreased the dry tensile strength.

Tensile Strength

This task of the project provided some information that illustrates the effect of compaction method and sample size on the dry tensile strengths (Table 23). The variables in this portion of the study included compaction method (G150 and M100); mixture source (Alabama, Colorado, and Nevada); and conditioning (dry, no freeze-thaw, and freeze-thaw). The loose mix aging was held constant (4 hr at 135 °C) and the compacted mix aging was held constant (96 hr at room temperature).

G150 Samples versus M100 Samples

Table 23 indicates that the dry tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 3 of 6 possible comparisons. In 3 of 6 comparisons, the dry tensile strengths were statistically the same.

NO FREEZE-THAW TENSILE STRENGTH

Comparison of Four Compaction Methods

This task of the project provided information that illustrates the effect of compaction method and sample size on the no freeze-thaw tensile strengths (Tables 13–19). The variables included in this task are mixture source (Alabama, Colorado, Maryland, Nevada, and Texas) and conditioning (dry, no freeze-thaw, and freeze-thaw). The aging of the samples was fixed (loose mix aging 4 hr at 135 °C and compacted mix aging at 96 hr at room temperature).

Tables 13–16 show statistical comparisons of samples prepared with the G150 compactor versus samples prepared with the G100 compactor, M100 compactor, and H100 compactor. This information is summarized below.

G150 Samples versus G100 Samples

Table 13 indicates that the no freeze-thaw tensile strengths of samples compacted by the G100 compactor were statistically the same as those of the samples compacted by the G150 compactor for 4 of 5 possible comparisons. In 1 of 5 comparisons, the G100 no freeze-thaw tensile strengths were statistically lower than the companion G150 compacted samples.

G150 Samples versus M100 Samples

Table 14 indicates that the no freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 1 of 5 possible comparisons. In 4 of 5 comparisons, the no freeze-thaw tensile strengths were statistically the same.

G150 Samples versus H100 Samples

Table 15 indicates that the no freeze-thaw strengths of samples compacted by the H100 compactor were statistically the same as those of the samples compacted by the G150 compactor for 4 of 5 possible comparisons. In 1 of 5 comparisons, the no freeze-thaw tensile strengths were statistically lower than the companion G150 compacted samples.

G150 Samples versus All 100-mm-Diameter Samples

Table 16 indicates that the no freeze-thaw tensile strengths of samples compacted by methods that produced 100-mm-diameter samples (Superpave gyratory, Marshall impact, and Hveem kneading) were statistically larger than those of the samples compacted by the G150 compactor for 1 of 15 possible comparisons. In 12 of 15 comparisons, the no freeze-thaw tensile strengths were statistically the same; in 2 of 15 comparisons, the 100-mm-diameter compacted samples had a lower no freeze-thaw tensile strength than the companion G150 compacted samples.

G100 Samples versus M100 Samples

Table 17 indicates that the no freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the G100 compactor for 2 of 5 possible comparisons. In 3 of 5 comparisons, the M100 samples had the same no freeze-thaw tensile strength as companion G100 compacted samples.

G100 Samples versus H100 Samples

Table 18 indicates that the no freeze-thaw tensile strengths of samples compacted by the H100 compactor were statistically the same as those of the G100 compactor for 4 of 5 possible comparisons. In 1 of 5 comparisons, the H100 samples had a lower no freeze-thaw tensile strength than the companion G100 compacted samples.

H100 Samples versus M100 Samples

Table 19 indicates that the no freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of samples compacted with the H100 compactor in 2 of 5 possible comparisons. In 3 of 5 comparisons, the no freeze-thaw tensile strengths were statistically the same.

Comparison of Two Compaction Methods (Complete Factorial)

This task of the project provided information that illustrates the effect of compaction method and sample size on the no freeze-thaw tensile strengths (Tables 20, 24, and 25). The variables included in this portion of the study were compaction method (G150 and M100); loose mix aging (none, 16 hr at 60 °C, 2 hr at 135 °C, and 4 hr at 135 °C); compacted mix aging (none and 96 hr at room temperature); and conditioning (dry, no freeze-thaw, and freeze-thaw). A single mixture source was used (Nevada).

Tables 20, 24, and 25 show the statistical comparisons from this portion of the study. This information is summarized below.

G150 Samples versus M100 Samples

Table 20 indicates that the no freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 3 of 24 possible comparisons. In 20 of 24 comparisons, the tensile strengths were statistically the same; in 1 of 24 comparisons, the M100 compacted samples had a lower no freeze-thaw tensile strength than the companion G150 compacted samples.

Loose Mix and Compacted Mix Aging

Tables 24 and 25 show the influence of loose mix aging and compacted mix aging on the no freeze-thaw tensile strength. Loose mix aging (Table 24) increases (to a statistically significant degree) the no freeze-thaw tensile strength in 10 of 36 possible comparisons. In 26 of 36 comparisons, the no freeze-thaw tensile strengths are statistically the same. Seven of the 10 data groups that illustrated an increase in no freeze-thaw tensile strengths with loose mix aging were associated with the G150 compacted samples.

Compacted mix aging (Table 25) does not significantly affect the dry tensile strength. In 19 of 24 possible comparisons, the no freeze-thaw tensile strengths of samples subjected to two levels of compacted mix aging were statistically the same. In 4 of 24 comparisons, compacted mix aging increased the no freeze-thaw tensile strength; in 1 of 24 comparisons, the compacted mix aging decreased the no freeze-thaw tensile strength.

Tensile Strength

This task of the project provided some information that illustrates the effect of compaction method and sample size on the no freeze-thaw tensile strengths (Table 23). The variables in this portion of the study included compaction method (G150 and M100); mixture source (Alabama, Colorado, and Nevada); and conditioning (dry, no freeze-thaw, and freeze-thaw). The loose mix aging was held constant (4 hr at 135 °C) and the compacted mix aging was held constant (96 hr at room temperature).

G150 Samples versus M100 Samples

Table 23 indicates that the no freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically the same as those of the samples compacted by the G150 compactor for 6 of 6 possible comparisons.

FREEZE-THAW TENSILE STRENGTH

Comparison of Four Compaction Methods

This task of the project provided information that illustrates the effect of compaction method and sample size on the freeze-thaw tensile strengths (Tables 13–19). The variables included in this task are mixture source (Alabama, Colorado, Maryland, Nevada, and Texas) and conditioning (dry, no freeze-thaw, and freeze-thaw).The aging of the samples was fixed (loose mix aging at 4 hr at 135 °C and compacted mix aging at 96 hr at room temperature).

Tables 13–15 show statistical comparisons of samples prepared with the G150 compactor with samples prepared with the G100, M100, and H100 compactors, respectively. Table 16 shows the comparison of all four samples. This information is summarized below.

G150 Samples versus G100 Samples

Table 13 indicates that the freeze-thaw tensile strengths of samples compacted by the G100 compactor were statistically the same as those of the samples compacted by the G150 compactor for 3 of 5 possible comparisons. In 2 of 5 comparisons, the freeze-thaw tensile strengths were statistically lower than those of the companion G150 compacted samples.

G150 Samples versus M100 Samples

Table 14 indicates that the freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 1 of 5 possible comparisons. In 2 of 5 comparisons, the freeze-thaw tensile strengths were statistically the same; in 2 of 5 comparisons, the M100 samples had a lower freeze-thaw tensile strength than those of the companion G150 compacted samples.

G150 Samples versus H100 Samples

Table 15 indicates that the freeze-thaw tensile strengths of samples compacted by the H100 compactor were statistically the same as those of the samples compacted by the G150 compactor for 3 of 5 possible comparisons. In 2 of 5 comparisons, the freeze-thaw tensile strengths were statistically lower than those of the companion G150 compacted samples.

G150 Samples versus All 100-mm-Diameter Samples

Table 16 indicates that the freeze-thaw tensile strengths of samples compacted by methods that produced 100-mm-diameter samples (Superpave gyratory, Marshall impact, and Hveem kneading) were statistically larger than those of the samples compacted by the G150 compactor for 1 of 15 possible comparisons. In 8 of 15 comparisons, the freeze-thaw tensile strengths were statistically the same; in 6 of 15 comparisons, the 100-mm-diameter compacted samples had a lower freeze-thaw tensile strength than the companion G150 compacted samples.

G100 Samples versus M100 Samples

Table 17 indicates that the freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the G100 compactor for 1 of 5 possible comparisons. In 3 of 5 comparisons, the M100 samples were statistically the same; in 1 of 5 comparisons, the M100 compacted samples had a lower freeze-thaw tensile strength than the companion G100 compacted samples.

G100 Samples versus H100 Samples

Table 18 indicates that the freeze-thaw tensile strengths of samples compacted by the H100 compactor were statistically the same as those of the G100 compactor for 4 of 5 possible comparisons. In 1 of 5 comparisons, the H100 samples had a lower freeze-thaw tensile strength than the companion G100 compacted samples.

H100 Samples versus M100 Samples

Table 19 indicates that the freeze-thaw tensile strength of samples compacted by the M100 compactor were statistically larger than those of the samples compacted with the H100 compactor in 1 of 5 possible comparisons. In 4 of 5 comparisons, the freeze-thaw tensile strengths were statistically the same.

Comparison of Two Compaction Methods (Complete Factorial)

This task of the project provided information that illustrates the effect of compaction method and sample size on the freeze-thaw tensile strengths (Tables 20, 26, and 27). The variables included in this portion of the study were compaction method (G150 and M100); loose mix aging (none, 16 hr at 60 °C, 2 hr at 135 °C, and 4 hr at 135 °C); compacted mix aging (none and 96 hr at room temperature); and conditioning (dry, no freeze-thaw, and freeze-thaw). A single mixture source was used (Nevada).

Tables 20, 26, and 27 show the statistical comparisons from this portion of the study. The information is summarized below.

G150 Samples versus M100 Samples

Table 20 indicates that the freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically the same as those of the samples compacted by the G150 compactor for 22 of 24 possible comparisons. In 2 of 24 comparisons, the M100 compacted samples had a lower freeze-thaw tensile strength than the companion G150 compacted samples.

Loose Mix and Compacted Mix Aging

Tables 26 and 27 show the influence of loose mix aging and compacted mix aging on the dry tensile strength. Loose mix aging (Table 26) increases (to a statistically significant degree) the freeze-thaw tensile strength in 3 of 36 possible comparisons. In 32 of 36 comparisons, the freeze-thaw tensile strengths are statistically the same. Loose mix aging decreases the freeze-thaw tensile strength in 1 of 36 possible comparisons.

Compacted mix aging (Table 27) does not significantly affect the freeze-thaw tensile strength. In 21 of 24 possible comparisons, the freeze-thaw tensile strengths of samples subjected to two levels of compacted mix aging were statistically the same. In 3 of 24 comparisons, compacted mix aging decreased the freeze-thaw tensile strength.

Tensile Strength

This task of the project provided information that illustrates the effect of compaction method and sample size on the freeze-thaw tensile strengths (Table 23). The variables in this portion of the study included compaction method (G150 and M100); mixture source (Alabama, Colorado, and Nevada); and conditioning (dry, no freeze-thaw, and freeze-thaw). The loose mix aging was held constant (4 hr at 135 °C) and the compacted mix aging was held constant (96 hr at room temperature).

G150 Samples versus M100 Samples

Table 23 indicates that the freeze-thaw tensile strengths of samples compacted by the M100 compactor were statistically larger than those of the samples compacted by the G150 compactor for 1 of 6 possible comparisons. In 3 of 6 comparisons, the freeze-thaw tensile strengths were statistically the same; in 2 of 6 comparisons, the freeze-thaw tensile strengths of the M100 compacted samples were lower than those of the G150 compacted samples.

DRY VERSUS NO FREEZE-THAW TENSILE STRENGTH

The water conditioning of HMA samples by vacuum saturation and soaking without a freeze-thaw cycle normally decreases tensile strength. Results obtained on portions of this study allow statistical comparisons to be made among groups of samples tested dry (without conditioning) and after water conditioning with vacuum saturation and soaking.

Comparison of Four Compaction Methods

Table 28 indicates that the no freeze-thaw tensile strength is statistically the same as the dry tensile strength in 8 of 20 possible comparisons. In 12 of 20 comparisons, the no freeze-thaw tensile strength was statistically lower than the dry tensile strength.

An examination of the data in Table 28 indicates that 9 of 12 comparisons with lower no freeze-thaw tensile strength as compared with dry tensile strength were associated with the G100 and H100 compacted samples. The mixtures made from the Nevada and Texas materials had lower conditioned tensile strengths in 7 of 8 possible comparisons.

Comparison of Two Compaction Methods (Complete Factorial)

Table 29 indicates that the no freeze-thaw tensile strength is statistically the same as the dry tensile strength in 15 of 48 possible comparisons. In 33 of 48 comparisons, the no freeze-thaw tensile strength was statistically lower than the dry tensile strength. This study was performed with only the Nevada mixture and with only the G150 and the M100 compactors.

DRY VERSUS FREEZE-THAW TENSILE STRENGTH

The water conditioning of HMA samples by vacuum saturation, soaking, and a freeze-thaw cycle normally decreases the tensile strength. Results obtained on portions of this study allow for statistical comparisons to be made among groups of samples tested dry (i.e., without conditioning) and after water conditioning with vacuum saturation and a freeze-thaw cycle.

Comparison of Four Compaction Methods

Table 30 indicates that the freeze-thaw tensile strength is statistically the same as the dry tensile strength in 7 of 20 possible comparisons. In 13 of 20 comparisons, the freeze-thaw tensile strength was statistically lower than the dry tensile strength.

An examination of the data in Table 30 indicates that 9 of the 12 comparisons with lower freeze-thaw tensile strength as compared with dry tensile strength were associated with the G100 and H100 compacted samples. The mixtures made from the Nevada and Texas materials had lower conditioned tensile strengths in 7 of 8 comparisons.

Comparison of Two Compaction Methods (Complete Factorial)

Table 31 indicates that the freeze-thaw tensile strength is statistically the same as the dry tensile strength in 9 of 48 possible comparisons. In 39 of 48 comparisons, the freeze-thaw tensile strength was statistically lower than the dry tensile strength. This study was performed with only the Nevada mixture and with only the G150 and M100 compactors.

NO FREEZE-THAW VERSUS FREEZE-THAW TENSILE STRENGTH

The water conditioning of HMA samples by vacuum saturation, soaking, and a freeze-thaw cycle normally decreases the tensile strength, as compared with samples subjected to vacuum saturation and water soaking (no freeze-thaw). Results obtained in portions of this study allow for statistical comparisons to be made among groups of samples tested with and without a freeze-thaw cycle.

Comparison of Four Compaction Methods

Table 32 indicates that the freeze-thaw tensile strength conditioning is statistically larger than the no freeze-thaw tensile strength in 1 of 20 possible comparisons. The freeze-thaw and no freeze-thaw tensile strengths are statistically the same for 18 of 20 comparisons; in 1 of 20 comparisons, the freeze-thaw tensile strength is lower than the no freeze-thaw tensile strength.

Comparison of Two Compaction Methods (Complete Factorial)

Table 33 indicates that the freeze-thaw tensile strength is statistically larger than the no freeze-thaw tensile strength in 3 of 48 possible comparisons. The freeze-thaw and no freeze-thaw tensile strengths are statistically the same for 38 of 48 comparisons; in 7 of 48 comparisons, the freeze-thaw tensile strength is lower than the no freeze-thaw tensile strength.

Five of the 7 data groups with lower freeze-thaw tensile strength as compared with no freeze-thaw tensile strengths were associated with the M100 compacted samples. This study was performed with only the Nevada HMA and with only the G150 and the M100 compactors.

LEVEL OF SATURATION

The complete factorial experiment defined in part the effect of the level of saturation on the AASHTO T283 method of test. This experiment investigated levels of saturation of 55, 75, and 90 percent on the mixture prepared with the Nevada aggregate and binder.

Tables 34–39 show the statistical comparisons of level of saturation on no freeze-thaw tensile strength and freeze-thaw tensile strength. These tables indicate that the level of saturation has little effect on the dry, no freeze-thaw, and freeze-thaw tensile strength.

TENSILE STRENGTH RATIO

Various tensile strength ratios were determined by dividing the conditioned tensile strength by the dry tensile strength. In general, on conditioning the samples, a decrease in tensile strength ratio is expected. The freeze-thaw tensile strength ratio is generally lower than the no freeze-thaw tensile strength ratio. Results obtained on portions of this study allow for comparisons to be made with tensile strength ratios.

Comparison of Four Compaction Methods

Tables 40–42 and Figures 4 and 5 show data from the "Comparison of Four Compaction Methods" portion of the study. The data presented in Figures 4 and 5 were generated from the compaction study that limited the loose mix aging to 4 hr at 135 °C, the compacted mix aging to 96 hr at room temperature, and the saturation level to 75 percent. The no freeze-thaw tensile strength ratios are shown in Table 40 and Figure 4; the freeze-thaw tensile strength ratios are shown in Table 41 and Figure 5. In general, the tensile strength ratios (both no freeze-thaw and freeze-thaw) are larger for the G150 and M100 samples than for the G100 and H100 samples.

The statistical comparisons previously presented show that the G100 and H100 compacted samples generally had higher dry tensile strengths and lower conditioned tensile strengths as compared with the G150 samples. The M100 compacted samples had dry and conditioned tensile strengths between those of the G150 and the G100 and H100 samples. This statistical difference in dry and conditioned tensile strengths accounts for the lower tensile strength ratios associated with both the G100 and H100 samples.

A nonstatistical comparison of no freeze-thaw and freeze-thaw tensile strength ratios is shown in Table 42. There is no clear relationship that indicates that the freeze-thaw tensile strength ratio is smaller than the no freeze-thaw tensile strength ratio.

WATER SENSITIVITY

Tensile strength ratios of 70 to 80 percent are typically used as acceptance levels for the AASHTO T283 method of test. The Superpave mixture design method suggests a value of 80 percent when using the G150 compactor. Tensile strength ratios from portions of this study are shown in Tables 43–45 and are discussed below.

Comparison of Four Compaction Methods

Table 43 shows the source of the materials, type of compaction, and conditioning associated with 70 and 80 percent minimum tensile strength ratios for this portion of the study. The mixtures prepared with the Maryland aggregate and

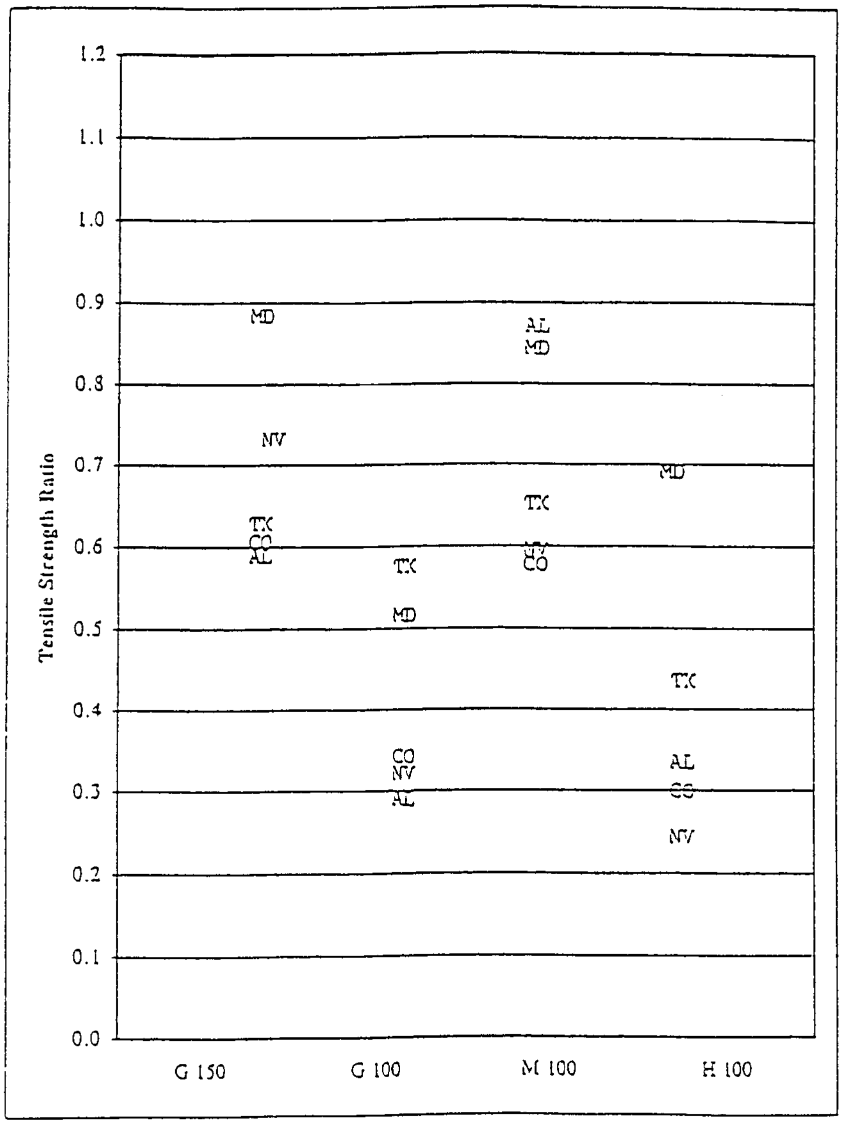

Figure 4. Comparison of tensile strength ratios with no freeze-thaw cycle.

binder would pass the 70 and 80 percent acceptance criteria for the most conditions (relative to other mixture sources). The Maryland aggregate has been described as water-sensitive. Only samples prepared with the Hveem impact kneading compactor failed the 70 percent acceptance criteria for both the no freeze-thaw and the freeze-thaw conditioning.

The Alabama and Texas aggregates have not been described as water-sensitive by their respective states; however, the Texas mixture failed to reach 70 percent tensile strength ratio for all conditions, and the Alabama mixture exceeded the 70 and 80 percent criteria only for the Marshall impact compaction method.

The Nevada and Colorado mixtures were both described as moderately to highly water-sensitive. The Colorado mixture did not exceed 70 percent for any compaction or conditioning method. The Nevada aggregate reached 70 percent tensile strength ratio when samples were prepared with the G150 compactor.

Comparison of Two Compaction Methods (Complete Factorial)

Tables 44 and 45 show the compaction methods, loose mix aging, compacted mix aging, and saturation levels associated with tensile strength ratios greater than 70 and 80 percent. Table 44 shows that for this Nevada aggregate test sequence and the no freeze-thaw conditioning, 13 of 48 possible data sets exceeded 70 percent tensile strength ratio, and 8 of 48 possible data sets exceeded 80 percent tensile strength ratio. Samples subjected to loose mix aging of 2 hr at 135 °C and compacted mix aging of 96 hr at room temperature have the largest number of sample groups exceeding the 70 and 80 percent tensile strength ratios.

Table 45 shows tensile strength ratio information for samples subjected to freeze-thaw conditioning. For this Nevada aggregate test sequence, 7 of 48 possible data sets exceeded 70 percent tensile strength ratio, and 1 of 48 possible data sets

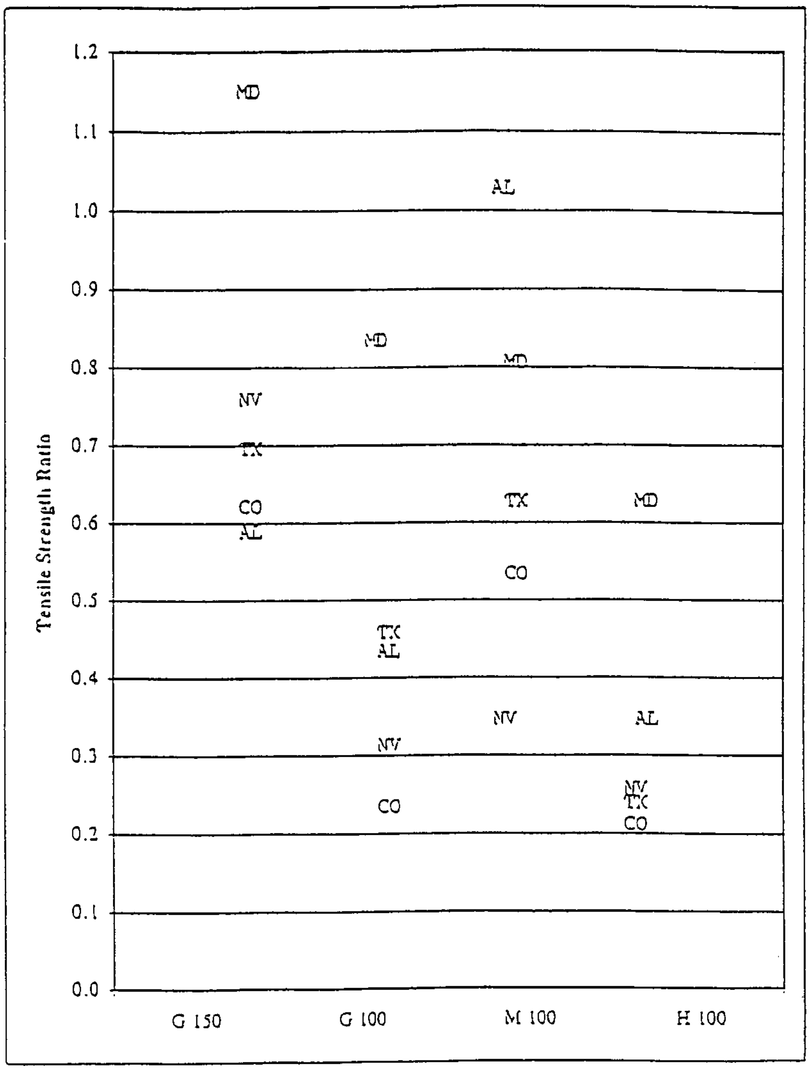

Figure 5. Comparison of tensile strength ratios with freeze-thaw cycle.

exceeded 80 percent tensile strength ratio. Samples subjected to compacted mix aging have the largest number of sample groups exceeding the 70 percent tensile strength ratios.

VARIABILITY AND COMPACTION METHOD

Tables 46 and 47 were developed to illustrate how the method of compaction influences tensile strength variability. Standard deviation and coefficient of variation are shown as measures of variability in the tables. Since G100 and H100 compacted samples generally had higher tensile strengths as compared with the G150 and M100 samples, the basis of comparison needs to be the coefficient of variation. Five of 15 data sets for the G100 and H100 compacted samples had coefficients of variation greater than 10 percent, while the G150 and M100 compacted samples had 7 and 8 data sets greater than 10 percent coefficient of variation, respectively. In general, there is little difference in the variability of test results among methods of compaction.

VARIABILITY AND MIXTURE SOURCE

Tables 48 and 49 were developed to illustrate how the mixture source influences tensile strength variability. Standard deviation and coefficient of variation are shown as measures of variability in the tables. Since Nevada and Texas mixtures generally had higher tensile strengths as compared with the other mixtures, the basis of comparison needs to be the coefficient of variation. The Maryland, Nevada, and Texas mixtures in general had lower coefficients of variation than mixtures prepared with Alabama and Colorado aggregates. The Alabama mixture—a coarse-graded, 25-mm nominal maximum size aggregate—caused considerable testing problems because the level of saturation was difficult to control, as permeability was high and coated aggregate particles would easily be dislodged from the corners and sides of the samples during conditioning and handling.

ANOVA STATISTICAL ANALYSIS

As was shown in Table 4, the evaluation of the AASHTO T283 moisture sensitivity test covers the combinations of several factors, including the following:

- Aggregate sources: 5 levels
- Compaction methods: 2 levels
- Loose mix aging: 4 levels
- Compacted mix aging: 2 levels
- Saturation level: 3 levels
- Conditioning method: 3 levels

The measured response variables are the tensile strength and resilient modulus of the HMA mixture. A complete factorial experiment including all of the factors listed above would require the fabrication and testing of 1,440 samples. In addition, some H100 and G100 samples were also evaluated. Therefore, a complete factorial experiment would have required the fabrication and testing of over 3,000 samples. This large number of samples was considered impractical, and the concept of partial factorial was used on 4 of the 5 aggregate sources. The Nevada aggregate source was kept at the complete factorial level in order to identify and evaluate the contribution of the individual factors, along with all the possible interactions among the various factors.

During the design of any statistics-based experiment, the concepts of *main effects* and *interactions* must be well understood. The *main effects* refer to the contribution of the individual factors that are being considered in the experiment. The *interactions* refer to the contribution of the factors as they interact with each other. When assessing the main effects, both the complete and partial factorial experiments are considered adequate. The major difference between a complete and a partial factorial experiment is that the partial factorial experiment would not allow for the examination of all possible interactions among the various factors.

In this research, the Nevada aggregate experiment was designed as a complete factorial experiment in order to examine all possible interactions among the main effects. The analysis of the Nevada experiment will identify the significant main effects along with all the significant interactions. A partial factorial experiment was developed for all five aggregate sources (including Nevada). The analysis of this partial factorial experiment will be used in conjunction with the Nevada experiment. More specifically, the Nevada complete factorial experiment will be analyzed first, and recommendations will be drawn based on all main effects and their interactions. The analysis of the partial factorial experiment will follow, and recommendations will be drawn based on all main effects and the possible interactions. The recommendations of the partial factorial experiment will then be checked against the Nevada complete factorial experiment in order to assess the effect of using complete factorial versus partial factorial experiments.

Previous data analyses were concerned with comparing the impact of two individual factors while maintaining all other factors at a constant level. In statistical terms, this analysis is referred to as the “pair-wise” comparisons. This type of analysis is an excellent tool to identify the contributions of the individual factors in terms of direction and magnitude. For example, using the pair-wise analysis, an engineer can assess (a) whether the dry tensile strength of G150 samples are equal to, lower than, or higher than the dry tensile strength of M100 samples and (b) the magnitude of their differences. The overall statistical analysis presented in this section is concerned with identifying which factors and which interactions among factors contribute significantly to the measured tensile strength and resilient modulus of the HMA mixtures.

The analysis of variance (ANOVA) technique will be used to conduct the statistical analysis of the overall data generated from both the complete and partial factorial experiments. F-tests based on the Type III SS (partial sums of squares) are used to identify the contribution of the main effects and their interactions. The magnitude of the F-statistics will be used to rank the relative importance of the main effects and their interactions, while the P-values less than or equal to 0.05 will be considered statistically significant. In other words, the ANOVA model will rank the main effects and their interactions in the order of importance (the higher the F-statistic, the more important the factor) and also will indicate whether a given main effect or interaction is statistically significant. The statistical significance measure will be a cutoff criterion. For example, if the F-statistics ranks the loose mix aging factor as #5, the engineer can use the P-value to identify whether the loose mix aging is statistically significant.

As was indicated earlier, this research effort measured the tensile strength and resilient modulus of the HMA mixtures at the dry, no freeze-thaw, and freeze-thaw stages. The conditions under which the tensile strength and resilient modulus values are measured will be considered in two different approaches:

1. The dry, no freeze-thaw, and freeze-thaw stages are considered as three levels of conditioning. In this case, the overall data are analyzed while sample conditioning is considered as a factor with three levels.
2. The tensile strength and resilient modulus at the dry, no freeze-thaw, and freeze-thaw are considered as independent response variables, and the overall data are analyzed to assess the impact of the main factors and their interactions on the individual responses (i.e., dry tensile strength, no freeze-thaw tensile strength, and freeze-thaw tensile strength).

Analysis of the Complete Factorial Experiment

The complete factorial experiment was conducted on the Nevada aggregate source. Therefore, the aggregate source will not be considered as a factor in the analysis of this experiment. The following presents the two data analysis approaches for the complete factorial experiment.

Analysis of Data with Three Levels of Sample Conditioning

As mentioned earlier, this approach treats the sample conditioning as a main factor with three levels: dry, no freeze-thaw, and freeze-thaw. This experiment includes the following factors and their corresponding levels.

Factor	*Number of Levels*	*Actual Levels*	*Abbreviation*
Compaction method	2	150-mm Superpave gyratory 100-mm Marshall impact	COMP
Loose mix aging	4	None 16 hr at 60 °C 2 hr at 135 °C 4 hr at 135 °C	LMA
Compacted mix aging	2	None 96 hr at room temperature	CMA
Saturation level	3	55% 75% 90%	SATLEV
Sample conditioning	3	Dry No freeze-thaw Freeze-thaw	SCOND

The measured response is the tensile strength. The factors listed above were identified as factors that may influence the magnitude of the tensile strength. The ANOVA analysis is used to identify the degree by which the main factors and their interactions would influence the magnitude of the tensile strength of the HMA mixtures. By treating the sample conditioning as an experimental factor, the analysis assumes that the tensile strength is a mixture property that is influenced by the sample conditioning process. Table 50 summarizes the ANOVA analysis for this part of the experiment; the complete ANOVA analysis table is presented in Appendix B. The analysis is presented in terms of rank and significance level. In other words, the ANOVA analysis uses the F-statistic to rank the importance of the main factors and their interactions, while the P-value is used to assess the statistical significance. The higher the F-statistic, the more important the factor or interaction. P-values less than 0.05 indicate statistically significant contributions, while P-values greater than or equal to 0.05 indicate statistically insignificant contributions.

As mentioned earlier, the advantage of conducting complete factorial experiments is the ability to identify all main effects and all possible interactions. As shown in Table 50, a total of 5 main effects, 10 two-way interactions, 10 three-way interactions, 5 four-way interactions, and 1 five-way interaction have been identified. Sample conditioning (SCOND) and loose mix aging (LMA) have been identified as the most important main effects; the compacted mix aging (CMA), compaction method (COMP), and saturation level (SATLEV) were ranked significantly below some of the interactions. This indicates that the these factors are not important by themselves, but they may become important as they interact with the sample conditioning and loose mix aging factors. As for the main factors alone, however, this experiment showed that the sample conditioning and loose mix aging are the most important contributors to the measured values of the tensile strength of HMA mixtures.

Analysis of the Dry Tensile Strength Data

This part of the analysis considered the dry tensile strength of the HMA mixtures by itself. The ANOVA analysis was used to assess the importance and significance of the main factors and their interactions on the dry tensile strength of the HMA mixtures. The main factors included compaction method, loose mix aging, and compacted mix aging. Table 51 summarizes the recommendations of the ANOVA analysis. Table 51 ranks the main factors and their interactions relative to their level of importance as indicated by their F-statistics. The data show that loose mix aging is the most important factor contributing to the value of the dry tensile strength of HMA mixtures, followed by the compacted mix aging. Compaction method becomes important after it interacts with the compacted mix aging and loose mix aging factors. Therefore, it can be concluded that loose mix aging and compacted mix aging are the most important factors affecting the value of the dry tensile strength of HMA mixtures.

Analysis of the No Freeze-Thaw Tensile Strength Data

This part of the analysis considered the no freeze-thaw tensile strength of the HMA mixtures by itself. The ANOVA analysis was used to assess the importance and significance of the main factors and their interactions on the wet no freeze-thaw tensile strength of the HMA mixtures. The main factors included compaction method, loose mix aging, compacted mix aging, and saturation level. Table 52 summarizes the recommendations of the ANOVA analysis. Table 52 ranks the main factors and their interactions relative to their level of importance as indicated by their F-statistics. The data show that the loose mix aging, compacted mix aging, and compaction method rank very close to one another. Saturation level ranks very low. Therefore, it can be concluded that loose mix aging, compacted mix aging, and compaction method are the most important factors affecting the value of the wet no freeze-thaw tensile strength of HMA mixtures.

Analysis of the Freeze-Thaw Tensile Strength Data

This part of the analysis considered the freeze-thaw tensile strength of the HMA mixtures by itself. The ANOVA analysis was used to assess the importance and significance of the main factors and their interactions on the freeze-thaw tensile strength of the HMA mixtures. The main factors included compaction method, loose mix aging, compacted mix aging, and saturation level. Table 53 summarizes the recommendations of the ANOVA analysis. Table 53 ranks the main factors and their interactions relative to their level of importance as indicated by their F-statistics. The data show that compacted mix aging and compaction method rank very close to each. Loose mix aging ranks relatively lower, and saturation level ranks very low. Therefore, it can be concluded that compacted mix aging, compaction method, and loose mix aging are the most important factors affecting the value of the freeze-thaw tensile strength of HMA mixtures.

Analysis of the Partial Factorial Experiment

The partial factorial experiment presented in Table 4 was conducted on all five sources of aggregates. The experimental cells with "X" were completed as part of the partial factorial experiment. Again, it should recognized that when dealing with partial factorial experiments, only a limited number of interactions can be evaluated. The partial factorial experiment included the following factors and their corresponding levels.

Factor	*Number of Levels*	*Actual Levels*	*Abbreviation*
Aggregate source	5	Nevada Alabama Colorado Maryland Texas	SOURCE
Compaction method	2	150-mm Superpave gyratory 100-mm Marshall impact	COMP
Loose mix aging	4	None 16 hr at 60 °C 2 hr at 135 °C 4 hr at 135 °C	LMA
Compacted mix aging	2	None 96 hr at room temperature	CMA
Saturation level	3	55% 75% 90%	SATLEV
Sample conditioning	3	Dry No freeze-thaw Freeze-thaw	SCOND

Analysis of the Dry Tensile Strength Data

This part of the analysis considered the dry tensile strength of the HMA mixtures by itself, using the partial factorial experiment. The ANOVA analysis was used to assess the importance and significance of the main factors and their interactions on the dry tensile strength of the HMA mixtures. The main factors included aggregate source (SOURCE), compaction method, loose mix aging, and compacted mix aging. Table 54 summarizes the recommendations of the ANOVA analysis. Table 54 ranks the main factors and their interactions relative to their level of importance as indicated by their F-statistics. The data show that aggregate source is the most important factor contributing to the value of the dry tensile strength of HMA mixtures. Loose mix aging, compaction method, and compacted mix aging showed some important contribution after they interact with the aggregate source. Therefore, it can be concluded that aggregate source is the most important factor affecting the value of the dry tensile strength of HMA mixtures.

Analysis of the No Freeze-Thaw Tensile Strength Data

This part of the analysis considered the no freeze-thaw tensile strength of the HMA mixtures by itself, using the partial factorial experiment. The ANOVA analysis was used to assess the importance and significance of the main factors and their interactions on the no freeze-thaw tensile strength of the HMA mixtures. The main factors included aggregate source, compaction method, loose mix aging, compacted mix aging, and saturation level. Table 55 summarizes the recommendations of the ANOVA analysis. Table 55 ranks the main factors and their interactions relative to their level of importance as indicated by their F-statistics. The data show that aggregate source is the most important factor contributing to the value of the no freeze-thaw tensile strength of HMA mixtures, followed by loose mix aging and compacted mix aging.

Analysis of the Freeze-Thaw Tensile Strength Data

This part of the analysis considered the freeze-thaw tensile strength of the HMA mixtures by itself, using the partial factorial experiment. The ANOVA analysis was used to assess the importance and significance of the main factors and their interactions on the freeze-thaw tensile strength of the HMA mixtures. The main factors included aggregate source, compaction method, loose mix aging, compacted mix aging, and saturation level. Table 56 summarizes the recommendations of the ANOVA analysis. Table 56 ranks the main factors and their interactions relative to their level of importance as indicated by their F-statistics. The data show that aggregate source is the most important factor contributing to the value of the freeze-thaw tensile strength of HMA mixtures, followed by the saturation level, loose mix aging, compacted mix aging, and compaction method. This analysis is the first to show that the saturation level plays an important role in the magnitude of the tensile strength of HMA mixtures.

Comparison of Complete and Partial Factorial Experiments

As discussed earlier, the partial factorial experiment was developed to produce a practical experiment that could be conducted within the budget and time constraints of the research project. The recommendations of the partial factorial experiment, however, may not be 100-percent reliable because of the omission of some experimental cells. Therefore, the recommendations of the partial factorial experiment must be checked against the recommendations of the complete factorial experiment. In other words, the complete factorial experiment will be used to draw conclusions about the effect of different variables; the partial factorial experiment will be used to verify that these recommendations can hold for multiple aggregate sources. The following represents a comparison of the recommendations generated from the two experiments.

Response	*Ranked Factors by Complete Factorial*	*Ranked Factors by Partial Factorial*
Dry tensile strength	LMA CMA	SOURCE LMA COMP
No freeze-thaw Tensile strength	LMA CMA COMP	SOURCE LMA CMA
Freeze-thaw Tensile strength	CMA COMP LMA SATLEV	SOURCE SATLEV LMA CMA COMP

In general, there is a good agreement among the findings of the complete and partial experiments. In the majority of the analyses, both experiments identified loose mix aging and compacted mix aging as the most important factors. The partial factorial experiment was consistent in identifying aggregate source as the most important factor. One discrepancy between the two experiments is that the partial factorial experiment identified saturation level as a more important factor than the other factors in the freeze-thaw tensile strength. This recommendation contradicts the findings of the complete factorial experiment and the pair-wise comparisons discussed earlier. This contradiction further emphasizes the fact the partial factorial experiments may not be 100-percent reliable.

TABLE 11 Statistical Comparison of Tensile Strengths for Samples Subjected to Resilient Modulus Testing and Samples Not Subjected to Resilient Modulus Testing—150-mm-Diameter Superpave Gyratory Compactor

Mixture	Conditioning	increase *	same *	decrease *
ALABAMA	DRY		1	
	NO F - T		1	
	F - T		1	
COLORADO	DRY		1	
	NO F - T		1	
	F - T		1	
NEVADA	DRY		1	
	NO F - T		1	
	F - T		1	
Total		0	9	0

Note: * Resilient modulus testing prior to performing tensile strength determination increases, decreases, or is statistically the same as tensile strength without prior resilient modulus testing.

TABLE 12 Statistical Comparison of Tensile Strengths for Samples Subjected to Resilient Modulus Testing and Samples Not Subjected to Resilient Modulus Testing—100-mm-Diameter Marshall Impact Compactor

Mixture	Conditioning	increase *	same *	decrease *
ALABAMA	DRY		1	
	NO F - T		1	
	F - T		1	
COLORADO	DRY		1	
	NO F - T		1	
	F - T		1	
NEVADA	DRY		1	
	NO F - T		1	
	F - T		1	
Total		0	9	0

Note: * Resilient modulus testing prior to performing tensile strength determination increases, decreases, or is statistically the same as tensile strength without prior resilient modulus testing.

TABLE 13 Statistical Comparison of 150-mm-Diameter and 100-mm-Diameter Superpave Gyratory Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama	1		
	Colorado	1		
	Maryland	1		
	Nevada	1		
	Texas		1	
	All	4	1	0
No Freeze-Thaw	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	4	1
Freeze-Thaw	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas			1
	All		3	2

Note: * The tensile strength of 100-mm-diameter Superpave gyratory compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 150-mm-diameter Superpave gyratory compacted samples.

TABLE 14 Statistical Comparison of 150-mm-Diameter Superpave Gyratory and 100-mm-Diameter Marshall Impact Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada	1		
	Texas			1
	All	1	3	1
No Freeze-Thaw	Alabama	1		
	Colorado		1	
	Maryland		1	
	Nevada		1	
	Texas		1	
	All	1	4	0
Freeze-Thaw	Alabama	1		
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas			1
	All	1	2	2

Note: * The tensile strength of 100-mm-diameter Marshall impact compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 150-mm-diameter Superpave gyratory compacted samples.

TABLE 15 Statistical Comparison of 150-mm-Diameter Superpave Gyratory and 100-mm-Diameter Hveem Kneading Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama	1		
	Colorado	1		
	Maryland		1	
	Nevada		1	
	Texas		1	
	All	2	3	0
No Freeze-Thaw	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	4	1
Freeze-Thaw	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas			1
	All		3	2

Note: * The tensile strength of 100-mm-diameter Hveem kneading compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 150-mm-diameter Superpave gyratory compacted samples.

TABLE 16 Statistical Comparison of 150-mm-Diameter Superpave Gyratory and 100-mm-Diameter Superpave Gyratory, Marshall Impact, and Hveem Kneading Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama	2	1	
	Colorado	2	1	
	Maryland	1	2	
	Nevada	2	1	
	Texas		2	1
	All	7	7	1
No Freeze-Thaw	Alabama	1	2	
	Colorado		3	
	Maryland		3	
	Nevada		1	2
	Texas		3	
	All	1	12	2
Freeze-Thaw	Alabama	1	2	
	Colorado		3	
	Maryland		3	
	Nevada			3
	Texas			3
	All	1	8	6

Note: * The tensile strengths of 100-mm-diameter Superpave gyratory, Marshall impact, and Hveem kneading compacted samples are statistically larger than, the same as, or smaller than the tensile strength of 150-mm-diameter Superpave gyratory compacted samples.

TABLE 17 Statistical Comparison of 100-mm-Diameter Superpave Gyratory and 100-mm-Diameter Marshall Impact Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama		1	
	Colorado			1
	Maryland			1
	Nevada		1	
	Texas			1
	All	0	2	3
No Freeze-Thaw	Alabama	1		
	Colorado		1	
	Maryland		1	
	Nevada	1		
	Texas		1	
	All	2	3	0
Freeze-Thaw	Alabama	1		
	Colorado		1	
	Maryland			1
	Nevada		1	
	Texas		1	
	All	1	3	1

Note: * The tensile strength of 100-mm-diameter Marshall impact compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 100-mm-diameter Superpave gyratory compacted samples.

TABLE 18 Statistical Comparison of 100-mm-Diameter Superpave Gyratory and 100-mm-Diameter Hveem Kneading Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	4	1
No Freeze-Thaw	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	4	1
Freeze-Thaw	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada		1	
	Texas			1
	All	0	4	1

Note: * The tensile strength of 100-mm-diameter Hveem impact compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 100-mm-diameter Superpave gyratory compacted samples.

TABLE 19 Statistical Comparison of 100-mm-Diameter Hveem Kneading and 100-mm-Diameter Marshall Impact Compacted Samples

Sample Conditioning	State	Larger*	Same*	Smaller*
Dry	Alabama		1	
	Colorado			1
	Maryland		1	
	Nevada	1		
	Texas			1
	All	1	2	2
No Freeze-Thaw	Alabama	1		
	Colorado		1	
	Maryland		1	
	Nevada	1		
	Texas		1	
	All	2	3	0
Freeze-Thaw	Alabama	1		
	Colorado		1	
	Maryland		1	
	Nevada		1	
	Texas		1	
	All	1	4	0

Note: * The tensile strength of 100-mm-diameter Marshall impact compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 100-mm-diameter Hveem kneading compacted samples.

TABLE 20 Statistical Comparison of 150-mm-Diameter Superpave Gyratory and 100-mm-Diameter Marshall Impact Compacted Samples

Sample Conditioning	Larger*	Same*	Smaller*
Dry	3	18	3
No Freeze-Thaw	3	20	1
Freeze-Thaw	0	22	2

Note: * The tensile strength of 100-mm-diameter Marshall impact compacted samples is statistically larger than, the same as, or smaller than the tensile strength of 150-mm-diameter Superpave gyratory compacted samples.

TABLE 21 Statistical Comparison of Dry Tensile Strength for Mixtures Subjected to Loose Mix Aging

Compaction Method	Compacted Mix Aging, Hours	Increase*	Same*	Decrease*
Gyratory 150 mm	0		3	
	96	3		
Marshall 100 mm	0	1	2	
	96		3	
Total		4	8	0

Note: * Loose mix aging increases, decreases, or maintains the same dry tensile strength as compared with the no loose mix aging.

TABLE 22 Statistical Comparison of Dry Tensile Strength for Mixtures Subjected to Compacted Mix Aging

Compaction Method	Loose Mix Aging, Hours	Increase*	Same*	Decrease*
Gyratory 150 mm	0			1
	16		1	
	2		1	
	4		1	
Marshall 100 mm	0		1	
	16		1	
	2		1	
	4		1	
Total			7	1

Note: * Compacted mix aging increases, decreases, or maintains the same dry tensile strength as compared with the no compacted mix aging data sets for dry tensile strength.

TABLE 23 Statistical Comparison of Tensile Strengths for 100-mm-Diameter Marshall Impact Samples and 150-mm-Diameter Superpave Gyratory Samples

Mixture	Conditioning	Prior Resilient Modulus	increase *	same *	decrease *
ALABAMA	DRY	N		1	
		Y		1	
	NO F - T	N		1	
		Y		1	
	F - T	N		1	
		Y	1		
COLORADO	DRY	N	1		
		Y		1	
	NO F - T	N		1	
		Y		1	
	F - T	N		1	
		Y		1	
NEVADA	DRY	N	1		
		Y	1		
	NO F - T	N		1	
		Y		1	
	F - T	N			1
		Y			1
	Total	N	2	6	1
		Y	2	6	1

Note: * The tensile strength of 100-mm-diameter Marshall impact compacted samples increases, decreases, or is statistically the same as tensile strength of 150-mm-diameter Superpave gyratory compacted samples.

TABLE 24 Statistical Comparison of No Freeze-Thaw Tensile Strengths for Mixtures Subjected to Loose Mix Aging

Compaction Method	Compacted Mix Aging, Hrs	Saturation Percent	Increase*	Same*	Decrease*
Gyratory 150 mm	0	55		3	
		75	2	1	
		90	2	1	
	96	55	1	2	
		75		3	
		90	2	1	
Marshall 100 mm	0	55	1	2	
		75		3	
		90	2	1	
	96	55		3	
		75		3	
		90		3	
All Gyratory			7	11	
All Marshall			3	15	
Total			10	26	

Note: * Loose mix aging increases, decreases, or maintains the same no freeze-thaw tensile strength as compared with the no loose mix aging.

TABLE 25 Statistical Comparison of No Freeze-Thaw Tensile Strength for Mixtures Subjected to Compacted Mix Aging

Compaction Method	Loose Mix Aging, Hrs.	Saturation, Percent	Increase*	Same*	Decrease*
Gyratory 150 mm	0	55		1	
		75		1	
		90		1	
	16	55		1	
		75		1	
		90		1	
	2	55	1		
		75	1		
		90		1	
	4	55		1	
		75		1	
		90		1	
Marshall 100 mm	0	55		1	
		75	1		
		90	1		
	16	55		1	
		75		1	
		90		1	
	2	55		1	
		75		1	
		90		1	
	4	55		1	
		75		1	
		90			1
All Gyratory			2	10	0
All Marshall			2	9	1
Total			4	19	1

Note: * An entry indicates the number of cases in which the compacted mix aging increases, decreases, or maintains the same no freeze-thaw tensile strength as compared with no compacted mix aging.

TABLE 26 Statistical Comparison of Freeze-Thaw Tensile Strength for Mixtures Subjected to Loose Mix Aging

Compaction Method	Compacted Mix Aging, Hrs	Saturation Percent	Increase*	Same*	Decrease*
Gyratory 150 mm	0	55		2	1
		75		3	
		90		3	
	96	55	1	2	
		75		3	
		90		3	
Marshall 100 mm	0	55	1	2	
		75		3	
		90		3	
	96	55	1	2	
		75		3	
		90		3	
All Gyratory			1	16	1
All Marshall			2	16	
Total			3	32	1

Note: * An entry indicates the number of cases in which loose mix aging increases, decreases, or maintains the same no freeze-thaw tensile strength as compared with the no loose mix aging.

TABLE 27 Statistical Comparison of Freeze-Thaw Tensile Strength for Mixtures Subjected to Compacted Mix Aging

Compaction Method	Loose Mix Aging, Hrs.	Saturation, Percent	Increase*	Same*	Decrease*
Gyratory 150 mm	0	55			1
		75		1	
		90			1
	16	55			1
		75		1	
		90		1	
	2	55		1	
		75		1	
		90		1	
	4	55		1	
		75		1	
		90		1	
Marshall 100 mm	0	55		1	
		75		1	
		90		1	
	16	55		1	
		75		1	
		90		1	
	2	55		1	
		75		1	
		90		1	
	4	55		1	
		75		1	
		90		1	
All Gyratory			0	9	3
All Marshall			0	12	0
Total			0	21	3

Note: * An entry indicates the compacted mix aging increases, decreases, or maintains the same no freeze-thaw tensile strength as compared with no compacted mix aging.

TABLE 28 Statistical Comparison of Dry Tensile Strength and No Freeze-Thaw Tensile Strength

Compaction Method	State	Larger*	Same*	Smaller*
Gyratory 150 mm	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas			1
	All	0	3	2
Gyratory 100 mm	Alabama			1
	Colorado			1
	Maryland			1
	Nevada			1
	Texas			1
	All	0	0	5
Marshall 100 mm	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	4	1
Hveem 100 mm	Alabama			1
	Colorado			1
	Maryland		1	
	Nevada			1
	Texas			1
	All	0	1	4
	Total	0	8	12

Note: * The no freeze-thaw tensile strength is statistically larger than, the same as, or smaller than the dry tensile strength.

TABLE 29 Statistical Comparison of Conditioning Method on Tensile Strength—No Freeze-Thaw Conditioning vs. No Conditioning

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0			3
		96		3	
	16	0			3
		96			3
	2	0			3
		96		3	
	4	0			3
		96		1	2
Marshall 100 mm	0	0		1	2
		96		2	1
	16	0			3
		96			3
	2	0			3
		96		3	
	4	0		1	2
		96		1	2
All Gyratory			0	7	17
All Marshall			0	8	16
Total			0	15	33

Note: * The tensile strength of no freeze-thaw conditioned samples increases, decreases, or is statistically the same as the tensile strength for samples not subjected to conditioning (dry).

TABLE 30 Statistical Comparison of Dry Tensile Strength and Freeze-Thaw Tensile Strength

Compaction Method	State	Larger*	Same*	Smaller*
Gyratory 150 mm	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas			1
	All	0	3	2
Gyratory 100 mm	Alabama			1
	Colorado			1
	Maryland		1	
	Nevada			1
	Texas			1
	All	0	1	4
Marshall 100 mm	Alabama		1	
	Colorado			1
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	3	2
Hveem 100 mm	Alabama			1
	Colorado			1
	Maryland			1
	Nevada			1
	Texas			1
	All	0	0	5
	Total	0	7	13

Note: * The freeze-thaw tensile strength is statistically larger than, the same as, or smaller than the dry tensile strength.

TABLE 31 Statistical Comparison of Conditioning Method on Tensile Strength—Freeze-Thaw Conditioning vs. No Conditioning

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0		1	2
		96		2	1
	16	0			3
		96			3
	2	0			3
		96			3
	4	0			3
		96		1	2
Marshall 100 mm	0	0		1	2
		96		1	2
	16	0			3
		96			3
	2	0			3
		96		3	
	4	0			3
		96			3
All Gyratory			0	4	20
All Marshall			0	5	19
Total			0	9	39

Note: * The tensile strength of freeze-thaw conditioned samples increases, decreases, or is statistically the same as the tensile strength of samples not subjected to conditioning (dry).

TABLE 32 Statistical Comparison of No Freeze-Thaw Tensile Strength and Freeze-Thaw Tensile Strength

Compaction Method	State	Larger*	Same*	Smaller*
Gyratory 150 mm	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada		1	
	Texas		1	
	All	0	5	0
Gyratory 100 mm	Alabama		1	
	Colorado		1	
	Maryland	1		
	Nevada		1	
	Texas		1	
	All	1	4	0
Marshall 100 mm	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada			1
	Texas		1	
	All	0	4	1
Hveem 100 mm	Alabama		1	
	Colorado		1	
	Maryland		1	
	Nevada		1	
	Texas		1	
	All	0	5	0
	Total	1	18	1

Note: * The freeze-thaw tensile strength is statistically larger than, the same as, or smaller than the no freeze-thaw tensile strength.

TABLE 33 Statistical Comparison of Conditioning Method on Tensile Strength—Freeze-Thaw Conditioning vs. No Freeze-Thaw Conditioning

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0	3		
		96		3	
	16	0		3	
		96		3	
	2	0		3	
		96		1	2
	4	0		3	
		96		3	
Marshall 100 mm	0	0		3	
		96		2	1
	16	0		3	
		96		2	1
	2	0		3	
		96		3	
	4	0		2	1
		96		1	2
All Gyratory			3	19	2
All Marshall			0	19	5
Total			3	38	7

Note: * The tensile strength of freeze-thaw conditioned samples increases, decreases, or is statistically the same as the tensile strength of samples of no freeze-thaw conditioned samples.

TABLE 34 Statistical Comparison of No Freeze-Thaw Tensile Strength Subjected to Different Levels of Saturation—75% vs. 55%

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
Marshall 100 mm	0	0		1	
		96	1		
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
All Gyratory			0	8	0
All Marshall			1	7	0
Total			1	15	0

Note: * The tensile strength for a saturation level of 75% increases, decreases, or is statistically the same as the tensile strength for a level of 55% for no freeze-thaw data sets.

TABLE 35 Statistical Comparison of No Freeze-Thaw Tensile Strength Subjected to Different Levels of Saturation—90% vs. 55%

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
Marshall 100 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0			1
		96		1	
All Gyratory			0	8	0
All Marshall			0	7	1
Total			0	15	1

Note: * The tensile strength for a saturation level of 90% increases, decreases, or is statistically the same as the tensile strength for a level of 55% for no freeze-thaw data sets.

TABLE 36 Statistical Comparison of No Freeze-Thaw Tensile Strength Subjected to Different Levels of Saturation—90% vs. 75%

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase *	Same*	Decrease*
Gyratory 150 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
Marshall 100 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
All Gyratory			0	8	0
All Marshall			0	8	0
Total			0	16	0

Note: * The tensile strength for a saturation level of 90% increases, decreases, or is statistically the same as the tensile strength for a level of 75% for no freeze-thaw data sets.

TABLE 37 Statistical Comparison of Freeze-Thaw Tensile Strength Subjected to Different Levels of Saturation—75% vs. 55%

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
Marshall 100 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
All Gyratory			0	8	0
All Marshall			0	8	0
Total			0	16	0

Note: * The tensile strength for a saturation level of 75% increases, decreases, or is statistically the same as the tensile strength for a level of 55% for freeze-thaw data sets.

TABLE 38 Statistical Comparison of Freeze-Thaw Tensile Strength Subjected to Different Levels of Saturation—90% vs. 55%

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
Marshall 100 mm	0	0		1	
		96		1	
	16	0		1	
		96		1	
	2	0		1	
		96		1	
	4	0		1	
		96		1	
All Gyratory			0	8	0
All Marshall			0	8	0
Total			0	16	0

Note: * The tensile strength for a saturation level of 90% increases, decreases, or is statistically the same as the tensile strength for a level of 55% for freeze-thaw data sets.

TABLE 39 Statistical Comparison of Freeze-Thaw Tensile Strength Subjected to Different Levels of Saturation—90% vs. 75%

Compaction Method	Loose Mix Aging, Hrs.	Compacted Mix Aging, Hrs.	Increase*	Same*	Decrease*
Gyratory 150 mm	0	0 96		1 1	
	16	0 96		1 1	
	2	0 96		1 1	
	4	0 96		1 1	
Marshall 100 mm	0	0 96		1 1	
	16	0 96		1 1	
	2	0 96		1 1	
	4	0 96		1 1	
All Gyratory			0	8	0
All Marshall			0	8	0
Total			0	16	0

Note: * The tensile strength for a saturation level of 90% increases, decreases, or is statistically the same as the tensile strength for a level of 75% for freeze-thaw data sets.

TABLE 40 No Freeze-Thaw Conditioned Tensile Strength Ratio and Method of Compaction

Method of Compaction *			
Gyratory 150 mm	Gyratory 100 mm	Marshall 100 mm	Hveem 100 mm
AL (0.60)	AL (0.29)	CO (0.59)	NV (0.25)
CO (0.620)	NV (0.34)	NV (0.59)	CO (0.31)
TX (0.63)	CO (0.35)	TX (0.66)	AL (0.34)
NV (0.73)	MD (0.52)	MD (0.83)	TX (0.40)
MD (0.88)	TX (0.57)	AL (0.87)	MD (0.69)

Note: * Arranged on the basis of tensile strength ratio.

TABLE 41 Freeze-Thaw Conditioned Tensile Strength Ratio and Method of Compaction

Method of Compaction *			
Gyratory 150 mm	Gyratory 100 mm	Marshall 100 mm	Hveem 100 mm
AL (0.59)	CO (0.24)	NV (0.35)	CO (0.23)
CO (0.62)	NV (0.32)	CO (0.54)	TX (0.23)
TX (0.70)	AL (0.42)	TX (0.63)	NV (0.26)
NV (0.76)	TX (0.46)	MD (0.81)	AL (0.35)
MD (1.15)	MD (0.85)	AL (1.03)	MD (0.63)

Note: * Arranged on the basis of tensile strength ratio.

TABLE 42 Comparison of No Freeze-Thaw and Freeze-Thaw Tensile Strength Ratios

Mixture	Method of Compaction			
	Gyratory 150	Gyratory 100	Marshall 100	Hveem 100
Alabama	S (s)	L	L	L (s)
Colorado	(s)*	S	S (s)	S
Maryland	L	L	S (s)	S (s)
Nevada	L (s)	S (s)	S	L (s)
Texas	L	S	S (s)	S

Notes: S—Freeze-thaw conditioned tensile strength ratio smaller than no freeze-thaw conditioned tensile strength ratio.
L—Freeze-thaw conditioned tensile strength ratio larger than no freeze-thaw conditioned tensile strength ratio.
(s)—Freeze-thaw conditioned tensile strength ratio smaller or larger than no freeze-thaw conditioned tensile strength but probably statistically the same.
*—Same reported ratios.

TABLE 43 Acceptable Mixtures

MIXTURE	CONDITIONING	METHOD OF COMPACTION			
		Gyratory 150	Gyratory 100	Marshall 100	Hveem 100
Alabama	No F-T			70, 80	
	F-T			70, 80	
Colorado	No F-T				
	F-T				
Maryland	No F-T	70*, 80		70, 80	
	F-T	70, 80	70, 80	70, 80	
Nevada	No F-T	70			
	F-T	70			
Texas	No F-T				
	F-T				

Note: * Meets 70% or 80% retained tensile strength ratio.

TABLE 44 Tensile Strength Ratio for No Freeze-Thaw Conditioning

Compaction Method	Loose Mix Aging, HRS	Compacted Mix Aging, HRS	Saturation Level					
			55		75		90	
			70%	80%	70%	80%	70%	80%
Gyratory 150 mm	0		x					
	16	0						
		96						
	2	0						
		96	x	x	x	x	x	
	4	0						
		96	x				x	
Marshall 100 mm	0	0						
		96			x	x	x	x
	16	0					x	
		96						
	2	0						
		96	x	x	x	x	x	x
	4	0					x	x
		96						
All Gyratory			3	1	1	1	2	0
All Marshall			1	1	2	2	4	3
Total			4	2	3	3	6	3

Note: x—Tensile strength ratio exceeded the value shown (13 data sets exceeded 70%; 8 data sets exceeded 80%).

TABLE 45 Tensile Strength Ratio for Freeze-Thaw Conditioning

Compaction Method	Loose Mix Aging, HRS	Compacted Mix Aging, HRS	Saturation Level					
			55		75		90	
			70%	80%	70%	80%	70%	80%
Gyratory 150 mm	0		x					
					x			
	16	0						
		96						
	2	0						
		96						
	4	0						
		96	x		x			
Marshall 100 mm	0	0						
		96						
	16	0						
		96						
	2	0						
		96	x		x	x	x	
	4	0						
		96						
All Gyratory			2	0	2	0	0	0
All Marshall			1	0	1	1	1	0
Total			3	0	3	1	1	0

Note: x—Tensile strength ratio exceeded the value shown (7 data sets exceeded 70%; 1 data set exceeded 80%).

TABLE 46 Variability and Method of Compaction

Method of Compaction	Standard Deviation (psi)				Coefficient of Variation (%)			
	>5	>10	>15	>20	>5	>10	>15	>20
Gyratory 150 mm	11*	3	1	0	8	7	2	1
Gyratory 100 mm	7	5	1	1	9	5	1	0
Marshall 100 mm	11	7	2	2	12	8	3	2
Hveem 100 mm	9	3	1	0	11	5	3	1

Note: * Number of data sets above the indicated standard deviation or coefficient of variation (15 possible data sets per method of compaction).

TABLE 47 Variability and Method of Compaction

Method of Compaction	Standard Deviation (psi)				Coefficient of Variation (%)			
	<5	<10	<15	<20	<5	<10	<15	<20
Gyratory 150 mm	3*	10	15	17	3	8	14	16
Marshall 100 mm	2	5	12	15	2	5	11	15

Note: * Number of data sets below the indicated standard deviation or coefficient of variation (18 possible data sets per method of compaction).

TABLE 48 Variability and Mixture Source

State	Standard Deviation (psi)				Coefficient of Variation (%)			
	>5	>10	>15	>20	>5	>10	>15	>20
Alabama	8*	6	0	0	11	8	1	1
Colorado	9	3	1	1	10	9	6	2
Maryland	3	0	0	0	6	1	0	0
Nevada	11	7	4	2	8	5	2	1
Texas	7	2	0	0	6	2	0	0

Note: * Number of data sets above the indicated standard deviation of coefficient of variation (12 possible data sets per mixture).

TABLE 49 Variability and Mixture Source

State	Standard Deviation (psi)				Coefficient of Variation (%)			
	<5*	<10	<15	<20	<5	<10	<15	<20
Alabama	2	5	10	12	1	5	9	10
Colorado	3	8	10	12	1	3	6	10
Nevada	0	2	7	8	3	5	9	11

Note: * Number of data sets below the indicated standard deviation or coefficient of variation (12 possible data sets per mixture).

TABLE 50 ANOVA Analysis for the Complete Factorial Experiment with Three Levels of Sample Conditioning

Factor or Interaction	*F* Value	Rank	Pr>*F*	Significant
SCOND	2130.95	1	0.0001	y
LMA	156.45	2	0.0001	y
CMA*SCOND	77.62	3	0.0001	y
COMP*LMA*CMA	56.91	4	0.0001	y
COMP*SCOND	51.41	5	0.0001	y
LMA*SCOND	39.97	6	0.0001	y
COMP*CMA*SCOND	35.73	7	0.0001	y
LMA*CMA	28.64	8	0.0001	y
LMA*CMA*SCOND	27.40	9	0.0001	y
COMP*CMA	26.03	10	0.0001	y
COMP*LMA	25.69	11	0.0001	y
COMP*LMA*SCOND	24.00	12	0.0001	y
CMA	23.92	13	0.0001	y
COMP*LMA*CMA*SCOND	19.10	14	0.0001	y
COMP*LMA*SATLEV	7.20	15	0.0001	y
COMP	7.03	16	0.0085	y
COMP*SATLEV	5.97	17	0.0029	y
COMP*LMA*CMA*SATLEV	5.38	18	0.0001	y
SATLEV	5.26	19	0.0057	y
CMA*SATLEV	5.25	20	0.0058	y
LMA*SATLEV	5.02	21	0.0001	y
COMP*LMA*CMA*SATLEV*SCOND	5.00	22	0.0001	y
LMA*SATLEV*SCOND	4.91	23	0.0001	y
SATLEV*SCOND	4.23	24	0.0024	y
COMP*SATLEV*SCOND	3.85	25	0.0046	y
COMP*CMA*SATLEV*SCOND	2.94	26	0.0208	y
LMA*CMA*SATLEV*SCOND	2.32	27	0.0076	y
CMA*SATLEV*SCOND	2.23	28	0.0664	n
COMP*LMA*SATLEV*SCOND	2.05	29	0.0203	y
LMA*CMA*SATLEV	1.59	30	0.1488	n
COMP*CMA*SATLEV	0.52	31	0.5973	n

Notes: COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

TABLE 51 ANOVA Analysis of the Complete Factorial Experiment for the Dry Tensile Strength

Source	*F* Value	Rank	Pr >*F*	Significant
LMA	142.86	1	0.0001	y
COMP*CMA	55.07	2	0.0001	y
CMA	54.92	3	0.0001	y
COMP*LMA*CMA	41.60	4	0.0001	y
COMP*LMA	34.27	5	0.0001	y
COMP	24.55	6	0.0001	y
LMA*CMA	20.02	7	0.0001	y

Notes: COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

TABLE 52 ANOVA Analysis of the Complete Factorial Experiment for the No Freeze Tensile Strength

Source	*F* Value	Rank	Pr > *F*	Significant
LMA	59.29	1	0.0001	y
CMA	51.53	2	0.0001	y
LMA*CMA	45.16	3	0.0001	y
COMP	43.17	4	0.0001	y
COMP*LMA	31.14	5	0.0001	y
COMP*LMA*CMA	25.83	6	0.0001	y
COMP*CMA	13.66	7	0.0004	y
COMP*SATLEV	9.62	8	0.0002	y
COMP*LMA*CMA*SATLEV	7.62	9	0.0001	y
CMA*SATLEV	7.03	10	0.0015	y
COMP*CMA*SATLEV	5.20	11	0.0001	y
SATLEV	4.93	12	0.0092	y
LMA*SATLEV	4.89	13	0.0002	y
COMP*CMA*SATLEV	4.87	14	0.0098	y
LMA*CMA*SATLEV	4.60	15	0.0004	y

Notes: COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

TABLE 53 ANOVA Analysis of the Complete Factorial Experiment for the Freeze-Thaw Tensile Strength

Source	*F* Value	Rank	Pr >*F*	Significant
CMA	77.13	1	0.0001	y
COMP	44.43	2	0.0001	y
COMP*CMA	28.82	3	0.0001	y
COMP*LMA*CMA	27.47	4	0.0001	y
LMA	23.94	5	0.0001	y
LMA*CMA	16.07	6	0.0001	y
LMA*SATLEV	11.03	7	0.0001	y
SATLEV	9.64	8	0.0002	y
COMP*LMA*CMA*SATLEV	8.08	9	0.0001	y
COMP*LMA	6.75	10	0.0004	y
COMP*LMA*SATLEV	6.49	11	0.0001	y
COMP*SATLEV	3.91	12	0.0234	y
CMA*SATLEV	2.55	13	0.0835	n
LMA*CMA*SATLEV	1.64	14	0.1461	n
COMP*CMA*SATLEV	1.53	15	0.2224	n

Notes: COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

TABLE 54 ANOVA Analysis of the Partial Factorial Experiment for the Dry Tensile Strength

Source	*F* Value	Rank	Pr > *F*	Significant
SOURCE	733.26	1	0.0001	y
COMP*CMA	99.59	2	0.0001	y
SOURCE*LMA	56.40	3	0.0001	y
LMA	46.16	4	0.0001	y
SOURCE*CMA	41.71	5	0.0001	y
SOURCE*COMP	36.44	6	0.0001	y
COMP	34.86	7	0.0001	y
SOURCE*LMA*CMA	30.07	8	0.0001	y
LMA*CMA	24.36	9	0.0001	y
CMA	23.14	10	0.0001	y
COMP*LMA	2.72	11	0.0447	y

Notes: SOURCE—aggregate source; COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

TABLE 55 ANOVA Analysis of the Partial Factorial Experiment for the No-Freeze-Thaw Tensile Strength

Source	*F* Value	Rank	Pr > *F*	Significant
SOURCE	399.56	1	0.0001	y
LMA	40.74	2	0.0001	y
CMA	38.61	3	0.0001	y
SOURCE*CMA	29.03	4	0.0001	y
SOURCE*LMA	23.13	5	0.0001	y
COMP	11.78	6	0.0001	y
SOURCE*SATLEV	6.94	7	0.0001	y
SATLEV	6.07	8	0.0029	y
SOURCE*LMA*SATLEV	5.00	9	0.0024	y
LMA*SATLEV	3.84	10	0.0013	y
COMP*SATLEV	3.17	11	0.0768	n
LMA*CMA	2.40	12	0.1236	n
COMP*LMA	1.10	13	0.2960	n

Notes: SOURCE—aggregate source; COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

TABLE 56 ANOVA Analysis of the Partial Factorial Experiment for the Freeze-Thaw Tensile Strength

Source	*F* Value	Rank	Pr > *F*	Significant
SOURCE	192.49	1	0.0001	y
SATLEV	20.22	2	0.0001	y
SOURCE*CMA	13.17	3	0.0001	y
CMA*SATLEV	10.11	4	0.0001	y
LMA	8.70	5	0.0001	y
LMA*CMA*SATLEV	8.06	6	0.0051	y
SOURCE*COMP	5.94	7	0.0159	y
CMA	5.80	8	0.0172	y
SOURCE*SATLEV	5.44	9	0.0243	y
COMP	5.17	10	0.0243	y
SOURCE*LMA*SATLEV	4.74	11	0.0001	y
LMA*CMA	3.21	12	0.0246	y
LMA* SATLEV	2.47	13	0.0257	y
SOURCE*LMA	2.30	14	0.0097	y

Notes: SOURCE—aggregate source; COMP—compaction method; LMA—loose mix aging; CMA—compacted mix aging; SATLEV—saturation level; SCOND—sample conditioning.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The information presented in this study suggests the following conclusions.

Dry Tensile Strength

G150 Samples versus M100 Samples

The dry tensile strength of M100 compacted samples is not consistently different than the dry tensile strength of samples prepared by the G150 compactor. This conclusion is based on the pair-wise statistical comparisons (Tables 14, 20, and 23) and on the ANOVA complete factorial (Table 51) and partial factorial (Table 54) studies.

G150 Samples versus G100 Samples

The dry tensile strength of G100 compacted samples is statistically larger than the dry tensile strength of samples prepared by the G150 compactor. This conclusion is based on a pair-wise statistical comparison (Table 13) in which 4 of 5 possible comparison groups exhibited the stated behavior.

G150 Samples versus H100 Samples

The dry tensile strength of H100 compacted samples is statistically larger than the dry tensile strength of samples prepared by the G150 compactor. This conclusion is based on a pair-wise statistical comparison (Table 15) in which 2 of 5 possible comparison groups exhibited the stated behavior.

Loose Mix Aging

Dry tensile strength is influenced by the method of loose mix aging. This conclusion is based on a pair-wise statistical comparison (Table 21) in which 4 of 12 possible comparison groups exhibited an increase in dry tensile strength with loose mix aging and on the ANOVA complete factorial (Table 51) and partial factorial (Table 54) studies, which identify loose mix aging as the most important factor influencing dry tensile strength.

Compacted Mix Aging

Dry tensile strength is influenced by the method of compacted mix aging. This conclusion is not supported by the pair-wise statistical comparisons shown in Table 21; however, the ANOVA complete factorial (Table 51) and the partial factorial (Table 54) studies identify compacted mix aging as among the most important factors influencing dry tensile strength.

Mixture Source

Dry tensile strength is influenced by the mixture source (aggregate and asphalt binder). All tasks of this study support this conclusion (*7–9*). The ANOVA for the partial factorial task (Table 54) identifies mixture source as the most important factor influencing dry tensile strength.

No Freeze-Thaw Tensile Strength

G150 Samples versus M100 Samples

The no freeze-thaw tensile strength of M100 compacted samples is not consistently different than the no freeze-thaw tensile strength of samples prepared by the G150 compactor. This conclusion is based on the pair-wise statistical comparisons (Tables 14, 20, and 23) and the ANOVA complete factorial (Table 52) and partial factorial (Table 55) studies. The complete factorial and partial factorial ANOVAs indicate that the method of compaction has some influence on the no freeze-thaw tensile strength (M100 versus G150).

G150 Samples versus G100 Samples

The no freeze-thaw tensile strength of G100 compacted samples is about equal to the no freeze-thaw tensile strength of samples prepared by the G150 compactor. This conclusion is based on a pair-wise statistical comparison (Table 13) in which 4 of 5 possible comparison groups exhibited the stated behavior. One comparison group indicated that the G100 samples had statistically lower no freeze-thaw tensile strengths than the G150 compacted samples.

G150 Samples versus H100 Samples

The no freeze-thaw tensile strength of H100 compacted samples is about equal to the no freeze-thaw tensile strength of samples prepared by the G150 compactor. This conclusion is based on a pair-wise statistical comparison (Table 15) in which 4 of 5 possible comparison groups exhibited the stated behavior. One comparison group indicated that the H100 samples had statistically lower no freeze-thaw tensile strengths than did the G150 compacted samples.

Loose Mix Aging

The no freeze-thaw tensile strength is influenced by the method of loose mix aging. This conclusion is based on a pair-wise statistical comparison (Table 24) in which 10 of 36 possible comparison groups exhibited an increase in no freeze-thaw tensile strength with loose mix aging and on the ANOVA complete factorial (Table 52) and partial factorial (Table 55) studies, which identify loose mix aging as the most important factor influencing the no freeze-thaw tensile strength.

Compacted Mix Aging

The no freeze-thaw tensile strength is influenced by the method of compacted mix aging. This conclusion is based on a pair-wise statistical comparison (Table 25) in which 4 of 24 possible comparison groups exhibited an increase in no freeze-thaw tensile strength with compacted mix aging and on the ANOVA complete factorial (Table 52) and partial factorial (Table 55) studies, which identify compacted mix aging as among the most important factors influencing the no freeze-thaw tensile strength.

Mixture Source

The no freeze-thaw tensile strength is influenced by the mixture source (aggregate and asphalt binder). All tasks of this study support this conclusion (*7–9*). The ANOVA for the partial factorial task (Table 55) identifies mixture source as the most important factor influencing the no freeze-thaw tensile strength.

Freeze-Thaw Tensile Strength

G150 Samples versus M100 Samples

The freeze-thaw tensile strength of M100 compacted samples is statistically different than the freeze-thaw tensile strength of samples prepared by the G150 compactor. This conclusion is based on the pair-wise statistical comparisons (Tables 14, 20, and 23) and on the ANOVA complete factorial (Table 53) and partial factorial (Table 56) studies.

The pair-wise comparisons suggests that the freeze-thaw tensile strength for the M100 samples is typically lower than the freeze-thaw tensile strength of the G150 samples (Tables 14, 20, and 23). It should be noted that some of these comparisons indicate that higher freeze-thaw tensile strengths can be obtained with the G150 samples as compared with the M100 samples (Tables 14 and 23). The ANOVA complete factorial (Table 53) and the partial factorial (Table 56) studies indicated that compaction method is among the important factors influencing freeze-thaw tensile strength.

G150 Samples versus G100 Samples

The freeze-thaw tensile strength of G100 compacted samples is statistically lower in value than the freeze-thaw tensile strength of samples prepared by the G150 compactor. This conclusion is based on a pair-wise statistical comparison (Table 13) in which 2 of 5 possible comparison groups exhibited the stated behavior. Three of 5 comparison groups indicated that the G100 and G150 samples had statistically the same freeze-thaw tensile strength.

G150 Samples versus H100 Samples

The freeze-thaw tensile strength of H100 compacted samples is statistically lower in value than the freeze-thaw tensile strength of samples prepared by the G150 compactor. This conclusion is based on a pair-wise statistical comparison (Table 15) in which 2 of 5 possible comparison groups exhibited the stated behavior. Three of the 5 comparisons groups indicated that the H100 and G150 samples had statistically the same freeze-thaw tensile strength.

Loose Mix Aging

Freeze-thaw tensile strength is influenced by the method of loose mix aging. This conclusion is supported by the results from the pair-wise statistical comparison (Table 26) in which 3 of 36 possible comparison groups exhibited an increase in freeze-thaw tensile strength with loose mix aging and by the ANOVA complete factorial (Table 53) and partial factorial (Table 56) studies, which identify loose mix aging as an important factor influencing freeze-thaw tensile strength.

Compacted Mix Aging

Freeze-thaw tensile strength is influenced by the method of compacted mix aging. This conclusion is supported somewhat by the results from the pair-wise statistical comparison (Table 27) in which 3 of 24 possible comparison groups exhibited a decrease in freeze-thaw tensile strength with compacted mix aging and by the ANOVA complete factorial (Table 53) and partial factorial (Table 56) studies, which identify compacted mix aging as an important factor influencing freeze-thaw tensile strength.

Dry versus No Freeze-Thaw Tensile Strength

Pairwise statistical comparisons shown in Tables 28 and 29 indicate that the no freeze-thaw tensile strength was lower than the dry tensile strength in 45 of 68 possible comparisons. The lower no freeze-thaw tensile strengths as compared with the dry tensile strengths were more frequently associated with l00-mm-diameter samples prepared with the Superpave gyratory and Hveem kneading compactors and with samples prepared with the Nevada and Texas materials.

Dry versus Freeze-Thaw Tensile Strength

Pairwise statistical comparisons shown in Tables 30 and 31 indicate that freeze-thaw tensile strength was lower than dry tensile strength in 52 of 68 possible comparisons. The lower freeze-thaw tensile strengths as compared with the dry tensile strengths were more frequently associated with 100-mm-diameter samples prepared with the Superpave gyratory and Hveem kneading compactors and with samples prepared with the Nevada and Texas materials.

No Freeze-Thaw versus Freeze-Thaw Tensile Strength

Pair-wise statistical comparisons shown in Tables 32 and 33 indicate that the freeze-thaw tensile strength was the same as the no freeze-thaw tensile strength in 56 of 68 possible comparisons. Freeze-thaw tensile strengths were lower than no freeze-thaw tensile strengths in 8 of 68 possible comparisons. These lower freeze-thaw tensile strengths were most frequently associated with the Nevada aggregate, which is considered water-sensitive.

The complete factorial ANOVA study indicates that sample conditioning (i.e., dry, no freeze-thaw, and freeze-thaw) is the most important factor influencing tensile strength (Table 50).

Level of Saturation

The complete factorial and partial factorial tasks of the experiment investigated the influence of saturation level on tensile strength of conditioned and aged samples. The complete factorial experiment performed with the Nevada aggregate and both the G150 and M100 compactors indicated that the level of saturation has little effect on the no freeze-thaw and freeze-thaw tensile strengths (Tables 34–39).

The ANOVA analyses conducted on the complete factorial and partial factorial tasks also indicate that saturation level is the least significant main factor influencing the tensile strength of the samples (Tables 50–56). The exception to this statement is shown in Table 56, which indicates that saturation level is among the most important factors influencing the freeze-thaw tensile strength (based on the partial factorial experiment).

Tensile Strength Ratio

The tensile strength ratio is obtained by dividing the conditioned tensile strength (i.e., no freeze-thaw or freeze-thaw) by the nonconditioned tensile strength (i.e., dry). In general, the tensile strength ratios of G150 compacted samples were larger than the tensile strength ratios of samples prepared with either the G100 compactor or the H100 compactor (Figures 4 and 5). These differences in tensile strength ratios are due to the generally higher dry tensile strengths and lower conditioned tensile strengths obtained on the G100 and H100 samples as compared with the G150 samples.

The tensile strength ratio obtained for the M100 compacted samples is similar to the ratio obtained for the G150 samples (Figures 4 and 5). This similarity is expected, based on the comparison of the dry and conditioned tensile strengths discussed above.

Water Sensitivity

Results obtained in this study indicate that the water sensitivities of the mixtures as described by the state DOTs did not satisfactorily match the observed behavior of the mixtures for a number of data groups in this study.

The Maryland aggregate was described as water-sensitive, and only samples prepared with the Hveem compactor failed a 70-percent retained tensile strength criteria (Table 43). The Alabama and Texas aggregates have been described as not water-sensitive. The Texas mixture failed to reach 70-percent tensile strength ratio for all conditions. The Alabama mixture exceeded the 70- and 80-percent criteria for only the Marshall impact compacted samples (Table 43).

The Nevada and Colorado mixtures were both described as moderately to highly water-sensitive. The Colorado mixture did not exceed the 70-percent acceptance level for any compaction or conditioning (Table 43). The Nevada mixture reached 70-percent tensile strength ratio when samples were prepared with the G150 compactor (Table 43). In the complete factorial experiment, the Nevada mixture exceeded the 70-percent acceptance criteria in 7 of 48 possible data groups and exceeded 80 percent in only 1 of 48 possible comparisons groups (Table 45). The Nevada mixture subjected to compacted mix aging had the largest number of sample groups exceeding the 70-percent tensile strength ratios.

The typical acceptance criteria of 70- and 80-percent retained tensile strength ratio ideally should be verified by each public agency for its particular aggregate, asphalt binder, climate, traffic volume, design standards, and construction specifications.

Variability and Compaction Method

In general, there is little difference in variability of test results among methods of compaction.

Variability and Mixture Source

Experience obtained on the Alabama mixture, which was prepared with a relatively large nominal maximum size Superpave coarse-graded aggregate, suggests that variability can be a problem. Numerous samples were retested because of the loss of aggregates on the corners and sides of the samples during conditioning. In addition, the degree of saturation was difficult to measure with these samples because the permeability was high and the ability to measure saturated surfaced dried mass was difficult.

RECOMMENDATIONS

Public agencies presently using samples compacted with the G100 or H100 compactors to determine the water sensitivity of HMA by AASHTO T283 should not switch to the G150 compactor for sample preparation without performing a structured laboratory testing program to determine the comparative behavior of their aggregates and binders.

Public agencies presently using samples compacted with the M100 compactor to determine the water sensitivity of HMA by AASHTO T283 are encouraged to perform a structured laboratory testing program to determine the comparative behavior of their aggregates and binders before switching to the G150 compactor.

During the conduct of the experimental laboratory programs recommended above, mixtures should be selected so that field performance information can be obtained and field performance can be correlated with laboratory test parameters. This information can be used to establish acceptance criteria based on laboratory test results, traffic, climate, and so forth.

A laboratory testing program investigating the influence of multiple freeze-thaw cycles and higher levels of saturation on tensile strength should be conducted on G150 compacted samples and compared with samples compacted to a l00-mm diameter.

Loose mix aging was identified as a significant factor impacting the measured dry and moisture conditioned tensile strength property (both no freeze-thaw and freeze-thaw) of HMA mixtures.

Based on the data obtained in this study, it is recommended that loose mix aging of 16 hr at 60 °C should be used with the proposed AASHTO T283 method of test. A copy of the proposed AASHTO T283 is in Appendix C.

The no freeze-thaw and freeze-thaw conditioning were identified as critical factors impacting the measured moisture-conditioned tensile strength property of HMA mixtures. The pairwise statistical comparisons showed that the no freeze-thaw and freeze-thaw conditioning had the same effect, with the exception of 8 of 68 possible comparisons in which the freeze-thaw conditioning showed lower conditioned tensile strength than the no freeze-thaw showed. Based on these data, and to be conservative, it is recommended that a freeze-thaw cycle be used with the proposed AASHTO T283 method of test.

The data generated and the statistical analyses performed in this study indicated that the level of saturation does not significantly affect the magnitude of the moisture-conditioned tensile strength (both no freeze-thaw and freeze-thaw). It is recommended that a saturation level between 50 and 80 percent be used in the proposed AASHTO T283 method of test.

The data generated in this study showed that the tensile strength ratios measured on the G150 samples are similar to the tensile strength ratios measured on the M100 samples. On the other hand, there was not strong agreement among the tensile strength ratios measured on the G150 samples and those measured on the H100 or G100 samples. Based on these data, it is recommended that a tensile strength ratio criteria that was developed based on M100 samples be used with the G150 samples, while a tensile strength ratio criteria that was developed based on H100 or G100 samples should be used with extreme caution.

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APPENDIX A

MATERIALS AND MIXTURES

INTRODUCTION

Asphalt binders and aggregates were obtained from five Superpave volumetric mixture design projects in five states. Projects in the states of Alabama, Colorado, Maryland, and Texas were constructed during the 1997 construction season. The materials from Nevada were obtained from the WesTrack project constructed in the fall of 1995. Table A-1 contains general information on the five projects (Table A-1 is a repeat of Table 2 in the main text of the report and is included to make the appendix complete). Project location, contractor, design traffic volume, asphalt binder grade, and aggregate information are included in this table.

The aggregates used on the Colorado, Maryland, and Nevada projects are considered water-sensitive by the state highway agencies that supplied the materials. The aggregates used in the states of Alabama and Texas are not considered water-sensitive by these states. As noted in Table A-1, hydrated lime was used as an antistrip agent in the Colorado and Nevada mixtures. Antistrip agents were not used by the states of Alabama, Maryland, and Texas on their projects.

ASPHALT BINDERS

Asphalt binder properties from these projects are shown in Table A-2. These data were supplied by the state highway agencies. It is not known if the asphalt binders were neat asphalts or modified asphalts. The Nevada asphalt binder was a neat asphalt cement.

AGGREGATES

Tables A-3, A-4, and A-5 contain aggregate property data. Superpave aggregate property data are shown in Table A-3. Specific gravity and absorption data are shown in Table A-4, while gradations are shown in Table A-5. The Alabama mixture used a 37.5-mm nominal maximum size aggregate. The Colorado and Nevada aggregates were 19-mm nominal maximum size, and the Maryland and Texas aggregates were 12.5-mm nominal maximum size. All of the reported aggregate information meets the Superpave requirements.

MIXTURE DESIGN

Mixture design information is shown in Table A-6. This information will be discussed for the individual projects.

Alabama

The Alabama materials were sampled by the National Center for Asphalt Technology at Auburn University under the direction of Doug Hanson. A PG 64-22 asphalt binder and a limestone aggregate were used on the project. The mixture design was performed by Whitaker Contracting Corporation. A design asphalt binder content of 4.4 percent by total weight of mixture was used.

Colorado

The Colorado materials were sampled by the Colorado Department of Transportation (DOT) under the direction of Tim Aschenbrener. A PG 64-28 asphalt binder and a partially crushed alluvial aggregate were used for the construction phase of the project. This binder was not available at the time of sampling and a PG 58-28 asphalt binder from the same refinery was used on the research project. The 1-percent hydrated lime was also removed from the field mixture for this research project. The minus No. 200 sieve size material was increased by 1 percent to account for this loss of fine material from the lime. Table A-6 shows the mixture design information supplied by Colorado DOT for the mixture with lime and with the PG 64-28 asphalt binder, and mixture design information obtained by the University of Nevada without lime and with the PG 58-28 asphalt binder. A design asphalt binder content of 5.6 percent by total weight of mixture was used.

Maryland

The Maryland materials were sampled by the Maryland State Highway Administration under the direction of Larry Michael. A PG 64-28 asphalt binder and limestone aggregate were used on the project. A design asphalt binder content of 5.5 percent by total weight of mixture was used.

TABLE A-1 General Project Information

State	Project Information		Contractor	Traffic Volume, 20 year ESAL, Million	Asphalt Binder Grade	Antistrip Used During Construction	Gradation	Aggregate Type	
	Number	*Highway*						Coarse	Fine
Alabama	IM-STPAAF-65-3 (141) Blount County	IH 65	Whitaker Contracting Corporation	10-30	PG 64-22 (AC-30)*	None	25.5 mm Coarse	Limestone	Limestone
Colorado	IR (CX) 025-1 (122)	IH 25	Corn Construction	5	PG 58-28**	1% Hydrated Lime	19.0 mm Fine	Alluvial (partially crushed)	Alluvial (partially crushed)
Maryland	SHA 73.0-39	Rt 40	Keystone	10-30	PG 64-28	None	12.5 mm Coarse	Limestone	Limestone
Nevada	WesTrack Lyon County	Test Track	Granite Construction	3-10	PG 64-22	1.5% Hydrated Lime	19.0 mm Fine	Alluvial (partially crushed)	Alluvial (partially crushed)
Texas	NH 97 (428) CSJ-44-3-38 Clay County	US 82	Duininck Brothers	3-10	PG 70-22	None	12.5 mm Coarse	Limestone	Limestone

Notes: * PG 67-22

** PG 58-28 used in laboratory study; PG 64-28 from Koch used for construction

TABLE A-2 Asphalt Binder Properties

State	PG Grade	Original Binder			RTFOT Aged Binder		PAV Aged Binder		
		Flash Point AASHTO T48, °C	Viscosity @ 135 °C ASTM D4402, Pa.s	DSR AASHTO TP5 Temp @ 1.00 kPa, °C	Mass Loss, Percent	DSR AASHTO TP5 Temp @ 2.2 kPa, °C	DSR AASHTO TP5 Temp @ 5000 kPa, °C	BBR AASHTO TP1	
								Temp @ S = 500 Mpa, °C	Temp @ m = 0.30, °C
Alabama	64-22 (AC-30) (Hunt Oil)	292–315	0.390 to 0.525	64	0.1–0.2	64	25.0	–12.0	–12.0
Colorado	58-28 (Conoco)		0.30	62.3	0.5	63.1	17.4	–19.0	–18.4
Maryland	64-28								
Nevada	64-22 (Huntway)	276	0.3	65.3	0.3	65.5	24.0	–14.3	–13.3
Texas	70-22 (NESTE)	310		(1)		(2)	(3)	(4)	(5)

Notes: (1) 1.336 kPa @ 70 °C

(2) 3.176 kPa @ 70 °C

(3) 2.764 mPa @ 28 °C

(4) 186.3 mPa @ –12 °C

(5) 0.348 @ –12 °C

TABLE A-3 Superpave Aggregate Properties

State	Nominal maximum Size, mm	Coarse Aggregate			Fine Aggregate		Blended Aggregate	
		Coarse Aggregate Angularity ASTM D5821*	Flat & Elongated ASTM D4791, Percent	Los Angeles Abrasion AASHTO T96, ASTM C131, C535	Fine Aggregate Angularity AASHTO TP33, Air Voids	Sand Equivalent AASHTO T176, Percent	Soundness AASHTO T104, ASTM C88, Percent	Deleterious Materials AASHTO T112, ASTM C142, Percent
Alabama	37.5	100/100	3:1–1.3 5:1–0.0	20	46	49	98	0
Colorado	19.0	/97	0.0	23	45.8	64		
Maryland	12.5	100/100	4	19	47	67		
Nevada	19.0	100/100	0.0		44.8	72.0		
Texas	12.5	100/100	0.0	29	55.1	87	22	0

Note: * Percent one and two faces.

TABLE A-4 Aggregate Properties

State	Apparent Specific Gravity			Bulk Specific Gravity			Water Absorption Capacity, Percent			Effective Specific Gravity	Asphalt Absorption, Percent
	Fine Aggregate	*Coarse Aggregate*	*Combined Aggregate*	*Fine Aggregate*	*Coarse Aggregate*	*Combined Aggregate*	*Fine Aggregate*	*Coarse Aggregate*	*Combined Aggregate*		
Alabama	2.740	2.719	2.722	2.687	2.697	2.690	0.5	0.5	0.5	2.716	0.37
Colorado	2.610	2.725	2.681	2.606	2.577	2.594	0.70	2.08	1.25	2.633	0.57
Maryland	2.704	2.714	2.708	2.644	2.689	2.660	1.34	0.55	0.73	2.684	
Nevada			2.715			2.569			2.07	2.628	0.90
Texas	2.659				2.644	2.647				2.653	

TABLE A-5 Aggregate Gradation

Sieve Size		Alabama	Colorado	Maryland	Nevada	Texas
mm	Inch (Designation)					
37.5	1.5	100	100	100	100	100
25	1	100	100	100	100	100
19	3/4	88.0	100	100	100	100
12.5	1/2	60.7	87.1	95.1	88.0	89.3
9.5	3/8	46.6	75.8	81.0	75.5	70.0
4.75	N° 4	25.2	52.5	53.1	50.4	42.4
2.36	N° 8	17.8	35.1	34.0	39.1	24.4
1.18	N° 16	11.7	23.3	21.1	34.6	17.5
0.6	N° 30	7.7	16.0	14.2	27.1	11.5
0.3	N° 50	5.6	7.6	8.7	14.4	5.5
0.15	N° 100	3.2	1.7	6.3	6.3	3.1
0.075	N° 200	2.2	0.3	2.3	3.3	0.2

TABLE A-6 Mixture Design Information

State	Design Asphalt Binder Content, Percent by Total Mass	Effective Design Asphalt Binder Content percent by Total Mass	Percent of Theoretical Maximum Density @			Voids in Mineral Aggregate, Percent	Voids Filled with Asphalt, Percent	Dust to Asphalt Ratio	Water Sensitivity, Tensile Strength Ratio
			N initial	N design	N max				
Alabama	4.40	4.03	84.2 (9)	96.0 (121)	97.8 (195)	13.4	71	1.07	0.92
Colorado	5.6 *		87.9 (8)	96.1 (109)	97.8 (174)	15.5	73	0.98	0.97
	5.6 **	5.1	97.5 (8)	96.0 (109)	97.3 (174)	15.4	74	1.18	
Maryland	5.5		84.6 (8)	96.0 (109)	97.6 (174)	15.6	75		0.90
Nevada	5.0	4.1	89.1 (8)	96.0 (96)	96.8 (152)	13.5	71	1.19	
Texas	4.5 (1) 4.8 (2)		84.2 (2) (8)	96.0 (2) (95)	97.6 (2) (150)	14.4 (1)*** 14.9 (2)	72.2 (2)	0.80 (2)	0.71 (2)

Notes: * Colorado DOT mix design with PG 64-28 and 1 percent lime
** University of Nevada mix design with PG 58-28 and no lime
*** Based on effective specific gravity of aggregate
(1) Production mix
(2) Lab design

Nevada

The Nevada materials were sampled by the University of Nevada in cooperation with Dean Weitzel of the Nevada DOT. The PG 62-22 asphalt binder was obtained from FHWA's Materials Reference Library, located in Reno, Nevada, and samples were obtained from the WesTrack project constructed in 1995.

The partially crushed alluvial aggregates were obtained from the same pit as that used on the WesTrack project (1994 production) but were sampled from aggregates produced during 1997. The mix design information shown in Table A-6 was developed in the University of Nevada Laboratory on aggregates without 1.5 percent lime. The WesTrack project used 1.5 percent lime in all mixtures. The minus No. 200 material was increased by 1.5 percent to reflect the removal of the lime from the WesTrack gradation. A design asphalt binder content of 5.0 percent by total weight of mixture was used.

Texas

The Texas materials were sampled by the Texas DOT under the direction of Maghsoud Tahmoressi. A PG 70-22 asphalt binder and a limestone aggregate were used on the project. The mixture design was performed by the Texas DOT. A design binder content of 4.8 percent by total weight of mix resulted from the laboratory design. The asphalt binder content was adjusted to 4.8 percent by total weight of mix in the field based on field-mixed–laboratory-compacted volumetrics.

MIXING AND COMPACTION

Table A-7 presents a summary of mixing and compaction temperatures and compaction efforts required to obtain the desired 7 percent air-void content in the laboratory compacted samples. Mixing and compaction temperatures were obtained either from the state highway agencies that supplied the binders or by performing high-temperature viscosity tests with the rotational viscometer. A summary of the methods used to establish the compaction efforts for each method of compaction is presented below.

Superpave Gyratory Compactor

Both 150-mm-diameter by 95 mm and 100-mm-diameter by 62 mm Superpave gyratory compacted samples were prepared on this project. The Superpave gyratory compactor was used in the height control mode with a pressure of 600 kPa. The number of gyrations varied with each sample prepared in order to obtain the specified height of the sample to produce the desired 7 percent ±1 percent air voids.

The mass of hot-mix asphalt (HMA) to be compacted to achieve the desired air-void content and sample size was determined by a trial-and-error procedure. An estimated desired quantity of HMA was determined by calculation. This estimated quantity was varied ±100 g, and samples were compacted by the gyratory compactor set in the height control mode to produce samples 95 mm or 62 mm in height, depending on the diameter of the samples. The data from these trials

TABLE A-7 Mixing and Compaction Conditions

State	Mix Temp., °C (°F)	Compaction Temp., °C (°F)	Compaction Effort			
			Gyratory 150 mm Diameter, (G150)	Gyratory 150 mm Diameter (G150)	Marshall Impact 100 mm Diameter (M100)	Hveem Kneading 100 mm Diameter (H100)
Alabama	149 (300)	143 (290)	(1)	(2)	40 blows/face	(3)
Colorado	163 (325)	149 (300)	(1)	(2)	35 blows/face	(3)
Maryland	163 (325)	143 (290)	(1)	(2)	40 blows/face	(3)
Nevada	151 (303)	141 (285)	(1)	(2)	58 blows/face	(3)
Texas	155 (311)	150 (302)	(1)	(2)	45 blows/face	(3)

Notes: (1) 600 kPa pressure with variable number of gyrations to obtain 95-mm height
(2) 600 kPa pressure with variable number of gyrations to obtain 62-mm height
(3) 25 tamps at 250 psi, static compaction to 62-mm height

(which were conducted for each mixture) were then plotted, and the quantity of material determined which quantity provided samples of the desired dimensions and air voids.

Marshall Impact Compactor

An estimated mass of the sample was determined based on calculation and on the mass of the samples used for the Hveem compacted samples. With the selected mass of the sample, groups of samples were compacted at 35, 45, and 55 blows per face. The number of blows were selected that produced the desired air voids and dimensions of the samples. For some mixtures, the mass of the material was increased or decreased to provide the desired samples. The number of blows per face for each mixture is shown in Table A-7. A leveling load was not applied to the samples.

Hveem Kneading Compactor

An estimated mass of HMA was determined to produce samples of the desired air voids and dimensions. Samples were prepared at this mass and ±100 g of the calculated mass. Sets of samples were compacted for each mixture using the following procedure:

1. 25 tamps at 250 psi foot pressure;
2. Application of leveling load (0.05 in.-per-min application rate); and
3. Holding the leveling load at the desired sample height for 1 min prior to unloading.

The time required to apply the leveling load to achieve the desired sample height and the magnitude of the load applied varied with mixture and with samples within mixtures.

APPENDIX B

ANOVA ANALYSIS TABLES

ANOVA ANALYSIS FOR COMPLETE FACTORIAL EXPERIMENT, THREE LEVELS OF SAMPLE CONDITIONING, NEVADA AGGREGATE

```
                                   comparison between scond and _scond                             23:09 Sunday,
April 4, 1999   1
                                                resp-ts

                                     General Linear Models Procedure
                                        Class Level Information

                                    Class     Levels     Values

                                    COMP           2     Gry Ms

                                    LMA            4     16h 2h 4h None

                                    CMA            2     0h 96h

                                    SATLEV         3     55 75 90

                                    SCOND          3     Noft dry ft

                                  Number of observations in data set = 432


                   NOTE: Due to missing values, only 421 observations can be used in this analysis.
                                   comparison between scond and _scond                             23:09 Sunday,
April 4, 1999   2
                                                resp-ts

                                     General Linear Models Procedure

                 Dependent Variable: TS   TS

                 Source                    DF         Sum of Squares          Mean Square      F Value          Pr > F

                 Model                    143       1443370.16760886       10093.49767559        45.84          0.0001

                 Error                    277         60989.13666668         220.17738869

                 Corrected Total          420       1504359.30427554

                                     R-Square                   C.V.             Root MSE                      TS Mean

                                     0.959458               9.347952          14.83837554                 158.73396675


                 Source                    DF            Type III SS          Mean Square      F Value          Pr > F

                 COMP                       1          1548.61886288        1548.61886288         7.03          0.0085
                 LMA                        3        103338.25507825       34446.08502608       156.45          0.0001
                 COMP*LMA                   3         16968.57900909        5656.19300303        25.69          0.0001
                 CMA                        1          5267.26644370        5267.26644370        23.92          0.0001
                 COMP*CMA                   1          5730.76976589        5730.76976589        26.03          0.0001
                 LMA*CMA                    3         18917.15349362        6305.71783121        28.64          0.0001
                 COMP*LMA*CMA               3         37592.40449678       12530.80149893        56.91          0.0001
                 SATLEV                     2          2315.19908277        1157.59954139         5.26          0.0057
                 COMP*SATLEV                2          2627.15310403        1313.57655201         5.97          0.0029
                 LMA*SATLEV                 6          6636.79235388        1106.13205898         5.02          0.0001
                 COMP*LMA*SATLEV            6          9511.06032086        1585.17672014         7.20          0.0001
                 CMA*SATLEV                 2          2310.16584318        1155.08292159         5.25          0.0058
                 COMP*CMA*SATLEV            2           227.32782998         113.66391499         0.52          0.5973
                 LMA*CMA*SATLEV             6          2105.81292376         350.96882063         1.59          0.1488
                 COMP*LMA*CMA*SATLEV        6          7110.15871987        1185.02645331         5.38          0.0001
                 SCOND                      2        938373.81933908      469186.90966954      2130.95          0.0001
                 COMP*SCOND                 2         22637.42357346       11318.71178673        51.41          0.0001
                 LMA*SCOND                  6         52806.16854187        8801.02809031        39.97          0.0001
                 COMP*LMA*SCOND             6         31701.68709643        5283.61451607        24.00          0.0001
                 CMA*SCOND                  2         34181.63297259       17090.81648629        77.62          0.0001
                 COMP*CMA*SCOND             2         15734.56562448        7867.28281224        35.73          0.0001
                 LMA*CMA*SCOND              6         36192.65292473        6032.10882079        27.40          0.0001
                 COMP*LMA*CMA*SCOND         6         25234.84334183        4205.80722364        19.10          0.0001
                 SATLEV*SCOND               4          3727.23810224         931.80952556         4.23          0.0024
                 COMP*SATLEV*SCOND          4          3393.59002300         848.39750575         3.85          0.0046
                 LMA*SATLEV*SCOND          12         12981.46125958        1081.78843830         4.91          0.0001
                 COMP*LMA*SATLE*SCOND      12          5421.77229949         451.81435829         2.05          0.0203
                 CMA*SATLEV*SCOND           4          1960.91464215         490.22866054         2.23          0.0664
                 COMP*CMA*SATLE*SCOND       4          2593.38232779         648.34558195         2.94          0.0208
                 LMA*CMA*SATLEV*SCOND      12          6142.10114180         511.84176182         2.32          0.0076
                 COM*LMA*CMA*SAT*SCON      12         13213.06570809        1101.08880901         5.00          0.0001
```

ANOVA ANALYSIS FOR COMPLETE FACTORIAL EXPERIMENT, DRY TENSILE STRENGTH, NEVADA AGGREGATE

```
                                      General Linear Models Procedure

Dependent Variable: TSDRY    TSDRY

Source                  DF          Sum of Squares              Mean Square          F Value            Pr > F

Model                   47        202107.57937500            4300.16126330            18.10            0.0001

Error                   96         22806.08000000             237.56333333

Corrected Total        143        224913.65937500

                  R-Square                    C.V.                 Root MSE                         TSDRY Mean

                  0.898601                6.906989              15.41308968                       223.15208333


Source                  DF             Type III SS              Mean Square          F Value            Pr > F

COMP                     1           5833.14062500            5833.14062500            24.55            0.0001
LMA                      3         101811.62187500           33937.20729167           142.86            0.0001
COMP*LMA                 3          24420.77187500            8140.25729167            34.27            0.0001
CMA                      1          13047.35062500           13047.35062500            54.92            0.0001
COMP*CMA                 1          13081.64062500           13081.64062500            55.07            0.0001
LMA*CMA                  3          14265.23187500            4755.07729167            20.02            0.0001
COMP*LMA*CMA             3          29647.82187500            9882.60729167            41.60            0.0001
SATLEV                   2              0.00000000               0.00000000             0.00            1.0000
COMP*SATLEV              2              0.00000000               0.00000000             0.00            1.0000
LMA*SATLEV               6              0.00000000               0.00000000             0.00            1.0000
COMP*LMA*SATLEV          6              0.00000000               0.00000000             0.00            1.0000
CMA*SATLEV               2              0.00000000               0.00000000             0.00            1.0000
COMP*CMA*SATLEV          2              0.00000000               0.00000000             0.00            1.0000
LMA*CMA*SATLEV           6              0.00000000               0.00000000             0.00            1.0000
COMP*LMA*CMA*SATLEV      6              0.00000000               0.00000000             0.00            1.0000


                                                                                       15:33 Wednesday, February 3, 19
```

ANOVA ANALYSIS FOR COMPLETE FACTORIAL EXPERIMENT, WET NO-FREEZE TENSILE STRENGTH, NEVADA AGGREGATE

```
                              General Linear Models Procedure

Dependent Variable: TSNOFT   TSNOFT

Source                  DF          Sum of Squares          Mean Square       F Value          Pr > F

Model                   47      184925.74014388        3934.59021583         17.13          0.0001

Error                   91       20901.10000000         229.68241758

Corrected Total        138      205826.84014388

                  R-Square                C.V.             Root MSE                     TSNOFT Mean

                  0.898453            11.13016          15.15527689                    136.16402878


Source                  DF             Type III SS          Mean Square       F Value          Pr > F

COMP                     1        9914.82085809        9914.82085809         43.17          0.0001
LMA                      3       40851.84290874       13617.28096958         59.29          0.0001
COMP*LMA                 3       21454.04323495        7151.34774498         31.14          0.0001
CMA                      1       11834.46204620       11834.46204620         51.53          0.0001
COMP*CMA                 1        3138.02145215        3138.02145215         13.66          0.0004
LMA*CMA                  3       31116.36316764       10372.12105588         45.16          0.0001
COMP*LMA*CMA             3       17797.32877023        5932.44292341         25.83          0.0001
SATLEV                   2        2266.79672696        1133.39836348          4.93          0.0092
COMP*SATLEV              2        4419.19562892        2209.59781446          9.62          0.0002
LMA*SATLEV               6        6733.77612801        1122.29602134          4.89          0.0002
COMP*LMA*SATLEV          6        7168.85185652        1194.80864275          5.20          0.0001
CMA*SATLEV               2        3228.24582108        1614.12291054          7.03          0.0015
COMP*CMA*SATLEV          2        2236.86356225        1118.43178113          4.87          0.0098
LMA*CMA*SATLEV           6        6337.28570149        1056.21428358          4.60          0.0004
COMP*LMA*CMA*SATLEV      6       10505.79693710        1750.96615618          7.62          0.0001

                                                                         15:33 Wednesday, February 3, 1
```

ANOVA ANALYSIS FOR COMPLETE FACTORIAL EXPERIMENT, WET FREEZE-THAW TENSILE STRENGTH, NEVADA AGGREGATE

```
                              General Linear Models Procedure

Dependent Variable: TSFT   TSFT

Source                  DF          Sum of Squares            Mean Square        F Value          Pr > F

Model                   47        114878.64804348          2444.22655412          12.73          0.0001

Error                   90         17281.95666667           192.02174074

Corrected Total        137        132160.60471014

                  R-Square                    C.V.                Root MSE                       TSFT Mean

                  0.869235                12.12899             13.85719094                    114.24855072


Source                  DF             Type III SS            Mean Square        F Value          Pr > F

COMP                     1          8531.41339869          8531.41339869          44.43          0.0001
LMA                      3         13788.21815785          4596.07271928          23.94          0.0001
COMP*LMA                 3          3886.97451786          1295.65817262           6.75          0.0004
CMA                      1         14809.98751634         14809.98751634          77.13          0.0001
COMP*CMA                 1          5534.43163399          5534.43163399          28.82          0.0001
LMA*CMA                  3          9257.97766156          3085.99255385          16.07          0.0001
COMP*LMA*CMA             3         15826.12125623          5275.37375208          27.47          0.0001
SATLEV                   2          3701.10728758          1850.55364379           9.64          0.0002
COMP*SATLEV              2          1503.11140523           751.55570261           3.91          0.0234
LMA*SATLEV               6         12710.02259170          2118.33709862          11.03          0.0001
COMP*LMA*SATLEV          6          7472.49899686          1245.41649948           6.49          0.0001
CMA*SATLEV               2           980.37964052           490.18982026           2.55          0.0835
COMP*CMA*SATLEV          2           587.14258170           293.57129085           1.53          0.2224
LMA*CMA*SATLEV           6          1885.91059587           314.31843265           1.64          0.1461
COMP*LMA*CMA*SATLEV      6          9307.45263150          1551.24210525           8.08          0.0001

                                                                        15:33 Wednesday, February 3,
```

ANOVA ANALYSIS FOR PARTIAL FACTORIAL EXPERIMENT, DRY TENSILE STRENGTH, ALL AGGREGATE SOURCES

```
Partial factorial (Dry)
                                               The SAS System                              20:01 Saturday,
pril 10, 1999   1
                                                  resp-ts

                                        General Linear Models Procedure
                                           Class Level Information

                                       Class     Levels     Values

                                       SOURCE         5     AL CO MD NV TX

                                       COMP           2     Gry Ms

                                       LMA            4     16h 2h 4h None

                                       CMA            2     0h 96h

                                       SATLEV         3     55 75 90

                                    Number of observations in data set = 426

                     NOTE: Due to missing values, only 413 observations can be used in this analysis.
                                                 The SAS System                              20:01 Saturday,
April 10, 1999   2
                                                    resp-ts

                                         General Linear Models Procedure

                  Dependent Variable: TS   TS

                  Source                  DF          Sum of Squares          Mean Square       F Value         Pr > F

                  Model                  141        1544567.46917599       10954.37921401         69.76         0.0001
                                                                                                                    .
                  Error                  271          42555.73284996         157.03222454

                  Corrected Total        412        1587123.20202595

                                    R-Square                    C.V.             Root MSE                        TS Mean

                                    0.973187                9.453783          12.53124992                   132.55275476

                  Source                  DF             Type III SS          Mean Square       F Value         Pr > F

                  SOURCE                   4         460582.80407775      115145.70101944        733.26         0.0001
                  COMP                     1           5474.18111223        5474.18111223         34.86         0.0001
                  SOURCE*COMP              4          22889.75312629        5722.43828157         36.44         0.0001
                  LMA                      3          21747.51950777        7249.17316926         46.16         0.0001
                  SOURCE*LMA              12         106274.43379109        8856.20281592         56.40         0.0001
                  COMP*LMA                 3           1282.98748315         427.66249438          2.72         0.0447
                  SOURCE*COMP*LMA          0              0.00000000                  .              .              .
                  CMA                      1           3634.34619735        3634.34619735         23.14         0.0001
                  SOURCE*CMA               4          26202.12202796        6550.53050699         41.71         0.0001
                  COMP*CMA                 1          15638.52000000       15638.52000000         99.59         0.0001
                  SOURCE*COMP*CMA          0              0.00000000                  .              .              .
                  LMA*CMA                  3          11474.49750718        3824.83250239         24.36         0.0001
                  SOURCE*LMA*CMA          12          56661.65085318        4721.80423777         30.07         0.0001
                  COMP*LMA*CMA             0              0.00000000                  .              .              .
                  SOURCE*COMP*LMA*CMA      0              0.00000000                  .              .              .
                  SATLEV                   2              0.00000000           0.00000000          0.00         1.0000
                  SOURCE*SATLEV            8              0.00000000           0.00000000          0.00         1.0000
                  COMP*SATLEV              2              0.00000000           0.00000000          0.00         1.0000
                  SOURCE*COMP*SATLEV       1              0.00000000           0.00000000          0.00         1.0000
                  LMA*SATLEV               6              0.00000000           0.00000000          0.00         1.0000
                  SOURCE*LMA*SATLEV       24              0.00000000           0.00000000          0.00         1.0000
                  COMP*LMA*SATLEV          0              0.00000000                  .              .              .
                  SOURC*COMP*LMA*SATLE     0              0.00000000                  .              .              .
                  CMA*SATLEV               2              0.00000000           0.00000000          0.00         1.0000
                  SOURCE*CMA*SATLEV        8              0.00000000           0.00000000          0.00         1.0000
                  COMP*CMA*SATLEV          0              0.00000000                  .              .              .
                  SOURC*COMP*CMA*SATLE     0              0.00000000                  .              .              .
                  LMA*CMA*SATLEV           6              0.00000000           0.00000000          0.00         1.0000
                  SOURC*LMA*CMA*SATLEV    19              0.00000000           0.00000000          0.00         1.0000
                  COMP*LMA*CMA*SATLEV      0              0.00000000                  .              .              .
                  SOU*COM*LMA*CMA*SATL     0              0.00000000                  .              .              .
```

ANOVA ANALYSIS FOR PARTIAL FACTORIAL EXPERIMENT, WET NO-FREEZE TENSILE STRENGTH, ALL AGGREGATE SOURCES

```
Partial factorial (Noft)

                                                       The SAS System                                    12:01 Sunday,

April 11, 1999   1
                                                          resp=ts

                                              General Linear Models Procedure
                                                 Class Level Information

                                             Class     Levels     Values

                                             SOURCE         5     AL CO MD NV TX

                                             COMP           2     Gry Ms

                                             LMA            4     16h 2h 4h None

                                             CMA            2     0h 96h

                                             SATLEV         3     55 75 90

                                            Number of observations in data set = 258

                          NOTE: Due to missing values, only 245 observations can be used in this analysis.
                                                       The SAS System                                    12:01 Sunday,
April 11, 1999   2
                                                          resp=ts

                                              General Linear Models Procedure

                 Dependent Variable: TS   TS

                 Source                  DF        Sum of Squares          Mean Square     F Value        Pr > F

                 Model                   85       316157.22555320        3719.49677121       45.54        0.0001

                 Error                  159        12985.89042951          81.67226685

                 Corrected Total        244       329143.11598270

                                   R-Square                  C.V.             Root MSE                   TS Mean

                                   0.960546              10.16257           9.03727098               88.92701991


                 Source                  DF           Type III SS          Mean Square     F Value        Pr > F

                 SOURCE                   4       130532.80094517       32633.20023629      399.56        0.0001
                 COMP                     1          962.49274032         962.49274032       11.78        0.0008
                 SOURCE*COMP              0            0.00000000                    .           .             .
                 LMA                      3         9981.49670131        3327.16556710       40.74        0.0001
                 SOURCE*LMA              12        22668.96849491        1889.08070791       23.13        0.0001
                 COMP*LMA                 1           89.78000000          89.78000000        1.10        0.2960
                 SOURCE*COMP*LMA          0            0.00000000                    .           .             .
                 CMA                      1         3153.48062998        3153.48062998       38.61        0.0001
                 SOURCE*CMA               3         7112.17031746        2370.72343915       29.03        0.0001
                 COMP*CMA                 0            0.00000000                    .           .             .
                 SOURCE*COMP*CMA          0            0.00000000                    .           .             .
                 LMA*CMA                  1          195.74205882         195.74205882        2.40        0.1236
                 SOURCE*LMA*CMA           0            0.00000000                    .           .             .
                 COMP*LMA*CMA             0            0.00000000                    .           .             .
                 SOURCE*COMP*LMA*CMA      0            0.00000000                    .           .             .
                 SATLEV                   2          992.14776912         496.07388456        6.07        0.0029
                 SOURCE*SATLEV            8         4536.16800939         567.02100117        6.94        0.0001
                 COMP*SATLEV              1          259.16462963         259.16462963        3.17        0.0768
                 SOURCE*COMP*SATLEV       0            0.00000000                    .           .             .
                 LMA*SATLEV               6         1880.41711097         313.40285183        3.84        0.0013
                 SOURCE*LMA*SATLEV        3         1224.28371954         408.09457318        5.00        0.0024
                 COMP*LMA*SATLEV          0            0.00000000                    .           .             .
                 SOURC*COMP*LMA*SATLE     0            0.00000000                    .           .             .
                 CMA*SATLEV               0            0.00000000                    .           .             .
                 SOURCE*CMA*SATLEV        0            0.00000000                    .           .             .
                 COMP*CMA*SATLEV          0            0.00000000                    .           .             .
                 SOURC*COMP*CMA*SATLE     0            0.00000000                    .           .             .
                 LMA*CMA*SATLEV           0            0.00000000                    .           .             .
                 SOURC*LMA*CMA*SATLEV     0            0.00000000                    .           .             .
                 COMP*LMA*CMA*SATLEV      0            0.00000000                    .           .             .
                 SOU*COM*LMA*CMA*SATL     0            0.00000000                    .           .             .
```

ANOVA ANALYSIS FOR PARTIAL FACTORIAL EXPERIMENT, WET FREEZE-THAW TENSILE STRENGTH, ALL AGGREGATE SOURCES

```
Partial Factorial (FT)

                                      comparison between satlev and _satlev                 20:18 Saturday,
April 10, 1999   1
                                                   resp=ts

                                       General Linear Models Procedure
                                           Class Level Information

                                      Class     Levels     Values

                                      SOURCE         5     AL CO MD NV TX

                                      COMP           2     Gry Ms

                                      LMA            4     16h 2h 4h None

                                      CMA            2     0h 96h

                                      SATLEV         3     55 75 90

                                     Number of observations in data set = 283

                      NOTE: Due to missing values, only 261 observations can be used in this analysis.
                                      comparison between satlev and _satlev                 20:18 Saturday,
April 10, 1999   2
                                                   resp=ts

                                       General Linear Models Procedure

                  Dependent Variable: TS   TS

                  Source                  DF          Sum of Squares          Mean Square      F Value          Pr > F

                  Model                   93      290417.24695680        3122.76609631        30.85          0.0001

                  Error                  167       16904.03315165         101.22175540

                  Corrected Total        260      307321.28010845

                                    R-Square                C.V.             Root MSE                        TS Mean

                                    0.944996            11.47745          10.06090232                    87.65798403


                  Source                  DF             Type III SS          Mean Square      F Value          Pr > F

                  SOURCE                   4       77937.40036042       19484.35009010       192.49          0.0001
                  COMP                     1         523.29621409         523.29621409         5.17          0.0243
                  SOURCE*COMP              1         601.03350000         601.03350000         5.94          0.0159
                  LMA                      3        2642.50946662         880.83648887         8.70          0.0001
                  SOURCE*LMA              12        2795.00415023         232.91701252         2.30          0.0097
                  COMP*LMA                 0           0.00000000              .                .               .
                  SOURCE*COMP*LMA          0           0.00000000              .                .               .
                  CMA                      1         586.65004520         586.65004520         5.80          0.0172
                  SOURCE*CMA               4        5334.24226166        1333.56056541        13.17          0.0001
                  COMP*CMA                 0           0.00000000              .                .               .
                  SOURCE*COMP*CMA          0           0.00000000              .                .               .
                  LMA*CMA                  3         973.67825064         324.55941688         3.21          0.0246
                  SOURCE*LMA*CMA           0           0.00000000              .                .               .
                  COMP*LMA*CMA             0           0.00000000              .                .               .
                  SOURCE*COMP*LMA*CMA      0           0.00000000              .                .               .
                  SATLEV                   2        4093.74020405        2046.87010202        20.22          0.0001
                  SOURCE*SATLEV            8        4401.74714988         550.21839373         5.44          0.0001
                  COMP*SATLEV              0           0.00000000              .                .               .
                  SOURCE*COMP*SATLEV       0           0.00000000              .                .               .
                  LMA*SATLEV               6        1501.19200847         250.19866808         2.47          0.0257
                  SOURCE*LMA*SATLEV       10        4799.06126794         479.90612679         4.74          0.0001
                  COMP*LMA*SATLEV          0           0.00000000              .                .               .
                  SOURC*COMP*LMA*SATLE     0           0.00000000              .                .               .
                  CMA*SATLEV               2        2046.56920257        1023.28460128        10.11          0.0001
                  SOURCE*CMA*SATLEV        0           0.00000000              .                .               .
                  COMP*CMA*SATLEV          0           0.00000000              .                .               .
                  SOURC*COMP*CMA*SATLE     0           0.00000000              .                .               .
                  LMA*CMA*SATLEV           1         816.00245098         816.00245098         8.06          0.0051
                  SOURC*LMA*CMA*SATLEV     0           0.00000000              .                .               .
                  COMP*LMA*CMA*SATLEV      0           0.00000000              .                .               .
                  SOU*COM*LMA*CMA*SATL     0           0.00000000              .                .               .
```

APPENDIX C

PROPOSED AASHTO T283

Standard Method of Test
for
Resistance of Compacted Bituminous Mixture to Moisture Induced Damage

AASHTO DESIGNATION: T 283-99

1. SCOPE

1.1 This method covers preparation of specimens and measurement of the change of diameter tensile strength resulting from the effects of *water* saturation and accelerated water conditioning *with a freeze-thaw cycle* of compacted bituminous mixtures in the laboratory. The results may be used to predict long-term stripping susceptibility of the bituminous mixtures, and to evaluate liquid anti-stripping additives which are added to the asphalt cement or pulverulent solids, such as hydrated lime *or Portland cement,* which are added to the mineral aggregate.

1.2 The values stated in SI units are to be regarded as the standard.

2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards:*

M 156	Requirements for Mixing Plants for Hot Mixed, Hot-Laid Bituminous Paving Mixtures
T 166	Bulk Specific Gravity of Compacted Bituminous Mixtures
T 167	Compressive Strength of Bituminous Mixtures
T168	Sampling Bituminous Paving Mixtures
T 209	Maximum Specific Gravity of Bituminous Mixtures Using Marshall Apparatus
T 245	Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus
T 246	Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus
T 247	Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor
T 269	Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
TP4	*Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the SHRP Gyratory Compactor.*

2.2 *ASTM Standards:*

D979	*Sampling Bituminous Paving Mixtures*
D 2041	Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
D 3387	Test Method for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM)
D3549	Test Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens

3. SIGNIFICANCE AND USE

3.1 As noted in the scope, this method is intended to evaluate the effects of *water* saturation and accelerated water conditioning *with a freeze-thaw cycle* of compacted bituminous mixtures in the laboratory. This method can be used (a) to test bituminous mixtures in conjunction with mixture design testing,*(lab mixed, lab compacted)* (b) to test bituminous mixtures produced at mixing plants, *(field mixed, lab compacted)* and (c) to test the bituminous concrete cores obtained from completed pavements of any age *(field mixed, field compacted).*

3.2 Numerical indices of retained indirect tensile properties are obtained by comparing the properties of laboratory specimens following saturation and accelerated water conditioned *with a freeze-thaw cycle* with the similar properties of dry specimens.

4. SUMMARY OF METHOD

4.1 Test specimens for each set of mix conditions, such as *those prepared with neat* asphalt, asphalt with anti-stripping agent, and aggregate treated with lime, are tested (Note 1). Each set of specimens is divided into subsets. One subset is tested in dry condition for indirect tensile strength. The other subset is subjected to vacuum saturation, *a* freeze cycle, followed by a warm-water *soaking* cycle before being tested for indirect tensile strength. Numerical indices of retained indirect tensile strength properties are computed from the test data obtained by the two subsets: dry and conditioned.

5. APPARATUS

5.1 Equipment for preparing and compacting specimens from one of the following: T 245 and T 247, *TP4* or ASTM D 3387.

5.2 Vacuum container, preferably Type D, from ASTM D 2041 and vacuum pump or water aspirator from ASTM D 2041 including manometer or vacuum gauge.

5.3 Balance and water bath from T 166.

5.4 Water bath capable of maintaining a temperature of 60 ± 1 °C (140 ± 1.8 °F).

5.5 Freezer maintained at -18±3 °C (0 ± 5 °F).

5.6 A supply of plastic film for wrapping, heavy-duty leak-proof plastic bags to enclose the saturated specimens, and masking tape.

5.7 10-mL graduated cylinder.

5.8 Aluminum pans having a surface area of 48400-64500 square millimeters (75-100 square inches) in the bottom and a depth of approximately 25 mm (1 inch).

5.9 Forced air draft oven capable of maintaining a temperature of 60 ± 1 °C (140 ± 1.8 °F).

5.10 Loading jack and ring dynamometer from T 245, or a mechanical or hydraulic testing machine from T 167 to provide a range of accurately controllable rates of vertical deformation including 50 mm per minute (2 in. Per minute).

5.11 *Loading Strips* - If used, steel loading strips with a concave surface having a radius of curvature equal to the nominal radius of the test specimen. For specimens 101.6 mm (4 in.) in diameter the loading strips shall be 12.7 mm (0.5 in.) wide, and for specimens 152.4 mm (6 in.) in diameter the loading strips shall be 19.05 mm (0.75 in.) wide. The length of the loading strips shall be rounded by grinding.

6. PREPARATION OF LABORATORY MIXED, LABORATORY COMPACTED TEST SPECIMENS

6.1 Make at least six specimens for each test, half to be tested dry and the other half to be tested after partial saturation and moisture conditioning *with a freeze-thaw cycle (Note 1).*

NOTE 1 - It is recommended that two additional specimens for the set be prepared. These specimens can then be used to establish the vacuum saturation technique as given in Section 9.3.

6.2 Specimens 101.6 mm (4 in.) in diameter and 63.5 mm (2.5 in.) thick *or 150 mm (6 in.) in diameter by 95 mm (3.75 in.) thick* are used. Specimens of *150 mm (6 in.) in diameter by 95 mm (3.75 in.) thick* should be used if aggregate larger than 25.0 mm (1 in.) is present in the mixture and/or is not permitted to be scalped out.

6.3 After mixing, the mixture shall be placed in an aluminum pan having a surface area of 48400-64500 square millimeters (75-100 square inches) in the bottom and a depth of approximately 25 mm (1 in.) and cooled at room temperature for 2 ± 0.5 hours. Then the mixture shall be placed in a 60 °C (140 °F) oven for 16 hours for curing. The pans should be placed on spacers to allow air circulation under the pan if the shelves are not perforated.

6.4 Prepare mixtures in batches large enough to make at least 3 specimens or, alternatively, prepare a batch large enough to just make one specimen at a time. If preparing a multi-specimen batch, split the batch into single specimen quantities before placing in the oven.

6.5 After curing, place the mixture in an oven for 2 hours *at the compaction temperature* prior to compaction. Compact the specimen in accordance with one of the following methods. T 245, T 247, *TP4 and* or ASTM 3387. The mixture shall be compacted to 7 ± 1.0 percent air voids or a void level expected in the field. This level of voids can be obtained by adjusting the number of blows in T 245; adjusting foot pressure, number of tamps, leveling load, or some combination in T 247; and adjusting the number of revolutions in TP4 and ASTM D 3387. The exact procedure must be determined experimentally for each mixture before compacting the specimens for each set.

6.6 After extraction from the molds, the test specimens shall be stored for *0* to *24* hours at room temperature.

7. PREPARATION OF FIELD MIXED, LABORATORY COMPACTED TEST SPECIMENS

7.1 Make at least six specimens for each test, half to be tested dry and the other half to be tested after partial saturation and moisture conditioning with a freeze-thaw cycle (Note 1).

7.2 Specimens 101.6 mm (4 in.) in diameter and 63.5 mm (2.5 in.) thick or 150 mm (6 in) in diameter by 95 mm (3.75 in.) thick are used. Specimens of 150 mm (6 in.) in diameter by 95 mm (3.75 in.) thick should be used if aggregate larger than 25.0 mm (1 in.) is present in the mixture and/or is not permitted to be scalped out.

7.3 Field mixed bituminous paving materials shall be sampled by ASTM D979.

7.4 After sampling, place the mixture in an oven for 2 hours at the compaction temperature prior to compaction. Compact the specimen in accordance with one of the following methods. T 245, T 247, TP4 and or ASTM D3387. The mixture shall be compacted to 7 ± 1.0 percent air voids. This level of voids can be obtained by adjusting the number of blows in T 245; adjusting foot pressure, number of tamps, leveling load, or some combination in T 247; and adjusting the number of revolutions in TP4 ASTM D 3387. The exact procedure must be determined experimentally for each mixture before compacting the specimens for each set.

7.5 After extraction from the molds, the test specimens shall be stored for 0 to 24 hours at room temperature.

7.6 No loose mix aging (section 6.3) shall be performed on the field mixed samples.

8. PREPARATION OF FIELD MIXED, FIELD COMPACTED SPECIMENS (CORES)

8.1 Select locations on the completed pavement to be sampled and obtain cores. The number of cores shall be at least six for each set of mix conditions.

8.2 Separate core layers as necessary by sawing or other suitable means and store layers to be tested at room temperature for 0 to 24 hours.

8.3 No loose mix aging (section 6.3) or compacted mix aging (section 6.6) shall be performed on the field mixed, field compacted or core specimens.

9. EVALUATION OF TEST SPECIMENS AND GROUPING

Note 2-A data sheet that is convenient for use with this test method is shown as Table 1

9.1 Determine theoretical maximum specific gravity (G) of mixture by T 209.

9.2 Determine specimen thickness by ASTM D 3549.

9.3 Determine specimen diameter (D)

9.4 Determine bulk specific gravity (F) by T 166. Express volume (E) of specimens in cubic centimeters.

9.5 Calculate air voids by T 269.

9.6 Calculate volume of air voids in cubic centimeters (I) by use of the following equation.

$$I=\frac{HE}{100}$$

where

I=volume of air voids, cubic centimeters

H=air voids, percent

E=volume of specimen, cubic centimeters

9.7 Sort the specimens into two subsets of at least three specimens each so that average air voids of the two subsets are approximately equal.

10. PRECONDITIONING OF TEST SPECIMENS

10.1 One subset will be tested dry and the other will be *partially vacuum saturated, subjected to freezing and water soaked* before testing.

10.2 The dry subset will be stored at room temperature until testing. The specimens shall be wrapped with plastic or placed in a heavy duty leak proof plastic bag. The specimens shall then be placed in a 25°C (77°F) water bath for a minimum of 2 hours and then tested as described in Section ~~10~~. 11

10.3 The other subset shall be conditioned as follows:

10.3.1 Place the specimen in the vacuum container supported above the container bottom by a spacer. Fill the container with distilled water at room temperature so that the specimens have at least one inch of water above their surface. Apply a vacuum of 13-67 kPa absolute pressure (10-26 in. Hg. partial pressure) for a short time (5-10 minutes). Remove the vacuum and leave the specimen submerged in water for a short time (5-10 minutes).

10.3.2 Determine bulk specific gravity *(F')* by T 166.

10.3.3 Calculate volume of absorbed water (J') in cubic centimeter by use of the following equation:

$$J'=B'-B$$

where:

J'= volume of absorbed water, cubic centimeter

B'=mass of saturated surface-dry specimen after partial vacuum saturation, grams

B=mass of surface-dry specimen prior to partial vacuum saturation, grams (section 9.4)

10.3.4 Determine *the* degree of saturation by comparing volume of absorbed water *(J')* with volume of air voids *(I)* from Section *9.6 with the following equation:*

$$S'=\frac{100J'}{I}$$

where

S'=degree of saturation, percent

J'=volume of absorbed water, cubic centimeter

I=volume of air voids, cubic centimeter

If the degree of saturation is between 55 percent and 80 percent, proceed to Section *10.3.6.*

10.3.5 If degree of saturation is less than 55 percent, repeat the procedure beginning with Section 10.3.1 using more vacuum and/or time. If volume of water is more than 80 percent, specimen has been damaged and is discarded. Repeat the procedure beginning with Section 10.3.1 using less vacuum and/or time.

10.3.6 Cover each of the vacuum-saturated specimens tightly with a plastic film (Saran Wrap or equivalent). Place each wrapped specimen in a plastic bag containing 10 mL of water and seal the bag. Place the plastic bags containing the specimens in a freezer at a temperature of -18 ± 3°C (0 ± 5°F) for a minimum of 16 hours. *Remove specimens from the freezer.*

10.3.7 Place the specimens in a bath containing distilled water at 60 ± 1°C (140 ± 2°F) for 24 ± 1 hours. As soon as possible after placement in the water bath, remove the plastic bag and film from each specimen.

10.3.8 After 24 ± 1 hours in the 60°C (140°F) water bath, remove the specimens and place them in a water bath already at 25 ± 0.5°C (77 ± 1°F) for1 hour. It may be necessary to add ice to the water bath to prevent the water temperature from rising above 25°C (77°F). Not more than 15 minutes should be required for the water bath to reach 25°C (77°F). *Remove the specimen from water bath and determine thickness (t") by ASTM D3549.*

10.3.9 Place specimen in a water bath already at 25 ± 0.5°C (77 ± 1°F) for a minimum of 2 hours. Test the specimens as described in Section 11.

11. TESTING

11.1 Determine the indirect tensile strength of dry and conditioned specimens at 25°C (77°F).

11.2 Remove the specimen from 25°C (77°F) water bath and place between the two bearing plates in the testing machine. Care must be taken so that the load will be applied along the diameter of the specimen as illustrated in Table 2. Apply the load to the specimen by means of the constant rate of movement of the testing machine head of 50 mm (2 in.) per minute.

NOTE 3-When reviewing a failure

or stripped pavement, the temperature of specimens in Sections *11.1* and *11.2* of 25°C (77°F) should be changed to 13°C (55°F).

11.3 If steel loading strips are used, record the maximum compressive strength noted on the testing machine and continue loading until a vertical crack appears. Remove the specimen from the machine and pull apart at the crack. Inspect the interior surface for stripping and record the observations.

11.4 If steel loading strips are not used, stop loading as soon as the maximum compressive load is reached. Record the maximum compressive load. Remove the specimen, measure, and record the side (edge) flattening to the nearest 0.1 mm (0.1 in.) The flattening may be easier to measure if the flattened edge is rubbed with the lengthwise edge of a piece of chalk. After recording the flattening, replace the specimen in the compression machine and compress until a vertical crack appears. Remove the specimen from the machine and pull apart at the crack. Inspect the interior surface for stripping and record the observations.

12. CALCULATIONS

12.1 If steel loading strips are used, calculate the tensile strength as follows:

SI Units:

$$S_t = \frac{2000\,P}{\pi t D}$$

where:

S_t = tensile strength, kPa
P = maximum load, N
t = specimen thickness, mm
D = specimen diameter, mm

U.S. Customary Units:

$$S_t = \frac{2P}{\pi t D}$$

where:

S_t = tensile strength, psi
P = maximum load, lbs
t = specimen thickness, in.
D = specimen diameter, in.

12.2 If steel loading strips are not used, calculate the tensile strength of a 101.6 mm (4 in.) diameter specimen as follows:

SI Units:

$$S_t = \frac{S_{10}P}{44000t}$$

where:

S_t = tensile strength, Pa
S_{10} = maximum tensile stress corresponding to the width of flattened area from Table 2
P = maximum load, newtons
t = specimen thickness, mm

U.S. Customary Units

$$S_t = \frac{S_{10}P}{10000t}$$

where:

S_t = tensile strength, psi
S_{10} = maximum tensile stress corresponding to the width of flattened area from Table 2
P = maximum load, pounds
t = specimen thickness, inches.

12.3 Express the numerical index or resistance of asphalt mixtures to the detrimental effect of water as the ratio of the original strength that is retained after the freeze-warm water conditioning. Calculate as follows:

Tensile Strength Ratio:

$$(\text{TSR}) = \frac{S_2}{S_1}$$

where:

S_1 = average tensile strength of dry subset
S_2 = average tensile strength of conditioned subset.

13. Report

13.1 Report the following information,

13.1.1 Number of specimens in each subset,
13.1.2 Average air voids of each subset,
13.1.3 Tensile strength of each specimen in each subset,
13.1.4 Tensile strength ratio,
13.1.5 Results of visually-estimated moisture damage observed when the specimen fracture, and
13.1.6 Results of observations of fractured or crushed aggregate.

Table 1: Moisture Damage Laboratory Data Sheet
(Non-Mandatory Information)

Project____________________________________

Additive_________________________ Dosage_______________

Compaction Method_________________________ Effort_______________

Date Tested_________________________ By_______________

Sample I.D									
Diameter, mm (in.)	D								
Thickness, mm (in.)	t								
Dry mass in air, g	A								
SSD mass, g	B								
Mass in water, g	C								
Volume (B-C), cc	E								
Bulk Sp. Gr. (A/E)	F								
Max Sp. Gr.	G								
%Air Void (100(G-F)/G)	H								
Volume Air void, HE/100, cc	I								
Load, N (lbf)	P								
Saturated min. @ kPa or mm Hg (in. Hg)									
SSD Mass, g	B'								
Mass in water, g	C'								
Volume (B'-C'), cc	E'								
Bulk Sp. Gr. (A/E')	F'								
Vol Abs. water (B'-B), cc	J'								
% Saturation (100J'/I)	S'								
Load, N (lbf)	P"								
Dry Strength, 2000 P/xtD (2P/xtD), kPa	S_{td}								
Wet Strength, 2000 P"/xt"D (2P"/xt"D), kPa	S_{tm}								
TSR, $100S_{tm}/S_{td}$									
Visual Moisture Damage									
Crack/Break Aggregate									

TABLE 2: Maximum Tensile Stress (S_{10}) for a Base Index of a 44000 Newton (10000 lb.) Load, 101.6 mm (4 in.) Diameter Specimen, 25.4 mm (1in.) In length.

Width of Flattened Area, in Millimeters (inches)	Maximum Tensile Stress, S_{10} kPa (psi)
0.0 (0.0)	11307 (1640)
2.5 (0.1)	11232 (1629)
5.0 (0.2)	11163 (1619)
7.6 (0.3)	11073 (1606)
10.2 (0.4)	10997 (1595)
12.7 (0.5)	10832 (1571)
15.2 (0.6)	10618 (1540)
17.8 (0.7)	10397 (1508)
20.3 (0.8)	10135 (1470)
22.9 (0.9)	9915 (1438)
25.4 (1.0)	9687 (1405

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway 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
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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