NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 409

Quality Control and Acceptance of Superpave-Designed Hot Mix Asphalt

Transportation Research Board
National Research Council

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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.

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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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FOREWORD

By Staff
Transportation Research Board

This report presents a plan, in the form of a draft AASHTO standard practice, for quality control (QC) and quality acceptance (QA) of field production, placement, and compaction of hot mix asphalt (HMA) prepared in conformance with Superpave materials specifications and mix designs. It will be of particular interest to materials engineers in state highway agencies and to those agency and contractor personnel responsible for control and acceptance of HMA paving projects. The report also contains the detailed research results supporting the development of the QC/QA plan, including experimental data obtained during the construction of pavement projects using Superpave mix designs across the United States.

A principal product of the Strategic Highway Research Program (SHRP) is the Superpave performance-based mix design and analysis method. This method incorporates new, performance-based material specifications, test methods, and design and analysis procedures for HMA. Interest in the Superpave method has grown rapidly since the conclusion of SHRP in 1993. The Superpave Lead State Team of the AASHTO Task Force on the Implementation of SHRP reported that in 1996, 28 states incorporated both binder and mix specifications in awarding 95 Superpave projects. Nationally, these projects represented approximately 1 percent of total projects and 2 percent of total tonnage. For 1997, projected figures indicated that the number of states using Superpave would increase to greater than 40, while planned projects totaled in excess of 300. However, to realize the maximum benefit of improved performance possible through the Superpave method, state highway agencies must ensure that the production, placement, and compaction of HMA in field projects are controlled to maintain compliance with the Superpave specifications and mix design.

Under NCHRP Project 9-7 “Field Procedures and Equipment to Implement SHRP Asphalt Specifications” Brent Rauhut Engineering Inc. was assigned the tasks of (1) establishing comprehensive procedures and, if required, developing equipment for QC/QA of field production, placement, and compaction to ensure that as-placed HMA conforms with the Superpave mix design and (2) preparing a training program for qualifying technicians to accomplish these QC/QA procedures.

The research team reviewed relevant domestic and foreign literature on established and innovative process control methods in the HMA industry as well as the wider manufacturing sector; carried out field QC/QA operations and conducted extensive laboratory testing on field- and laboratory-compacted specimens from 15 pavement projects constructed in 1994, 1995, and 1996; evaluated a variety of test methods and equipment for contractor control of field operations with Superpave-designed HMA; and developed a prototype *field shear test (FST) device* to measure key HMA performance properties during pavement construction.

This NCHRP report presents several products expected to facilitate the wider implementation of the Superpave mix design method: a QC/QA plan, including tolerances for key materials and volumetric mix properties, for field production and lay down of HMA produced in accordance with Superpave material specifications and mix designs method (Chapter 2); guidelines for adjustment of production and placement of HMA to maintain conformance with Superpave specifications and mix designs (Chapter 3); a training program (available in the form of a Microsoft Powerpoint presentation) for qualifying technicians to use the procedures set forth in the QC/QA plan (Chapter 4); and equipment requirements, test procedures, and data analysis techniques for use of the Superpave gyratory compactor as the principal tool in QC/QA operations, and for the FST device and the rapid triaxial test that with further development may complement the gyratory compactor in such operations (Chapter 5).

The QC/QA plan presented in Chapter 2 establishes minimum requirements and activities for a contractor's QC system related to Superpave mix design, production, placement, and compaction. These requirements include a listing of the inspections and tests necessary to substantiate material and product conformance to the Superpave mix design. The primary method of field QC employs the Superpave gyratory compactor and evaluation of the volumetric properties of the mix.

The plan also establishes requirements for a state highway agency's assessment and acceptance of a project incorporating Superpave-designed HMA. This plan, coupled with the contractor's QC plan, provides the necessary quality assurance for control, verification, and acceptance of the project.

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AUTHOR ACKNOWLEDGMENTS

The research effort reported herein was performed under NCHRP Project 9-7 by Brent Rauhut Engineering Inc., which served as the prime contractor. Subcontractors for the project included the Pennsylvania Transportation Institute, the Asphalt Institute, Advanced Asphalt Technologies, the Texas Transportation Institute, and Law Engineering. In addition, Industrial Process Controls generously provided test equipment and staff involvement at no cost to the project.

Mr. Ronald J. Cominsky, formerly of BRE Inc., now Executive Director of the Pennsylvania Asphalt Pavement Association, served as the Principal Investigator for the project and primary author of this report. Valuable assistance in conducting the project and authoring the report was provided by Mr. Brian M. Killingsworth of BRE Inc. Others who contributed to this report include Dr. David A. Anderson (Pennsylvania Transportation Institute), Mr. R. Michael Anderson (Asphalt Institute), Mr. Vince Aurilio (Advanced Asphalt Technologies), Dr. Thomas W. Kennedy (University of Texas at Austin), Dr. Robert L. Lytton (Texas Transportation Institute), and Dr. Bill Crockford (formerly of the Texas Transportation Institute, now a representative of Industrial Process Controls through TSL Services and Equipment).

The authors also acknowledge the valuable assistance of Ms. Terhi Pellinen (formerly of Advanced Asphalt Technologies, now with the University of Maryland) for her efforts. Three consultants also provided valuable assistance: Dr. Matthew Witczak, Mr. Garland Steele, and Mr. James Scherocman. Mr. Barry Tritt (Industrial Process Controls) is also acknowledged for providing valuable information and test data to the project from test equipment developed by IPC.

The authors also acknowledge the cooperation of several State Highway Agencies and contractors who participated in the production and construction of field test sites. The States that participated include Kentucky, Virginia, Florida, Texas, Mississippi, Alabama, Georgia, Kansas, Maryland, and Louisiana. Material was also sampled and tested from test sections constructed at WesTrack in Nevada.

CHAPTER 1

QUALITY CONTROL AND ACCEPTANCE OF SUPERPAVE-DESIGNED HOT MIX ASPHALT

1.1 INTRODUCTION

Interest in the Superpave performance-based mix design and analysis system, developed through the asphalt research program of the Strategic Highway Research Program (SHRP), is rapidly growing throughout the nation. AASHTO member departments are actively gearing up for Superpave implementation. The AASHTO Task Force on SHRP Implementation has targeted SHRP's asphalt products as one of its priorities. Members of the AASHTO Highway Subcommittee on Materials are evaluating more than 20 specific products in the asphalt area. A pooled-fund study has assisted the states to obtain the necessary laboratory test equipment. The Federal Highway Administration (FHWA) has established five Superpave Regional Centers nationally to assist state highway agencies (SHAs) with Superpave implementation. Industry must be involved, however, to fully implement SHRP's recommendations and will need the knowledge and tools to comply with the new requirements. To that end, user-producer groups are operating on a regional basis, involving SHAs, contractors, and materials manufacturers and suppliers. Information presented to these groups, initially by SHRP and now by the FHWA, has built wide-ranging support for adoption of this new system of material specifications, test methods and equipment, design and analysis practices, and software.

Such significant improvements in asphalt binders, test equipment and procedures, analysis of test results, and specifications should provide a substantially greater level of performance from paving mixes designed with the Superpave system. However, to realize these improvements, SHAs must ensure that the production, placement, and compaction of paving mixes in field projects are controlled to maintain compliance with the specifications.

A general approach to field control procedures was developed under SHRP to assist field technicians in adjusting mix design and monitoring production. The need was identified for additional research to specifically provide SHAs and paving contractors with appropriate quality control and quality assurance (QC/QA) procedures for the field implementation of the Superpave material specifications and mix designs. NCHRP Project 9-7, "Field Procedures and Equipment to Implement SHRP Asphalt Specifications," was initiated to satisfy this requirement.

NCHRP Project 9-7 had two key objectives:

- To establish comprehensive procedures and, if required, develop equipment for QC/QA at the asphalt plant and lay down site to ensure that hot mix asphalt (HMA) meets the Superpave performance-based specifications and
- To develop a framework for a training program for qualifying technicians to accomplish these QC/QA procedures.

After a review of the SHRP asphalt research program results and discussion with the NCHRP Project 9-7 panel, a decision was made to consider only permanent deformation as a distress factor. Permanent deformation is a short-term phenomenon that can be evaluated by QC/QA field testing. Pavement fatigue is a long-term phenomenon that is generally addressed through pavement layer thickness determination during the pavement design process. Low-temperature cracking is addressed during the Superpave mix design process by the selection of the appropriate performance grade of asphalt binder.

This report presents QC/QA procedures developed on the basis of experimental data obtained from 14 field paving projects during the course of the project. The report assumes a familiarity with the Superpave mix design procedures including the use of the Superpave gyratory compactor (SGC).[1]

Although the current focus of the SHAs is on the Superpave volumetric mix design method (originally termed *Superpave level 1*), Project 9-7 also considered the original *Superpave level-2* and *Superpave level-3* design procedures (now termed *abbreviated* and *full mix analyses*) recommended by SHRP. Further, in this report the QC function is assigned specifically to the paving Contractor and the QA function is assigned solely to the SHA.

The report is organized in two parts. Part I (Chapters 2 through 6) provides specific details of the products delivered by the research project and is intended for the practitioner and the user. Part I includes the following:

- A QC/QA plan for field production and lay down of HMA produced in accordance with Superpave material specifications and mix design method (Chapter 2);

[1]AASHTO TP4, *Standard Method for Preparing and Determining the Density of HMA Specimens by Means of the SHRP Gyratory Compactor.*

- Guidelines for adjustment of production and placement of Superpave-designed HMA (Chapter 3);
- A training program for qualifying technicians to use the procedures set forth in the QC/QA plan (Chapter 4);
- A description of two field-testing devices that support the SGC for QC practices and provisional test procedures and data analysis for their use (Chapter 5); and
- A summary of the research results of NCHRP Project 9-7 and the conclusions drawn from the results that form the basis for the QC/QA practices and suggested guidelines for mix and placement adjustments (Chapter 6).

The appendices form Part II of the report. They provide complete experimental details and results upon which the products presented in Chapters 2 through 5 are based. The appendices include the following:

- Additional training information that can be used for assisting in the implementation of Superpave activities (Appendix A);
- Test procedures for the field QC devices developed during the project (Appendices B and C);
- The Stage I research approach: Superpave mix designs for six experimental construction projects conducted in 1994; QC data for the six projects; statistical analyses; and conclusions for the Version 1 QC/QA plan (Appendix D);
- The Stage II research approach: Superpave mix designs for seven experimental construction projects in 1995; QC data for the seven projects; statistical analyses; and conclusions for the Version 2 QC/QA plan (Appendix E);
- Verification of the Version 2.0 QC/QA plan; Superpave mix design for a project in Louisiana on which the Version 2.0 plan was used; statistical control charts; compaction data, and statistical analyses (Appendix F);
- Dispute resolution: Statistically based guidelines for comparison of QC and QA data adopted by AASHTO (Appendix G);
- Shear displacement rheometer (SDR) (Appendix H); and
- Gyratory sensitivity (Appendix I).

CHAPTER **2**

QC/QA PLAN FOR PRODUCTION AND LAY DOWN OF SUPERPAVE HMA

This chapter presents the specific details necessary to effectively control the production and lay down of Superpave mixes. The need for and use of a QC function cannot be overemphasized for the Superpave mix. Quality cannot be tested or inspected into the Superpave mix; it must be "built in." As discussed in the AASHTO *QC/QA Specification and Implementation Guide*, QC should be completed by the Contractor. Thus, it is imperative that the Contractor have a functional, responsive QC Plan. When a Contractor's QC Plan is initially required, minimum requirements are helpful as a guide to the Contractor. This approach provides a uniform basis for bidding and ensures a minimum level of QC. It is important that a QC Plan address the actions needed, including the frequency of testing to (a) keep the process in control, (b) quickly determine when it goes out of control, and (c) respond adequately to bring the process back into control.

2.1 SCOPE

This QC Plan establishes minimum requirements and activities for a Contractor's QC system related to the Superpave mix design. These requirements pertain to the inspections and tests necessary to substantiate material and product conformance to the Superpave mix design requirements and to all related inspections and tests. The primary method of field QC employs the use of the SGC and evaluation of the volumetric properties of the mix.

This QC Plan shall apply to all construction projects using a Superpave mix design when so indicated in the contract documents. If there are inconsistencies between the contract documents and this QC Plan, the contract documents shall control.

2.1.1 Functions and Responsibilities

2.1.1.a SHA

The SHA will verify the Superpave volumetric mix designs, inspect plants, and monitor control of the operations to ensure conformity with the Superpave mix requirements.

At no time will the SHA representative issue instructions to the Contractor or Producer about setting dials, gauges, scales, and meters. However, the SHA representatives will have the responsibility to question and warn the Contractor against the continuance of any operations or sequence of operations that will obviously not result in satisfactory compliance with Superpave mix requirements.

2.1.1.b The Contractor

The Contractor shall be responsible for development and formulation of the Superpave mix design, which will be submitted to the SHA for verification. In addition, the Contractor shall be responsible for the process control of all materials during the handling, blending, mixing, and placing operations.

2.1.2 QC System

2.1.2.a General Requirements

The Contractor shall provide and maintain a QC system that will provide reasonable assurance that all materials and products submitted to the SHA for acceptance conform to the Superpave specification requirements whether manufactured or processed by the Contractor or procured from suppliers or subcontractors. The Contractor shall perform or have performed the inspection and tests required to substantiate product conformance to the Superpave volumetric mix design requirements and shall also perform or have performed all inspections and tests otherwise required by the SHA contract. The Contractor's QC procedures, inspections, and tests shall be documented and shall be available for review by the SHA for the life of the contract.

2.1.2.b Documentation

The Contractor shall maintain adequate records of all inspections and tests. The records shall indicate the nature and number of observations made, the number and type of deficiencies found, the quantities approved and rejected, and the nature of corrective action taken as appropriate. The Contractor's documentation procedures will be subject to the review and approval of the SHA before the start of the work and the compliance checks during the progress of the work.

All charts and records documenting the Contractor's QC inspections and tests shall become property of the SHA upon completion of the work.

2.1.2.c Charts and Forms

All conforming and nonconforming inspections and test results shall be recorded on appropriate forms and charts, which shall be kept up to date and complete and shall be available at all times to the SHA during performance of the work. Test properties for the various materials and mixtures shall be charted on forms or other appropriate means, which are in accordance with the applicable requirements of the SHA.

2.1.2.d Corrective Action

The Contractor shall take prompt action to correct conditions that have resulted or could result in the submission of materials, products, and completed instructions that do not conform to the requirements of the SHA Superpave specification requirements.

2.1.2.e Measuring and Testing Equipment

The Contractor shall provide and maintain measuring and testing apparatus necessary to ensure that the materials and products conform to the Superpave specification requirements. To ensure continued accuracy, the apparatus shall be inspected and calibrated at established intervals against relevant SHA standards. In addition, the Contractor's personnel shall be appropriately qualified through specified accreditation procedures for obtaining and processing samples and for operating such apparatus and for verifying their accuracy and condition. Calibration results shall be available to the SHA at all times.

2.2 SUPERPAVE PERFORMANCE-GRADED ASPHALT BINDER (PGAB) CERTIFICATION

2.2.1 PGAB QC

The QC of the Superpave PGAB will be in accordance with AASHTO PP26-96, "Standard Practice For Certifying Suppliers of Performance-Graded Asphalt Binders."

2.2.2 AASHTO PP26-96 Standard

AASHTO PP26-96 specifies requirements and procedures for a certification system that shall be applicable to all suppliers of PGAB. The requirements and procedures shall apply to materials that meet the requirements of AASHTO standard MP1 "Specifications for Performance-Graded Asphalt Binders," Section 5, Materials and Manufacture, and that are manufactured at refineries, mixed at terminals, in-line blended, or modified at the HMA plant. Sections 9 and 13 of the AASHTO PP26-96 are of primary importance to the HMA plant operations related to PGAB certification and QC.

2.3 SUPERPAVE MIX DESIGN AND PRODUCTION

2.3.1 Laboratory Trial Mix Formula (LTMF) and HMA Plant Laboratory Verification

The Contractor shall develop a Superpave LTMF for the HMA paving courses by the Superpave mix design procedure employing the volumetric mix design concept with the gyratory compactor. The Contractor will perform a mix analysis using the Superpave performance tests when deemed necessary by the SHA Superpave specifications.

At least 1 month before the start of construction (or when the construction materials are available), the Contractor shall verify *in the laboratory* that the paving mixes prepared from the asphalt binder, coarse and fine aggregate, and mineral filler, when necessary, planned for use in the pavement construction yield mix composition and gyratory-compacted (AASHTO Standard Method TP4) properties within the LTMF tolerances listed in Table 2-1. The Contractor shall be responsible for setting the HMA plant to produce the hot mix within the LTMF tolerances (standard deviation) specified in Table 2-1 for the mix composition and gyratory-compacted mix properties. Annex I provides an alternative approach using conformal indices in lieu of standard deviations. The values in Table 2-1 were developed for individual samples ($n = 1$). For larger sample sizes, the standard deviation values in Table 2-1 must be adjusted by the following equation:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

where

$\sigma_{\bar{x}}$ = standard deviation of sample means of sample size n
σ = standard deviation from Table 2-1
n = sample size

The Contractor shall report to the SHA, in writing, the results of this laboratory verification and any actions necessary in the Contractor's judgment to bring the paving mixes produced with the materials planned for use in the pavement construction into conformance with the LTMF Superpave tolerances. The Contractor shall not proceed to the field verification (Section 2.3.2) without the approval of the SHA.

2.3.2 Field Verification and Adjustment to the LTMF

At the beginning of the project, the contractor shall produce a minimum of 500 tons but not exceed a day's produc-

TABLE 2-1 Superpave LTMF tolerances based on standard deviations (mixture composition and gyratory properties)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.25	± 0.18	± 0.13	---
Gradation Passing 4.75mm (No. 4) and Larger Sieves	± 3	--	--	± 3
Passing 2.36mm (No. 8) to 150um (No. 100) Sieve	± 2	--	--	± 2
Passing 75μm (No. 200) Sieve	± 0.7	--	--	± 0.7
Maximum Theoretical Specific Gravity (G_{mm})	± 0.015			
Gyratory Compacted Mix Property				
Air Voids (V_a)	± 1			
Voids in Mineral Aggregate (VMA)	± 1			
Voids Filled With Asphalt (VFA)	± 5			
Bulk Specific Gravity (G_{mb})	± 0.022			
Compaction Curve Slope (m)	± 0.40			

tion of HMA of uniform composition and shall verify that the plant-produced HMA is within the Superpave LTMF tolerances shown in Table 2-1. The contractor may opt to compare the performance-based test results on plant-produced material to those developed from the performance-based test results from the LTMF.

The Contractor and the SHA shall *each* randomly (Annex II) obtain one 200-lb sample of cold feed aggregate and plant-produced Superpave mix from each 100-ton sublot. The SHA and the Contractor shall split each sample into two sets of specimens to determine the arithmetic means and standard deviations of the following properties for each 100-ton sublot and for the minimum 500-ton production:

1. The gradation of the cold-feed aggregate;
2. The asphalt content and combined aggregate gradation (AASHTO T 165);
3. The maximum specific gravity of the HMA (AASHTO T 209);
4. The gyratory compaction curve for N_{max} (AASHTO Standard Method TP4);
5. The bulk specific gravity (AASHTO T 166, SSD method) at N_{design} gyrations (AASHTO Standard Method TP4);
6. The air void content (percent V_a) at N_{init}, N_{design} and N_{max} gyrations (AASHTO Standard Method TP4);
7. The voids in the mineral aggregate (percent VMA) and the voids filled with asphalt (percent VFA) at N_{design} gyrations (AASHTO Standard Method TP4); and
8. The slope of the gyratory compaction curve.

The Contractor and the SHA shall statistically evaluate their independent sets of test results (e.g., with the Student's *t*-test) and compare them with those for the LTMF of the paving mix with due consideration given to test type and variations associated with the applicable tests. The 500-ton lot of Superpave mix must meet an acceptable quality level of 90 percent within the LTMF limits for each of the following characteristics: asphalt content, aggregate gradation, and volumetric properties identified in Table 2-1.

If deemed necessary, the Contractor shall adjust the HMA plant operation to bring all characteristics of the Superpave mix into compliance with the LTMF established tolerances.

The Contractor shall employ test data obtained for the HMA produced in compliance with the LTMF to establish initial control charts for the HMA production process (Annex III); these charts shall be used to determine whether variability has occurred because of assignable causes that must be remedied. Control charts shall be refined with test results obtained during the first week of routine HMA mix production in accordance with the Superpave mix design.

2.3.3 Establishment of Compaction Rolling Pattern (Control Strip)

During field verification production of the Superpave-designed HMA (Section 2.3.2), the Contractor shall place and compact at least 500 tons of HMA produced in compliance with the LTMF tolerances to establish compaction patterns and verify that the equipment and the processes planned for lay down and compaction are satisfactory.

The HMA shall be placed in a trial area (control strip) at the thickness required by the pavement cross-section design. The Contractor shall employ a nuclear density gauge or other approved method of test to establish a compaction pattern that meets the specification criteria for in-place density.

2.4 SAMPLING AND TESTING

The QC Plan recognizes that the LTMF generally is not representative of the HMA that is produced in the field. The target values developed from the field verification of the plant-produced HMA and the control strip will become the control values. The target levels for key mix properties will be established through the field verification of HMA production (Section 2.3.2) and the lay down of the control strip (Section 2.3.3). These include the maximum theoretical bulk specific gravity, gyratory compaction parameters that will subsequently be used as QC indicators, volumetric properties such as percent air voids, percent VMA, percent VFA, and, if opted for by the Contractor, the performance properties.

The *QC Plan is based on a concept of continuous sampling of Superpave HMA at the plant.* Lots and sublots are considered in the QC Plan only for in-place compaction. The QC sampling will progress continuously as long as the target values are within the LTMF tolerances and do not change substantially as monitored by the control chart values. The objective of sampling and testing associated with this QC Plan is to ensure conformance of the mean properties of the "plant-produced" mix with the "target" mix and to minimize variability in the HMA.

The Contractor's QC Plan shall be based on random sampling and testing of the HMA at its point of production to determine compliance with the LTMF tolerances. The Contractor shall measure by means approved by the SHA and record a daily summary including the following:

- Quantities of asphalt binder, aggregate, mineral filler, and (if required) fibers used;
- Quantities of HMA produced; and
- HMA production and compaction temperatures.

The QC Plan shall include a statistically sound, randomized sampling plan to provide samples representative of the entire HMA production and to ensure that all sampling is conducted under controlled conditions.

2.5 QC ACTIVITIES

2.5.1 Plant-Produced Superpave Mix QC

The primary method of field QC makes use of the SGC and the volumetric properties of the HMA. If the results of testing are within LTMF tolerances of Section 2.3.2 (field verification and adjustments to the LTMF), the production is considered in control. Subsequent sampling and testing will be performed with the estimated bulk specific gravities (G_{mb} est.) at design number of gyrations (N_{des}) obtained from the gyratory compactor by the following:

1. A sample is randomly obtained. A known weight is measured into the heated mold.
2. The specimen is compacted to $N_{maximum}$. Heights are recorded at each gyration.
3. The operator performs a calculation to determine the estimated G_{mb} at N_{design}.
4. The estimated bulk specific gravity is corrected by the laboratory correction ratio

$$C = \frac{G_{mb}\,(\text{measured})}{G_{mb}\,(\text{estimated})}$$

5. The slope of the gyratory compaction curve is calculated by the method used in report SHRP-A-407, Section 3.7.4.1, as follows: The compaction or densification curve is characterized by three parameters. C_{init} is the percent of maximum theoretical specific gravity after N_{init} gyrations; C_{max} is the percent of maximum theoretical specific gravity after N_{max} gyrations. The slope of the densification curve, m, is calculated from the best-fit line of all data points assuming that the gyratory compaction curve is approximately linear. In situations where density begins to approach 100 percent, and the densification curve begins to bend downward, the slope is calculated from the straight line portion of the curve. The slope is calculated by the following equation:

$$\text{slope, } m = \frac{\log N_{max} - \log N_{init}}{C_{max} - C_{init}}$$

The Contractor shall use statistical control charts for the corrected, estimated G_{mb} and the slope of the gyratory compaction curve to determine whether the process target or variability in the HMA production is due to random or assignable causes. Periodically, the Contractor will determine a measured G_{mb} to validate the correction factor for control comparison.

Target values and upper and lower control limits for the control charts are determined from the gyratory mix properties (estimated G_{mb} and compaction curve slope) measured during the field verification process (Section 2.3.2) and the first few days of production. The grand mean and average range of the test data shall be used to develop *x-bar (mean) and R (range)* control charts for each material property. Upper and lower control limits shall be set at $\pm 2s$ and $\pm 3s$, defined as *warning* and *action* control limits, respectively where s is the *sample standard deviation.* These initial measurements for routine HMA production shall agree with those of the verification samples tested in accordance with the requirements of Section 2.3.2. If the control limits are not within the allowable LTMF tolerance limits, the Contractor shall modify the HMA production process to reduce the variability and bring the control limits within the specification limits.

Eight consecutive plotted points on either side of the target value or one point outside the warning or action limit indicates a mix composition change. At this point, another

G_{mb} measurement must be conducted to confirm compliance with the target. If the results indicate noncompliance, adjustments must be made to the asphalt content or aggregate gradation to provide mixture compliance. Once adjustments have been made, G_{mm}, G_{mb}, asphalt content, gradation, air voids, VMA, and VFA determinations must be made and compared with the LTMF allowable tolerances. The Contractor may opt to conduct the field shear test to evaluate engineering properties.

2.5.2 QC of In-Place Compaction

The Contractor shall develop and implement a plan approved by the SHA to control the compaction of the HMA and ensure its compliance with the project specification.

The QC Plan for compaction shall include a statistically sound, randomized sampling and testing plan using procedures to provide measurements of the in-place air voids contents representative of the entire pavement course and to ensure that all sampling or testing is conducted under controlled conditions. Methods for sampling or testing the in-place pavement shall be approved in advance by the SHA. For purposes of QC, a lot shall be defined as a pavement section 5,000 ft long and 12 ft wide; for sampling purposes, each lot shall be divided into a *minimum* of five sublots.

The Contractor shall measure and record a daily summary of the following: the amount (truck loads and tons per truck) of HMA delivered to the paver; the temperature (±1°C) of the HMA in each truck on the surface of the load; and the temperature (±1°C) of the mat at the approximate start of the compaction process.

The Contractor shall establish a statistical control chart for the in-place air voids content based on the percent of maximum theoretical density. The minimum requirement is 93 percent of maximum theoretical density and the maximum is 98 percent. This property shall be determined *through in situ, nondestructive measurement or sampling and testing of core specimens.* Four in situ, nondestructive measurements shall be made *or* two pavement cores shall be taken and tested per sublot at randomly selected pavement locations. The Contractor shall use the statistical control chart to determine whether variability in the compaction is due to assignable causes. Corrective action shall be taken by the Contractor, when necessary, to bring the in-place compaction process under control.

Target values and control limits for the control chart will be determined from compaction data measured during establishment of the compaction (rolling) patterns (Section 2.3.3) and the first day's pavement construction. The grand mean and average range of the test data shall be used to develop *x-bar (mean) and R (range)* control charts for compaction. Upper and lower control limits shall be set at ±2s and ±3s, defined as *warning* and *action* control limits, respectively, where s is the *sample standard deviation.* If the control limits are not within the allowable tolerance limits, namely, 93–98 percent of maximum theoretical density, the Contractor shall modify the HMA lay down and compaction process to reduce the variability and bring the control limits within the specification limits.

The Contractor shall provide the SHA with copies of the control charts. One test point outside the upper or lower *warning* control limit shall be considered an indication that the control of the lay down and compaction process may be unsatisfactory and shall require the Contractor to confirm that the process parameters are within acceptable bounds. One test point outside the upper or lower *action* control limit *or* eight consecutive test points on one side of the target value shall be judged as a lack of control in the lay down and compaction process and shall require the Contractor to stop HMA production and lay down until the assignable cause for the lack of control is identified and remedied. The Contractor shall report within 24 h to the SHA (1) the assignable cause for the stop in production and (2) the action taken to remedy the assignable cause.

2.6 NONCONFORMING MATERIALS

The Contractor shall establish and maintain an effective and positive system for controlling nonconforming material, including procedures for its identification, isolation, and disposition. Reclaiming or reworking nonconforming materials shall be in accordance with procedures acceptable to the SHA. Chapter 3 provides suggested guidelines for adjusting the components and HMA mix during the production and lay down processes.

2.7 SHA INSPECTION AT SUBCONTRACTOR OR SUPPLIER FACILITIES

The SHA may inspect materials not manufactured within the Contractor's facility. SHA inspection shall not constitute acceptance nor shall it in any way replace the Contractor's inspection or otherwise relieve the Contractor of the responsibility to furnish an acceptable material or product. When inspection of the Subcontractor's or Supplier's product is performed by the SHA, such inspection shall not be used by the Contractor as evidence of effective inspection of such Subcontractor's or Supplier's product.

Subcontracted or purchased materials shall be inspected by the Contractor when received, as necessary, to ensure conformance to contract requirements. The Contractor shall report to the SHA any nonconformance found on SHA source-inspected material and shall require the supplier to take necessary corrective action.

2.8 SUPERPAVE QUALITY ACCEPTANCE PLAN

Acceptance sampling and testing of a Superpave-designed HMA is a prescribed procedure, usually involving stratified sampling, which is applied to a series of lots of HMA. The acceptance sampling and testing enable the SHA to decide on the basis of a limited number of tests whether to accept a given lot of plant mix or construction from the Contractor. It must be emphasized that the objective of acceptance sampling and testing is to determine a course of action (accept or reject). It is not an attempt to "control" quality.

2.8.1 Scope

Acceptance sampling is performed in accordance with an Acceptance Plan. The Acceptance Plan is the method of taking a sample and making measurements on the sample, for the purpose of determining the acceptability of a lot of material or construction. Briefly, in terms of acceptance sampling, the Acceptance Plan for the Superpave-designed HMA defines the following:

1. Lot size,
2. Number of samples or measurements,
3. Sampling or measuring procedure,
4. Point(s) of sampling or measurement,
5. Method of acceptance, and
6. Numerical value of specification limits.

The acceptance sampling and testing frequency is less than that used by the Contractor for QC purposes. Because the Contractor tests more frequently to ascertain that the process variation is within specification tolerances, the SHA needs only to carry out additional work in accordance with the specification Acceptance Plan to ensure the degree of the HMA with the Superpave mix design specification.

2.8.2 Acceptance Plan Approach for Superpave-Designed HMA

The Acceptance Plan consists of the evaluation of the percent of material or construction within the specification limits (PWL) established for the Superpave-designed HMA. The following is the Acceptance Plan for estimating the PWL.

1. Locate n sampling positions on the lot by use of the table of random numbers.
2. Make a measurement at each location or take a test portion and make the measurement on the test portion.
3. Average the lot measurements to find $\bar{x}$

$$\bar{x} = \sum_{i=1}^{n} \frac{x_i}{n}$$

4. Determine the standard deviation, s, of the lot measurements.

$$s = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}}$$

5. Find the quality index, Q_u, by subtracting the average, $\bar{x}$, of the measurements from the upper specification limit, U, and dividing the results by s.

$$Q_U = \frac{U - \bar{x}}{s}$$

6. Find the quality index, Q_L , by subtracting the lower specification limit, L, from the average $\bar{x}$ and dividing the result by s.

$$Q_L = \frac{\bar{x} - L}{s}$$

7. Estimate the percentage of material that will fall within the upper tolerance limit, UTL, by entering Table 2-2, with Q_u, using the column appropriate to the total number, n, of measurements.
8. Estimate the percentage of material that will fall within the lower tolerance limit, LTL by entering Table 2-2 with Q_L using the column appropriate to the total number, n, of measurements.
9. In cases where both UTL and LTL are concerned, find the percent of material that will fall within tolerances by adding the percent, P_u, within the UTL to the percent, P_L , within the LTL and subtract 100 from the sum.

$$\text{Total PWL} = (P_u + P_L) - 100$$

2.8.3 SUPERPAVE PGAB CERTIFICATION

2.8.3.a Acceptance Criteria

The acceptance of the Superpave PGAB will be in accordance with AASHTO PP26-96 "Standard Practice For Certifying Suppliers of Performance-Graded Asphalt Binders."

2.8.3.b AASHTO PP26-96 Standard

AASHTO P26-96 specifies requirements and procedures for a certification system that shall be applicable to all suppliers of PGAB. The requirements and procedures shall apply to materials that meet the requirements of AASHTO Standard MP1 "Specifications for Performance-Graded Asphalt Binders," Section 5, Materials and Manufacture, and that are manufactured at refineries, mixed at terminals, in-line blended, or modified at the HMA plant. AASHTO P26-96. Sections 9, 10, 12, and 13 are of primary importance to

TABLE 2-2 Quality index values for estimating percent within limits

PWL	n = 3	n = 4	n = 5	n = 7	n = 10	n = 15
99	1.16	1.47	1.68	1.89	2.04	2.14
98	1.15	1.44	1.61	1.77	1.86	1.93
97	1.15	1.41	1.55	1.67	1.74	1.80
96	1.15	1.38	1.49	1.59	1.64	1.69
95	114	1.35	1.45	1.52	1.56	1.59
94	1.13	1.32	1.40	1.46	1.49	1.51
93	1.12	1.29	1.36	1.40	1.43	1.44
92	1.11	1.26	1.31	1.35	1.37	1.38
91	1.10	1.23	1.27	1.30	1.32	1.32
90	1.09	1.20	1.23	1.25	1.26	1.27
89	1.08	1.17	1.20	1.21	1.21	1.22
88	1.07	1.14	1.16	1.17	1.17	1.17
87	1.06	1.11	1.12	1.12	1.13	1.13
86	1.05	1.08	1.08	1.08	1.08	1.08
85	1.03	1.05	1.05	1.05	1.04	1.04
84	1.02	1.02	1.02	1.01	1.00	1.00
83	1.00	0.99	0.98	0.97	0.96	0.96
82	0.98	0.96	0.95	0.94	0.93	0.92
81	0.96	0.93	0.92	0.90	0.89	0.89
80	0.94	0.90	0.88	0.87	0.85	0.85
79	0.92	0.87	0.85	0.83	0.82	0.82
78	0.89	0.84	0.82	0.80	0.79	0.78
77	0.87	0.81	0.79	0.77	0.76	0.75
76	0.84	0.78	0.76	0.74	0.72	0.72
75	0.82	0.75	0.73	0.71	0.69	0.69
74	0.79	0.72	0.70	0.67	0.66	0.66
73	0.77	0.69	0.67	0.64	0.63	0.62
72	0.74	0.66	0.64	0.61	0.60	0.59
71	0.71	0.63	0.60	0.58	0.57	0.56
70	0.68	0.60	0.58	0.55	0.54	0.54
69	0.65	0.57	0.55	0.53	0.51	0.51
68	0.62	0.54	0.52	0.50	0.48	0.48
67	0.59	0.51	0.49	0.47	0.46	0.45
66	0.56	0.48	0.46	0.44	0.43	0.42
65	0.53	0.45	0.43	0.41	0.40	0.40
64	0.49	0.42	0.40	0.38	0.37	0.37
63	0.46	0.39	0.37	0.35	0.35	0.34
62	0.43	0.36	0.34	0.33	0.32	0.31
61	0.39	0.33	0.31	0.30	0.30	0.29
60	0.36	0.30	0.28	0.25	0.25	0.25

Note 1: For negative values of Q_U or Q_L, P_U or P_L is equal to 100 minus the tabular P_U or P_L.
Note 2: If the value of Q_U or Q_L does not correspond exactly to a value in the table, use the next higher value.

the SHA related to PGAB certification and acceptance procedures.

2.8.4 Superpave Specifications and Mix Verifications

2.8.4.a Superpave Specifications

The mix shall be designed with the Superpave mix design method to obtain an LTMF based on the following criteria:

- **Control points and restricted zone.** The Superpave mix design resulting in the LTMF shall provide for the selection of aggregate gradation for the paving mix by means of control points and a restricted zone. The control points and restricted zone are graphed on the FHWA's grading chart on which the percent of aggregate passing a sieve size is plotted against the sieve opening size raised to the 0.45 power. Table 2-3 identifies the control points for gradations with nominal maximum sizes of 37.5, 25.0, 19.0, 12.5, and 9.5 mm.

TABLE 2-3 Superpave aggregate gradation control points

(A) 37.5mm Nominal Maximum Size

Sieve Size	Control Point (Percent Passing)	
	Minimum	Maximum
75 µm	0	6
2.36mm	15	41
25.0mm	--	90
Nominal maximum (37.5mm)	90	100
Maximum (50.0mm)	100	---

(B) 25.0 Nominal Maximum Size

Sieve Size	Control Point (Percent Passing)	
	Minimum	Maximum
75 µm	1	7
2.36mm	19	45
19.0mm	--	90
Nominal maximum (25.0mm)	90	100
Maximum (37.5mm)	100	---

(C) 19.0mm Nominal Maximum Size

Sieve Size	Control Point (Percent Passing)	
	Minimum	Maximum
75 µm	2	8
2.36mm	23	49
12.5mm	--	90
Nominal maximum (19.0mm)	90	100
Maximum (25.0mm)	100	---

(D)12.5mm Nominal Maximum Size

Sieve Size	Control Point (Percent Passing)	
	Minimum	Maximum
75 µm	2	10
2.36mm	28	58
9.5mm	–	90
Nominal maximum (12.5mm)	90	100
Maximum (19.0mm)	100	---

(E) 9.5mm Nominal Maximum Size

Sieve Size	Control Point (Percent Passing)	
	Minimum	Maximum
75 µm	2	10
2.36mm	32	67
4.75mm	--	90
Nominal maximum (9.5mm)	90	100
Maximum (12.5mm)	100	---

TABLE 2-4 Superpave coarse aggregate angularity requirements

Traffic (ESALs)	Depth from Surface	
	< 100mm	> 100mm
$< 3 \times 10^5$	55/-	-/-
$< 1 \times 10^6$	65/-	-/-
$< 3 \times 10^6$	75/-	50/-
$< 1 \times 10^7$	85/80	60/-
$< 3 \times 10^7$	95/90	80/75
$< 1 \times 10^8$	100/100	95/90
$> 1 \times 10^8$	100/00	100/00

Note: "85/80" denotes that 85 percent of the coarse aggregate has one fractured face and 80 percent has two fractured faces.

- **Coarse aggregate angularity.** The LTMF shall be based on design traffic levels associated with the coarse aggregate angularity value shown in Table 2-4 being the minimum.
- **Fine aggregate angularity.** The LTMF shall be based on a design traffic level associated with the fine angularity value shown in Table 2-5 being the minimum.
- **Flat and elongated particles.** The LTMF shall be based on a maximum percent by weight of 10 percent for flat and elongated particles. Note: a 5:1 ratio may be changed to 3:1 based on review by FHWA mixtures expert task group (ETG).
- **Clay content.** The LTMF shall be based on a design traffic level and the minimum sand equivalent value expressed as a ratio of the sand to clay readings as a percent. Table 2-6 identifies the minimum values.
- **Dust proportion.** The dust proportion or dust-to-effective asphalt ratio shall be between 0.6 and 1.2 for all design traffic levels.
- **Air void (V_a).** The design air voids (V_a,) for the LTMF shall be 4 percent for all traffic levels.
- **Voids in the mineral aggregate (VMA).** The acceptable values for the VMA for the LTMF at 4 percent air voids based on the nominal maximum size aggregate are shown in Table 2-7.
- **Voids filled with asphalt (VFA).** The acceptable range of values for the VFA for the LTMF at 4 percent air voids and the design traffic level is identified in Table 2-8.
- **Gyratory compaction.** The number of initial (N_{init}), design (N_{des}), and maximum (N_{max}) gyrations shall be based on the design traffic level and the average design high air temperature and selected from Table 2-9. Compaction shall be carried out at an equiviscous temperature. Density shall be evaluated as the initial number of gyrations (N_{init}), the design number of gyrations (N_{des}), and the maximum number of gyrations(N_{max}).
- **Compaction requirements.** The gyratory-compacted specimens for the LTMF shall meet the density requirements specified in Table 2-10.
- **Moisture sensitivity.** The compacted specimens of the LTMF shall exhibit a minimum tensile strength ratio of 80 percent as determined by AASHTO T283.

TABLE 2-5 Superpave fine aggregate angularity requirements

Traffic (ESALs)	Depth from Surface	
	< 100mm	> 100mm
$< 3 \times 10^5$	--	--
$< 1 \times 10^6$	40	--
$< 3 \times 10^6$	40	40
$< 3 \times 10^7$	45	40
$< 1 \times 10^8$	45	45
$< 1 \times 10^8$	45	45

Note: Criteria are presented as minimum percent air voids in loosely compacted fine aggregate.

TABLE 2-6 Superpave clay content requirements

Traffic (ESALs)	Sand Equivalent
$< 3 \times 10^6$	40
$< 3 \times 10^7$	45
$\geq 3 \times 10^7$	50

TABLE 2-7 Superpave VMA requirements

Nominal Maximum Size	Minimum Voids in Mineral Aggregate (%)
9.5mm	15.0
12.5mm	14.0
19.0mm	13.0
25.0mm	12.0
37.5mm	11.0
50.0mm	10.5

TABLE 2-8 Superpave VFA requirements

Traffic Level (ESALs)	Design VFA (%)
$< 3 \times 10^5$	70-80
$< 3 \times 10^6$	65-78
$< 1 \times 10^8$	65-75
$> 1 \times 10^8$	65-75

2.8.5 Acceptance Criteria for Superpave-Designed HMA

The HMA will be accepted on a lot-by-lot basis by obtaining stratified random samples and performing the required acceptance tests.

2.8.5.a HMA Plant Production

The HMA shall be randomly sampled by the SHA at the point of production either at the plant or from a hauling unit. Sampling methods shall be in compliance with AASHTO T 168, ASTM D 979, or standard state practices.

- **Plant acceptance sampling and lot size.** A stratified random sampling plan shall be followed to obtain a minimum of five samples per lot. The lot shall be at least 1,000 tons or one day's production of HMA.
- **Acceptance testing.** Each lot sample shall be split. One split sample will be tested for asphalt content by the approved SHA procedure. One split will be compacted immediately with the SGC in accordance with AASHTO TP4. The V_a from the gyratory compaction curve shall be determined. The SHA may opt also to determine the VMA and the VFA.
- **PWL.** The PWL will be determined for the asphalt content and V_a in accordance with the acceptance plan identified in Section 2.8.2. The upper and lower specification limits for determining the quality indices for asphalt content shall be those identified for the appropriate SHA test method shown in Table 2-1. The upper and lower specification limits for determining the quality indices for V_a shall be those identified in Table 2-1.

TABLE 2-9 Superpave gyratory compaction effort

Design ESALs (millions)	Average Design High Air Temperature											
	<39°C			39-40°C			41-42°C			43-44°C		
	N_{ini}	N_{des}	N_{ma}	N_{ini}	N_{des}	N_{ma}	N_{ini}	N_{des}	N_{ma}	N_{ini}	N_{des}	N_{ma}
<0.3	7	68	104	7	74	114	7	78	121	7	82	127
0.3-1	7	76	117	7	83	129	7	88	138	8	93	146
1-3	7	86	134	8	95	150	8	100	158	8	105	167
3-10	8	96	152	8	106	169	8	113	181	9	119	192
10-30	8	109	174	9	121	195	9	128	208	9	135	220
30-100	9	126	204	9	139	228	9	146	240	10	153	253
>100	9	143	233	10	158	262	10	165	275	10	172	288

TABLE 2-10 General Superpave compaction requirements

Compaction Level	Required Density
N_{init}	< 89.0% of G_{mm}
N_{des}	= 96.0% of G_{mm}
N_{max}	< 98.0% of G_{mm}

The SHA may opt also to determine the PWL for VMA and VFA. The lower specification limits for determining the lower quality indices for VMA and VFA shall be those established for the LTMF.

2.8.6 Pavement Compaction

The Superpave-designed HMA shall be sampled by the SHA after appropriate compaction.

2.8.6.a Pavement Acceptance Sampling and Lot Size

A stratified random sampling plan shall be followed to obtain a minimum of five samples per lot. The lot shall be at least 1,000 tons or one day's production of HMA placed on the project site.

2.8.6.b Acceptance Testing

Each lot shall be tested with a calibrated nuclear gauge or core samples as determined by the SHA. The percent of maximum theoretical density will be determined for each test.

2.8.6.c PWL

The PWL will be determined for density in accordance with the acceptance plan identified in Section 2.0. An upper and lower quality index value, Q_L, will be calculated for the lot from the following formula:

$$Q_u = \frac{0.98T - \overline{x_n}}{s}$$

$$Q_L = \frac{\overline{x_n} - 0.93T}{s}$$

$$PWL = (PWL_{Upper} + PWL_{Lower}) - 100$$

where

$\overline{x}_n$ = average of n density measurements, lbs/ft^3
T = maximum theoretical density, lbs/ft$_3$
s = sample standard deviation
Q_L = lower quality index value
Q_u = upper quality index value
PWL_{upper} = PWL on upper side of specification
PWL_{lower} = PWL on lower side of specification
PWL = total PWL

ANNEX I

CONFORMAL INDEX APPROACH

An alternative approach to the use of the standard deviations from which the tolerances shown in Table 2-1 were derived is a statistic referred to as the conformal index (CI). This approach was originally identified by Materials Research and Development, Inc. This statistic is a direct measure of process capability and can be used to accurately estimate the size and incidence of deviations (variations) from the quality level target such as the approved target job mix formula (JMF).

The CI, like the standard deviation, is a statistical measure of variation. However, the standard deviation is the root mean square of differences from the arithmetic average, or central value, whereas the CI is the root mean square of the differences from a target such as the JMF value. In other words, the *standard deviation is a measure of precision, and the CI is a measure of exactness (accuracy) or degree of conformance with the target.*

In equation form

$$\sigma = \frac{\sqrt{\sum (x-\bar{x})^2}}{(n-1)} \qquad CI = \frac{\sqrt{\sum (x-T)^2}}{n}$$

The value T in the CI equation refers to the target value (JMF, design thickness, design density, etc.). The relationship between the standard deviation (σ) and the CI is given by the equation

$$CI = \frac{\sqrt{n-1\sigma^2 - nd^2}}{n}$$

where d is the average bias or offset of the average of a group of measurements from the target value.

The CI statistic may be used directly with both percent within limits/percent defective and the loss function approaches. The attractiveness of this statistic is that it focuses on the target value and it is this target value that is defining the quality level.

Figure I-1 presents an illustration of CI values for asphalt content from an SHA for various contractors producing to SHA-approved JMFs. CI values equal to zero meet the target value. The dashed vertical lines are the SHA's tolerances permitted about the JMF (or target) or the lower (L) and upper (U) specification tolerances. The symbols $(PWL)_I$, $(POL)_I$, and $(POL)_U$ refer to the total percent within limits, percent-out-of-limits on the lower specification limit side, and percent out of limits on the upper specification limit side, respectively.

Because these CI values are "normalized" to a specific target value, direct comparison may be made by the contractor as to the magnitude of variation about the target for QC purposes; comparisons by the SHA of the contractor's conformance to the specification for acceptance purposes; and, if desired, comparisons of performance between contractors, projects, etc. This procedure may be used for one-sided or two-sided specification acceptance. This approach also provides for the use of percent defective and percent within limits as quality indicators. Table I-1 provides Superpave LTMF tolerances based on CI values. These values could be used as previously discussed. The values in Table I-1 were developed for individual samples (n = 1). For larger sample sizes, the CI values must be adjusted by the following equation:

$$CI_n = \frac{CI}{\sqrt{n}}$$

where

$CI_{(n)}$ = CI based on sample size n
CI = CI from Table I-1
n = sample size

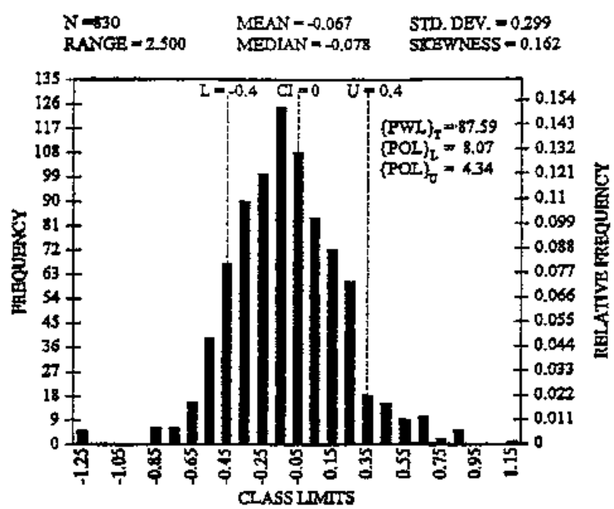


Figure I-1. Example of CI evaluation of asphalt content.

TABLE I-1 Superpave LTMF tolerances based on CI values (mixture composition and gyratory properties)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.31	± 0.24	± 0.18	---
Gradation Passing 4.75-mm (No. 4) and Larger Sieves	± 4	---	---	± 4
Passing 2.36-mm (No. 8) to 150-µm (No. 100) Sieve	± 3	---	---	± 3
Passing 75-µm (No. 200) Sieve	± 0.8	---	---	± 0.9
Maximum Theoretical Specific Gravity (G_{mm})	± 0.015			
Gyratory Compaction Property				
Air Voids (V_a)	± 1			
Voids in Mineral Aggregate (VMA)	± 1.5			
Voids Filled With Asphalt (VFA)	± 5			
Bulk Specific Gravity (G_{mb})	± 0.28			
Compaction Curve Slope (m)	± 0.50			

ANNEX II

STRATIFIED RANDOM SAMPLING APPROACH

SCOPE

This method outlines the procedures for selecting sampling sites in accordance with accepted random sampling techniques. Random sampling is the selection of a sample in such a manner that every portion of the material or construction to be sampled has an equal chance of being selected as the sample. It is intended that all samples, regardless of size, type, or purpose, shall be selected in an unbiased manner, based entirely on chance.

SECURING SAMPLES

Samples shall be taken as directed by the QC representative for QC purposes and the state highway representative for acceptance purposes.

Sample location and sampling procedure are as important as testing. It is essential that the sample location be chosen in an unbiased manner.

RANDOM NUMBER TABLE

For test results or measurements to be meaningful, it is necessary that the sublots to be sampled or measured be selected at random, which means using a table of random numbers. The following table of random numbers has been devised for this purpose. To use the table in selecting sample locations, proceed as follows.

Determine the lot size (continuous production for QC at HMA plant) and stratify the lot into a number of sublots per lot for the material being sampled.

For each lot, use consecutive two-digit random numbers from Table II-1. For example, if the specification specifies five sublots per lot and the number 15 is randomly selected as the starting point from column X (or column Y) for the first lot, numbers 15 to 19 are the five consecutive two-digit random numbers. For the second lot, another random starting point, number 91 for example, is selected and the numbers 91 to 95 are used for the five consecutive two-digit random numbers. The same procedure is used for additional lots.

For samples taken from the roadway, use the decimal values in column X and column Y to determine the coordinates of the sample locations.

In situations where coordinate locations do not apply (i.e., plant samples, stockpile samples, etc.), use those decimal values from column X *or* column Y.

DEFINITION OF TERMS

lot: An isolated quantity of a specified material from a single source or a measured amount of specified construction assumed to be produced by the same process.

sublot: A portion of a lot, the actual location from which a sample is taken. The size of the sublot and the number of sublots per lot for acceptance purposes are specified in the specifications.

THE RANDOM SAMPLE

A random table is a collection of random digits. The random numbers that are presented in this annex are shown in a two-place decimal format. Note that there are two columns, labeled X and Y. The numbers in either column can be used to locate a random sample when only a single dimension is required to locate the sample (e.g., time, tonnage, and units). When two dimensions are required to locate the sample, the number in the X column is used to calculate the longitudinal location, and the number in the Y column is used to calculate the transverse location. In the Y column, each number is preceded by L or R, designating that the sample increment is to be located transversely from the left or right edge of the pavement. Figure II-1 illustrates the procedure.

The following examples demonstrate the use of the random sampling technique under various conditions.

EXAMPLE 1: SAMPLING BY TIME SEQUENCE

Assume that HMA for use in paving is to be sampled to determine the percent asphalt. It will be sampled at the place of manufacture. The task is to select a random sampling plan to distribute the sampling over the half day or the full day, whichever is more applicable. Assume that the lot size is a day's production and that five samples are required from each lot. The plant is assumed to operate continuously for 9 h (beginning at 7:00 am and continuing until 4:00 pm) with no break for lunch.

1. *Lot size.* The lot size is a day's production. The plant starts at 7:00 am and stops at 4:00 pm. Hence, the lot size is 9 h of production.
2. *Sublot size.* Stratify the lot into five equal sublots, because five samples are required. To accomplish this, select five equal time intervals during the 9 h that the plant is operating.

TABLE II-1 Random positions in decimal fractions (two places)

Sequence No.	X	Y	Sequence No.	X	Y
1.	0.29	R 0.66	51.	0.87	L 0.36
2.	0.74	R 0.49	52.	0.34	L 0.19
3.	0.89	L 0.79	53.	0.37	R 0.33
4.	0.60	R 0.39	54.	0.97	L 0.79
5.	0.88	R 0.31	55.	0.13	R 0.56
6.	0.72	L 0.54	56.	0.85	R 0.64
7.	0.12	R 0.08	57.	0.14	L 0.04
8.	0.09	L 0.94	58.	0.99	R 0.74
9.	0.62	L 0.11	59.	0.40	L 0.76
10.	0.71	R 0.59	60.	0.37	L 0.09
11.	0.36	L 0.38	61.	0.90	R 0.74
12.	0.57	R 0.49	62.	0.09	L 0.70
13.	0.35	R 0.90	63.	0.66	L 0.97
14.	0.69	L 0.63	64.	0.89	L 0.55
15.	0.59	R 0.68	65.	0.67	L 0.44
16.	0.06	L 0.03	66.	0.02	R 0.65
17.	0.08	L 0.70	67.	0.93	R 0.17
18.	0.67	L 0.68	68.	0.40	R 0.50
19.	0.83	R 0.97	69.	0.44	R 0.15
20.	0.54	R 0.58	70.	0.03	L 0.60
21.	0.82	R 0.50	71.	0.19	L 0.37
22.	0.66	R 0.73	72.	0.92	L 0.45
23.	0.06	L 0.27	73.	0.20	L 0.85
24.	0.03	L 0.13	74.	0.05	R 0.56
25.	0.55	L 0.29	75.	0.46	R 0.58
26.	0.64	L 0.77	76.	0.43	R 0.91
27.	0.30	R 0.57	77.	0.97	L 0.55
28.	0.51	R 0.67	78.	0.06	R 0.51
29.	0.29	R 0.09	79.	0.72	L 0.78
30.	0.63	R 0.82	80.	0.95	L 0.36
31.	0.53	L 0.86	81.	0.16	L 0.61
32.	0.99	R 0.22	82.	0.29	R 0.47
33.	0.02	R 0.89	83.	0.48	R 0.15
34.	0.61	L 0.87	84.	0.73	R 0.64
35.	0.76	R 0.16	85.	0.05	L 0.94
36.	0.87	L 0.77	86.	0.43	L 0.05
37.	0.41	L 0.10	87.	0.87	R 0.98
38.	0.28	R 0.23	88.	0.37	L 0.71
39.	0.22	L 0.18	89.	0.94	L 0.26
40.	0.21	L 0.94	90.	0.57	L 0.63
41.	0.27	L 0.52	91.	0.26	R 0.80
42.	0.39	R 0.91	92.	0.01	L 0.79
43.	0.57	L 0.10	93.	0.83	R 0.59
44.	0.82	L 0.12	94.	0.71	L 0.21
45.	0.14	L 0.94	95.	0.65	L 0.63
46.	0.50	R 0.58	96.	0.65	L 0.87
47.	0.93	L 0.03	97.	0.72	R 0.92
48.	0.43	L 0.29	98.	0.85	L 0.78
49.	0.99	L 0.36	99.	0.04	L 0.46
50.	0.61	R 0.25	100.	0.29	L 0.95

X = Decimal fraction of total length measured along the road from starting point.

Y = Decimal fraction measured across the road from either outside edge towards center line of the paved lane.

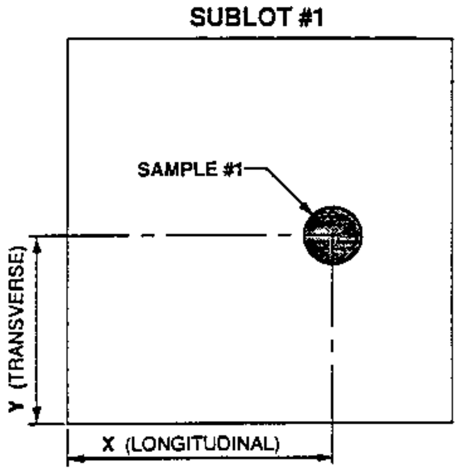


Figure II-1. Determination of sample location using random numbers.

$$\text{Sublot time interval} = \frac{(9\ \text{h/lot})(60\ \text{min/h})}{5\ \text{sublots/lot}}$$
$$= 108\ \text{min/sublot}$$

3. *Sublot samples.* Next, choose five random numbers from the random number table. The first block randomly selected is reproduced below.

Sequence number	*X*	*Y*
12	0.57	R 0.46
13	0.35	R 0.60
14	0.69	L 0.63
15	0.59	R 0.68
16	0.06	L 0.03

The selected random numbers taken from the X column are 0.57, 0.35, 0.66, 0.56, and 0.06. To randomize the sampling times within each sublot, the time interval (108 min) computed in Step 2 is used. This time interval is multiplied by each of the five random numbers previously selected:

Sublot 1: $0.57 \times 108 = 62$ min
Sublot 2: $0.35 \times 108 = 38$ min
Sublot 3: $0.69 \times 108 = 75$ min
Sublot 4: $0.59 \times 108 = 64$ min
Sublot 5: $0.06 \times 108 = 6$ min

These times are added to the starting times for each sublot. This results in the randomized time at which the sample is to be obtained. The sampling sequence is as follows:

Sublot Number		*Sampling Time*
1	7:00 am + 62 min =	8:02 am
2	8:48 am + 38 min =	9:26 am
3	10:36 am + 75 min =	11:51 am
4	12:24 pm + 64 min =	1:28 pm
5	2:12 pm + 6 min =	2:18 pm

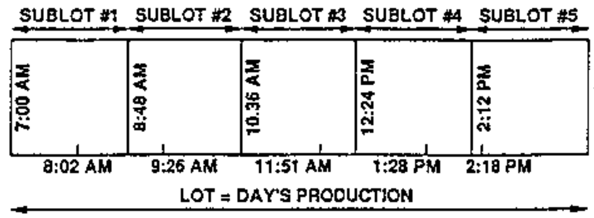


Figure II-2. Sublot sample times based on time sequence.

The random sampling times are shown in Figure II-2. If production is not available at the indicated time, a sample should be obtained at the first opportunity after the indicated time.

Sampling on a time basis is practical only when the process is continuous. Intermittent processes obviously present many difficulties.

EXAMPLE 2: SAMPLING BY MATERIAL TONNAGE

HMA for use in paving must be sampled to determine the asphalt content. The specifications define the lot size as 5,000 tons and state that five samples must be obtained from the lot. The sampling is to be done from the hauling units at the manufacturing source. The total tonnage for the project is 20,000 tons.

This solution follows the same basic pattern as the solution given for the previous example. First, identify the lot size and then determine the number of lots, sublot size, and, finally, the point at which samples will be obtained.

1. *Lot size and number of lots.* The lot size is 5,000 tons. Because there are 20,000 tons of bituminous mix required for the project, the total number of lots is

$$\text{Number of lots} = \frac{20{,}000\ \text{tons}}{5{,}000\ \text{tons/lot}} = 4\ \text{lots}$$

2. *Sublot size.* Stratify each lot into five equal sublots. The sublot size is

$$\text{Sublot size} = \frac{5{,}000\ \text{tons/lot}}{5\ \text{sublots/lot}} = 1{,}000\ \text{tons/sublot}$$

   The relationship between lot and sublot size is shown in Figure II-3.

3. *Sublot samples.* The number of samples per lot is five, one per sublot. Five random numbers are therefore selected from the table of random numbers. Again, the first block of numbers from the random number table is reproduced below. This time, a different set of numbers is selected

Sequence number	*X*	*Y*
67	0.93	R 0.17
68	0.40	R 0.50
69	0.44	R 0.15
70	0.03	L 0.60
71	0.19	L 0.37

The selected random numbers this time are from the Y column (disregard the L or R): 0.17, 0.50, 0.15, 0.60, and 0.37. These numbers are then multiplied by each of the five sublots as follows:

Sublot number	*Sublot random number*	*Size (tons)*	*Ton to be sampled*
1	0.17	1,000	170
2	0.50	1,000	500
3	0.15	1,000	150
4	0.60	1,000	600
5	0.37	1,000	370

The technician must obtain the first sample at approximately the 170th ton of the first sublot. The technician must then wait until the first sublot is completed (1,000 tons) before selecting the second sample at the 500th ton of the second sublot. The same sequence is followed for obtaining the remaining three samples.

The sampling sequence for the lot (5,000 tons) should be

Sublot 1: 170th ton
Sublot 2: 1,000 + 500 = 1,500th ton
Sublot 3: 2,000 + 150 = 2,150th ton
Sublot 4: 3,000 + 600 = 3,600th ton
Sublot 5: 4,000 + 370 = 4,370th ton

Different random numbers are selected for the other four lots.

Sampling by production unit is a simple means of obtaining a random sample. Interruptions in the process do not affect randomization, and the relationship between the number of samples and the lot remains unchanged (Figure II-4).

EXAMPLE 3: SAMPLING AN AREA

Suppose that HMA from the roadway is to be sampled to determine the density for QC or acceptance purposes. The

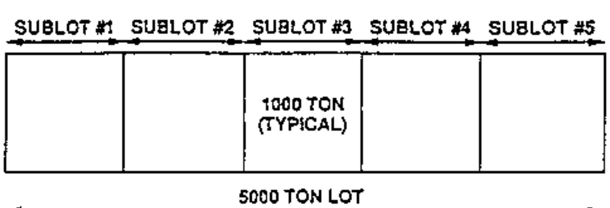


Figure II-3. Relationship between lot and sublots based on tonnage.

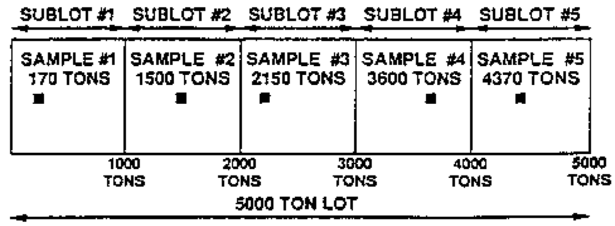


Figure II-4. Sublot sample based on tonnage.

specifications state that the lot size is 5,000 linear ft, and five samples per lot are required. In addition, assume that the paving width is 12 ft and that the project begins at Station 100+00 and ends at Station 300+00.

1. *Lot size and number of lots.* The specifications require a lot size of 5,000 linear ft. The distance from Station 100+00 to Station 300+00 is 20,000 ft. The number of lots is

$$\text{Number of Lots} = \frac{20{,}000 \text{ ft}}{5{,}000 \text{ ft/lot}} = 4 \text{ lots}$$

2. *Sublot size.* The beginning station for the first lot is 100+00. This lot ends at Station 150+00 as shown in Figure II-5. This is equal to 5,000 ft. The 5,000 ft of paving must be stratified into five equal sublots, because five samples per lot are required.

$$\text{Sublot size} = \frac{5{,}000 \text{ ft/lot}}{5 \text{ sublots/lot}} = 1{,}000 \text{ ft/sublot}$$

   Figure II-5 shows how this lot is divided.

3. *Sublot samples.* The location at which each sample will be obtained must be randomized in the longitudinal as well as the transverse direction. This was illustrated in Figure II-1. The random number selection procedure is the same as used for the previous examples except that two sets (columns, rows, etc.) of random numbers are selected: one for the transverse position, the other for the longitudinal position. A set of five random numbers for the longitudinal (X) and transverse (Y) position of the sample is chosen by using the first and second

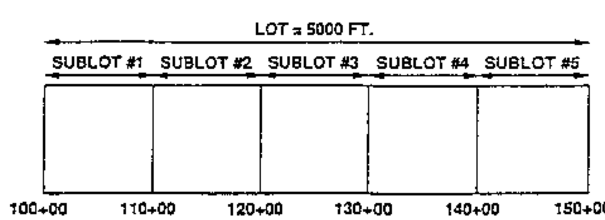


Figure II-5. Relationship between lot and sublots based on area.

blocks of random numbers from the random number table. These are reproduced as follows:

Sequence number	*X*	*Y*
37	0.41	L 0.10
38	0.28	R 0.23
39	0.22	L 0.18
40	0.21	L 0.94
41	0.27	L 0.52

The numbers are selected from both X and Y columns. Include the L or R in the Y column:

Longitudinal (X):	0.41	0.28	0.22	0.21	0.27
Transverse (Y):	L 0.10	R 0.23	L 0.18	L 0.94	L 0.52

These X and Y random numbers are multiplied by the sublot length and paving width respectively, as shown below:

Sublot 1 (starting Station 100+00)
Coordinate X = 0.41 × 1,000 ft = 410 ft
Coordinate Y = 0.10 × 12 ft = 1.2 ft
Sublot 2 (starting Station 110+00)
Coordinate X = 0.28 × 1,000 ft = 280 ft
Coordinate Y = 0.23 × 12 ft = 2.8 ft
Sublot 3 (starting Station 120+00)
Coordinate X = 0.22 × 1,000 ft = 220 ft
Coordinate Y = 0.18 × 12 ft = 2.2 ft
Sublot 4 (starting Station 130+00)
Coordinate X = 0.21 × 1,000 ft = 210 ft
Coordinate Y = 0.94 × 12 ft = 11.3 ft
Sublot 5 (starting Station 140+00)
Coordinate X = 0.27 × 1,000 ft = 270 ft
Coordinate Y = 0.52 × 12 ft = 6.2 ft

The longitudinal distance (X) is added to the beginning station of the sublot and the companion transverse distance (Y) is measured from the selected edge of paving. The L values of Y will be measured from the left edge of paving (looking ahead) and the R values of Y will be measured from the right edge of paving.

Sample no.	
1	Station 100+00 + 410 ft = 104+10 @ 1.2 ft from left edge
2	Station 110+00 + 280 ft = 112+80 @ 2.8 ft from right edge
3	Station 120+00 + 220 ft = 122+20 @ 2.2 ft from left edge
4	Station 130+00 + 210 ft = 132+10 @ 11.3 ft from left edge
5	Station 140+00 + 270 ft = 142+70 @ 6.2 ft from left edge

Figure II-6 illustrates the sampling locations based on these calculations.

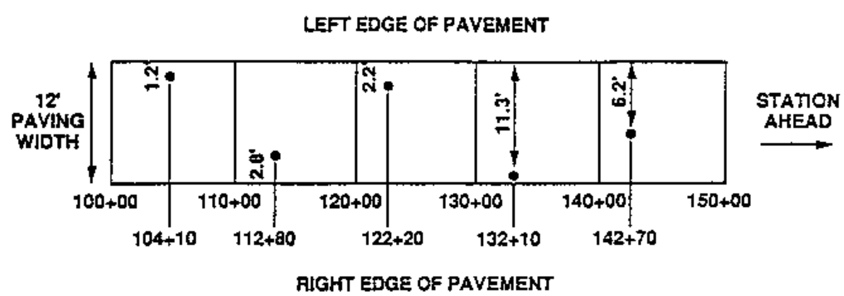


Figure II-6. Sublot sample location based on area.

ANNEX III

STATISTICAL CONTROL CHARTS

The process control procedure recommended is the use of control charts, particularly statistical control charts. Control charts provide a means of verifying that a process is in control. It is important to understand that statistical control charts **do not** get or keep a process under control. The process must still be controlled by the plant or construction personnel. Control charts simply provide a visual warning mechanism to identify when the Contractor or material supplier should look for possible problems with the process.

Variation of construction materials is inevitable and unavoidable. The purpose of control charts, then, is not to eliminate variability but to distinguish between the inherent or **chance causes** of variability and a system of **assignable causes**. Chance causes (sometimes known as common causes) are a part of every process and can be reduced but generally not eliminated. Assignable causes (sometimes known as special causes) are factors that can be eliminated, thereby reducing variability. Chance causes are something that a Contractor or material supplier must learn to live with. They cannot be eliminated, but it may be possible to reduce their effects. The second cause of variation, assignable causes, can create major problems. However, assignable causes *can* be eliminated **if** they can be identified. Examples of assignable causes might be the gradation for an aggregate blend going out of specification because of a hole in one of the sieves or because the cold feed conveyor setting is incorrectly adjusted.

The statistical control charts enable the Contractor to distinguish between chance and assignable causes. Based on statistical theory, construction materials, when under production control, exhibit a "bell-shaped" or normal distribution curve.

The data, therefore, can be assumed to be within $\pm 3\sigma$ of the mean or target when the process is in control and only chance causes *(variability that the Contractor cannot control)* are acting on the system. Statistical control charts for average or means rely on the fact that, for a normal distribution, essentially all the values fall within $\pm 3\sigma$ from the mean. The normal distribution can be used because the distribution of sample means is normally distributed.

A statistical control chart can be viewed as a normal distribution curve on its side (Figure III-1). For a normal curve, only about 0.27 percent (1 of 370) of the measurements should fall outside $\pm 3\sigma$ from the average or mean. Therefore, control limits (indicating that an investigation for an assignable cause should be conducted) are set at $+3\sigma\bar{x}$ and $-3\sigma\bar{x}$

A statistical control chart includes a target value, upper and lower control limits, and a series of data points that are plotted. The target is based on the population or production mean and the control limits are established from the population or production standard deviation as shown in Figure III-2.

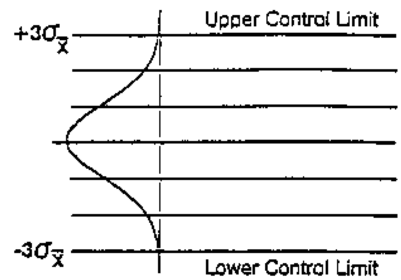


Figure III-1. Example of statistical control chart.

There are many forms of statistical control charts, but two forms are most practical and useful for construction materials and processes. These are the control charts for means or averages (commonly referred to as x, called x-bar chart) and the control chart for ranges (commonly referred to as an R-chart). The x-chart is typically used to control the production process about the average or target value. The R-chart considers the variability of the material and prevents extremely large positive and negative results from canceling out and not being detectable on the control chart for means or averages. The range, which is the easiest measure of spread to use in the field, is usually used in place of the standard deviation.

Population or production parameters (i.e., averages and ranges) are either known (or specified) or are estimated from the early stages of the production process. In most cases, the latter is true. It is not a good idea for a producer to use the mean, range, or standard deviation that were specified or

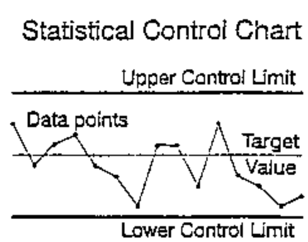


Figure III-2. Elements of statistical control chart.

TABLE III-1 Factors for statistical control charts

n	A_2	D_3	D_4
2	1.88	0	3.27
3	1.02	0	2.58
4	0.73	0	2.28
5	0.58	0	2.12
6	0.48	0	2.00
7	0.42	0.08	1.92

used by the highway agency when it developed the specification limits. The mean, range, and standard deviation of a producer's process are independent of the specification limits; they are established by the process capability.

When the mean and standard deviation are not known (this is usually the case), they are estimated by the *grand average or mean* ($\bar{\bar{X}}$) and the *average range* ($\bar{R}$). The grand average or mean is defined as the average value of a group of averages. The average range is defined as the average of individual range values. For the $\bar{X}$-chart, the grand mean becomes the target value; for the R-chart, the average range becomes the target value.

The following formulas are used to construct the two control charts:

TABLE III-2 Data for demonstration example

	Percent Passing 4.75mm (No. 4) Sieve					
No.	X_1	X_2	X_3	X_4	$\bar{X}$	R
1	18.9	18.2	19.3	17.2	18.4	2.1
2	18.2	16.3	17.2	20.4	18.0	4.1
3	18.5	19.5	17.8	19.1	18.7	1.7
4	19.7	17.6	18.3	19.2	18.7	2.1
5	23.5	22.5	14.9	23.6	21.1	8.7
6	16.6	16.9	17.4	18.8	17.4	2.2
7	19.0	17.9	15.8	18.4	17.8	3.2
8	14.5	17.7	18.0	20.1	17.6	5.6
9	18.5	16.3	17.3	17.2	17.3	2.2
10	15.2	20.4	20.4	16.4	18.1	5.2
11	19.5	16.4	20.7	17.7	18.6	4.3
12	17.4	17.9	17.7	22.4	18.9	5.0
13	15.6	18.1	18.7	19.8	18.1	4.2
14	22.2	17.1	16.7	21.2	19.3	5.5
15	20.1	12.8	18.5	17.0	17.1	7.3
16	19.6	18.0	17.4	14.8	17.5	4.8
17	19.5	19.9	20.1	15.7	18.8	4.4
18	19.9	20.7	19.8	18.3	19.7	2.4
19	20.9	19.9	16.5	16.2	18.4	4.7
20	14.2	18.1	17.1	16.2	16.4	3.9
21	16.7	13.6	11.4	18.4	15.0	7.0
22	18.7	17.3	16.1	15.8	17.0	2.9
23	22.7	18.3	23.8	15.3	20.0	8.5
24	17.3	18.2	16.8	17.2	17.4	1.4
25	20.8	16.7	16.0	22.1	18.9	6.1
26	17.5	21.3	19.1	20.2	19.5	3.8
27	13.6	16.8	19.2	12.1	15.4	7.1
28	19.5	18.3	16.5	18.1	18.1	3.0
29	17.7	18.5	17.4	16.9	17.6	1.6
30	16.4	17.5	15.2	17.8	16.7	2.6
31	15.3	14.5	17.3	21.2	17.1	6.7
32	13.7	18.4	16.1	19.1	16.8	5.4
33	13.4	20.3	18.8	19.5	18.0	6.9
34	14.6	21.9	18.5	14.9	17.5	7.3
35	16.0	20.4	14.7	20.0	17.8	5.7
36	17.2	18.5	15.8	20.0	17.9	4.2
37	18.8	15.0	20.2	15.2	17.3	5.2
38	21.4	17.7	13.1	19.6	18.0	8.3
39	16.5	18.8	20.0	19.2	18.6	3.5
40	19.4	18.6	15.4	22.0	18.9	6.6

$\overline{X}$-chart

$$\text{Upper Control Limit (UCL)} = \overline{\overline{X}} + (A_2 \times \overline{R})$$
$$\text{Lower Control Chart (LCL)} = \overline{\overline{X}} - (A_2 \times \overline{R})$$

R-chart

$$\text{Upper Control Limit (UCL)} = D_4 \times \overline{R}$$
$$\text{Lower Control Limit (LCL)} = D_3 \times \overline{R}$$

The factors A_2, D_3, and D_4 are obtained from Table III-1 for the appropriate sample size n. Note that the sample size is always greater than 1. For each QC test, the samples are grouped to form a subgroup of 2 or larger.

EXAMPLE: CONTROL CHARTS WHEN MEAN AND STANDARD DEVIATION ARE UNKNOWN

The data shown in Table III-2 will be used to illustrate the calculation for a control chart when the population parameters are unknown and are estimated from the early production process. The table contains the gradation results for percent passing the 4.75-mm (No. 4) sieve for 40 production days (four tests per day). The average and range of the first 20 subgroups are used to estimate the mean and standard deviation of the population. When this is done

$$\overline{X} = \frac{18.4 + 18.0 + \ldots + 18.4 + 16.4}{20} = \frac{365.9}{20} = 18.3$$
$$\overline{R} = \frac{2.1 + 4.1 + \ldots + 4.7 + 3.9}{20} = \frac{83.6}{20} = 4.2$$

Having found these values, the UCL and LCL can be calculated from the formulas previously identified. Note that the values for A_2, D_3, and D_4 are for a sample subgroup of $n = 4$ because four samples are used to find each average, $\overline{X}$, and range, R.

$\overline{X}$-chart

$$\text{UCL} = \overline{X} + (A_2 \times \overline{R} = 18.3 + (0.73 \times 4.2) = 21.4$$
$$\text{LCL} = \overline{X} - (A_2 \times \overline{R} = 18.3 - (0.73 \times 4.2) = 15.2$$
$$\text{Target Value} = \overline{X} = 18.3$$

R-chart

$$\text{UCL} = D_4 \times \overline{R} = 2.28 \times 4.2 = 9.6$$
$$\text{LCL} = D_3 \times \overline{R} = 0.0 \times 4.2 = 0.0$$
$$\text{Target Value} = \overline{R} = 4.2$$

Once the target value and control limits are established, the control charts can be constructed with the data in Table III-2. Figures III-3 and III-4 illustrate the $\overline{X}$ and R-charts for the data.

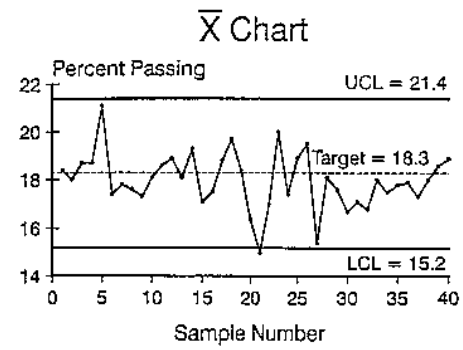


Figure III-3. $\overline{X}$-chart for percent passing 4.75-mm (No. 4) sieve.

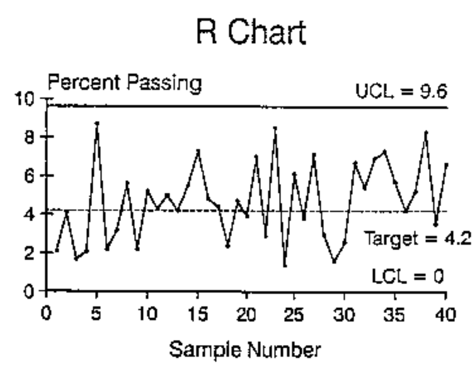


Figure III-4. R-chart for percent passing 4.75-mm (No. 4) sieve.

CHAPTER 3

GUIDELINES FOR ADJUSTING THE PRODUCTION AND PLACEMENT OF SUPERPAVE-DESIGNED HMA

This chapter contains guidelines for solving problems that occur during production of the HMA designed in accordance with the Superpave method. These problems can be classified as noncomplying gradation and HMA test properties, undesirable placement characteristics, and undesirable characteristics of the finished pavement. Solutions often require additional testing, analysis, and adjustments. These guidelines are based on the National Asphalt Pavement Association's (NAPA) publication QIP-97, "Quality Control for Hot-Mix Plant and Paving Operations." These practices were followed on the NCHRP Project 9-7 construction projects and are applicable to the Superpave-designed HMA production and placement operations.

3.1 NONCOMPLYING GRADATION TESTS

3.1.1 Incoming Aggregates

If a reliable estimate of the actual gradation of the different sizes of aggregates indicates that it will not be possible to produce a mixture meeting the Superpave mix specifications and the LTMF requirements, and if these requirements cannot be modified, one of the following courses of action is suggested:

- Compute an acceptable theoretical combined gradation based on wasting some portions of the delivered material.
- Check to see if blending an additional size of aggregate with delivered material will produce an acceptable combined gradation.
- Reject aggregate and procure material from an alternative source.

3.1.2 Combined Hot Bin Aggregate

If the combined gradation of the hot bin aggregate does not fall within the LTMF tolerances, the following procedures are recommended:

- Resample fine aggregate bin and make gradation tests to check previous sampling.
- If resampling results check closely with previous sampling, recompute the gradation to see if changing bin weights will produce an acceptable combined gradation. If this is not possible because of a lack of one or more sieve sizes in the raw aggregates, follow the procedures described previously for incoming aggregates.
- If resampling does not check with previous sampling
  1. Check sampling methods to make sure that the sample truly represents bin contents,
  2. Make a series of tests on the bins where variations in gradation occur to determine if differences are due to
     a. Hole in the screen.
     b. Temporary overrun into the bin caused by crowding the plant and exceeding the capacity of the screen.
     c. Continued overrun caused by blinding of the screen; this condition occurs when particles of aggregate plug up the openings in the screen; blinding can usually be avoided or reduced by substituting a slotted screen or one with slightly larger openings.
     d. Problems in the cold feed; check cold feed for proportions and consistency; moisture in fine aggregate can cause inconsistent feedings.

3.2 NONCOMPLYING HMA TEST RESULTS

3.2.1 Air Voids Above or Below Specifications

The percent of air voids in the compacted HMA depends on the percent of voids in the mineral aggregate and the percent of asphalt. When the percent of air voids is too high or too low, placement problems will occur. The standard deviation in a normal determination of percent air voids is about 1 percent. This means that at least six different samples of HMA should be tested and averaged to determine if the percent air voids is within the specified range. The usual range is 3 to 5 percent. If the air voids are not within the Superpave mix design specifications, the following actions should be taken:

- Check that the correct value of maximum theoretical specific gravity has been used in the computations; small variations in the maximum theoretical specific gravity can cause significant differences in the calculated air voids content.

- Check the procedure used to determine the bulk specific gravity of the specimen.
- Check that the mix sampled is representative; if the asphalt content of the sample is not in agreement with the LTMF, the voids' properties will not match the mix design.
- If all checks show that correct values are being used, the asphalt content may be adjusted to produce an average of 4 percent (or other specified value) of air voids.
- If it is not possible to change the asphalt content, the VMA must be adjusted by changing the gradation as described in the following paragraphs.

3.2.2 VMA

The VMA are the bulk volume of the compacted paving minus the volume of the aggregate determined from its bulk specific gravity. It can also be viewed as the volume of air voids plus the volume of effective asphalt binder. It is expressed as a percent of the bulk volume of the compacted mix.

The VMA is very important in the Superpave mix design method, particularly for wearing and surface course mixtures. Space must be left in the compacted mixture to allow room for the specified asphalt content and air voids. The unfilled voids (air voids) must be present to allow room for the asphalt to expand and for compaction under traffic loads during periods of hot summer temperatures. This will prevent the asphalt from flushing to the surface and causing the mixture to become plastic.

The Superpave mix design procedure aims to produce wearing course mixes that have, after traffic compaction, about 4 percent by volume of air voids, with about 75 or 80 percent of the VMA filled with asphalt binder. To meet these conditions, the Superpave minimum VMA design requirements are based on the nominal maximum aggregate size. Dense gradations that produce mixes below these values do not have enough room for the asphalt binder. This is particularly a problem when natural sand and bank-run gravel are used as aggregates. Mixes made with these rounded particles have been observed to flush and ravel at the same time. The fine particles collected by baghouse dust collectors can also reduce the air voids content and cause a low value of voids in the mineral aggregate.

Assuming ultimate traffic compaction, VMA depends on the following:

- Roundness or lack of angularity of aggregate particles;
- Gradation of coarse and fine aggregate; and
- Amount of filler or material passing the No. 200 sieve.

3.2.3 Increasing VMA

The percent of VMA can be increased by any of the following:

- Using more angular crushed aggregate in the mix. Substituting manufactured fine aggregate or screenings produced by crushing is usually effective if the fraction passing the 0.075-mm (No. 200) sieve is controlled.
- Decreasing the percentage of material passing the 0.150-mm (No.100) sieve by wasting all or part of the dust returned from the dust collector. Reducing the percent of minus 0.150-mm (No.100) material will increase the VMA.
- Increasing the amount of 4.75-mm (No. 4) to 0.150-mm (No. 100) aggregate. This may require an increase in the amount of asphalt binder.
- Moving gradation away from the maximum density line 0.45 power curve.

3.2.4 Decreasing VMA

The percent of VMA can be decreased by any of the following:

- Use of rounded or cubical coarse aggregate;
- Use of a fine aggregate consisting of natural sand with rounded particles;
- Increasing the amount of filler in the mixture (Note: there is a practical limit on the amount passing the 0.075-mm (No. 200) sieve that can be tolerated in a mix; the rule of thumb is that the percent of filler by weight should not exceed approximately 1.2 times the percent of effective asphalt by weight).

3.2.5 VFA

The percent of VFA affects the durability and flexibility of the pavement. A good target value is about 75 percent. For a mix designed for a wearing course for normal highway traffic, values of less than 65 percent can cause premature or excessive hardening of the asphalt binder in the pavement, cracking, and even raveling. Values greater than 85 percent can lead to flushing, shoving, and rutting. The optimum VFA can be obtained when the air voids content is 4 percent and the VMA is that specified in the Superpave mix design method for the nominal maximum aggregate size. Adjustments in the percent of air voids and VMA are made by the methods discussed in the preceding paragraphs.

3.3 NONCOMPLYING FIELD DENSITY TESTS

Studies have shown that the density of an asphalt paving course is usually highest in the center of the lane, because of overlapping roller coverages. It is lower at the edges of the lane because of fewer coverages. This causes a variation in density when nuclear density or pavement cores are taken at random locations across the lane.

If an accurate measurement of pavement density falls below the specified percent of reference density, it may be due to the following conditions:

1. Use of a maximum theoretical density based on inaccurately measured or assumed specific gravities of aggregates and asphalt binder. The maximum theoretical specific gravity of the mixture as determined by procedures described in AASHTO Method ASTM D2041 (the “Rice Method”) is a way to test the total mix rather than base the result on the properties of the individual aggregates.
2. Use of a reference density based on gyratory-compacted specimens that were overcompacted or made at too high a temperature.
3. Insufficient field compaction caused by underweight rollers, the wrong type of roller, or insufficient coverages.
4. Rolling at too low a temperature.
5. Difficulties in compacting tough mixtures. These HMA may have a high strength or too much filler in relation to the amount and properties of the asphalt binder in the mix. The resulting pavement may have high air voids content.
6. Presence of clay dust in the material passing the 0.075-mm (No. 200) sieve in the mixture.
7. Compacting against soft and yielding bases and subbases. The pavement cannot be compacted if the material beneath it is soft and yielding. The specified density and the deflection of the surface on which HMA pavement is to be constructed should be checked before start of laydown.
8. Tender mix.

3.4 MISCELLANEOUS IRREGULARITIES IN PAVEMENT

3.4.1 Checking and Cracking of Newly Constructed Pavement

This condition is usually caused by improper rolling techniques. A competent roller operator will avoid the following situations:

1. Overrolling a tender mix;
2. Rolling a mat that has cooled on the surface but is plastic underneath or rolling when the roller wheels are too cold;
3. Rolling a dense mix while it is too hot;
4. Overrolling when the base deflects;
5. Rolling too fast, turning abruptly, or starting and stopping abruptly; and
6. Using a highly temperature-susceptible asphalt binder.

3.4.2 Shoving of the Compacted Pavement

Shoving of paving mixtures during construction may be caused by

1. Using a too-heavy roller;
2. Operating a breakdown roller when drive wheels are not toward the paver;
3. Rolling a plastic mix, caused by temperatures that are too high or by a mix design with too high a VFA value; and
4. Moisture in mix.

3.4.3 Raveling in the Finished Pavement

Raveling may be caused by

1. Asphalt content too low;
2. Excessive segregation while loading trucks;
3. Rolling at too low a temperature, parts of load too cold;
4. Rolling a wet mat, too much water on roller wheels;
5. Dirt coating on aggregates, incomplete coating of aggregates, unsuitable filler; and
6. Excessive hardening of asphalt, caused by too high a temperature in one or more of the aggregate hot bins.

3.4.4 Tender Pavements

Tender HMA will push and shove under the roller. It will take an unusually long time to set and will scuff or scar under turning wheels. Tender HMA and pavement are caused by the following:

1. Slow setting asphalt (slow to develop strength needed during construction);
2. Contaminated asphalt/cement;
3. Too much diesel oil (used as release agent) in the bottom of trucks;
4. Too much asphalt binder in the mix;
5. Too little asphalt binder in the mix;
6. Too much dust in a batch; and
7. Excessive moisture in a dense hot mix.

CHAPTER 4

A TRAINING COURSE TO IMPLEMENT QC/QA PLANS FOR PRODUCTION AND PLACEMENT OF SUPERPAVE-DESIGNED HMA

4.1 INTRODUCTION

The training course developed through NCHRP Project 9-7 should assist agencies, contractors and others in implementing the Superpave QC/QA recommendations from the project. The training package was developed with several different modules so that training could be tailored to the specific needs of the audience. The modules are as follows:

Module I: Introduction to the Training Course
Module II: Superpave Mix Design and Analysis
Module III: QC/QA Concepts
Module IV: Plant Activities
Module V: Laboratory Activities
Module VI: QC Plan for Superpave-Designed HMA
Module VII: QA Plan for Superpave-Designed HMA

4.2 OVERVIEW OF TRAINING COURSE

The detailed outline of the training course presented below illustrates all the various topics that are covered and provides insight on how to use the modular structure of the course effectively.

Module I. Introduction to the Training Course
- Course objectives
- Certification

Module II. Superpave Mix Design and Analysis
- Introduction to the Superpave mix design and analysis system
- Performance-graded binder testing and selection
- Aggregate testing and selection
- Volumetric mix design concepts
- Superpave volumetric mix design process
- Superpave mix analysis concepts

Module III. QC/QA Concepts
- Definitions of QC/QA
- Statistical background
- Randomized sampling techniques
- Lot/sublot concepts
- Statistical control charts
- PWL
- Conformal indices (optional)

Module IV. Plant Activities
- Plant calibration
- Plant gradation controls
- Mix temperature requirements
- Proper sampling techniques
- Plant adjustments

Module V. Laboratory Activities
- Laboratory testing equipment calibration
- Frequency and sequence of tests
- Testing protocols and procedures
- Test results and interpretations

Module VI. QC Plan for Superpave-Designed HMA

Part I
- Background/objectives of NCHRP Project 9-7
- Development and assumptions of QC/QA procedures
- Development of field shear testing devices
- Contractor responsibilities
- Development of tolerance limits
- Application of statistical control charts
- Gyratory procedures for QC/QA

Part II
- Binder certification
- Establishing the LTMF
- Selection of properties for control
- Laboratory verification of LTMF
- Field verification of LTMF
- Mix production QC
- In-place QC
- Courses of action throughout QC process

Module VII. QA Plan for Superpave-Designed HMA
- Agency responsibilities
- PWL approach
- Binder acceptance

- Specification/tolerance limits for acceptance
- Selection of properties for acceptance
- Acceptance of LTMF/JMF (lab, field, mix, in-place)
- Comparison of QC and QA data-dispute resolution

This chapter includes the slides and instructor's notes for Modules VI and VII. Appendix A contains the slides for Modules I through V. The instructors notes and slides were developed assuming that those presenting the course material have a thorough knowledge of the Superpave mix design and analysis system and an understanding of the statistical concepts related to QC and QA procedures.

Slide 1 This module will provide information detailing the basis for the QC Plan developed for Superpave-designed mixes. Superpave QC/QA needed to be developed to help implement the overall Superpave system. The Superpave system includes mixture design, mixture analysis, and production/construction.

Superpave Quality Control Plan

Part I - Background and Development

Module VI — Part 1: Slide 1

Slide 2 After the end of the SHRP research effort, the need for a Superpave QC/QA Plan was identified by both government and industry groups. NCHRP Project 9-7 was awarded in March 1993 to address this need.

National Cooperative Highway Research Program

Project 9-7

Field Procedures and Equipment to Implement SHRP Asphalt Specifications

BRE Inc.

Module VI — Part 1: Slide 2

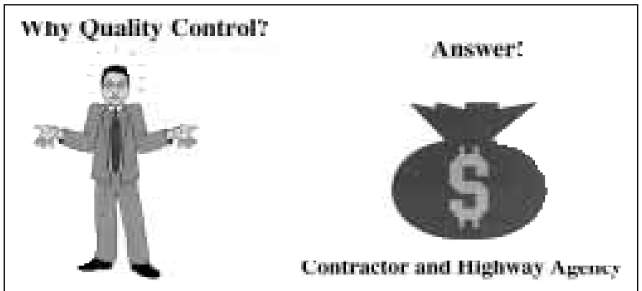
Slide 3 The objectives established for this contract were to establish procedures and develop equipment for QC/QA at the plant and lay down as well as develop a mechanism for training technicians and engineers on Superpave QC/QA procedures.

NCHRP Project 9-7 Objectives:

- Establish procedures and develop equipment for quality control/quality assurance at the asphalt plant and laydown site.
- Develop training program framework for qualifying technicians.

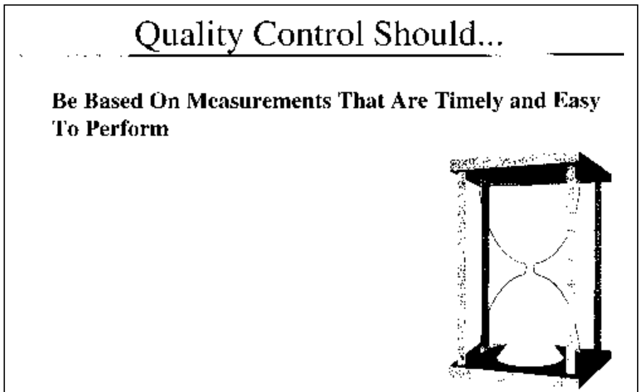
Module VI — Part 1: Slide 3

Slide 4 There are several reasons for ensuring quality throughout the production of HMA, but the bottom line comes down to money. Generally, the contractors make more money when they produce a quality product and highway agencies (i.e., the taxpayers) save money in future maintenance costs if quality is built into pavements.



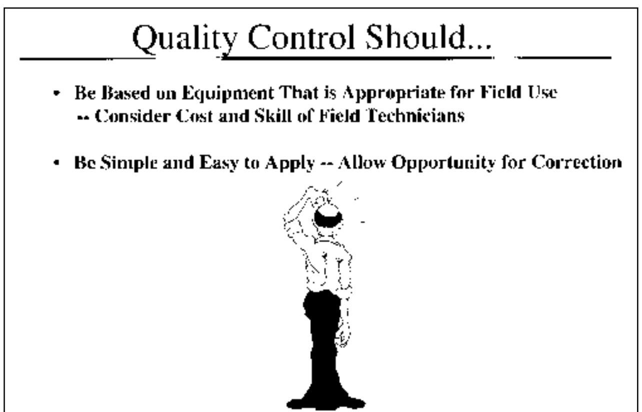
Module VI — Part 1: Slide 4

Slide 5 Some of the basic principles of HMA QC state that QC should be based on measurements that are timely and easy to perform. The contractor and client do not want to wait a long time before they find out that the HMA does not conform to required specifications. Extended waits will cost significant amounts of money.



Module VI — Part 1: Slide 5

Slide 6 QC also should be based on equipment that is appropriate for field use and the QC process should also be simple and easy to apply. Agencies do not want to spend large sums of money to obtain QC equipment, nor do they want to have to hire additional technicians with specialized skills or training. Agencies will want to train existing employees.



Module VI — Part 1: Slide 6

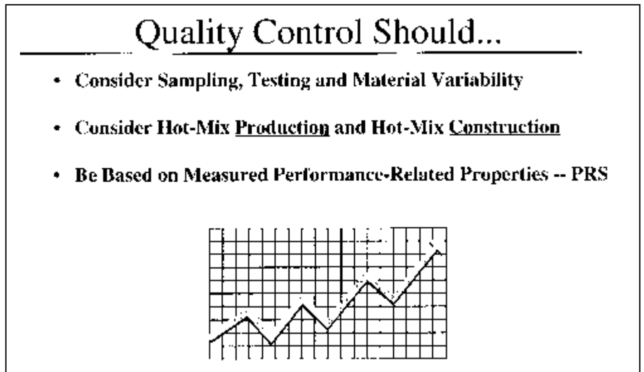
Slide 7 There are three basic areas where variation can be introduced into the QC process. They are sampling, testing, and material variability. A QC Plan that is developed correctly should account for each of these areas.

A QC Plan should also differentiate between HMA production and construction.

Production: material coming out of the plant. Is it correct?

Construction: material being placed on the roadway. Is it correct?

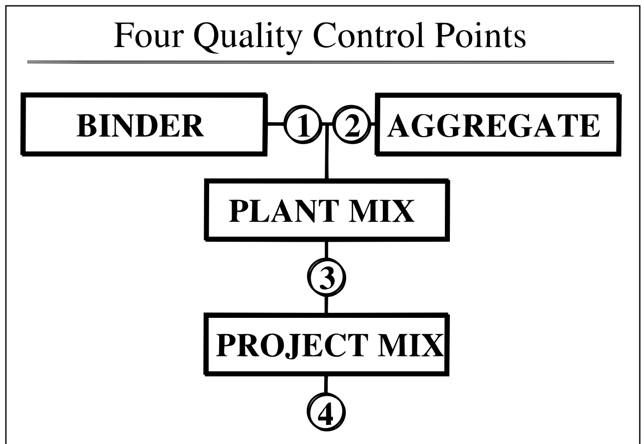
Finally, a QC plan also should be based on performance-related properties or properties that can be used to determine how a mixture will perform if a deviation occurs from the original mix design (i.e., poor QC). Performance-related specifications are typically based on these types of properties and are important when pay factors are involved.



Module VI — Part 1: Slide 7

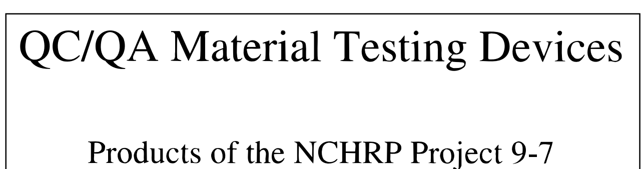
Slide 8 There are essentially four points at which QC should occur throughout the HMA production/construction process. Points one and two are the QC processes that occur with the materials used in the production of HMA mixtures. Binder (or asphalt cement) should be checked to make sure that it conforms to the performance-graded (PG) properties determined during the mix design process. The aggregates should also be checked to ensure that the blended materials meet the gradation requirements (or other properties as identified by the QC Plan) determined in the initial mix design.

The third point in the QC process occurs after the materials have been mixed through the plant production process. Various properties of the HMA mix should conform, within specified tolerances, to those values established in the mix design process. These properties traditionally have included air voids, percent asphalt, VMA, and some type of strength parameter. The final point in the QC process is the determination of the in-place properties. This occurs after the HMA has been placed by a lay down machine and compacted by a series of passes of heavy rollers. Typically, in-place compaction is checked against some minimum value of air voids that must be attained by the use of nondestructive testing (NDT) methods. The NDT values are verified with a small sample of in-place cores (or destructive sampling).



Module VI — Part 1: Slide 8

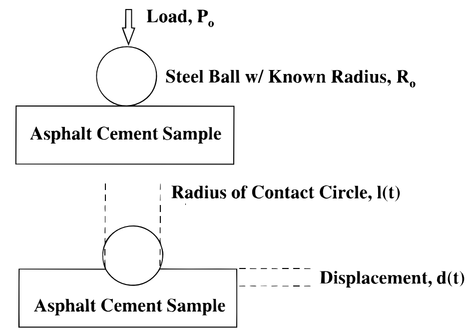
Slide 9 Several devices that can be used in the QC process were evaluated or developed in the NCHRP Project 9-7 research effort. These products include devices for performing QC on binders, aggregates, and mixtures.



Module VI — Part 1: Slide 9

Slide 10 The SDR is a device that can be used to quickly determine the quality of asphalt binders at the plant lab. The device at first glance looks like the ring and ball test but it is very different from that device because the SDR operates only in the elastic region of the material (i.e., all deformation is recoverable). In the SDR test an indentor of known weight is placed on a sample at a given temperature for a given time period. The displacement of the sample is measured and various properties of the sample are determined.

Shear Displacement Rheometer (SDR)



Module VI — Part 1: Slide 10

Slide 11 The parameters determined from the test include the shear modulus and the phase angle.

SDR Test Parameters

- Known Load Applied to Binder Surface by Indentor
- Depth of Indentation <u>vs</u> Time
- Given Load, Depth and Diameter of Indentor, Modulus of Binder Calculated
- Phase Angle Calculated (Observing Rate of Modulus Change Over Time)

Module VI — Part 1: Slide 11

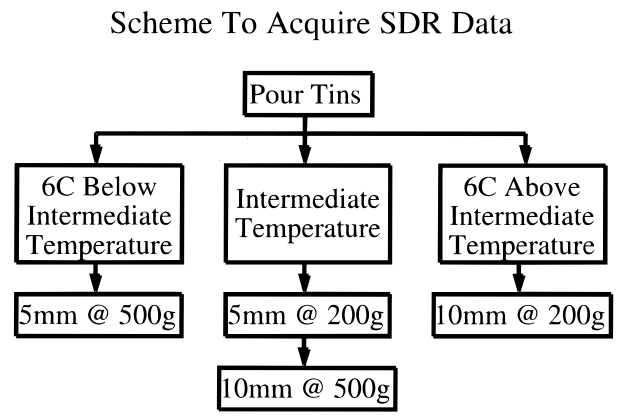
Slide 12 The SDR can be used as a quick field QC test of PG binders because the parameters determined from the SDR include those properties used in the PG determination for asphalt binders using the other SHRP binder characterization equipment.

SDR - Field QC/QA

- Quick Field Check on SHRP PG Binders
- Dynamic Shear Modulus, G*
- Phase Angle, d
- Creep Stiffness, S(t), and m

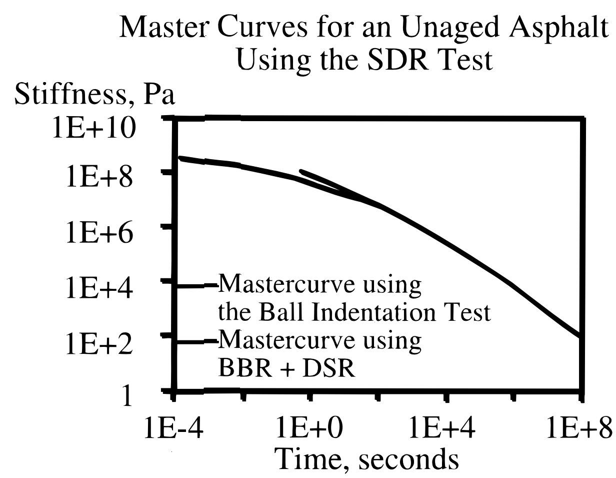
Module VI — Part 1: Slide 12

Slide 13 The SDR test is conducted at three different temperatures with various times to deformation and indentation ball weights. The combination of the results can be used to generate the material properties for the sample.



Module VI — Part 1: Slide 13

Slide 14 The sample's master curve is generated by using the results from the various temperatures.



Module VI — Part 1: Slide 14

Slide 15 The aggregate video grader can be used to determine the blended gradation of the aggregates used for the HMA. The video grader can either be used in-line on the cold feed aggregate conveyor or in the lab with the portable unit. The video grader provides quick gradation results comparable to the results of traditional sieve analysis.

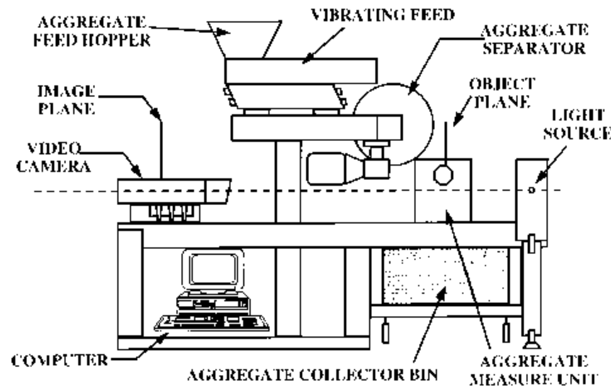
Aggregate Video Grader

- In-Line Cold-Feed and Laboratory Versions
- Adapted from French Technology
- Comparable Results with Traditional Sieve Analysis

Module VI — Part 1: Slide 15

Slide 16 The video grader operates with an image analyzer examining the aggregate as it passes by a high-speed video camera. The aggregate free-falls past the video camera and the image is analyzed by computer software that determines the size fraction gradation.

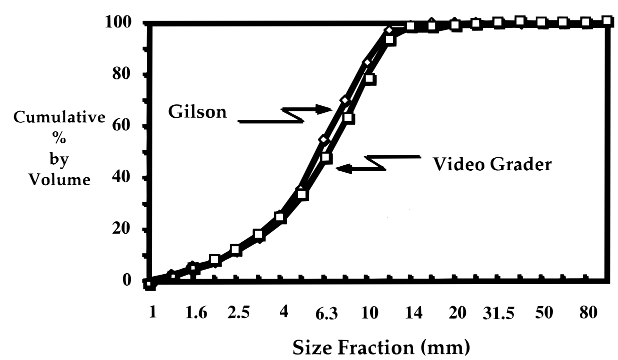
Video Grader (Image Analyzer)



Module VI — Part 1: Slide 16

Slide 17 The video grader provides results comparable to those determined by the more traditional sieve analysis methods and provides the results more quickly. This is especially important for QC activities when time is of the essence.

Aggregate Gradation Comparison



Module VI — Part 1: Slide 17

Slide 18 Devices were also investigated and developed that provide engineering properties that can be used to predict pavement performance. These devices were specifically developed for field control and are easy to operate, low cost, and portable.

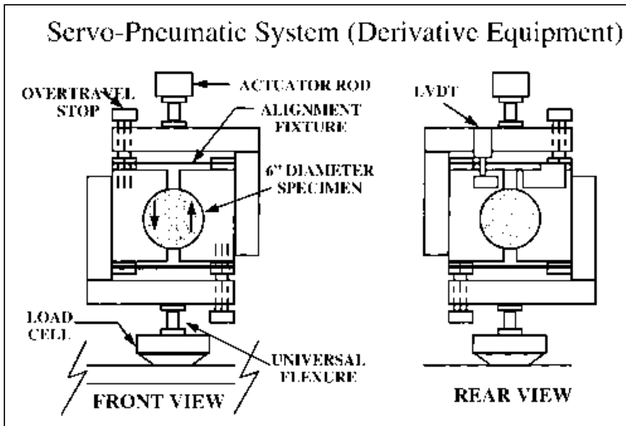
Field Shear Devices

Determination of Fundamental Engineering Properties for HMA Field Control

Module VI — Part 1: Slide 18

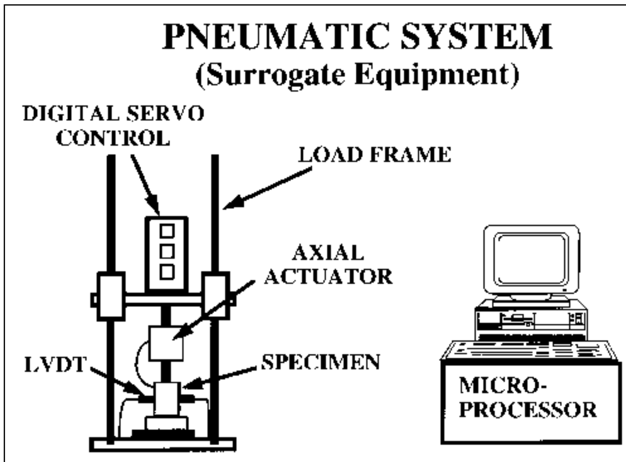
Slide 19 The Field Shear Tester (FST) was developed under the technical direction of the NCHRP Project 9-7 research personnel. This device is considered a derivative of the Superpave Shear Tester (SST) developed under the SHRP A-003 contract because it has the ability to run tests and generate properties similar to those from the SST. However, there are some significant differences between these two devices that must be recognized.

First, the loading configuration of the FST is similar to a direct shear load as opposed to the simple shear loading of the SST. The loading configuration for the FST was developed with simplicity in mind. It was believed by the NCHRP 9-7 researchers that sample preparation for a field control device should be minimal. To achieve this, the loading mechanism shown in the slide was developed. Second, control of the closed-loop pneumatic system is handled by the loading mechanism as opposed to the deformation control that the SST uses for many tests. The deformation measuring device of the FST is different from the SST measuring device, again for simplicity. The linear variable differential transformer is not physically attached to the specimen and thus is not recommended as a control mechanism because slippage could occur.



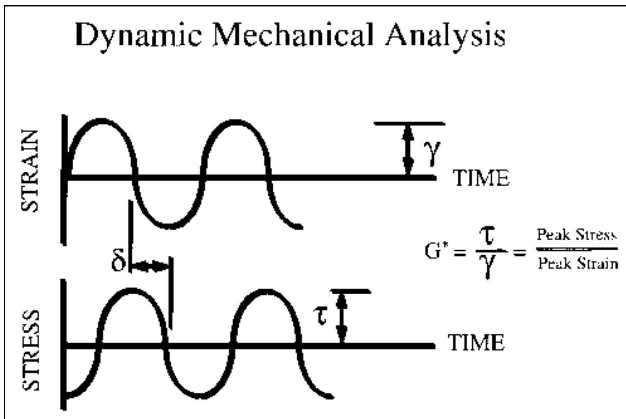
Module VI — Part 1: Slide 19

Slide 20 The rapid triaxial test apparatus is another field device that can be used to generate engineering properties of asphalt mixes for QC/QA. The device is a digital servo-controlled pneumatic system that applies an axial load while the specimen is under pressure from a triaxial cell. The device has the ability to run creep tests as well as frequency tests loaded in the axial direction. The test is considered a surrogate to the SST because of the differences in loading and inclusion of triaxial pressure.



Module VI — Part 1: Slide 20

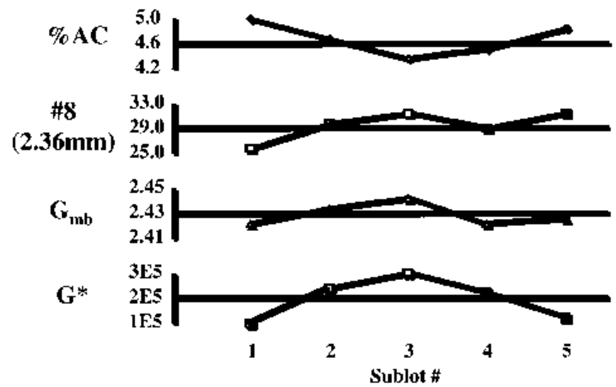
Slide 21 The properties generated from these types of testing devices are considered fundamental engineering properties because they measure the response characteristics of the material due to load. These responses can be used to estimate the anticipated performance of the material with traffic over time.



Module VI — Part 1: Slide 21

Slide 22 An engineering property used in the analysis of asphalt mixtures is the Complex Shear Modulus or G*. This value is a measurement of stiffness and can be related to performance with modeling techniques. As shown, the variation of many material properties can affect the stiffness of the mix and thus the desired performance. Engineering properties are also useful because they can indicate how a change in a combination of material properties will affect the performance of an asphalt mix.

Relationship of G* to HMA Materials



Module VI — Part 1: Slide 22

Slide 23 In developing the QC/QA Plan for the Superpave mixtures the research team assumes that the responsibilities of the SHA and Contractor will be divided as shown.

Functions and Responsibilities

HIGHWAY AGENCY
- Verify SUPERPAVE Mix Design
- Inspect Plants
- Monitor Control of Operations
- Acceptance

CONTRACTOR
- Formulation of Superpave Mix Designs
- Process Control

Module VI — Part 1: Slide 23

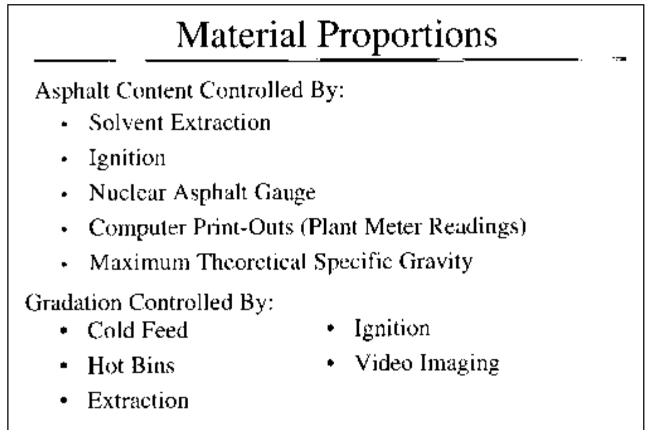
Slide 24 There are three basic areas that can be checked during the QC and QA processes. These are checking the material proportions (i.e., asphalt content and gradation), the volumetric properties of the mix, and the engineering properties.

Areas of Quality Control

- Material Proportions
- Volumetric Properties
- Engineering Properties

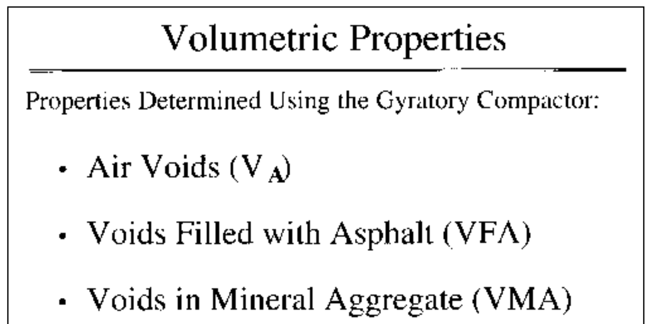
Module VI — Part 1: Slide 24

Slide 25 The material proportions can be checked by several different methods, which are shown in the lists. An important concept must be followed, which is the concept of consistency. Whatever means are used in checking the material proportions initially must be used throughout the QC/QA process. Also, the tolerance limits set for the QC/QA process must have been developed for the method used to check the proportions.



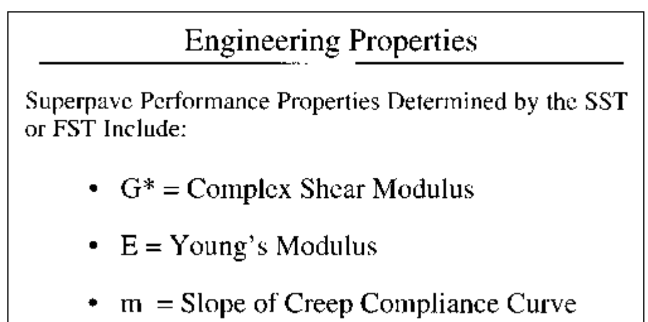
Module VI — Part 1: Slide 25

Slide 26 Volumetric properties that should be determined throughout the QC/QA process are the air voids, the VMA, and the VFA. These should be calculated from the information obtained from the gyratory compactor and can be checked with actual measured values. These properties were suggested based on the fact that they are properties that must meet certain specification criteria during the mix design process and indicate how the mix will perform.



Module VI — Part 1: Slide 26

Slide 27 Engineering properties suggested for field control include (but are not limited to) the complex shear modulus, the elastic (or Young's) modulus, and the slope of the creep compliance curve. The determination of these values hinges on the type of performance-related test that is being run in the field and the test procedures that can be run on the device. The FST developed under NCHRP Project 9-7 can determine these values. It should also be noted that the larger SST device and test procedures produce these same types of engineering properties.



Module VI — Part 1: Slide 27

Slide 28 The procedures developed under NCHRP Project 9-7 recommend the use of statistically based control charts for QC and QA. Statistical control charts can be used to distinguish between chance and assignable causes. The two most useful control charts for construction materials are the mean (or x-bar chart) and the range (or R-chart) charts.

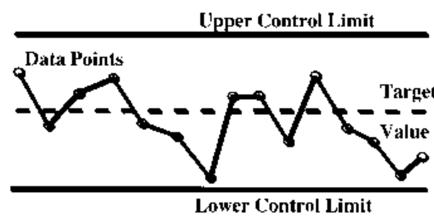
Application of Statistical Control Charts

Approach Adopted for Superpave Hot Mix Asphalt Production and Construction

Module VI — Part 1: Slide 28

Slide 29 Control charts are used to graphically represent the continuous control process. They include the target value that is to be achieved for a certain material property and acceptable upper and lower limits. When a measured value is determined and plotted on the control chart, it should fall within the control limits. Mixture adjustments can be made in response to the values plotted on these control charts.

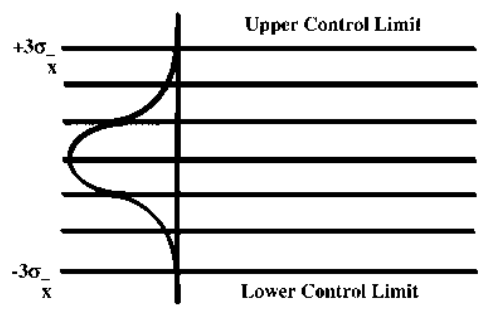
Statistical Control Chart



Module VI — Part 1: Slide 29

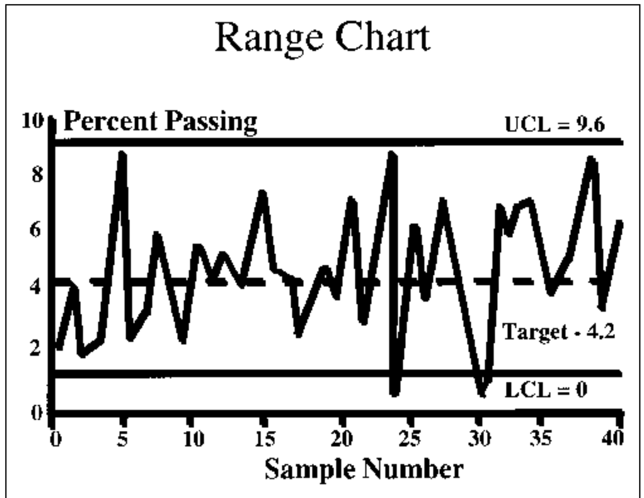
Slide 30 Control limits can be set on the basis of historical information or they can be project specific. In general, the control limits are established based on statistical concepts that assume the material parameter in question follows a normal distribution. Typically, the UCL and LCL are set at ±3σ (standard deviations). However, these can be adjusted depending on the specific parameter being measured and the effect of the parameter on mixture performance.

Statistical Control Chart



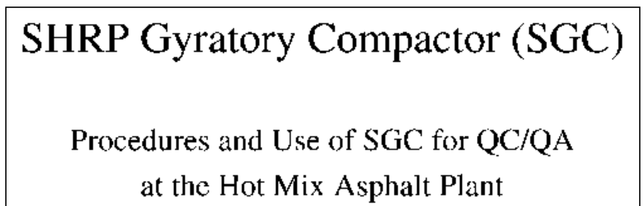
Module VI — Part 1: Slide 30

Slide 31 Two charts are needed to determine whether the QC process is in control. The x-bar chart is used to determine when the process average (mean) has changed and the R-chart is used to determine when the process variability has changed.



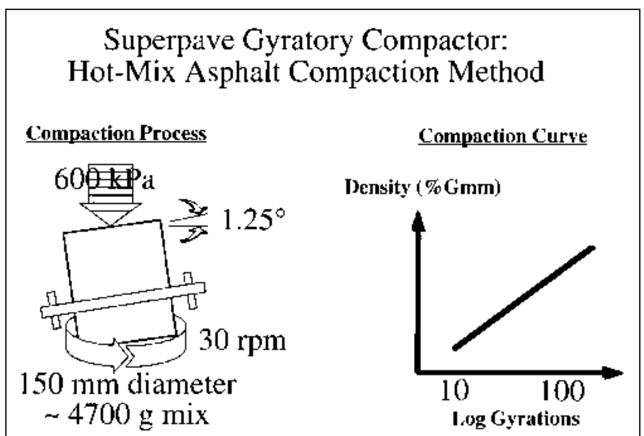
Module VI — Part 1: Slide 31

Slide 32 The SHRP Gyratory Compactor is the primary tool for Superpave QC/QA activities.



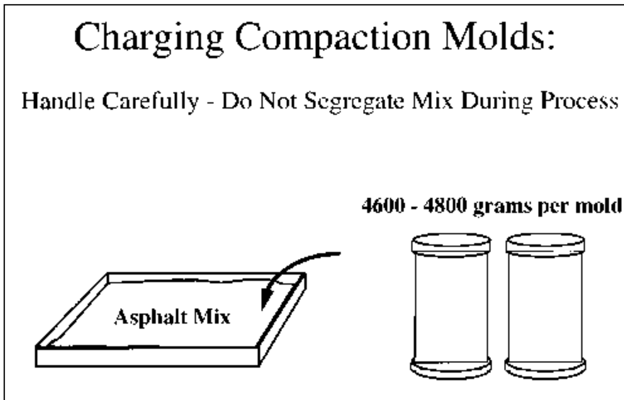
Module VI — Part 1: Slide 32

Slide 33 The gyratory compaction process consists of a pressure applied to a sample of HMA in a mold that is rotated at a certain speed. The orientation of the mixture aggregate takes place because of the applied load and the slight plate angle (1.25°) that is induced on the specimen. The HMA specimen height is measured at each gyration; by using weight-volume relationships, the compacted HMA properties can be determined throughout the compaction process. From this information a compaction curve can be established.



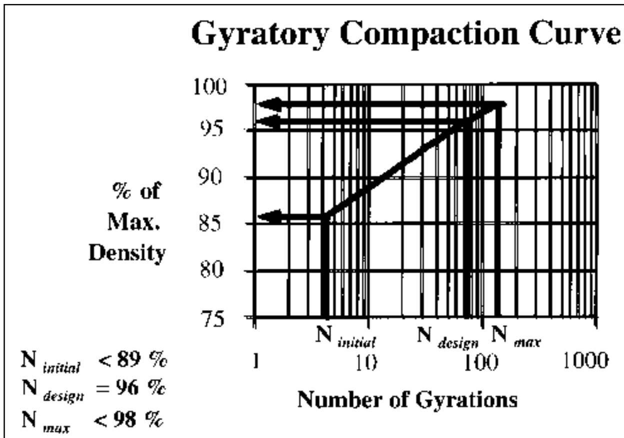
Module VI — Part 1: Slide 33

Slide 34 It is very important that HMA homogeneity be maintained when loading the compactor mold with material. Steps must be taken to reduce material segregation when charging the compaction molds with HMA. This will reduce the measurement error and provide more accurate results for the QC/QA process.



Module VI — Part 1: Slide 34

Slide 35 The mix design process requires that the mix in question meet certain volumetric criteria. It is assumed in the QC/QA plan that these requirements will be met within certain tolerances.



Module VI — Part 1: Slide 35

Slide 36 When looking at an example set of gyratory data it can be observed that the bulk specific gravity determined by using the weight-volume relationships is not the true or actual bulk gravity of the mix when measured. This is due to the assumption that the gyratory specimen is a smooth-sided cylinder, which it is not. Therefore, a correction factor must be determined and is considered an important parameter in the Superpave QC/QA plan.

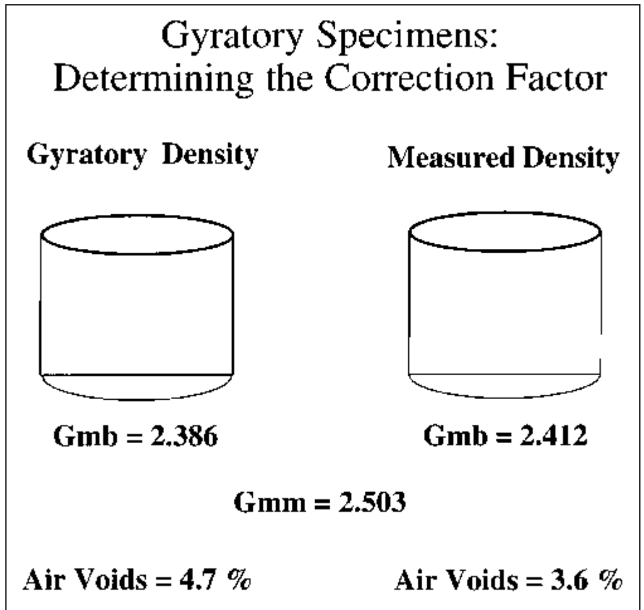
Weight = 4700 grams

No. Gyrations	G_{mb} (est)	G_{mb} (corr)	% G_{mm} (corr)	% V_a
5	2.180	2.198	87.4	12.6
(N_i) 8	2.217	2.236	88.9	11.1
10	2.236	2.255	89.7	10.3
.	.	.	.	.
.	.	.	.	.
100	2.397	2.418	96.2	3.8
(N_d) 106	2.402	2.422	96.3	3.7
128	2.410	2.431	96.7	3.3
.	.	.	.	.
.	.	.	.	.
160	2.413	2.434	97.2	2.8
(N_m) 169	2.423	2.444	97.4	2.6

G_{mm} (meas) = 2.514
G_{mb} (meas) = 2.444
Correction Factor = 1.0085

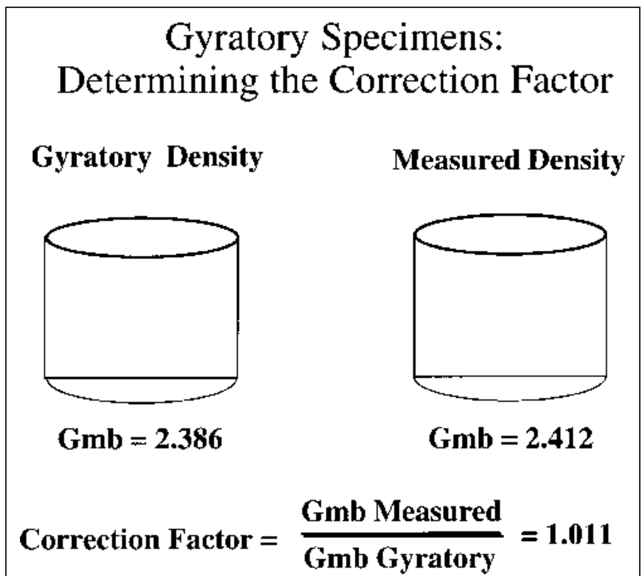
Module VI — Part 1: Slide 36

Slide 37 Properly determining the correction factor is very important because the properties calculated by using the mixture bulk specific gravity can be misrepresented if the uncorrected bulk is used in the volumetric calculations. For example, the difference in air voids for a specimen can be substantial when the uncorrected value is used instead of the corrected value.



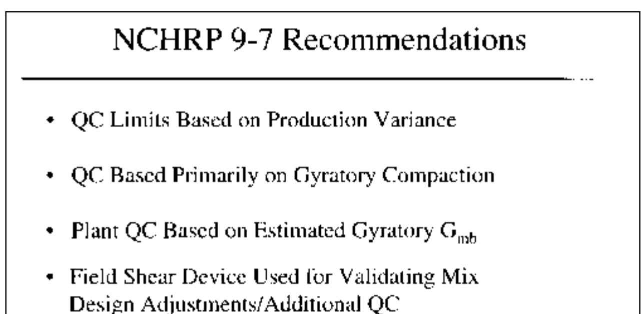
Module VI — Part 1: Slide 37

Slide 38 Determining the correction factor is a simple calculation in which the actual bulk specific gravity is divided by the bulk gravity determined from the weight-volume relationships from the gyratory compactor.



Module VI — Part 1: Slide 38

Slide 39 After all the concepts shown in the previous slides were considered, a QC/QA plan was established for Superpave HMA production and construction by the NCHRP Project 9-7 research personnel. The plan established assumes that the QC limits will be based on the production variance, that the primary tool for QC will be the gyratory compactor, the corrected bulk specific gravity of the plant-produced mix will be used as the primary QC parameter, and a field device can (and should) be used to provide fundamental engineering properties for field control.



Module VI — Part 1: Slide 39

Slide 1 This module will provide information detailing the QC Plan developed for Superpave-designed HMA mixtures.

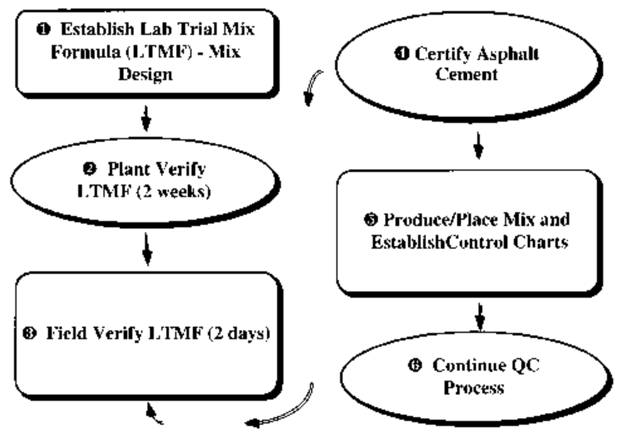
Superpave Quality Control Plan

Part II - Step-by-Step Review

Module VI — Part 2: Slide 1

Slide 2 The Superpave QC Plan developed by NCHRP Project 9-7 is a six-step process that includes mixture verification, production control, and paving placement control. Step 1 consists of developing the LTMF, which is basically the mix design process. The second step is verifying the LTMF at the plant laboratory with the latest stockpiles that will be used in the production process. This step should occur about 2 weeks before HMA production. Step 3 is field verification of the HMA, which consists of ensuring that the plant can produce the LTMF designed in the lab. This should occur about 2 days before the production process. The fourth step is certification of the asphalt binder that will be used in production of the HMA. This step should be continuous throughout the production of the HMA. The fifth step includes development of the QC control charts, and the final step is the actual production/construction process control.

Flow of Superpave QC Plan



Module VI — Part 2: Slide 2

Slide 3 Before any QC activities, the mix design must be completed for the mix that will eventually be used on the project. This can occur several weeks or months before actual construction. The basic steps in developing the LTMF include determining the design aggregate structure, the volumetric properties, and performance properties, if required.

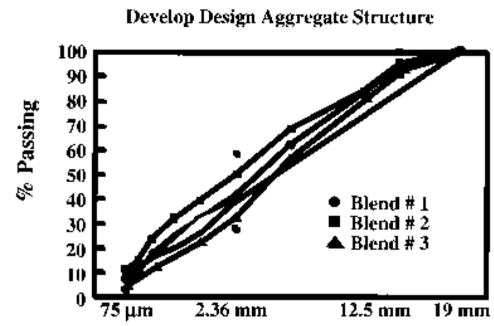
Superpave Laboratory Trial Mix Formula (LTMF)

❶ Determine Laboratory Trial Mix Formula - (LTMF)
- Design Aggregate Structure
- Volumetrics
  - » **Compaction Curve Characteristics**
  - » **Corrected Bulk Specific Gravity**
  - » **Void Properties**
- Performance Properties

Module VI — Part 2: Slide 3

Slide 4 Determining the design aggregates structure in the Superpave mix design system includes developing various blends of aggregates that, when plotted on a 0.45 power curve, meet Superpave specification criteria.

Superpave Laboratory Trial Mix Formula (LTMF)



Module VI — Part 2: Slide 4

Slide 5 During the compaction process, the volumetric properties are determined, which include the gyratory bulk specific gravity, the gyratory correction factor, and the percent compaction in relation to the mixture maximum specific gravity.

Generate Gyratory Data

weight = 4700grams

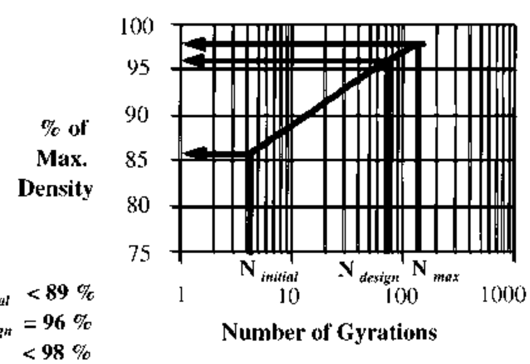
No. Gyrations	G_{mb} (est)	G_{mb} (corr)	% G_{mm} (corr)	% V_a
5	2.180	2.198	87.4	12.6
(N_i) 8	2.217	2.236	88.9	11.1
10	2.236	2.255	89.7	10.3
.	.	.	.	.
.	.	.	.	.
100	2.397	2.418	96.2	3.8
(N_d) 106	2.402	2.422	96.3	3.7
128	2.410	2.431	96.7	3.3
.	.	.	.	.
.	.	.	.	.
160	2.413	2.434	97.2	2.8
(N_m) 169	2.423	2.444	97.4	2.6

G_{mm} (meas) = 2.514
G_{mb} (meas) = 2.444
Correction Factor = 1.0085

Module VI — Part 2: Slide 5

Slide 6 After the volumetric properties from the mix design are determined from the gyratory compactor, compaction curves are generated and the volumetric properties are checked at three different points in the compaction process to ensure adherence to specification criteria.

Plot Gyratory Compaction Curve



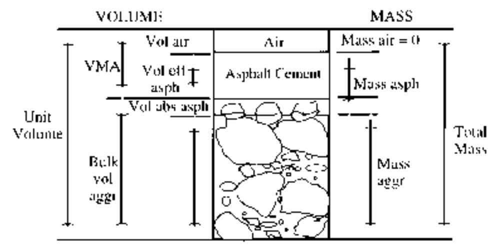
$N_{initial}$ < 89 %
N_{design} = 96 %
N_{max} < 98 %

Module VI — Part 2: Slide 6

Slide 7 The bulk specific gravity of the mix is a measure of the bulk volume of the total mix, which includes the total aggregate volume (including the aggregate surface pores), the asphalt volume, and the air volume.

Superpave Laboratory Trial Mix Formula (LTMF)

Determine Volumetric Properties



Module VI — Part 2: Slide 7

Slide 8 The second step in the QC process is to verify the LTMF at the contractor's plant lab with the plant materials that will actually be used on the project. This should occur about 2 weeks before production and the mix should conform to the original mix design criteria within specified tolerance limits. Any corrections or adjustments to the LTMF should be reported and documented.

Superpave Laboratory Trial Mix Formula (LTMF)

❷ Contractor Laboratory Verification

- Two Weeks Prior to Construction
- Produce Mix in Lab Within LTMF Tolerances
- Provide Plant With LTMF Results/Corrections
- Move to Field Verification With Agency Approval

Module VI — Part 2: Slide 8

Slide 9 The third step in the QC process is called the field verification. This step includes actual production of the LTMF through the hot mix plant. This step is conducted to ensure that the plant can produce the LTMF within certain tolerances. The field verification step provides important information about how the mixture components will react to the actual production process.

Field verification should occur within 2 days of actual production by producing a minimum of 300 tons of mix after the plant has stabilized and measuring various mixture properties. Random sampling of the HMA should occur so that statistical control concepts can be used to evaluate the process.

Superpave Plant Production

❸ Field Verification

- Two Days Prior to Construction
  -Produce/Place min. of 300 tons of Superpave Mix
- Randomly Sample Sublots
- Determine × and S
- Statistically Evaluate Results (90 PWL)

Module VI — Part 2: Slide 9

Slide 10 From each sublot sampled, certain properties must be determined to be 90 PWL. These QC parameters include component proportions, volumetric properties from gyratory-compacted specimens, and in-place properties.

Properties for Each Sublot

- Cold Feed Aggregate Gradation
- % AC and Combined Aggregate Gradation
- G_{mm}
- Gyratory Compaction Curve to N_{max}
- Measured G_{mb} at N_{max}
- V_a at N_{init}, N_{des} and N_{max}
- VMA and VFA at N_{des}

Module VI — Part 2: Slide 10

Slide 11 The fourth step in the QC process is certification of the asphalt cement that will be used on the project. QC checks of the binder should be conducted at various times throughout the production process to ensure that it conforms to the properties of the binder that was used to develop the LTMF.

Superpave Performance-Graded (PG) Asphalt Binder Certification

❹ Quality Control Criteria

- PG Asphalt Binder Quality Control
- AASHTO PP 26-96 Standard

Module VI — Part 2: Slide 11

Slide 12 The AASHTO PP26-96 Standard and its procedures for PG asphalt binder certification can be used for this purpose. Other acceptable methods also can be used for this purpose, including SDR, which is a field control test for binders.

AASHTO PP 26-96 Standard

Certifying Suppliers of Performance-Graded Asphalt Binders

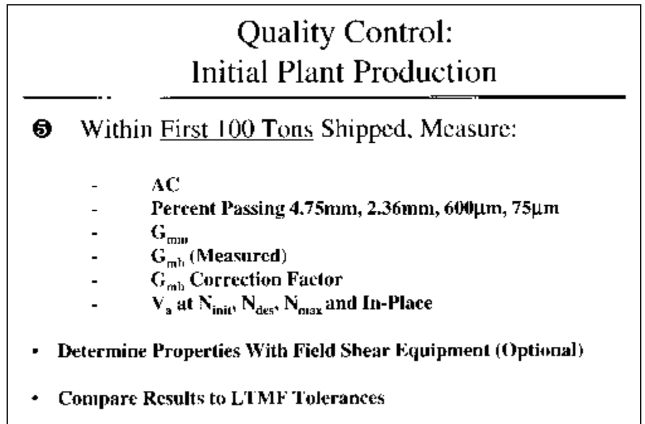
✓ Specifies Requirements and Procedures for Certification System Applicable to All Suppliers of PG Asphalt Binder

✓ Sections 9 and 13 Specifically Applicable to HMA Plant Quality Control

Module VI — Part 2: Slide 12

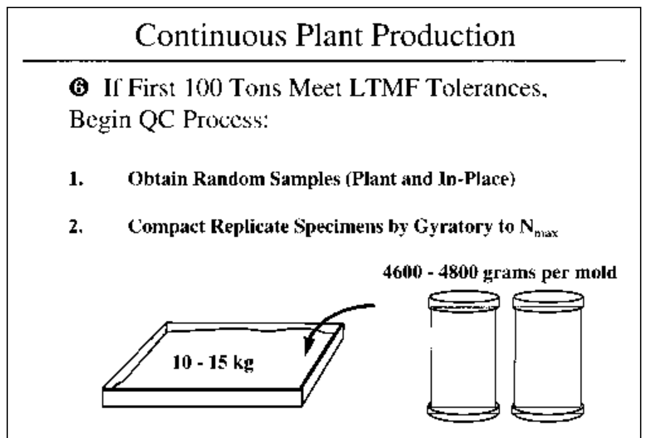
Slide 13 After lab and field verification and certification of the asphalt cement, the mix is ready to be produced and placed. The fifth step in the QC process occurs within the first 100 tons of mix produced after the plant has stabilized. Lab measurements on the listed properties are obtained and compared with the mix design values. These measured values must fall within certain acceptable ranges as set by the QC plan.

The FST also can be used to determine mixture properties and can be used in the QC process.



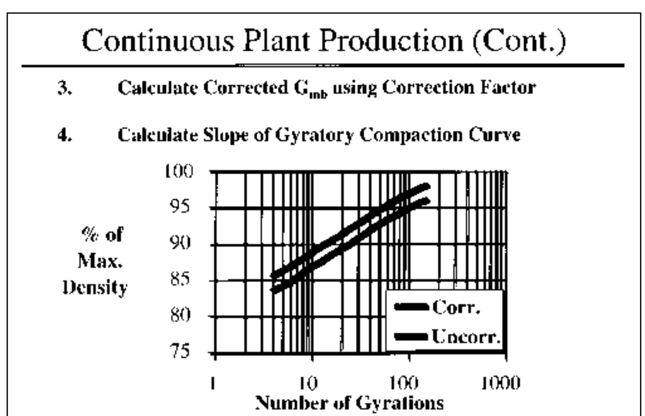
Module VI — Part 2: Slide 13

Slide 14 If the measured properties fall within the appropriate tolerances, the actual QC process can begin. The first step is to obtain random samples from the plant and in the field. For plant samples, the gyratory compactor is used to compact replicate specimens for each sublot.



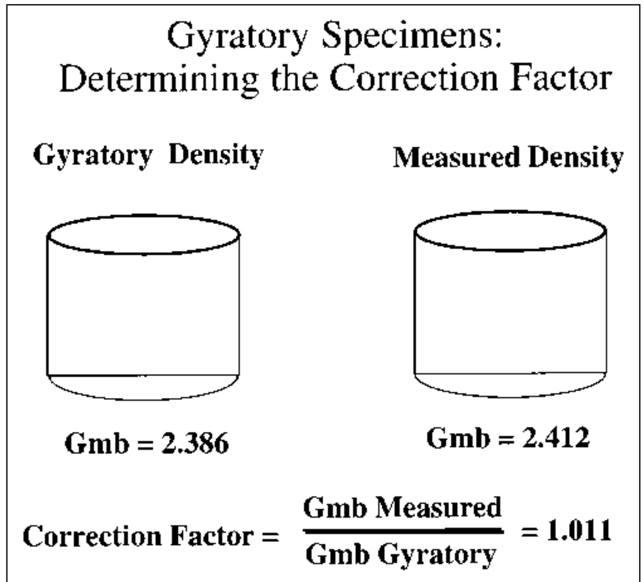
Module VI — Part 2: Slide 14

Slide 15 The corrected bulk specific gravity is determined with the correction factor obtained from the field verification stage. Also, the slope of the compaction curve is calculated and compared with the slopes calculated at previous steps in the QC process. Deviations of this property and the bulk specific gravity from the values previously determined will give an indication of when the mix production process begins to lose control.



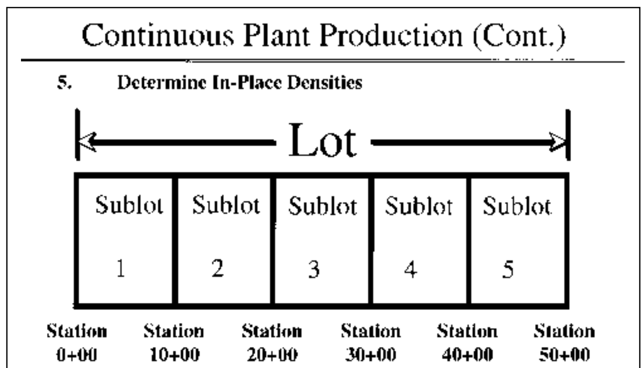
Module VI — Part 2: Slide 15

Slide 16 Determining the correction factor is a simple calculation in which the measured bulk gravity is divided by the estimated bulk gravity determined from the gyratory compactor. The correction factor should be established throughout the mix design, lab verification, and field verification. This value also should be checked periodically throughout the production QC process to ensure that it has not changed from the values obtained throughout the previous stages.



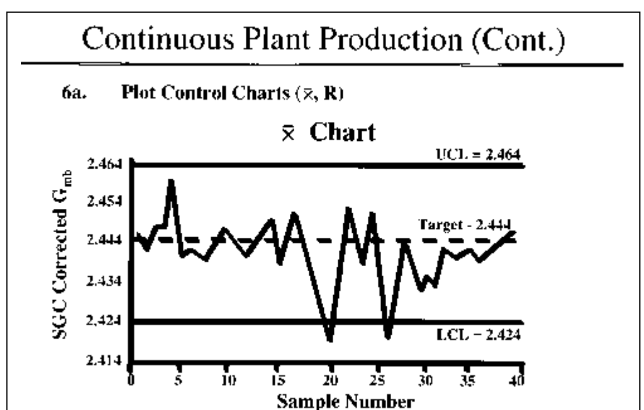
Module VI — Part 2: Slide 16

Slide 17 In-place densities also must be taken during the QC process. Densities must meet minimum and maximum density requirements set by the QC plan. Densities should be taken by NDT techniques, which are calibrated with field core information. Random sampling techniques also should be used so that statistically based tolerances can be applied.



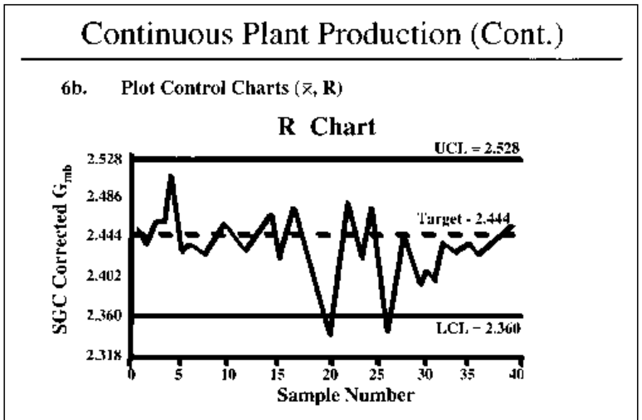
Module VI — Part 2: Slide 17

Slide 18 Control charts are used in the QC process to give a graphic representation of the QC process. The corrected bulk specific gravity is plotted to determine whether it falls within the specified tolerance limits for the project. An x-bar or mean chart is plotted.



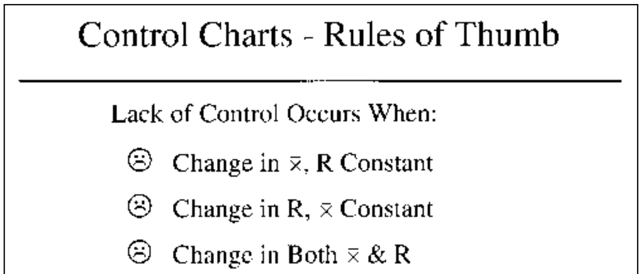
Module VI — Part 2: Slide 18

Slide 19 A range chart is also used in conjunction with the x-bar chart. Also applicable to the QC process is a control chart utilizing the standard deviation instead of the range.



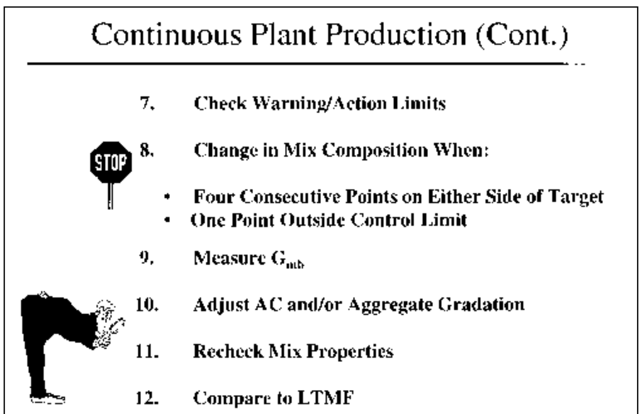
Module VI — Part 2: Slide 19

Slide 20 Basic rules of thumb for control charts state that a lack of control occurs when there is a change in either x-bar or the range or when there is a change in both values.



Module VI — Part 2: Slide 20

Slide 21 After the process parameter has been plotted on the control chart, it is checked against the control limits. Warning and action limits may also be set by using the variances of the production process. These limits act as triggering mechanisms for the control process. It can be assumed that mixture composition change occurs when there are four consecutive points on either side of the target value or when one point plots outside the control limit. When this occurs, the mixture must be adjusted and properties must be measured and compared with the LTMF. When all appropriate properties are within specified tolerances, the normal QC process can proceed.



Module VI — Part 2: Slide 21

Slide 22 Adjustments that can be made to the mix to include changing the gradation, adjusting the amount of material passing the 0.075-mm sieve (i.e., adjusting baghouse fines return), or changing the shape and texture of the aggregate (must be sure to comply with CAA and FAA requirements of Superpave).

SUPERPAVE MIX ADJUSTMENTS (Volumetric Properties)

- Change Gradation
- Change Percent Passing 0.075mm Sieve
- Change Surface Texture and Shape of Aggregates

Module VI — Part 2: Slide 22

Slide 23 When all measured properties meet the QC tolerances, plant production and lay down may continue as well as the normal QC activities.

Continuous Plant Production (Cont.)

13. Continue With Production When <u>All</u> Properties Meet Specifications

Module VI — Part 2: Slide 23

Slide 24 Summary of Superpave QC process.

QC Summary

- **Produce Lab Trial Mix Formula**
- **Verify Binder and LTMF w/Plant Material**
- **Field Verify LTMF, Adjust Mix if Necessary**
- **Determine Project Variance (Statistics)**
- **Establish Control Charts**
- **Continue QC**

Module VI — Part 2: Slide 24

Slide 1 This module provides information about the QA Plan developed for Superpave HMA. QA is generally the responsibility of the SHA or the entity paying for the HMA material.

Superpave Quality Acceptance Plan

State Highway Agency

Procedures for Accepting Hot Mix Asphalt Production and Placement

Module VII — Slide 1

Slide 2 The agency is responsible, in this QA Plan, for verifying that the mix design meets the Superpave specification criteria, reviewing the lab verification process of the contractor, randomly sampling the field verification production in conjunction with the contractor, and accepting the asphalt binder. After all these steps have been taken, the agency is then responsible for performing the duties and sampling required for the established QA plan.

Superpave Quality Acceptance - Agency Responsibilities

1. **Verify Mix Design for Conformance to Superpave Specifications**
2. **Review Contractor Laboratory Mix Verification (2 weeks before construction)**
3. **Randomly Sample Contractor Plant Verification (2 days before construction)**
4. **Accept/Certify Asphalt Binder**
5. **Continue With QA Based on Specified Lots/Sublots**

Module VII — Slide 2

Slide 3 Verifying that the mix conforms to the Superpave specifications includes checks on all the aggregate criteria from the combined stockpiles using the LTMF proportions.

Mix Conformance to Superpave Specifications

1. Verify that Mix Design Meets Specifications on ...

Aggregate Criteria

- **Control Points and Restricted Zone**
- **Coarse Aggregate Angularity**
- **Fine Aggregate Angularity**
- **Flat and Elongated Particles**
- **Clay Content**

Module VII — Slide 3

Slide 4 Verifying that the mix conforms to the Superpave specifications includes checks on all the mixture volumetric properties as determined from the mix design process.

Mix Conformance to Superpave Specifications

❶ Verify that Mix Design Meets Specifications on ...
- Volumetric and Mixture Criteria
  - » **Air Voids**
  - » **Voids in Mineral Aggregate**
  - » **Voids Filled with Asphalt**
  - » **Gyratory Compacted % G_{mm} at N_{init}, N_{des} and N_{max}**
  - » **Dust Proportion**
  - » **Moisture Sensitivity**

Module VII — Slide 4

Slide 5 Verifying that the mix conforms to the Superpave specifications also includes checks on all the mixture performance properties as determined from the mix design process (if performed).

Mix Conformance to Superpave Specifications

❶ Verify that Mix Design Meets Specifications on ...
- Mixture Performance Property Criteria
  - » **Performance Properties from SST or FST, if required**
  - » **Performance-Graded Binder Properties**

Module VII — Slide 5

Slide 6 The second step in the QA process is approval of the contractor's laboratory verification. The agency approves the lab verification if the appropriate properties fall within the specified tolerances.

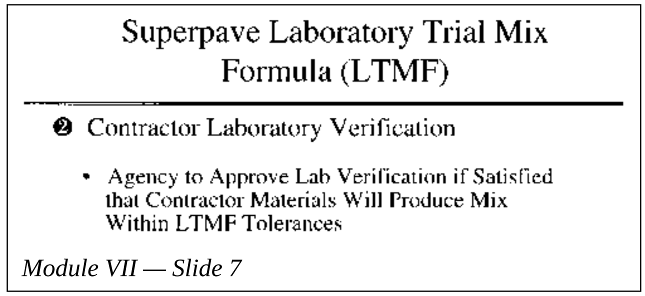
Superpave Laboratory Trial Mix Formula (LTMF)

❷ Contractor Laboratory Verification
- Two Weeks Prior to Construction
- Produce Mix in Lab Within LTMF Tolerances
- Provide Plant With LTMF Results/Corrections
- Move to Field Verification With Agency Approval

Module VII — Slide 6

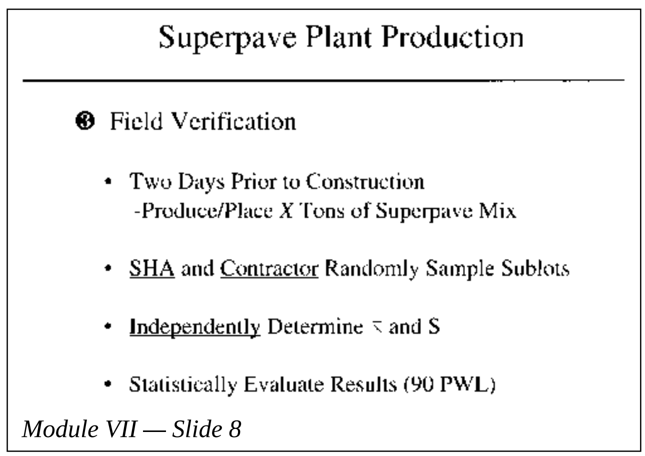
Slide 7 The third step in the QA process is field verification. This step includes the actual production of the LTMF through the hot mix plant. This step is conducted to ensure that the plant can produce the LTMF within certain tolerances. The field verification step provides important information about how the mixture components will react to the actual production process.

Field verification should occur within 2 days of actual production by producing a minimum of 300 tons of mix after the plant has stabilized and measuring various mixture properties. Random sampling of the HMA should occur so that statistical control concepts can be used to evaluate the process. The contractor and agency independently sample and determine the average and standard deviation for specific properties.



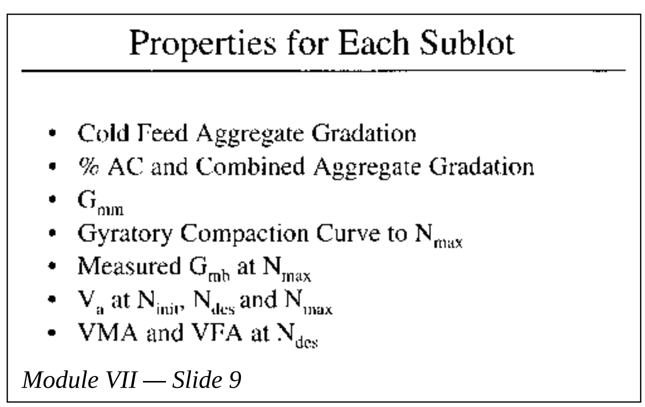
Module VII — Slide 7

Slide 8 The properties measured include gradation and volumetric properties.



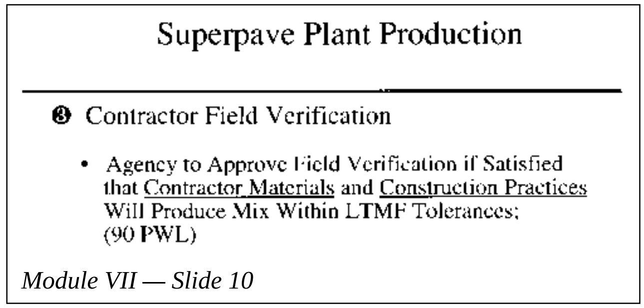
Module VII — Slide 8

Slide 9 If all properties achieve 90 PWL for both the contractor and agency samples, the production process may begin.



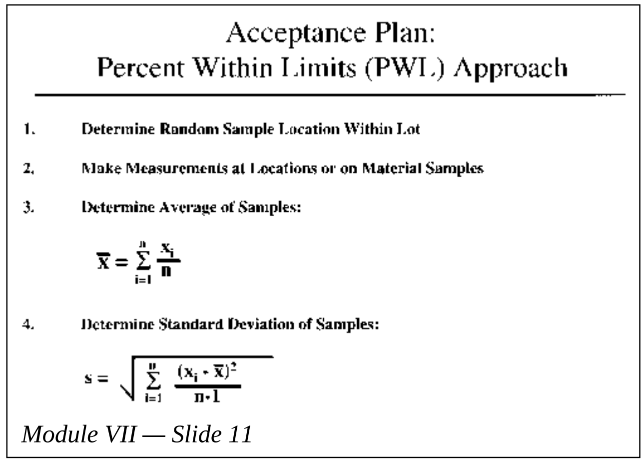
Module VII — Slide 9

Slide 10 The steps for determining PWL include determination of the average (denoted as x-bar) and the standard deviation (denoted as S) for each property for a given set of samples.



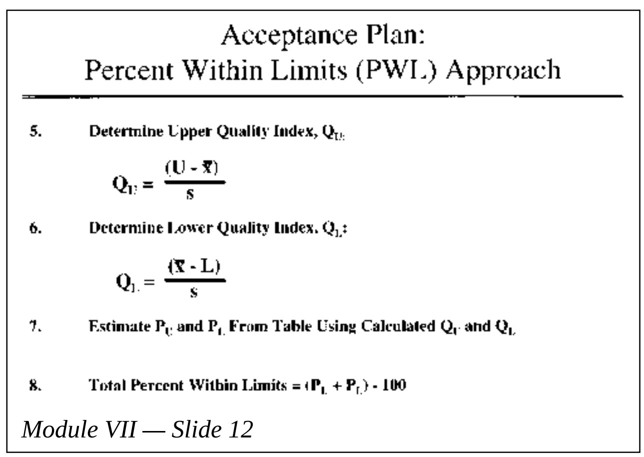
Module VII — Slide 10

Slide 11 The upper and lower quality indices are then determined as well as the upper and lower PWL (from the use of a table). The total PWL is the summation of the upper and lower percent within −100.



Module VII — Slide 11

Slide 12 The fourth step in the QA process is acceptance of the asphalt cement that will be used on the project. QA checks of the binder should be conducted at various times throughout the production process to ensure that it conforms to the properties of the binder that was used to develop the LTMF.



Module VII — Slide 12

Slide 13 The AASHTO PP26-96 Standard and its procedures for PG acceptance can be used for this purpose.

Superpave Performance-Graded (PG) Asphalt Binder Certification

❹ Quality Acceptance Criteria

- PG Asphalt Binder Quality Acceptance
- AASHTO PP 26-96 Standard

Module VII — Slide 13

Slide 14 The fifth step in the QA process is acceptance of the mix produced from the plant and constructed by the paving operations during continuous plant production. The QA plan is established on stratified random sampling techniques and a specified lot size. Each lot is divided into five sublots.

AASHTO PP 26-96 Standard

Certifying Suppliers of Performance-Graded Asphalt Binders

✓ Specifies Requirements and Procedures for Certification System Applicable to <u>All</u> Suppliers of PG Asphalt Binder

✓ Sections 9, 10, 12 and 13 Specifically Applicable to SHA Certification and Acceptance Procedures

Module VII — Slide 14

Slide 15 Acceptance testing is conducted on split samples; the air voids, VMA, VFA, and in-place density are determined for each sublot. The lot average and standard deviation are determined for each of these properties.

Continuous Plant Production

❺ Acceptance Procedures

1. Develop Stratified Random Sampling Plan
2. Lot Size = 1,000 tons or a Day's Production
   (If Project < 1,000 tons: Lot = Quantity Produced for Project)
3. Number of Sublots = 5 per Lot

Module VII — Slide 15

Slide 16 The upper and lower quality limits are determined based on the tolerances set by the QA Plan. The PWL are determined for each property. Each property must fall within 90 PWL for the lot to be accepted.

Continuous Plant Production (cont.)

❺ Acceptance Testing

1. Split Samples
2. Determine For Each Sublot:

✔ Air Voids
✔ Voids in Mineral Aggregate (*Optional*)
✔ Voids Filled With Asphalt (*Optional*)
✔ In-Place Density

Module VII — Slide 16

Slide 17 Proper comparison of QC and QA data is important in resolving conflicts that arise between the contractor and the agency. The following information is provided to show a statistically based procedure for comparing two independently determined sets of data.

Continuous Plant Production (cont.)

❺ Acceptance Criteria

1. Determine Q_U and Q_L Using Superpave Tolerances
2. Determine PWL For Each Parameter:

✔ Air Voids
✔ Voids in Mineral Aggregate (*Optional*)
✔ Voids Filled With Asphalt (*Optional*)
✔ In-Place Density

Module VII — Slide 17

Slide 18 Comparison of QC and QA data answers the question of how different QC and QA data can be and still be considered to be from the same population.

Comparison of QC and QA Data

Dispute Resolution

Module VII — Slide 18

Slide 19 The answer can be readily determined by using statistically based procedures. Hypothesis testing from statistics can be used to determine whether the population variances and means are the same or different. Basic assumptions that are made for these tests include the assumption of normality for each of the control properties (i.e., assume the population of air voids follows a normal distribution) and that the material is sampled randomly.

Comparison of QC and QA Data

The BIG Question:

How different can QC and QA data be and still be considered to have come from the same population?

Module VII — Slide 19

Slide 20 Initially the variances for each population must be compared to determine whether they are statistically the same. The F-test is used to perform this check.

Comparison of QC and QA Data

- Statistics to the Rescue !!
  - Hypothesis Testing
    - **F-tests for checking population variances**
    - **t-tests for checking population means**
  - Assume Populations are Normally Distributed
  - Populations Must be Randomly Sampled

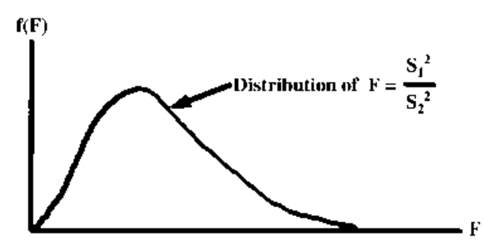
Module VII — Slide 20

Slide 21 The means of the populations are then compared by using the t-test. This determination will tell whether the population means are equal or unequal.

Comparison of QC and QA Data

Comparing Variability by Means of the F-test

Compare Variances of Two Sets of Data



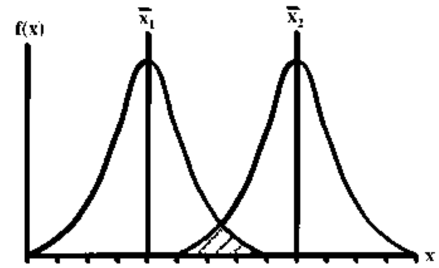
Module VII — Slide 21

Slide 22 In summary, dispute resolution includes a comparison of the population variances and means by using statistical methods to determine whether the data generated for each population are the same or different.

Comparison of QC and QA Data

Comparing Variability by Means of the t-test

Compare Means of Two Sets of Data



Module VII — Slide 22

Slide 23 Successful dispute resolution will require two distinct, but related sets of computations.

First, the variance of each data set is computed and the F-statistic is calculated to determine whether the variances are equal or not. Next, if they are equal *statistically*, then the mean of each set is computed and the t-statistic is calculated to determine whether the computed means are equal or unequal.

If the means are also equal *statistically*, the two data sets are representative of the same population. The combined data set can then be compared with the target values to determine whether all requirements are met within tolerances.

If either the variances or the means are *statistically* unequal, the two data sets are representative of different populations and cannot be combined. In this situation, the agency's quality acceptance data only are used to determine conformance with target values within tolerances.

Comparison of QC and QA Data

Steps to Successful Dispute Resolution:

- **Compute Variance, s^2, for Each Set of Tests**
- **Compute F-test Statistic Using Largest s^2 in the Numerator**
- **Determine if Population Variances are Equal or Unequal**
- **Compute the Mean, $\bar{x}$, for Each Set of Tests**
- **Compute t-test Statistic**
  - Use Pooled Variance if Population Variances are Equal
  - Use Individual Variances if Population Variances are Unequal
- **Determine if Population Means are Equal or Unequal**

Module VII — Slide 23

CHAPTER 5

EQUIPMENT TO SUPPORT SUPERPAVE QC/QA PLAN

5.1 INTRODUCTION

The Superpave mix design and analysis system extends beyond the scope of existing mix design systems in that it integrates specific elements of field control into the mix design. NCHRP Project 9-7 started with the system recommended for QC by the original SHRP research.

After a review of the SHRP research program results and discussion with the NCHRP Project 9-7 panel, a decision was made to consider only permanent deformation as a distress factor. Permanent deformation is a short-term phenomenon that can be evaluated by QC/QA field testing. Pavement fatigue is a long-term phenomenon that is generally addressed through pavement layer thickness determination during the pavement design process. Low-temperature cracking is addressed during the Superpave mix design process by the selection of the appropriate performance grade of asphalt binder.

Typically, field control of HMA pavement construction is defined by the SHA. Existing field control systems vary greatly from mix design validation to limited material proportion control. The Superpave mix design method formalizes field control systems by incorporating a selection of tests and tools to verify the mix design in the field. As such, the Superpave method provides components that can be incorporated into an agency-defined QC/QA system.

The following five general levels of field control are available in the Superpave mix design method:

- Gyratory compaction control,
- Volumetric property control,
- Performance-based property control,
- In situ pavement property control, and
- Asphalt binder control.

5.2 GYRATORY COMPACTION CONTROL

Gyratory compaction control is achieved by compacting HMA samples and measuring the bulk density of the compacted specimens after application of the design number of gyrations (termed N_{design}). If the type of aggregate and asphalt binder, the aggregate gradation, the amount of each aggregate fraction, and the asphalt binder content do not change during production, then the density should remain constant within normal experimental behavior. A change in the type of materials or in their amounts will cause a change in density.

This approach minimizes the amount of testing required for QC by the agency or contractors. Periodically, or if a change in density is detected, it will be necessary to determine the volumetric properties, the performance properties (as measured by the frequency sweep and simple shear at constant height tests[1]), or both. Information obtained from the performance tests provides a gauge of the rutting that can be expected as a result of the changes in the mix. If deemed necessary, however, a full Superpave mix analysis can be performed on HMA or compacted specimens sent to a central laboratory.

5.2.1 Volumetric Property Control

Volumetric property control is based on confirming that the properties of plant-mixed material agree within established tolerances to those of the Superpave volumetric mix design. If HMA sampled from plant production is compacted in the SGC, specification values for air voids content, VMA, and VFA should be met at N_{design}. In addition, the densities at N_{init} and N_{max} (the *initial* and *maximum* numbers of gyrations, determined by the value selected for N_{design}) should also meet specification values. Aggregate properties as well as gradation and asphalt content can also be used for this purpose.

Volumetric property controls include the following:

- Asphalt content,
- Gradation,
- Coarse aggregate angularity
- Fine aggregate angularity,
- Clay content,
- Elongated particles,
- Deleterious materials,
- Percent air voids (V_a),
- Percent VMA, and
- Percent VFA.

[1]AASHTO TP7, *Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt Using the Simple Shear Test.*

Asphalt content can be monitored by the following:

- Solvent extraction,
- Nuclear asphalt content gauge,
- Ignition oven,
- Plant meter readings, and
- Maximum theoretical specific gravity determination (by the Rice method[2]).

Gradation can be monitored by sieve analysis with the following:

- Extracted aggregate, and
- Aggregate cold feed sampling.

The air voids content, VMA, and VFA are measured on plant mix samples compacted to N_{design} gyrations with the SGC. The air void contents are calculated by using the SGC-corrected bulk specific gravity of the compacted specimens. The maximum theoretical specific gravity is measured on material split from the same material used to prepare compacted specimens. VMA is calculated by using the compacted specimen bulk specific gravity and the aggregate bulk specific gravity. The VFA is calculated by using the air voids content and VMA for that specimen.

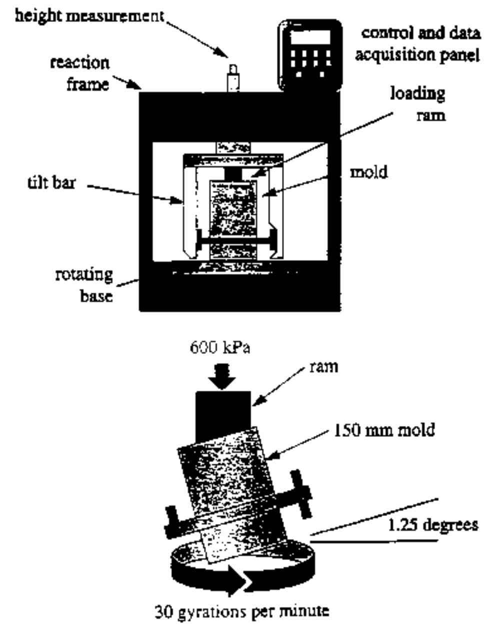


Figure 5-1. The SHRP gyratory compactor. (Top) Schematic. (Bottom) Principle of operation.

5.2.2 Gyratory Compaction

The Superpave mix designs and field QC operations in NCHRP Project 9-7 employed SGCs built by several commercial sources to specifications provided by the FHWA as well as two other gyratory compactors manufactured commercially in Finland and Australia. The latter units have equivalent capabilities and operate by the same principles as the SGCs. A schematic of a typical SGC is shown in Figure 5-1.

SGCs are capable of quickly molding specimens with minimal specimen-to-specimen variation. They yield compacted specimens whose performance properties simulate those of cores from pavements constructed with the same combination of asphalt binder and aggregate. Some models were portable or transportable. The compatibility of the HMA can also be evaluated with the SGC, including both an estimate of the final air voids content under traffic (related to the probability of the paving mix becoming plastic under traffic) and a measure of the structuring of the aggregate in the mix.

The SGC (Figure 5-1) has the following key characteristics:

- An angle of gyration of 1.25° ± 0.02°,
- A rate of 30 gyrations per minute,
- A vertical pressure during gyration of 600 kPa, and
- The capability to produce 150 × 150 mm specimens.

[2]AASHTO T 209, *Maximum Specific Gravity of Bituminous Paving Mixtures.*

During compaction, the relative density of the specimen is monitored and displayed. Typical results are shown in Figure 5-2. Density as a percent of maximum theoretical specific gravity (as measured by AASHTO T209) can be plotted against either the number of gyrations or the log of the number of gyrations. This allows a visual evaluation of the compatibility and the aggregate structure of the paving mix.

The three compaction levels specified in the Superpave volumetric mix design procedure are as follows:

- N_{init}, the initial compaction effort,
- N_{design}, the design compaction effort, and
- N_{max}, the maximum compaction effort.

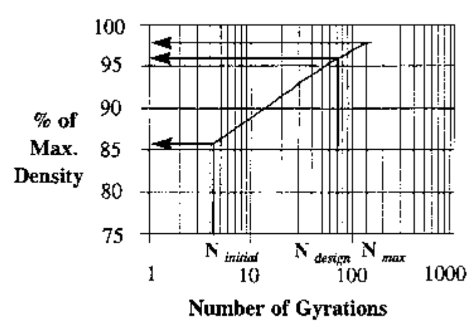


Figure 5-2. Typical densification curve obtained with the SHRP gyratory compactor.

TABLE 5-1 Superpave design gyratory compactive effort

Design ESALs (millions)	Average Design High Air Temperature											
	< 39°C			39 - 40°C			41 - 42°C			43 - 44°C		
	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}	N_{ini}	N_{des}	N_{max}
< 0.3	7	68	104	7	74	114	7	78	121	7	82	127
0.3 - 1	7	76	117	7	83	129	7	88	138	8	93	146
1 - 3	7	86	134	8	95	150	8	100	158	8	105	167
3 - 10	8	96	152	8	106	169	8	113	181	9	119	192
10 - 30	8	109	174	9	121	195	9	128	208	9	135	220
30 - 100	9	126	204	9	139	228	9	146	240	10	153	253
>100	9	143	235	10	158	262	10	165	275	10	172	288

Values of N_{init}, N_{design}, and N_{max} are a function of average design air temperature and project equivalent single axle loads (ESALs) as shown in Table 5-1.

N_{init} and N_{max} are used to evaluate the compactibility of the mix, and N_{design} is used to select the asphalt content. Corresponding to these compactive efforts are three densities, C_{init}, C_{design}, and C_{max}, which are expressed as a percent of maximum theoretical specific gravity.

Mixes exhibiting relatively steep slopes and low C_{init} values are typical of mixes with good aggregate structure or internal resistance to densification. Although it is possible to select a design asphalt content for a mix with a weak aggregate structure, the design will result in poorer performance, especially in its resistance to permanent deformation. To ensure adequate aggregate structure, the specifications require that

$$C_{init} \leq 89 \text{ percent}$$

where the number of gyrations, N_{init}, varies from about 7 to 10.

A maximum density requirement at N_{max} ensures that the mix will not compact excessively under the anticipated traffic, become plastic, and produce permanent deformation. Thus, the specification requires that

$$C_{max} \leq 98 \text{ percent}$$

In other words, the air voids content of a specimen compacted to N_{max} must be 2 percent or greater. Because N_{max} represents a compactive effort that would be equivalent to that induced by traffic that greatly exceeds the design traffic (ESALs), this requirement guards against development of excessive compaction (V_a less than 2 percent) and plastic deformation under traffic.

5.2.3 Field QC Using the SGC

Field QC procedures using the SGC are uncomplicated. Volumetric properties of HMA can be obtained from the gyratory compactor by the following procedure for field QC:

1. A sample of HMA is randomly obtained. A known weight is measured into the heated SGC mold.
2. The specimen is compacted to N_{max}. Its height is recorded at each gyration.
3. The operator estimates an uncorrected value of G_{mb} at N_{design} based on weight and volume relationships.
4. The estimated bulk specific gravity is corrected by the laboratory correction ratio, C, defined by the equation

$$C = \frac{G_{mb}(\text{measured})@N_{max}}{G_{mb}(\text{estimated})@N_{max}}$$

5. The slope of the gyratory compaction curve is calculated by the procedure set forth in report SHRP-A-407, Section 3.7.4.1.

Determination of G_{mb} (estimated) is conducted for QC purposes because it can be obtained very quickly. It also provides an indirect control for the air voids content and the VMA as shown in the following two equations:

$$V_a = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100$$

where

V_a = air voids in compacted sample
G_{mm} = maximum theoretical specific gravity of the paving mixture
G_{mb} = corrected bulk specific gravity of compacted mixture

$$VMA = 100 - \frac{G_{mb} - P_s}{G_{sb}}$$

where

VMA = voids in mineral aggregate
G_{mb} = bulk specific gravity of the compacted mix
P_s = aggregate as a percent of the total weight of the mix
G_{sb} = bulk specific gravity of the aggregate

An example of SGC compaction data is shown in Table 5-2.

During compaction, the height of the specimen in the mold is measured after each gyration. The values of G_{mb} (estimated) are determined with the following two equations:

$$V_m = \frac{\lambda d^2 h}{4} \times 0.001$$

where

V_m = volume of specimen in mold after each gyration during compaction, cm^3
d = diameter of mold (= 150 mm)
h = height of specimen in mold after each gyration during compaction (mm)

and

$$G_{mb}(\text{estimated}) = \frac{W_m}{V_m}\left(\frac{1}{d_w}\right)$$

where

G_{mb}(estimated) = estimated bulk specific gravity of specimen in the mold after each gyration during compaction
W_m = mass of the specimen, g
V_m = volume of specimen in the mold after each gyration during compaction, cm^3
d_w = density of water (1.00 g/cm^3)

This calculation assumes that the specimen is a smooth-sided cylinder, which, of course, it is not. The volume of the specimen is slightly less than the volume of a smooth-sided cylinder because of surface irregularities. To correct for this difference, G_{mb}(estimated) at any given number of gyrations is corrected by the **ratio** of the **measured** to the **estimated** bulk specific gravity at N_{max} by the formula

$$C = \frac{G_{mb}(\text{measured})}{G_{mb}(\text{estimated})}$$

where

C = correction factor
G_{mb}(measured) = measured bulk specific gravity at N_{max}
G_{mb}(estimated) = estimated bulk specific gravity at N_{max}

Figures 5-3 and 5-4 illustrate the results of QC by using the slope of the gyratory compaction curve. The parallelism of the compaction curves in Figure 5-3 indicates good control between sublots. The variation in the change in slope of the compaction curves in Figure 5-4 suggests a potential problem between sublots.

TABLE 5-2 Example of field gyratory compaction data

No. Gyrations		G_{mb} (est)	G_{mb} (corr)	% G_{mm} (corr)	% V_a
	5	2.180	2.198	89.8	12.6
(N_i)	8	2.217	2.236	91.3	11.1
	10	2.236	2.255	92.1	10.3
	•				
	•				
	100	2.397	2.418	98.8	3.8
(N_d)	106	2.402	2.422	98.9	3.7
	128	2.410	2.431	99.3	3.3
	•				
	•				
	160	2.413	2.434	99.5	2.8
(N_m)	169	2.423	2.444	99.8	2.6

G_{mm} (meas) = 2.514 G_{mb} (meas) = 2.444 Correction Factor = 1.0085

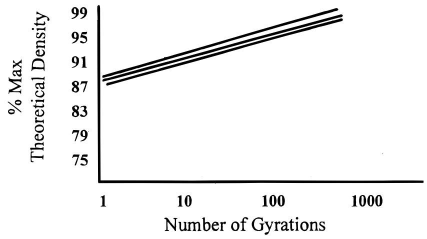


Figure 5-3. Slope of compactor curve (Alabama).

Statistical control charts of corrected G_{mb} may be used with the process target value to determine whether the variability in HMA production is due to random or assignable causes. Periodically, a measured G_{mb} for control comparisons is required to evaluate the correction factor. Figures 5-5 and 5-6 illustrate control charts developed by NCHRP Project 9-7 during the Louisiana IH-10 paving project in 1996. Both an x-bar and a range chart are shown for evaluating the corrected G_{mb}(estimated). For comparative purposes, values of G_{mb}(measured) were also plotted. As long as the plots are within the UCL and LCL, the process is deemed in control.

5.3 PERFORMANCE-BASED PROPERTY CONTROL

At times, the measured volumetric properties may fail to detect changes in gradation or asphalt content and will indicate the process is in control when it is not. This can occur most commonly when the asphalt content and gradation are varying simultaneously. Therefore, field test devices have been developed that a contractor may use in concert with gyratory compaction to measure performance-based engineering properties for the purpose of QC.

After a review of the SHRP asphalt research program results and discussion with the NCHRP Project 9-7 panel, a decision was made to consider only permanent deformation as a distress factor. Permanent deformation is a short-term phenomenon that can be evaluated by QC/QA field testing. Pavement fatigue is a long-term phenomenon that is generally addressed through pavement layer thickness determination during the pavement design process. Low-temperature

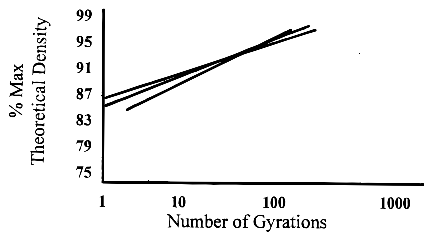


Figure 5-4. Slope of compaction curve (Texas).

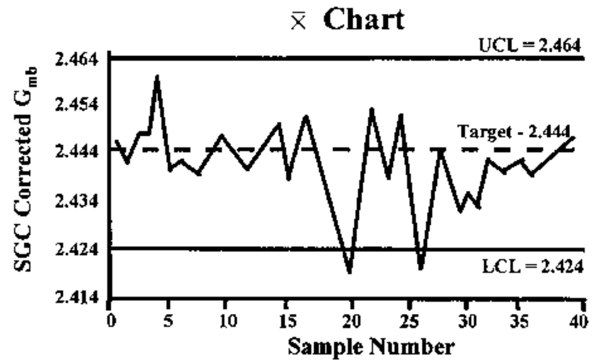


Figure 5-5. Average chart.

cracking is addressed during the Superpave mix design process by the selection of the appropriate performance grade of asphalt binder.

Performance-based properties should be measured periodically or when the density of gyratory-compacted specimens indicates a change in the paving mix. A subset of the performance-based tests used in the Superpave abbreviated and full mix analysis methods (AASHTO TP7) can be conducted and values compared with those of the original mix design. In particular, the simple shear and frequency sweep at constant height tests are suitable to monitor HMA conformance to the mix design and to estimate the amount of rutting that can be expected due to variation in the HMA during production or lay down.

Two devices were developed to measure the engineering properties related to permanent deformation in field laboratories as part of a QC plan. These are the field shear device and the rapid triaxial device. The field shear device was developed with funding provided through NCHRP Project 9-7. The rapid triaxial device was developed with private funding by Industrial Process Controls of Melbourne, Australia. Each is discussed separately in following sections of this chapter. Table 5-3 provides a comparison of various characteristics of the two devices.

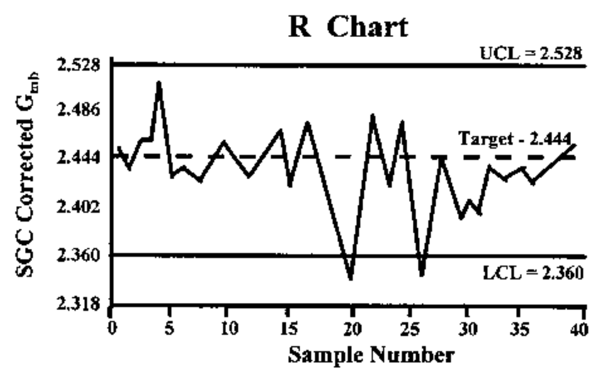


Figure 5-6. Range chart.

TABLE 5-3 Comparison of the FST and rapid triaxial devices

	Field Shear Device	Triaxial Creep Device
Manufacturer	Endura-Tech	Industrial Process Controls
Costs (US Dollars)	$30,000 - $40,000	$30,000 - $40,000
Load Frame Dimensions (w x d x h)[a]	300 x 300 x 800 mm	365 x 305 x 845 mm
Load Frame Weight[a]	160 kg	100 kg
Loading Mechanism[b]	Servo-Controlled Pneumatic	Servo-Controlled Pneumatic
Specimen Preparation[c]	Gyratory Compactor	Gyratory Compactor
Specimen Size (diameter x length)	150 x 50mm to 150 x 140mm	150 x 140mm
Response Measurement[d]	LVDT (Automated)	LVDT (Automated)
Test Time[e]	2 to 10 minutes	2 to 20 minutes
Portability	Prototype Requires Dolley	Self-Contained With Wheels
Power Requirements	110 Volts w/ 550 kPa Air	110 Volts w/ 750 kPa Air

Notes:
a - Load frame dimensions and weight only, other accessories will increase size and weight.
b - Digitially controlled pneumatic actuators. Industrial Process Controls device also includes digital servocontrolled triaxial pressure cell.
c - Roadway cores also acceptable for Endura-Tech device.
d - No sawing of specimen or gluing of linear variable differential transformers required.
e - Test times dependent on test protocols that are performed.

5.3.1 FST Device

The testing of performance-based engineering properties of plant-produced HMA is one of the key requirements for QC of Superpave-designed paving mixes. During the initial phases of NCHRP Project 9-7, it became clear that proper QC could not be conducted with only the SGC and that an additional test was necessary to assess the rutting susceptibility of HMA in the field. Hence, as part of Project 9-7, a prototype FST was developed by Endura-Tec Systems of Eden Prairie, Minnesota. In April 1996, this device was delivered to Project 9-7 subcontractor Advanced Asphalt Technologies, LP (AAT), and a study plan was established to evaluate its functionality.

5.3.1.a FST Device Shakedown Testing

The FST device was designed to perform two of the Superpave load-related mix analysis tests: frequency sweep at constant height and simple shear at constant height (AASHTO TP7-94). The device was designed and built by Endura-Tec Systems of Eden Prairie, Minnesota, and procured under contract to Brent Rauhut Engineering Inc., as a requirement of Project 9-7. The Endura-Tec prototype was selected from two proposed designs. The field shear device is considered a derivation of the larger device developed under SHRP.

The FST uses a servopneumatic loading (load controlled) device capable of applying repetitive loads of various wave forms. The 10-kip test frame and the environmental chamber are standard designs already used by Texas Department of Transportation to conduct long-term asphalt creep tests. Also, the software is very similar to the program developed by The Interlaken for the SHRP SST, now installed at the five regional Superpave centers. The SST and orientation are new designs and are different from the laboratory SST. These changes were made to address the more practical issues related to field operation and to minimize specimen preparation time. The use of the platens, specimen gluing, and mounting of external extensiometry are not required with the FST. The equipment is capable of testing gyratory-compacted specimens up to 150 mm in height as well as field cores.

The main differences between the FST device and the laboratory SST are the loading condition (i.e., the FST tests are conducted in load control) and the specimen orientation. The shear stresses are applied in the vertical direction across the diameter of the specimen, similar to direct shear testing (i.e., diametrically). The face-to-face "parallelism" is maintained by clamping the specimen in the shear fixture. A schematic of the prototype shear fixture is presented in Figure 5-7.

5.3.1.b Testing Methodology

To simulate the loading conditions of the laboratory SST frequency sweep test, which is a strain-controlled test, the load and stresses are adjusted as the frequency decreases to maintain a constant strain. Testing with the FST was con-

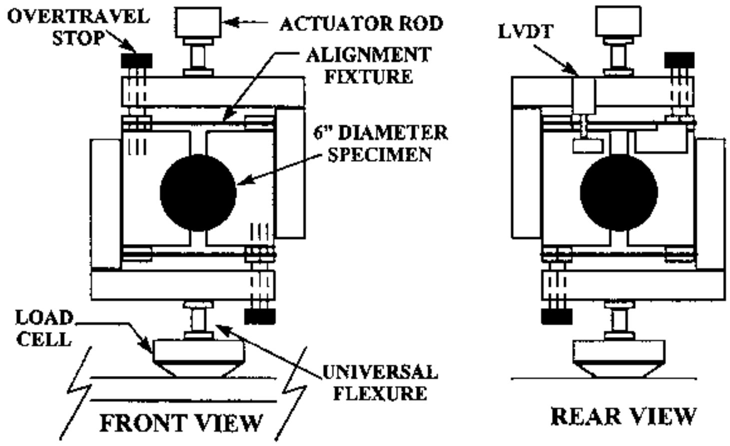


Figure 5-7. Schematic of field shear device.

ducted at frequency intervals of 1 decade (e.g., 10 to 1 Hz, 2 to 0.2 Hz) and at stress levels similar to the levels used when testing with the laboratory SST for the same mixture [i.e., 12 psi is the stress level used to attain the constant strain at frequencies of 5 and 10 Hz]. The stress selected was established by maintaining the strain in the range of 50 to 150 microstrains.

A summary of the shear modulus slope (S) determined from the linear portion of each plot is presented in Table 5-4. The shear slopes calculated from the FST device data are systematically lower than the laboratory SST slope values. This may be due to the strain measurements and the stress levels used to model the operation of the laboratory SST device.

5.3.1.c Analysis of Data

Tables 5-4 through 5-9 present the FST frequency sweep test data from the FST device compared with that obtained with the laboratory SST; Figures 5-8 through 5-14 show the relationship between frequency and G* on a log-log plot for each mix tested by project. These plots were developed by compiling the data for the selected stress levels corresponding to each test frequency. The data show a definite trend with respect to the dynamic shear modulus at 40°C. At 20°C, the error is much higher and the modulus values are significantly lower with the FST.

5.3.1.d Summary of Findings

Based on the testing of a limited number of samples, the following observations are noted:

- The complex shear modulus, G* (stiffness), for the specimens testing at 40°C revealed a fairly similar trend at frequencies of 0.2 to 2 Hz compared with the laboratory SST results. At 10 Hz the FST device generally indicates that the mixes have lower stiffness values whereas at 0.2 Hz the testing indicates higher G* values. The corresponding strain values show a reverse trend (i.e., higher

TABLE 5-4 Summary of shear modulus slope values at 40°C

Project	Lot No.	$S_{(+)}$	$S_{(-)}$	Mean *S*	S_{SST}
Wes Track	15-1 15-2	0.347 0.440	0.289 0.423	0.316 0.432	0.550 0.559
	16	0.398	0.324	0.357	0.580
	18	0.202	0.209	0.206	0.527
MD SMA	2-4	0.285 0.240	0.252 0.261	0.268 0.251	0.589
MD US-40	1-1				
Alabama	3-3	0.305	0.230	0.273	0.316

TABLE 5-5 Maryland SMA frequency sweep data at 40°C

Laboratory SST Frequency Hz	Strain in/in	G* psi	δ	G' psi	G" psi
10	0.000097	79409	50.09	50950	60908
5	0.000095	56254	52.97	33880	44907
2	0.000092	33684	56.88	18407	28210
1	0.000092	22160	58.34	11631	18862
0.5	0.000092	14248	58.26	7496	12117
0.2	0.00009	8446	55.44	4791	6955
0.1	0.000092	5007	55.25	2854	4114
0.05	0.000095	3948	56	2207	3273
0.02	0.000096	2320	53.64	1375	1868
0.01	0.00096	1891	48.83	1245	1423

Positive Shear (+) Frequency	Strain	G*	δ	G'	G"
10	0.000014	51100	47.16	34745	37470
5	0.00004	32662	37.7	25842	19974
2	0.000023	27438	36.69	22002	16394
1	0.000037	21417	30.89	18379	10997
0.5	0.000054	16215	26.92	14458	7340
0.2	0.000068	13069	24.75	11868	5472
0.1	0.000275	5446	33.87	4522	3035
0.05	0.00009	5591	11.73	5474	1136
0.02	0.000047	9070	14.73	8772	2307
0.01	0.000018	7839	28.99	6856	3799

Negative Shear (-) Frequency	Strain	G*	Delta	G'	G"
10	0.000018	40237	35.6	32716	23423
5	0.000045	30721	31.39	26225	16001
2	0.000024	25759	29.79	22355	12798
1	0.000039	20422	27.36	18137	9385
0.5	0.00005	17047	27.46	15126	7862
0.2	0.000065	13663	23.38	12541	5423

Positive Frequency Hz	Strain in/in	G* psi	Delta	G' psi	G" psi
10	0.000019	37403	39.14	29010	23610
5	0.00005	26742	34.95	21919	15319
2	0.000028	22542	28.09	19886	10615
1	0.000043	18633	25.04	16882	7885
0.5	0.000057	15327	22.56	14155	5879
0.2	0.000073	12335	18.85	11673	3986
0.1	0.000318	4811	32	4080	2550
0.05	0.000109	4614	14.4	4469	1147
0.02	0.00005	8723	11.62	8544	1758
0.01	0.000018	8164	11.59	7997	1640

Negative Frequency	Strain	G*	Delta	G'	G"
10	0.000018	40237	35.60	32716	23423
5	0.000045	30721	31.39	26225	16001
2	0.000025	25513	24.98	23126	10775
1	0.000041	19550	23.24	17963	7714
0.5	0.000054	16156	21.49	15033	5918
0.2	0.000067	13259	17.25	12662	3932

TABLE 5-6 Lot 15 WesTrack

Frequency	Strain	G*	Delta	G'	G"
10	0.00009	55518	50.84	35057	43049
5	0.000095	38966	53.03	23433	31132
2	0.000095	23110	55.19	13191	18976
1	0.000096	15475	55.36	8796	12733
0.5	0.000095	10306	53.66	6108	8302
0.2	0.000093	6234	53.3	3725	4998
0.1	0.000094	4406	55.75	2479	3642
0.05	0.000097	2974	47.28	2018	2185
0.02	0.000097	1963	34.74	1613	1119
0.01	0.000095	1366	41.8	1019	911
Positive Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.000146	28192	40.29	21504	18230
5	0.000196	21643	38.47	16944	13465
2	0.000071	20736	37.63	16422	12661
1	0.000102	15686	34.22	12970	8822
0.5	0.000163	12083	30.97	10361	6218
0.2	0.00021	9325	28.07	8228	4388
Negative Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.00014	29266	35.23	23907	16881
5	0.000179	23518	31.93	19959	12439
2	0.000067	21846	34.27	18054	12300
1	0.000094	16974	31.02	14547	8746
0.5	0.000142	13824	26.9	12329	6254
0.2	0.000175	11229	23.36	10308	4452

strains at the lower frequency). This shows that the measured strain is not truly constant. It appears that these discrepancies are due to the measurement of either stress or strain in the FST.

- At 20°C the complex shear modulus values are systematically much lower than the laboratory SST values for the entire range of frequencies tested.
- The shear slope calculated from the FST testing is typically lower (i.e., flatter slope) than that determined with laboratory SST data. This implies that the mixes would be less prone to rutting. However, because of errors in the measurements, these values may not reflect the material behavior.
- The simple shear test at constant height exhibited a poor correlation for testing conducted at 20°C. For higher test temperatures, the shear strain measured with the FST is on the order of 65 percent higher than the SST maximum shear strain. It should be noted that only one project (Alabama) is included in this analysis.
- Appendix B provides the test procedure in the AASHTO format.

5.3.1.e Conclusions and Recommendations

The initial testing proposed for study of the FST device needs to continue for further evaluation of the device. Additional work is necessary to examine the effects of the measured stresses and strains and the specimen orientation with this device on the material properties. Also, additional evaluation is recommended to better define the test protocols of the FST as a field QC/QA device and mix design evaluation device. The objectives of the study should be to evaluate different mix types, specimen sizes, and changes in mix composition and material properties. Additional objectives would be to identify modifications to the FST to improve its performance and develop preliminary test methods.

TABLE 5-6 Lot 15 WesTrack (continued)

Frequency	Strain	G*	Delta	G'	G"
10	0.000097	60839	52.41	37110	48210
5	0.000097	42461	54.59	24605	34606
2	0.000096	25683	57.44	13821	21647
1	0.000095	17188	58.15	9069	14601
0.5	0.000093	11203	57.43	6032	9441
0.2	0.000093	6665	58.54	3478	5686
0.1	0.000093	4578	57	2493	3840
0.05	0.000097	3654	50.93	2303	2837
0.02	0.000098	2152	50.36	1373	1657
0.01	0.000096	1821	36.9	1456	1093
Positive Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.000166	28025	48.33	18633	20933
5	0.000241	19938	44.71	14171	14026
2	0.000061	26898	50.33	17172	20703
1	0.000102	17517	44.61	12470	12302
0.5	0.000152	12851	40.76	9733	8390
0.2	0.000201	9756	34.93	7998	5586
Negative Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.00015	30957	44.74	21989	21791
5	0.000203	23672	40.56	17984	15393
2	0.000047	35065	46.95	23938	25623
1	0.000076	23452	43.36	17050	16102
0.5	0.000117	16753	39.74	12882	10711
0.2	0.000149	13154	33.77	10935	7311

5.3.1.f Implementation

The G* (complex modulus) value calculated from the FST device data can be used for QC purposes. Figure 5-15 shows the relationship between asphalt content, 2.36 mm, G_{mb} and G*. Although the void properties are apparently in control, the variation of G* indicates a change in aggregate structure and possible rutting potential.

5.3.2 Rapid Triaxial Testing Approach to Flexible Pavement QC/QA

Most pavement structural models in use today are, or were, developed with the expectation that triaxial testing data would be used to provide the input for the material properties in the structural model. The triaxial test has been used with notable success in the field of geotechnical engineering for applications such as earthquake and tunnel modeling as well as pavements.

Two of the main components of pavement modeling are the material properties and the structural model. Without these two components, performance prediction reduces to a strictly empirical process. The way the two main modeling components interact is sometimes misunderstood but is really quite simple. Basically, tests are performed on materials to establish their engineering properties and these properties are then used by the structural model to determine stresses/strains that lead to performance predictions. Because of a set of conditions called boundary conditions in the structural model, it is not necessary for a material property test to exactly mimic the field condition. However, the testing should, if practical, span a range of expected conditions so that extrapolations inside the structural model are kept to a minimum. The boundary conditions of the structural model handle things such as the loads at the surface of the pavement and, for very sophisticated models, even the free surface at the edge of the pavement in the form of drainage ditches. When the structural model is “loaded” by a tire, it computes

TABLE 5-7 Lot 16 WesTrack

Frequency Hz	Strain in/in	G* psi	Delta	G' psi	G" psi
10	0.000096	42280	55.42	23998	34809
5	0.000094	28434	56.52	15687	23714
2	0.000093	16623	55.96	9305	13774
1	0.000091	11130	55.98	6228	9225
0.5	0.000089	7724	57.2	4185	6492
0.2	0.000089	4241	52.77	2566	3377
0.1	0.000092	3169	40.72	2401	2067
0.05	0.000099	2666	45.96	1854	1917
0.02	0.000097	1971	41.33	1480	1302
0.01	0.000096	1306	34.69	1074	743
Positive Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.000187	24577	49.03	16113	18557
5	0.000257	17824	45.69	12452	12754
2	0.000071	21914	47.32	14857	16109
1	0.000119	15202	42.08	11283	10189
0.5	0.000162	11838	36.89	9468	7106
0.2	0.000222	8757	32.16	7413	4662
Negative Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.000163	28095	41.83	20934	18737
5	0.000212	21770	37.19	17342	13160
2	0.000063	25105	44.29	17972	17529
1	0.000102	17982	38.63	14048	11225
0.5	0.000128	15068	32.86	12657	8175
0.2	0.000164	11907	28.01	10513	5592

what the effect is on the various layers and, depending on the form of the boundary conditions and the nature of the loading, will generate the deflections due to the three-dimensional state of stress based on how it has been told to react by the material properties. This characteristic of these structural models is the fundamental reason why some of the guesswork is removed when questions arise concerning, for example, what will be the difference in rutting for material having the same thickness and mixture design when placed on a portland cement concrete layer versus when placed on a granular base material layer. If the pavement layers have the correct material properties and the structural model behaves according to these properties, the answer is automatic. Good structural and performance models that address both elastic behavior and damage can predict rutting and will allow an upward vertical movement at the edge of the rut as is often observed in the field. In most formulations that are being commonly used at present, the three-dimensional equations used in the structural model can be expressed in terms of either shear properties or triaxial properties because there is a mathematical relationship between the two in these relatively simple, but adequate, formulations.

The triaxial approach to determining material properties is useful for a variety of reasons. One of the more important reasons for this utility is the ability to handle the characterization of different types of materials, including those materials in the pavement system that do not stick together very well (e.g., unbound base and subgrade materials and asphalt concrete at high temperature). Of particular interest here is the role of triaxial testing of asphalt mixtures at elevated temperatures for QC/QA.

5.3.2.a Testing System

Triaxial Cell. In the past, the traditional fluid-filled geotechnical-type triaxial cell has been the major apparatus used in this type of testing. A standard geotechnical cell is not suitable for production use in the field. The standard cell and most standard geotechnical test procedures take too much

TABLE 5-8 Lot 18 WesTrack

Frequency Hz	Strain in/in	G* psi	Delta	G' psi	G" psi
10	0.000097	51657	51.22	32357	40268
5	0.000096	36805	52.88	22212	29347
2	0.000094	22470	54.51	13045	18296
1	0.000094	15360	55.42	8718	12646
0.5	0.000092	10606	54.94	6092	8682
0.2	0.000091	6616	52.3	4046	5235
0.1	0.000092	4704	52.16	2887	3718
0.05	0.000098	3552	47.24	2412	2608
0.02	0.000097	2480	29.81	2152	1233
0.01	0.000096	2376	40.81	1798	1553
Positive Shear Frequency	Strain	G*	Delta	G'	G"
10	0.000056	30871	33.14	25850	16875
5	0.000129	23396	32.34	19767	12515
2	0.000061	19559	27.68	17321	9085
1	0.000086	15336	25.59	13831	6625
0.5	0.000037	14634	20.17	13737	5045
0.2	0.000045	12197	17.7	11619	3708
Negative Shear Frequency	Strain	G*	Delta	G'	G"
10	0.000056	32423	31.56	27626	16972
5	0.000123	24965	29.22	21789	12185
2	0.000058	20397	25.68	18389	8840
1	0.000079	16673	23.74	15262	6712
0.5	0.000035	15242	18.06	14491	4725
0.2	0.000042	12734	15.66	12262	3437

time and attention to detail to be used in a production environment for QC/QA. The triaxial system used in the apparatus that is the subject of this discussion is based on a concept that has been in use with the Texas Department of Transportation (TxDOT) for many years. In TxDOT, the Texas triaxial cell is used for classifying soils by performing confined strength tests and plotting what are known as Mohr's circles. These are semicircles plotted on a graph that has the triaxial stress magnitudes on the x-axis and the computed shear stress on the y-axis. The cell used in the QC/QA apparatus is an extension of the Texas triaxial cell concept. The primary enhancements over the Texas triaxial cell are the following:

- Full instrumentation for temperature and both vertical and horizontal strains, and
- Automated control of cell movement for specimen handling.

The strain measurements allow computation of parameters that are important for structural models and field performance such as Poisson's ratio (which is basically the ratio of how much a specimen expands horizontally to how much it shrinks vertically when a vertical load is applied) and phase angle (which is basically how long it takes the peak strain to happen after the peak load is applied, analogous to the concept used in the performance graded (PG) system for the binder).

The automated control of the physical movement of the cell turns the extremely tedious job of getting a specimen in and out of a standard geotechnical cell and positioning all the instrumentation in the standard cell into a quick and easy operation taking less than a minute. The cell pressure is software controlled. Because of this control capability, a vacuum can be applied to the cell that draws the pressure membrane and the horizontal strain instrumentation away from the sides of the specimen. Once the vacuum has been applied, a pneumatic actuator lifts the entire cell up out of the way so that the previously tested specimen may be removed and the next specimen may be placed in position. Finally, the cell is lowered by the pneumatic actuator on the command of the operator with a single keystroke command to the software.

TABLE 5-9 Alabama laboratory SST and FST data

Lab SST Frequency Hz	Strain in/in	G* psi	Delta	G' psi	G" psi
10	0.000096	76721	40.51	58329	49838
5	0.000098	62587	39.48	48310	39791
2	0.000096	47338	42.04	35158	31699
1	0.000093	37037	41.76	27629	24666
0.5	0.000093	28969	41.32	21756	19128
0.2	0.000093	21307	39.81	16367	13641
0.1	0.000093	16888	38.3	13253	10467
0.05	0.000097	13701	34.92	11235	7842
0.02	0.000096	10961	30.98	9397	5641
0.01	0.000095	9142	31.31	7811	4751
Positive Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.000103	37988	34.7	31230	21628
5	0.000185	28563	32.42	24111	15313
2	0.000024	23920	31.95	20297	12657
1	0.000168	18811	31.24	16084	9755
0.5	0.000074	23161	28.99	20260	11224
0.2	0.000096	18755	27.49	16638	8658
Negative Shear Frequency Hz	**Strain in/in**	**G***	**Delta**	**G'**	**G"**
10	0.000111	37923	31.47	32345	19799
5	0.000174	30611	28.77	26832	14733
2	0.000111	26935	27.25	23945	12333
1	0.000142	22330	25.89	20088	9750
0.5	0.000084	21370	23.07	19661	8374
0.2	0.000104	17563	20.96	16401	6284

Specimen Size. The cell is designed for a 150-mm-diameter specimen approximately 150 mm tall, which is easily fabricated in most gyratory compactors. A uniaxially or triaxially loaded specimen needs to be relatively tall to minimize end effects and ensure a reasonably consistent stress and strain field. Conventional wisdom (e.g., AASHTO T 22, paragraph 8.2, and AASHTO TP46 paragraph 7.1) suggests that a height-to-diameter ratio of 2:1 is best for compression tests on cylinders. However, Button et al. ("Design and Evaluation of Large Stone Asphalt Mixtures," *NCHRP Report 386*, 1996) showed reasonable consistency of results down to ratios of 1:1. For this reason, the triaxial QC/QA test procedure is based on specimens with minimum height-to-diameter ratios of approximately 1:1.

Loading System. Weighing in at 175 lb (79.4 kg) and having a space-saving size of only 14.25 × 12 × 33.25 in. (362 × 305 × 845 mm), the triaxial QC/QA test frame uses a pneumatic actuator to apply the vertical load to the specimen. Recent advancements in control technology have enabled the use of pneumatics for applications that were previously attempted with hydraulics. Power requirements include a supply of compressed air and standard 110-V electrical service. A picture of the system with the triaxial cell in the raised position is presented in Figure 5-16. The machine is designed to apply a constant confining pressure and a sinusoidal vertical loading at various frequencies. However, the machine is also capable of controlling the confining pressure at other than constant levels such as would be required for hydrostatic compression testing, for example.

Test Procedures. Because the apparatus can perform tests at multiple frequencies as well as multiple stress states, it can be used for both QC/QA and mixture design and analysis. These two capabilities enable the machine to quantify not only the time-dependent response but also the stress-dependent response of the material—two features that are required for flexible pavement materials characterization.

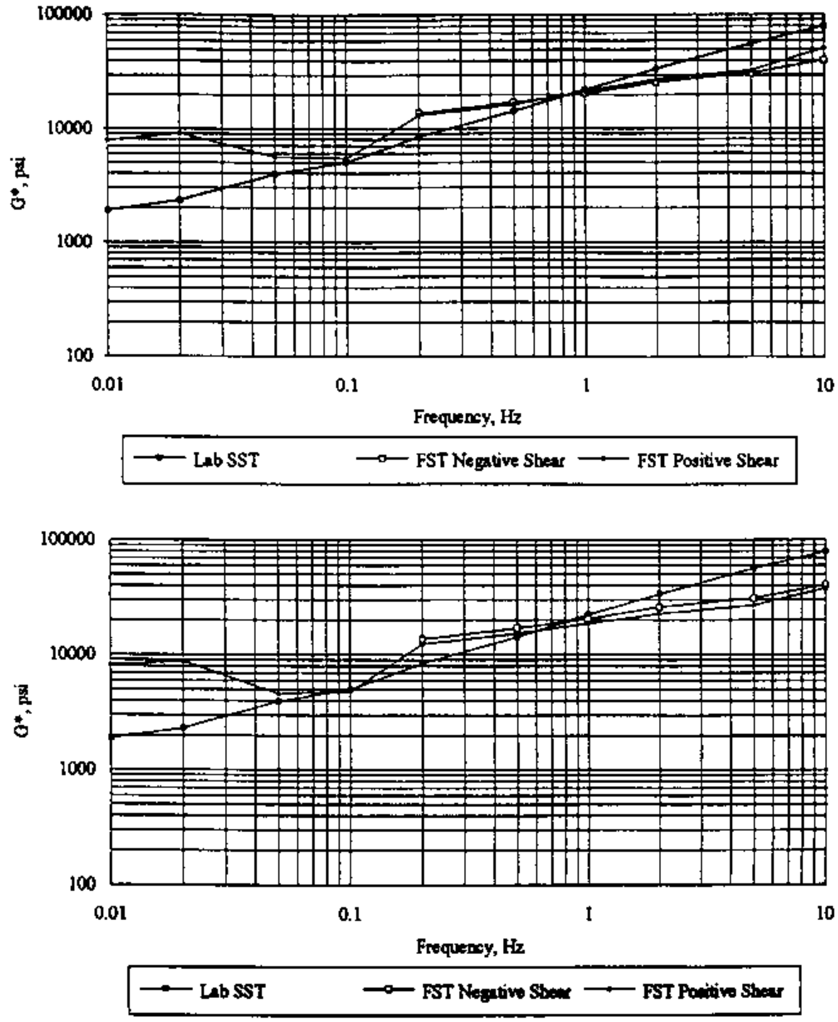


Figure 5-8. Maryland: SMA Lot No. 4. (Replicate 1, top; Replicate 2, bottom)

For QC testing, it is envisioned that the user would test a specimen straight out of a gyratory compactor at high temperature where the role of the viscosity of the asphalt cement is of reduced importance in the overall response. In the interest of speed and production efficiency, this testing would be accomplished using only one stress condition (i.e., confining pressure). The user may elect to test at multiple frequencies or at a single frequency that is representative of the expected speed of traffic on the pavement. Typical test durations for multiple frequency tests are on the order of 5 min per specimen, whereas single frequency tests take about 2 min.

For QA testing, it is expected that more time would be available to condition the specimens and conduct more detailed tests. For this type of testing, specimens are conditioned to the desired temperature (and, if desired, moisture condition) over a suitable period and then tested with four stress conditions and up to five frequencies per stress condition. The test itself requires 20 min per specimen unless slower frequencies are used.

In the current triaxial QC/QA test procedures, the four stress states being used include two levels of strictly compression tests, one strictly extension test, and one fully reversed compression-extension test. The extension test is a procedure in which the horizontal stress is larger than the vertical stress during a cycle. Extension testing yields results that are analogous to axial tension tests, but they have the advantage of not requiring the technician to glue end caps on specimens. The fully reversed compression-extension test is used for the QC testing as well as for the first of the four stress states in the QA testing. Before the cyclic portion of the test from which the engineering properties are derived, the specimen shape is retained by ramping up both the horizontal and vertical pressures simultaneously (i.e., an all-around hydrostatic stress state is maintained while the spec-

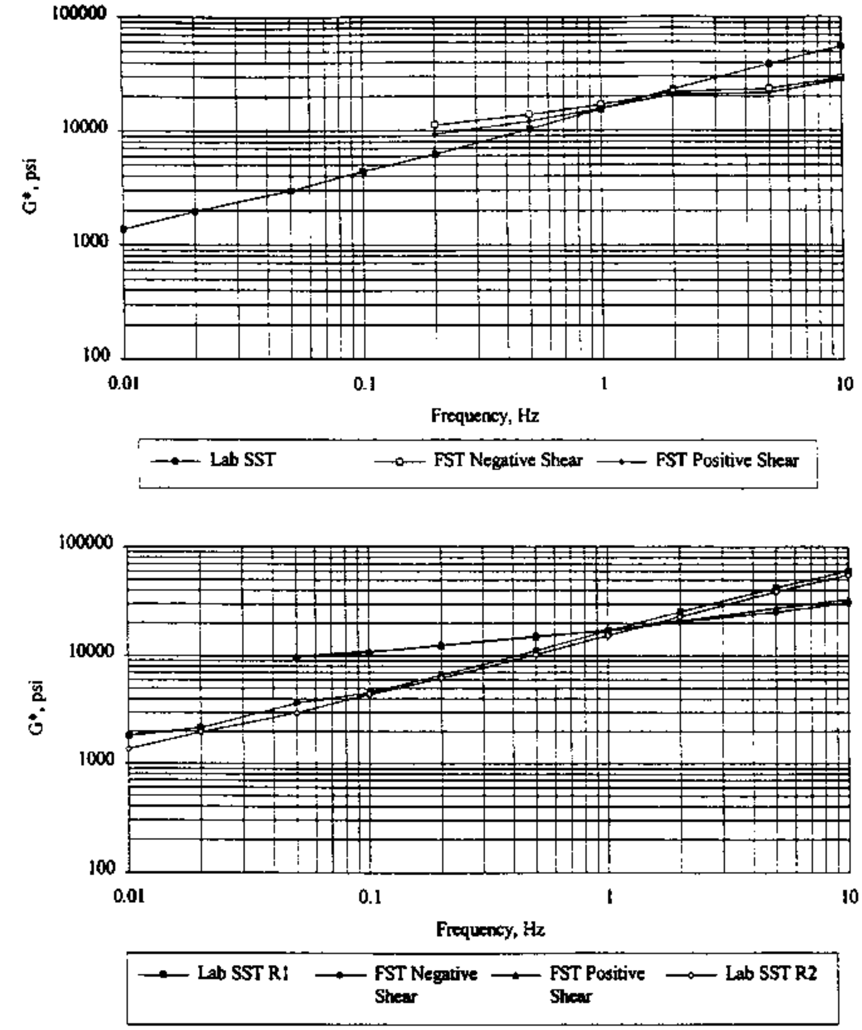
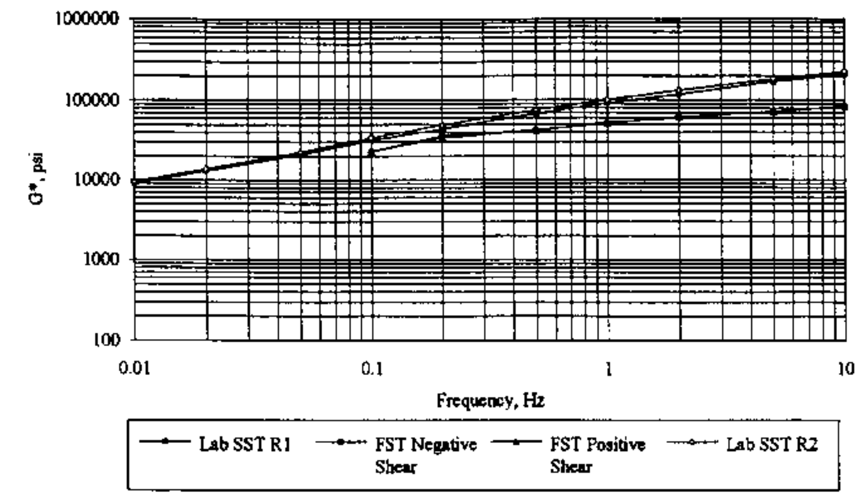
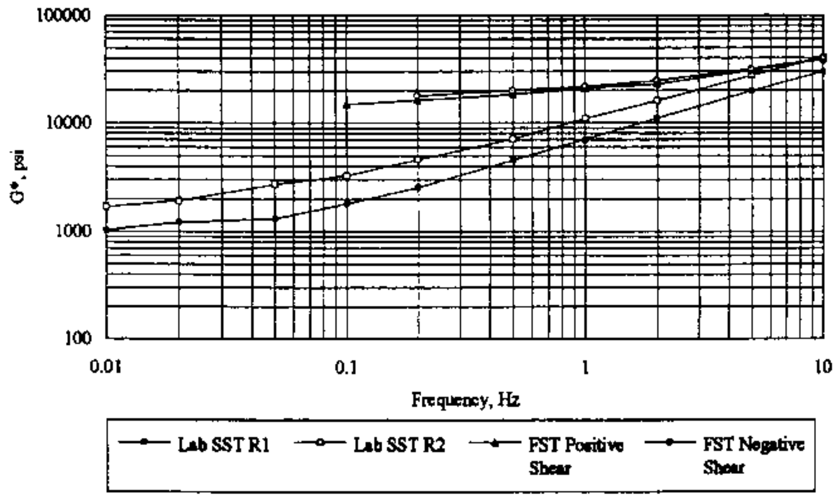


Figure 5-9. Nevada WesTrack Section 15. (Replicate 1, top; Replicate 2, bottom)



a) 20 °C

Figure 5-10. WesTrack Section 16.



b) 40 °C

Figure 5-11. WesTrack Section 18.

imen is being pressurized from atmospheric pressure up to the confining pressure that will be used for the stress state being applied). Maintaining this hydrostatic condition during the initial loading is particularly useful for unbound materials and asphalt mixtures at high temperatures. This two-channel control capability could also be used for subjecting the specimen to what is called a pure shear stress condition, the details of which are beyond the scope of the current discussion but are readily available from the author.

Output. The data analysis provides dynamic modulus values in compression and extension, Poisson's ratio in compression and extension, phase angle for the vertical load and strain response, and a rut resistance index based on characteristics of the overall nonlinear response during the period of the test. For the QA test, the results from the various stress states and frequencies can be combined to determine the parameter estimates for relatively sophisticated models of material properties.

5.3.2.b Applications

To date, the testing apparatus has been used to test mixes from an LTPP SPS-9 project, an NCHRP 9-7 field project, and the WesTrack project. It has been operated in both the QC and the QA modes.

Test Results. *SPS 9.* Approximately 130 tests were completed with the QC/QA machine in Canada on an SPS-9 project. Figure 5-17 illustrates typical results. The generally low modulus values are to be expected because the testing was done straight out of the gyratory compactor (hot) on

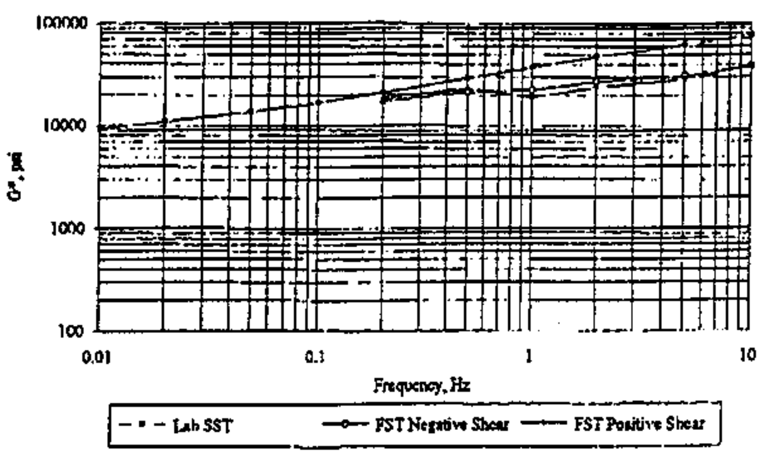


Figure 5-12. Alabama Lot No. 3, Sublot No. 3.

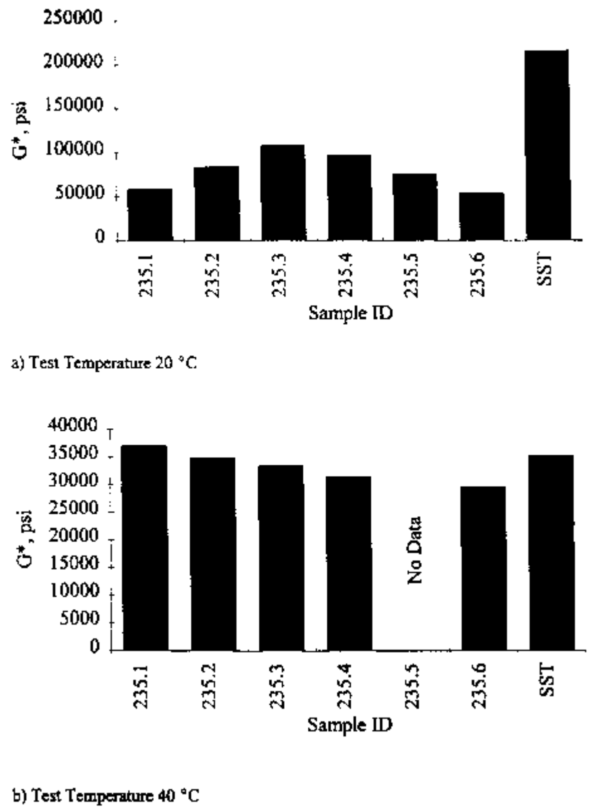


Figure 5-13. Alabama 25-mm nominal size, frequency sweep.

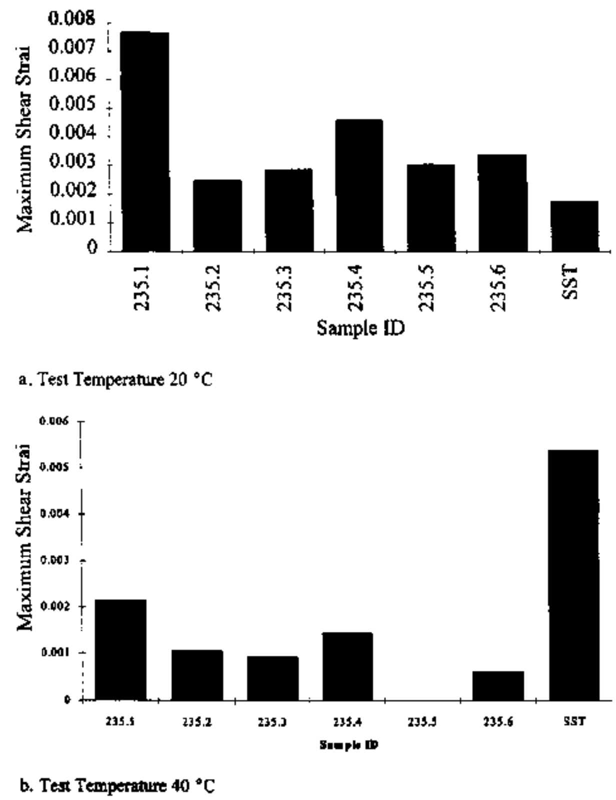


Figure 5-14. Alabama 25-mm nominal size, simple shear.

these particular specimens. The chart indicates that the QC test appears to be sensitive to changes in gradation. Mix code 1 is the Saskatchewan DOT standard mix, and 2 and 62 are Superpave mix designs with apparently improved stone skeleton load transfer. An analysis of variance of these data shows a statistically significant difference. The average values plotted are from data sets having a minimum of 8 (a maximum of 12) specimens per mix. The Superpave-designed mixes had larger variances than the traditional DOT mix, confirming the construction experience in which some difficulties were encountered with the contractor's plant calibration and production on the Superpave-designed HMA.

NCHRP 9-7. Alabama mixtures were tested (Lot 8, Sublots 2 and 4, and Lot 6, Sublot 3) and typical results are presented in Figures 5-18 and 5-19. Four specimens were available for each sublot. All tests were conducted at 40°C. In Figure 5-18, an analysis of variance confirmed that the materials in Lot 6 were significantly different from those in Lot 8, whereas the two sublots in Lot 8 were not significantly different. Figure 5-19 illustrates the overall trend of modulus with frequency for all the data combined (i.e., modulus increases with frequency as expected).

WesTrack. WesTrack mixes 6, 13, and 21 yielded typical results as presented in Figures 5-20 through 5-22. A minimum of two specimens were available for each mix in this testing (three specimens for mix 21). Figure 5-20 illustrates a strong relationship between the rut depth observed in the field and the measurements of modulus taken in a confined laboratory test. A linear relationship is indicated here, but

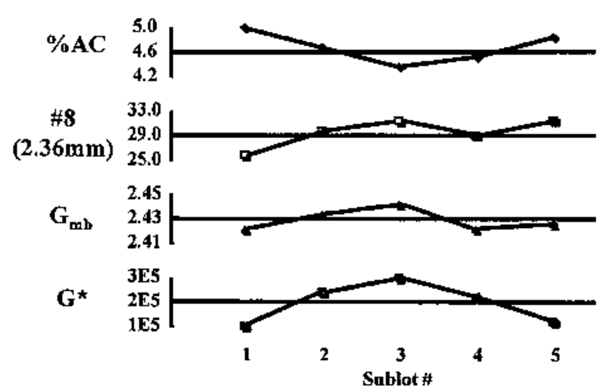


Figure 5-15. Comparison of composition and engineering properties for QC.

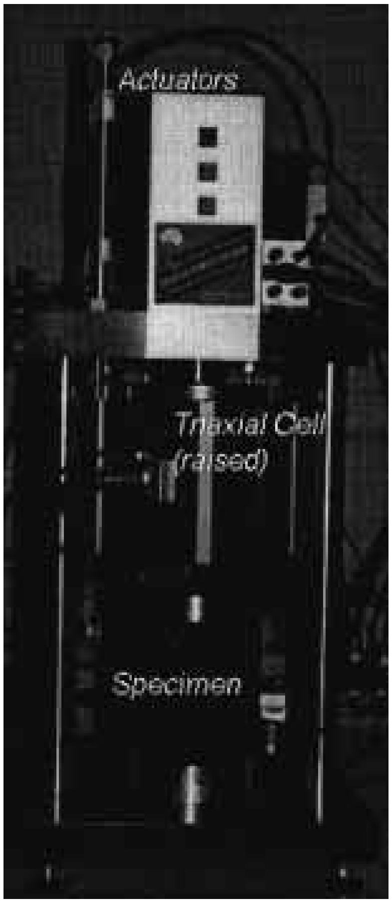


Figure 5-16. Triaxial QC/QA device.

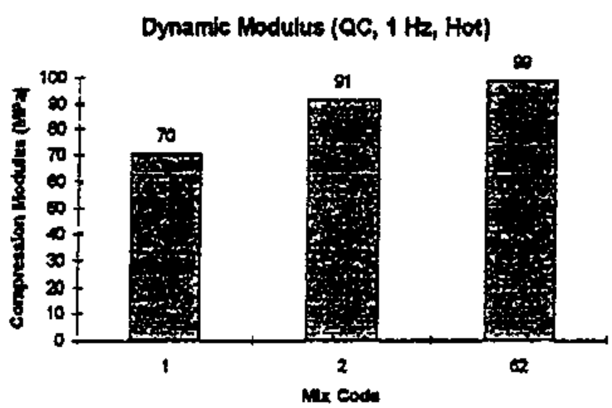


Figure 5-17. Example of SPS-9 results with a triaxial QC/QA machine.

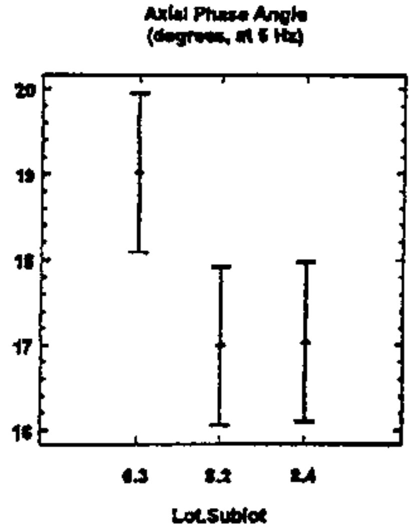


Figure 5-18. Phase angle at 5 Hz.

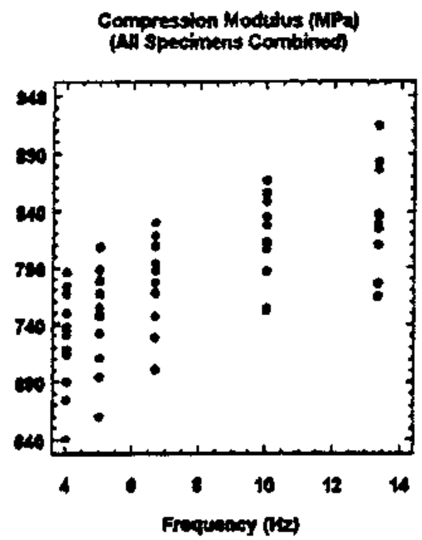


Figure 5-19. Frequency response.

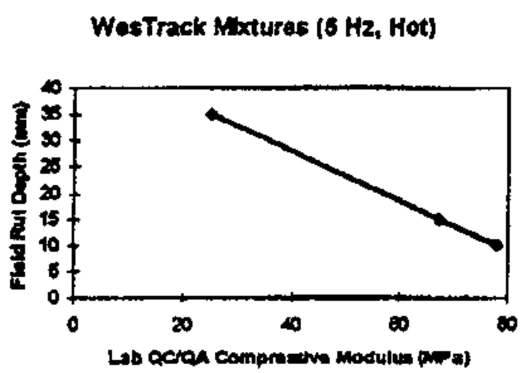


Figure 5-20. Modulus measured with a triaxial apparatus in the lab versus field rut depths.

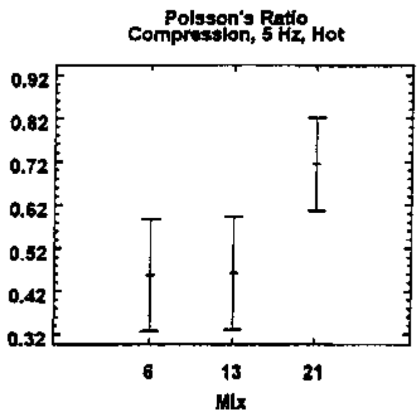


Figure 5-21. Poisson's ratio in triaxial compression.

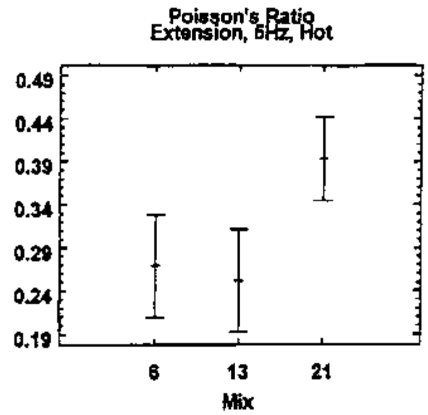


Figure 5-22. Poisson's ratio in triaxial extension.

further testing with a wider range of mixtures may indicate a nonlinear relationship. Figures 5-21 and 5-22 document the values of Poisson's ratio for the three mixtures. Although high values of Poisson's ratio are generally desirable, values that are too high can be indicative of failure, as is apparently the case with mix 21, which is the mix with the worst rutting in the field.

Implementation. The triaxial QC/QA system has been implemented in a portable unit with no temperature control for QC applications and with an integral environmental control system for both QC and QA applications. The machines are portable and can be moved by either standard-sized or small pickup trucks. Because of their small footprint and light weight, they are well suited to field trailer applications as well. The measured engineering properties of the specimens are compatible with most pavement response models and can be used as additional components in standard QC/QA methodology, such as computation of composite pay factors.

CHAPTER **6**

SUMMARY OF THE RESEARCH PROJECT

6.1 INTRODUCTION

Approximately 60 percent of the state highway departments in the United States currently use some form of QC/QA specifications. Under this type of specification, the contractor manufacturing and placing the HMA is responsible for the quality of the material produced—ensuring that it meets the specifications of the owner agency. The pavement owner is responsible for ensuring that the material it is paying for actually conforms to those specifications. Generally, there is a well-defined division between the QC and the QA functions, with each party to the contract having specified responsibilities for testing and inspection of the product.

Highway construction specifications are a means to an end. Their objectives are to provide the traveling public with an adequate and economical pavement on which vehicles can move easily and safely from point to point. A practical specification is one that is designed to ensure satisfactory performance at minimum cost. A realistic specification is one that recognizes variations in materials and construction are inevitable and characteristic of the best construction possible today.

It is well known that significant differences may occur between the properties of asphalt paving mixes prepared in the laboratory and the "same" mixes manufactured in an HMA plant. Changes in the characteristics of the mix are caused by one or more of many factors encountered in the manufacture of HMA, including the type of plant used, changes in the aggregate materials, changes in the asphalt binder material, and changes due to the plant-production process. It is important to determine whether the Superpave test procedures used to measure the characteristics and properties of the binder material and the HMA in the laboratory can also be used to measure and control those same characteristics and properties of the plant-produced mix.

6.2 OBJECTIVES AND ORGANIZATION OF THE RESEARCH

The objectives of NCHRP Project 9-7 were the following:

- To establish comprehensive procedures and, if required, develop equipment for QC/QA at the asphalt plant and lay down site to ensure that asphalt pavements meet the Superpave performance-related specifications developed by SHRP; and
- To develop a framework for a training program for qualifying technicians to accomplish the QC/QA field procedures developed.

NCHRP divided the project into three phases to accomplish the two objectives. These phases and related tasks are as follows:

Phase I

Task 1. Review and analyze SHRP performance-related specifications and research results, including SHRP recommendations for field control procedures as well as data from LTPP SPS-9 pilot projects.

Task 2. Review and evaluate other applicable research activities in asphalt paving mix QC/QA.

Task 3. Review QC/QA issues and relationships in related industries or industries with similar control or production procedures to identify applicable concepts.

Task 4. Recommend the appropriate level of control (i.e., tests or other measures) for the quality of materials delivered to the asphalt plant, including asphalt cement, aggregate, modifiers, and additives.

Task 5. Propose a statistically based experimental plan to collect field data that can be used to develop procedures to verify, accept, and control the asphalt mix. Verification will ensure that the mix produced by the plant and laid in the field meets the performance-based specifications developed through SHRP.

Task 6. Submit an interim report that presents the results of Tasks 1 through 5 and describes in detail the work proposed for the remaining tasks. NCHRP approval was required before proceeding with Tasks 7 through 14.

Phase II

Task 7. Conduct the series of field experiments approved in Phase I.

Task 8. Based on data collected in Task 7, establish the allowable tolerances and variabilities of the various test results. The test procedures must produce results in a timely manner.

Task 9. Based on the results of Task 8, identify the need for modified or additional field testing equipment, and, if needed, develop the equipment in accordance with NCHRP approval.

Phase III

Task 10. Finalize QC/QA procedures. These procedures shall include a family of statistically based sampling and test plans appropriate for the Superpave mix design and analysis method for various levels of pavement service (based on traffic volume).

Task 11. Develop guidelines using QC/QA procedures that define the circumstances when mix adjustments, which may be made in the field, are applicable versus those circumstances that require a complete new mix design.

Task 12. Develop guidelines for implementation of these research results.

Task 13. Design a framework for a training program for qualifying technicians.

Task 14. Submit a final report documenting the entire research effort.

This chapter presents the major findings of the research accomplished in Phases I, II, and III.

6.3 CONDUCT OF THE RESEARCH

The research effort was carried out according to the sequence set forth in the three phases. Each task within a phase was completed and used as a "building block" or "stepping stone" for the subsequent research activities.

6.3.1 Phase I: Literature Surveys

The purpose of Phase I was to review and evaluate existing programs, as related to field control procedures, and to develop a detailed work plan for establishing the QC/QA procedures using SHRP products.

6.3.1.a Summary of Review and Analysis of SHRP Performance-Related Specifications and Research Results

The purpose of the research effort was to review and analyze the Superpave performance-based specifications and research results with emphasis on the applicability of these specifications to the production and placement of HMA. The review and recommendations were performed by a Technical Review Committee. The Superpave specifications developed by SHRP include a set of laboratory procedures and test methods to determine the properties of both asphalt binder materials and HMA. The applicability of the procedures to the actual production and placement of HMA was examined.

For this task, 19 different Superpave specifications, practices, and test methods were reviewed. These procedures were in the form of AASHTO Provisional and Proposed Provisional Standards. They were divided into one of two groups: binder standards and HMA standards.

The standards were reviewed with emphasis on the applicability of each standard for use in controlling the production, placement, and compaction of the HMA. The review was carried out on each type of standard—binder and HMA—separately. Emphasis was placed on the following factors:

- Sampling techniques,
- Turnaround of the test results (speed of the test),
- Precision and bias of the test,
- Complexity of the test equipment and procedures,
- Engineering properties and control tolerances as related to field control practices,
- Cost, and
- Training and implementation.

The Technical Review Committee recognized that the test procedures must be applicable to the day-to-day production of HMA and must be functional in both the contractor's QC laboratory and in the owner's QA laboratory and that, in general, three approaches could be taken to control quality during production:

- Attempt to use an entire suite of SHRP Superpave tests on a frequent (multiple tests per production day) basis. Cost and time factors would appear to make this approach impractical, at least for the present.
- After a mix design is authorized for production, use a rigorous recipe approach and increase the number of conventional recipe tests severalfold so that production quality is actually controlled by test results rather than test results being entirely a forensic exercise. This is possible, but the test frequency would be so much greater than those generally followed in the past that considerable resistance would likely be generated because of the need to significantly increase the number of technicians necessary to implement this approach.
- Use a combination of automated or semiautomated tests that would provide test data on the components of the recipe at the frequency required for control and include tests on the final mix that can be completed in less than 4 h (preferably less than 1 h) and that simulate or are a surrogate for the engineering properties of interest in accordance with the Superpave mix design level under production.

The third alternative would require an initial capital expenditure (which can be authorized) but would allow the test frequencies required for control to be implemented with no increase in staffing, thus providing a major advance in production control with entirely reasonable unit costs. This appeared to be the approach that should receive careful analysis and consideration.

Recognizing the absolute necessity to be able to correlate performance to material characteristics in the current research program, the Technical Review Committee agreed that the following tests should receive careful consideration for inclusion in the planned research projects. These are not control tests. They are intended solely to provide fully supportable evidence of the engineering characteristics of the HMA produced and placed on the roadway in terms of suites of tests used in designing the mix and determining the binder properties.

- *Binder*: Follow a stratified random sampling plan to obtain a minimum of five samples per lot with a maximum lot size of 10,000 tons of mix produced (using the same binder), or, if less than 10,000 tons is produced for a project (using the same binder), the lot should be the quantity of HMA produced (using the same binder) for the project. Obtain the samples from the line that conveys the binder into the HMA plant after any blending operation has been completed. Perform the entire suite of *binder tests that were required for approval of the binder under the AASHTO MP1 Superpave performance-graded specification on all samples obtained*.
- *HMA prior to compaction*: Follow a stratified random sampling plan to obtain a minimum of five samples per lot, with a lot size of 25,000 tons of each mix produced, or, if less than 25,000 tons is produced for a project, the lot should be the quantity used on the project. Obtain samples from the plant output, compact immediately at the field laboratory (TP4 or 1015), and send to an appropriately equipped laboratory where, *using the same suite of tests and the same parameters followed in the project mix design, the tests are performed*.
- *HMA after compaction*: Follow a stratified random sampling plan to obtain a minimum of five cores per lot, with a lot size of 25,000 tons of each mix produced, or, if less than 25,000 tons is produced for a project, the lot should be the quantity used on the project. Obtain cores from the finished roadway and send to an appropriately equipped laboratory where, *using the same suite of tests and the same parameters followed in the project mix design*, the tests are performed. Further, recover samples of the binder and perform appropriate binder tests.

6.3.1.b Summary of Other Research Activities on HMA QC/QA

The main purpose of this research task was to perform a detailed literature review of other asphalt and HMA research. Major emphasis is placed on those QC/QA activities currently in place that may be applicable to field implementation of the Superpave asphalt specifications.

A Transportation Research Information System (TRIS) literature search was initiated in concert with the literature reviews completed within NCHRP Project 10-39 (Construction Testing and Inspection Levels) and FHWA Contract DTFH61-92-C-00097 (Quality Management and Statistical Quality Control in Highway Construction).

The literature research documents were grouped to provide pertinent information within key categories related to the Superpave mix design and analysis method:

- Materials proportions and mixture volumetric properties,
- Plant mixture engineering properties, and
- Road mixture engineering properties.

In addition, a telephone survey was made of all 50 SHAs and a number of asphalt paving contractors. The SHAs were surveyed to determine which agencies are currently using a contractor QC/agency QA-type specification program. A copy of the SHA's current specification for bituminous paving mixtures was requested from all agencies contacted. The contractors surveyed were generally asked how well the QC/QA specifications were working and what mix or construction items they controlled. In general, a contractor was selected for each of three different categories:

- Contractor in a metropolitan area who owned multiple stationary or portable asphalt batch or drum mix plants,
- Contractor in a rural area who owned several portable plants, and
- Small contractor who owned only one or two stationary plants.

Thus, the selection includes both large and small asphalt paving contractors, those located both in urban and rural geographic areas, and those who owned both stationary and portable HMA plants.

Materials Proportions and Mixture Volumetric Properties. The literature review and survey clearly indicated that mix design systems used today in North America were designed as laboratory-based systems for central laboratories. Construction and field control requirements are considered to be outside the scope of a mix design method. The mix design method is intended to be implemented in a laboratory and application of the design from the laboratory to the field is considered to be the responsibility of construction engineers. Although there has been unity in specifying the design method, the literature shows that field control varies widely. For example, both the Marshall and Hveem methods of mix design are documented in standards such as ASTM, manuals such as the Asphalt Institute's Manual MS-2, and SHAs' standard specifications. Field control methods, on the other hand, are not well documented in industry publications or standards. Each field control system is typically developed by individual agencies with various procedures, methods, objectives, and capabilities.

Some SHAs have not changed the way they design asphalt paving mixes for many years. In addition, many SHAs conduct field QC operations related to the HMA. Figure 6-1 compares design methods used by the SHAs.

Historically, field control systems have developed as recipe control systems. Once the mix design was issued by the laboratory, field control focused on verifying that the correct amount of asphalt binder was added to the aggregate and that the aggregate blend satisfied the design gradation. This approach is based on the premise that if the recipe as constructed matches that recipe as designed, the mixture performance will meet design expectations.

Control of the HMA mix volumetric properties, such as air voids content and VMA, was developed more recently. Experience showed that, when moving from the mix design in the laboratory to construction, the properties of the mixture could not always be ensured by controlling the mixture recipe. A central laboratory design with asphalt content and gradation chosen to meet volumetric criteria could be constructed according to the recipe, but the resulting volumetric criteria could be significantly different from the design. For example, a specified aggregate gradation mixed with a specified percentage of asphalt might produce a Marshall-designed mixture with 4 percent air voids. If construction confirms that gradation and asphalt content meet the design, air voids of a Marshall-compacted specimen may be as much as 2 percent less than the design level.

Volumetric property control requires that tests, which historically have been done in a central laboratory, be performed in a field laboratory. Some highway agencies have been controlling volumetric properties for many years, others are currently implementing field control, and others have not begun to change from recipe control.

Since the 1980s, SHAs have been focusing on QC/QA specifications. This is especially true since the "National Policy on the Quality of Highways" was established by representatives of AASHTO, FHWA, and industry in 1992. This policy establishes a continuing commitment for quality products, information, and services through the following:

- Proper design, construction specifications related to performance, adherence to specifications, use of quality materials, use of qualified personnel, and sufficient maintenance;
- Constant improvement of highway engineering technology by increasing emphasis on cooperative research, implementation, and technology sharing;
- Flexibility, coupled with responsibility, for designers, contractors, workers, and suppliers;
- Adequate assurances of quality achievement in planning, design, and construction by owner agencies;
- Incentives that reward achievements and innovations in providing a demonstrated level of value-added quality; and
- Cooperative development of quality management systems and specifications between federal, state, and local agencies; academia; and industry.

The AASHTO Joint Construction/Materials Quality Assurance Task Force developed a QC/QA Specification and Implementation Guide in relation to the national policy. The main reasons for developing the guide were the following:

- The use of QC/QA specifications will better define the responsibilities of both the contractor and the agency;
- The use of QC/QA specifications should allow more effective use of existing resources;
- Financial incentives given to contractors should be considered and should be commensurate with the value received from the highway product, provide a consistent product, and reduce nonspecification work;

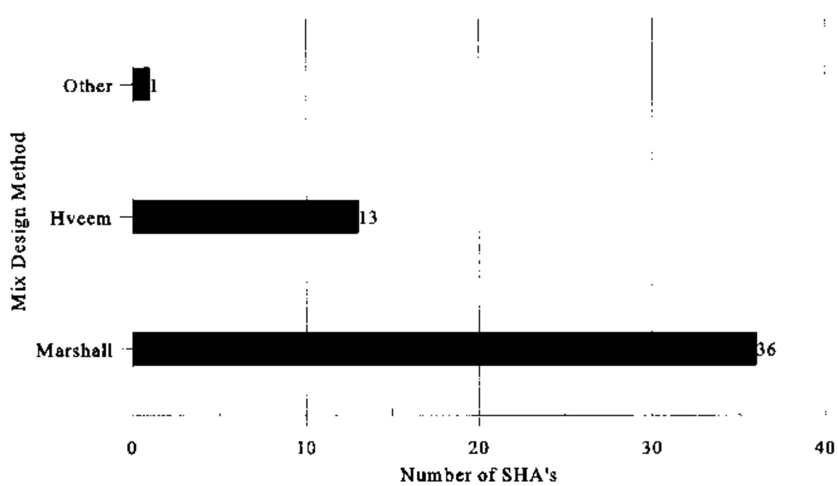


Figure 6-1. Comparison of design methods used in the United States.

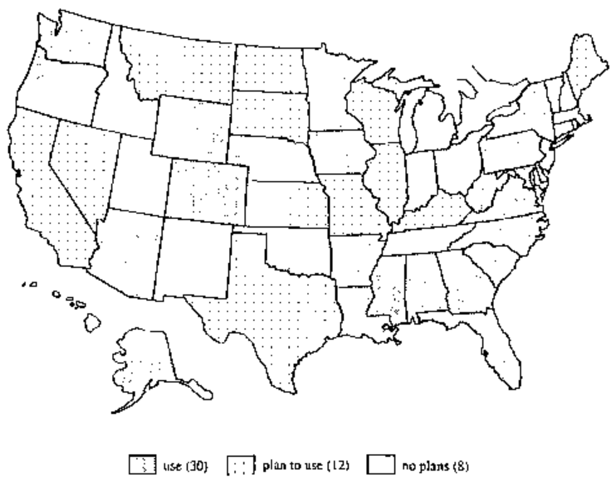


Figure 6-2. SHAs using QC/QA specifications based on AASHTO 1992 Survey.

- The use of QC/QA specifications should help ensure a high-quality product; and
- A properly written QC/QA specification should clearly define the agency's and contractor's risks in producing a consistent high-quality product and therefore should result in fewer contractor claims.

The key feature of the QC/QA specifications is the distinct division of responsibilities between the SHA and the contractor:

- The contractor is responsible for all QC activities.
- The SHA is responsible for acceptance and QA activities.

Figure 6-2 shows the results of an AASHTO survey conducted in 1992 of those states using or planning to use QC/QA-type specifications.

The literature indicates that SHAs demonstrate a similar distribution between the use of the two most common mix design procedures (Marshall and Hveem) with the QC/QA specifications. Figure 6-3 illustrates this distribution. An interesting point is the number of SHAs that now allow the use of contractor mix designs. Of the 50 SHAs contacted, 27 now allow the use of some form of contractor mix design. These states also have placed the responsibility of QC with the contractor.

During the survey, information was obtained from each of the SHAs contacted about the properties used to control and accept according to QC/QA specifications. The more common mix properties used by SHAs are listed in Table 6-1, along with the number of agencies that specify those properties for the design, control, and acceptance of paving mixes.

Lot size, sample size, and testing frequency for the control and acceptance of HMA are highly variable from agency to agency. Some states use an area or length basis as a unit for determining lot size, whereas others use a day's production basis or a tonnage basis. Typically, lot sizes defined by some SHAs range from 500 to 4,000 tons.

Specification values associated with those mixture properties listed for the design, control, and acceptance of asphalt concrete mixtures vary greatly from one agency to another. For example, the minimum Marshall stability value used to design asphalt paving mixes was found to vary from as low as 1,000 pounds to a high value of 3,000 pounds. In some agencies, stability is a function of traffic or layer type, whereas in other agencies it is not (i.e., a minimum value is used for design). Similarly, the design air void level was found to vary from a value as low as 2 percent to as high as 6 percent; with the more typical range being 3 percent to 5 percent, as expected.

For control or acceptance testing, similar variations between the mix properties exist from agency to agency. For example, the controls on gradation were found to vary from

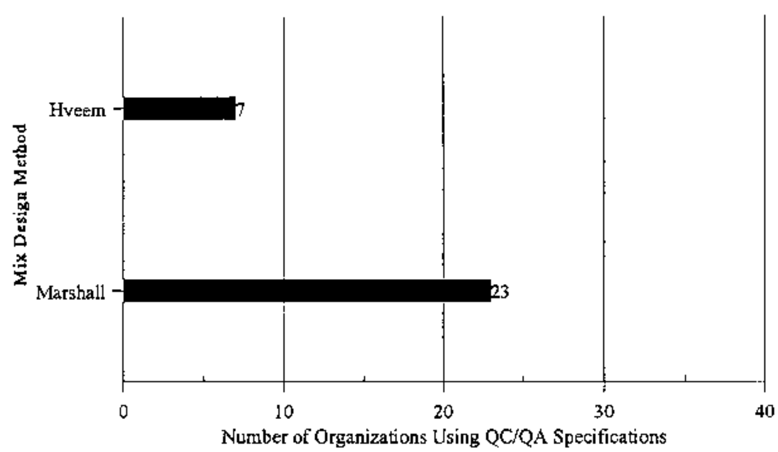


Figure 6-3. Mix design methods of SHAs using QC/QA specifications.

TABLE 6-1 Mixture properties evaluated by SHAs using QC/QA specifications

Mix Property	Number of SHA's Using Mix Property For:		
	Design	Control	Acceptance
Gradation	23	20	20
Asphalt Content	23	20	23
Stability	23	14	10
Flow (Marshall Only)	23	10	--
Air Voids/Density	23	26	23
VMA	16	11	8

±2 percent to ±4 percent for percent passing 0.075-mm (No. 200) material, ±4 percent to ±8 percent for sand-sized aggregate, and ±5 percent to ±8 percent for gravel-sized aggregate. Figure 6-4 compares the frequency of occurrence for different tolerances specified for *asphalt content* for those SHAs that use a QC/QA-type specification. The consequences of these different tolerances may greatly influence the quality of the HMA produced.

The SHAs vary in the requirements for control of asphalt content. Most states requiring asphalt content control use some form of binder extraction from the mix. Chemicals such as 1,1-trichloroethane and trichloroethylene are used as the solvent. Environmental concerns related to the use of such chemicals have caused some states to use biodegradable solvents. The chemical-type extraction tests have always been considered time-consuming and costly from both an acceptance and a QC standpoint. These tests also have a relatively high degree of variability.

Other states permit the use of nuclear asphalt content gauges for QC purposes. These gauges are generally mix specific and must be recalibrated whenever the mix design changes. The big advantage of their use is the shorter testing time. The degree of variability between gauges of different manufacturers can be high.

Some states (e.g., New York and Pennsylvania) permit the use of the production plant computerized readout (printed ticket) for acceptance and QC. In fact, New York uses this procedure to eliminate the environmental concerns associated with chemical solvents. The literature indicates that the degree of variability associated with asphalt batch weights, for example, is much smaller than that associated with extracted asphalt binders.

In terms of aggregate control, most SHAs require some form of QC on the fine and coarse aggregate mix blend. This is accomplished primarily by plant laboratory sieve analyses from plant cold feed, hot bins, etc. Tolerances are generally specified about an approved mix design. The sieve analyses are time consuming. The French have developed and implemented a unique "real-time" test for aggregate gradation analysis. The device is an in-line grading system termed the video grader. A smaller, portable unit has also been developed for off-line use in the laboratory. The device is capable of grading aggregates by measuring the real dimension of aggregates 1 to 60 mm in size. It utilizes an optical scanning

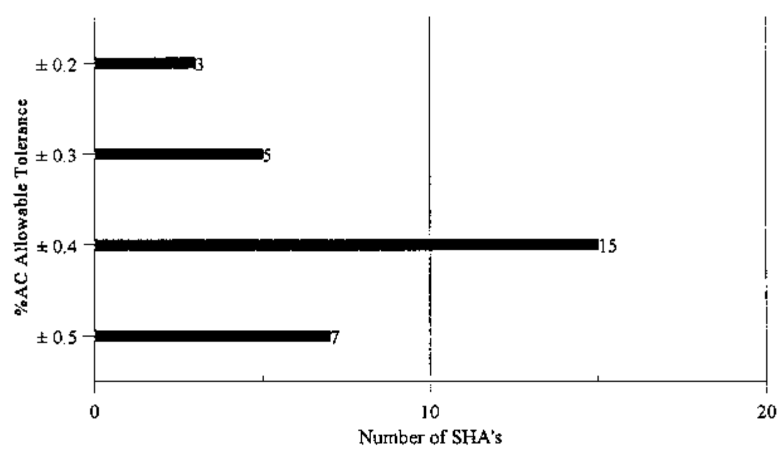


Figure 6-4. Distribution of asphalt content tolerances for SHAs using QC/QA specifications.

approach and uses exact coordinates of aggregates to obtain the size fractions. The grading curve and volume passing is obtained within 10 min. The French use this approach routinely and are eliminating the sieve-analysis procedure for QC.

FHWA Demonstration Project 74 provided information on the Superpave volumetric (Level 1) field control practices. Part of this demonstration was an early evaluation of Level 1 mix designs and associated QC. Table 6-2 shows the sampling and testing frequency for this evaluation. The project produced two early effects on the industry. The field laboratory demonstrated (1) the use of laboratory tests in a field environment and (2) the inability of recipe control alone to ensure that design volumetric properties were obtained.

Summary. The following summarizes the findings of the literature review related to material properties and mix volumetric properties.

Material Proportions. The literature clearly indicates that most states require a "recipe-type" control. The controlled items are primarily asphalt content and aggregate gradation.

Asphalt content is controlled primarily by the following:

- Solvent extraction,
- Nuclear asphalt age,
- Ignition oven,
- Plant meter readings, and
- Rice theoretical specific gravity determination.

Gradation is controlled primarily by sieve analysis using

- Extracted aggregate, and
- Aggregate cold feed sampling.

Mixture Volumetric Properties. The literature demonstrates that control of volumetric properties is performed primarily on laboratory-compacted specimens of plant mix. The objective of volumetric proportion control is to confirm the volumetric design on plant-mixed materials. Volumetric properties (i.e., air voids content, VMA, and VFA) take precedence over material proportions. Therefore, if asphalt content and gradation meet the design mixture but air voids do not, adjustments must be made to either asphalt content or gradation to bring air voids, VMA, and VFA into line.

Items controlled for mix volumetric control include material and volumetric proportions. These are as follows:

- Asphalt content,
- Gradation,
- Percent air voids,
- Percent VMA, and
- Percent VFA.

TABLE 6-2 FHWA Demonstration Project 74 sampling and testing frequency for SHRP mix

PRELIMINARY TESTS:

- Stockpile Aggregate Specific Gravities (AASHTO T84 and T85)
- Stockpile Aggregate Gradations (AASHTO T27 and T11)
- Stockpile Aggregate Sand Equivalency (AASHTO T176)
- Asphalt Cement Penetration (AASHTO T49)
- Asphalt Cement Viscosities (AASHTO T228 and ASTM D4402)
- Asphalt Cement Specific Gravity (AASHTO T228)
- Asphalt Cement Complex Shear Modulus and Phase Angle (SHRP Protocol)
- Calibration of Nuclear Asphalt Content Gauge
- 3 Point Mix Design Using SHRP Gyratory Compactor
- 3 Point Mix Design Using Marshall Compactor

PRODUCTION TESTS:

- 4 Hot Mix Asphalt Samples per Day
- 2 Combined Aggregate Cold Feed Samples (Minimum) per Day (AASHTO T11)
- 2 Moisture Sensitivity Tests per Job (ASTM D4867)
- 4 Maximum Specific Gravities of Uncompacted Mix per Day (AASHTO T209)
- 4 Extracted Asphalt Contents per Day (AASHTO T164)
- 4 Asphalt Cement Contents by Nuclear Method (ASTM D4125)
- 4 Sets of Compacted Mix Specimens by SHRP Gyratory Compactor per Day
- 4 Sets of Compacted Mix Specimens by Marshall Compactor per Day
- Particle Size Analysis of Fines to Determine Effect Upon Mix Void Properties

Design asphalt content, gradation, and mix volumetric properties are generally supplied by the design laboratory. Percent air voids, VMA, and VFA are measured on plant mix samples compacted to a design density.

The air voids content is calculated by using the bulk specific gravity of the compacted specimen and the Rice theoretical maximum specific gravity measured on a companion sample. VMA is calculated by using the compacted specimen bulk specific gravity of the compacted specimen and the aggregate bulk specific gravity. VFA for a specimen are calculated by using the air voids content and the VMA from that specimen.

Plant and Road Mix Engineering Properties Control. The literature shows that the engineering property of the laboratory mix measured most frequently by most states is stability. Stability is believed to be related empirically to field performance. This holds true for both the Marshall and the Hveem design procedures.

Over the past 10 years, however, research has focused on developing laboratory tests that provide material properties directly related to pavement performance. The pavement distress factors of *primary* importance identified in the literature have been low-temperature cracking, fatigue cracking, and permanent deformation (rutting). The literature search revealed that a number of test methods have been developed and evaluated in relation to the primary distress factors.

The NCHRP AAMAS [Project 9-6(1)] promoted five tests as tools for mix evaluation and potential field control related to the mixture engineering properties. The tests are the diametral resilient modulus, indirect tensile strength, gyratory shear strength, and indirect tensile and uniaxial unconfined compression creep. These tests are primarily geared to a laboratory. These tests were also related to the volumetric properties as indicators of engineering properties from a QC viewpoint. The measured resilient modulus, static creep modulus, indirect tensile strength, and failure strains are used for load-associated and thermal cracking evaluations. The unconfined compressive strength, resilient modulus, and static creep modulus are used for permanent deformation evaluation.

Researchers in the United Kingdom have worked toward simple test methods for the purposes of mix design, QC, end-product specification, pavement evaluation, failure investigation, and assessment of new products. The equipment is known as the Nottingham Asphalt Tester (NAT). The researchers identified that traditional methods of QC, using compositional analysis and some means of determining the degree of compaction, are indirect and not totally satisfactory.

Permanent deformation was of primary interest to the researchers in the United Kingdom. They identified that a uniaxial creep test is necessary to display accumulations of permanent deformation, which are not demonstrated by static loading or creep tests. Also, the researchers identified that elastic stiffness quantifies the relationship between stress and strain under speeds of loading associated with moving traffic or lower temperatures. It is a measure of load-spreading ability for the asphalt dictating the general levels of stress and strain in the pavement structure. Elastic stiffness is influenced by the grade of asphalt and the volumetric composition of the mix, which may be quantified, for example, by VMA. The repeated load indirect tensile test (diametral test) is used for determining the elastic stiffness. This test and the uniaxial creep test may be used on either laboratory specimens or cores taken from the road.

Numerous deformation tests performed on laboratory-prepared specimens and road cores suggest that good material performance can be expected if the mix formulation exhibits less than 1 percent permanent strain at the end of the creep test. Similarly, data obtained from repeated load indirect tensile testing indicate that satisfactory mixes will have values of elastic stiffness in excess of 3,000 MPa at the particular test conditions. To allow for the variability of this test, a tolerance of 500 MPa has been applied to this value. Hence the criteria of acceptability proposed for the two tests are as follows:

- Elastic stiffness ≥ 2,500 Mpa, and
- Permanent strain ≤ 1 percent.

The Australians have also developed a similar piece of equipment for mix design and QC purposes. The equipment is known as the Industrial Process Controls Materials Testing Apparatus (MATTA). The equipment was developed in close cooperation with the Australian Road Research Board, Australian State Road Authorities, and the Australian Asphalt Pavements Association. The range of tests are as follows:

- Static load asphalt creep test with uniaxial loading,
- Repeated load asphalt creep test with uniaxial loading,
- Repeated load indirect tensile asphalt fatigue test using diametral loading, and
- Indirect tensile resilient modulus (repeated load) using diametral loading.

The Dutch and the French have implemented a creep test similar to the United Kingdom's test for QC. Early work was done with the static creep test. However, the Dutch found, like the researchers in the United Kingdom, that the static creep test measures only permanent deformation resulting from viscous flow of the binder films. Once aggregate to aggregate contact develops, creep will stop. The uniaxial creep test captures the accumulation of permanent deformation.

The French [specifically LCPC (Laboratorie Central des Ponts Chausées)] have also developed a gyratory compactor for mix design and field QC purposes. This gyratory compactor has an angle of gyration of 1x, a vertical pressure of 0.6 MPa, and a rotation speed of 6 gyrations per min. The French gyratory compactor was the basis of development for the SGC. Based on the initial, design, and maximum number of gyrations related to mix design, the French use the gyratory compactor in the field to control air voids and VMA. The French are convinced that the gyratory compactor provides a QC total to ensure the following:

- Provide adequate VMA at the design number of gyrations at 4 percent air voids;
- Meet density requirements at the initial number of gyrations; and
- Meet density requirements at the maximum number of gyrations.

The French have published numerous articles supporting the notions that the contractor should be held to the "recipe" mix and that the mix design should clearly specify the mix proportioning. The French strongly believe that the contractor's QC should include specific controls on mix proportions or a recipe mix.

The original Superpave approach to field QC employs the SGC. From a QC standpoint, HMA sampled from plant production is compacted. Specification values for air voids content, VMA, and VFA should be met at the design number of gyrations. Density at the initial number of gyrations and the maximum number of gyrations should also meet specifications. The SHRP researchers believed that if the type of aggregate and asphalt binder, aggregate gradation, amount of each aggregate, and asphalt binder content do not change, the density should remain constant. A change in the type of materials or the amount will cause a change in density (Figure 6-5).

This approach should minimize the amount of testing for QC by the SHA or contractor on a periodic basis, or, if a change in density is detected as shown in Figure 6-5, it would be necessary to determine the volumetric properties or the engineering (performance properties) of the mix. A subset of the Superpave performance-based tests would then be conducted and compared with the original mix design.

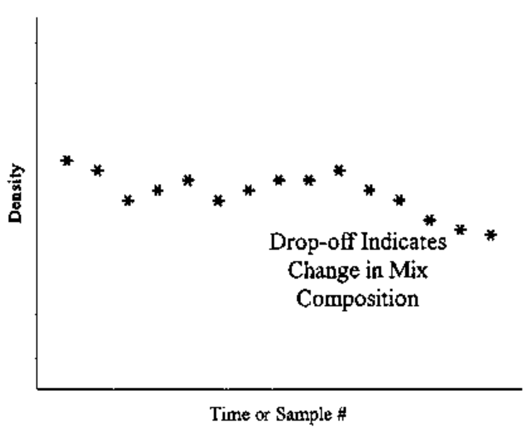


Figure 6-5. Field control for density.

SHRP, through its 5-year research effort, developed specific tests related to the primary distress factors. The specimens used with the SHRP tests are compacted in the laboratory using the SGC. The compacted specimens must meet specific volumetric property criteria as discussed previously. The following tests are performed on the compacted specimens depending on the level of mix design (AASHTO TP7 and TP9):

- Repeated shear at constant stress ratio,
- Frequency sweep at constant height,
- Simple shear at constant height,
- Uniaxial strain,
- Volumetric (hydrostatic state of stress),
- Indirect tensile creep, and
- Indirect tensile strength.

The material properties produced from these tests are linked to pavement performance by prediction models. The test equipment is specifically geared for the laboratory mix design environment. With the exception of the gyratory compactor, the equipment does not lend itself directly to field QC.

The test results are used in the SHRP performance models via the SHRP Superpave software to predict pavement performance based on the mix properties. Figure 6-6 illustrates a flow diagram of the performance model. The mixture characterization program (material property model) calculates the nonlinear elastic, viscoelastic, plastic, and fracture properties of a mixture from the laboratory tests.

The frequency sweep is used to determine the linear viscoelastic properties (i.e., complex modulus) and the parameters of the power law. The volumetric (hydrostatic), uniaxial, and simple shear tests are used concurrently to determine the resilient (k_1 to k_6) and plastic (Vermeer properties) properties of the mixture. The repeated shear load test resembles both the frequency sweep test and the shear load test; however, the loading is repeated for several thousand cycles. Material parameters are not specifically calculated from this test, but the results of the test are used in the Superpave mix design as a quality check on the other test regimes.

The frequency sweep test provides the complex modulus. When the log of the complex modulus is plotted against the log of the frequency, the slope of the resulting line, S, can be related to another mixture property, m, which is the slope of the log creep compliance curve. The parameter m is used in both the fatigue (to determine a Paris law coefficient) and the permanent deformation calculation.

The uniaxial, volumetric (hydrostatic), and simple shear test provide the same information but along different stress paths. The resilient (elastic) components, k_1 to k_6, are used in the calculations of the elastic modulus (k_1, k_2, k_3, k_6) and the Poisson's ratio (k_4, k_5) of the asphalt concrete. The plastic components (α, x, ϕ_p, ϕ_{cv}) are used in the Vermeer model in determination of the permanent deformation characteristics of the asphalt concrete.

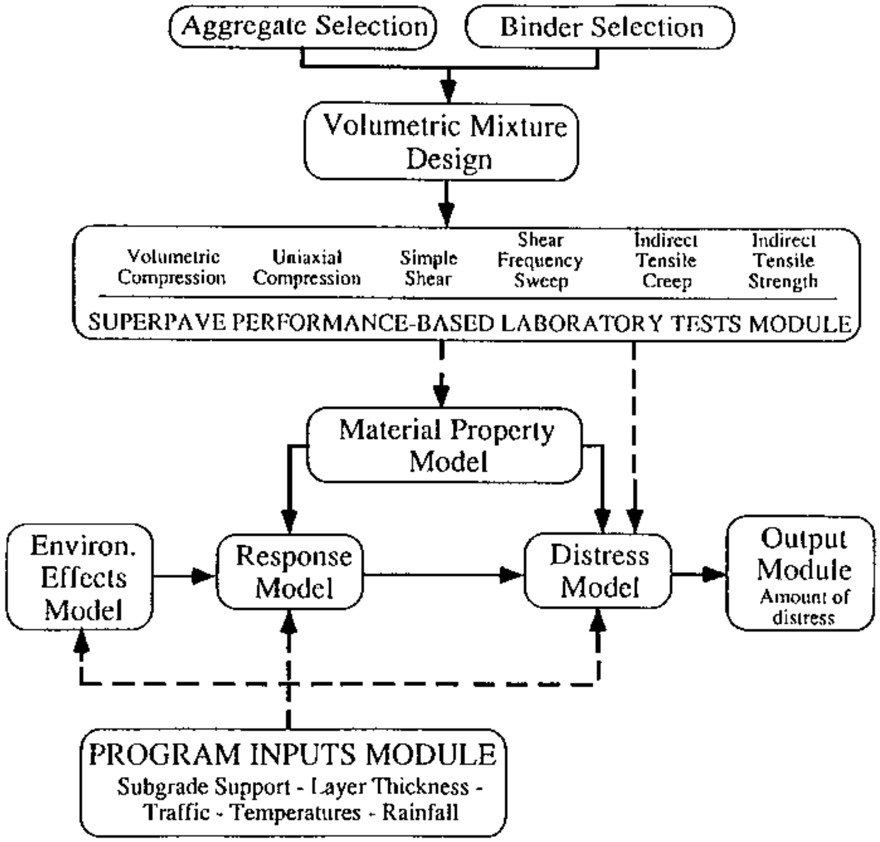


Figure 6-6. Flow diagram of Superpave performance model.

The non-load-related portion of the Superpave performance models predicts crack spacing as a function of age (number of seasonal cycles) and is based on parameters obtained from the indirect tensile creep and failure tests. The material parameters needed for the thermal cracking are m, as mentioned previously, and the undamaged tensile strength of the mix. The parameters are used in determining a Paris law coefficient also mentioned previously.

SHRP researchers considered the control of permanent deformation in the field as the key issue in mix design. In their opinion, low-temperature performance should effectively be controlled through the selection of the performance-grade binder and laboratory evaluation with the performance-based tests. Load-associated fatigue should be properly accounted for by proper pavement design thickness accounting for the design traffic loading.

The SHRP researchers, as stated previously, believed that monitoring volumetric properties in QC should assure proper control of permanent deformation. However, if a change in these properties occurs, a subset of the Superpave performance-based tests for permanent deformation should be used for QC. For example, a repeated shear test at constant height could be used to estimate the amount of permanent deformation.

Summary. A variety of tests have been developed to evaluate the HMA material properties associated with low-temperature cracking, load-associated fatigue cracking, and permanent deformation. Most of these tests are designed for the mix design laboratory and are not necessarily applicable to field QC. Some tests identified in the literature search may have potential as field QC devices. The equipment is as follows:

- SHRP gyratory compactor;
- Repeated load creep with uniaxial loading (NAT and MATTA);
- Indirect tensile resilient modulus using diametral loading (NAT and MATTA); and
- Repeated shear at constant height (Endura-Tec).

6.3.1.c Summary of QC/QA Issues in Other Industries

The primary objective of this research effort was to identify QC/QA issues and relationships from unrelated industries with similar control or production procedures that possibly could be applicable to this project. Also included in this task was a survey of QC/QA activities in selected European countries.

Statistical Process Control at the Raw Material Manufacturing Facility or Site Where Product is Used. Most industries identify the importance of quality in the following three broad areas of a business:

- Quality of design,
- Quality of conformance to design, and
- Quality of performance.

The quality of the design of a product is concerned with the stringency of the specifications for manufacture of the product. The literature indicates that quality of design is greatly influenced by the market for the product.

Quality of conformance to design is concerned with how well a manufactured product conforms to the original design requirements—that is, generally speaking, how well quality is controlled from materials procurement through shipment and storage of finished goods. QC, as it has been known and used in the past, has been closely associated with conformance quality. Also, this area is where most of the sampling and statistical techniques have been used.

Quality of performance considers how the product is put to work and how it performs. Quality of performance depends on both the quality of design and the quality of conformance. It can be the best design possible but poor conformance control can cause poor performance. Conversely, the best conformance control in the world cannot make a product function properly if the design is not right. Thus, a continuing feedback system is necessary for providing quality information to act as a basis for decision making regarding the optimizing of a quality product. The key word here, in each case, is optimum, which does not necessarily mean the most stringent quality requirement but rather the best in the sense that it will yield the greatest long-term return on the investment in QC.

Most industrial and administrative situations involve a combination of materials, machines, and personnel. Each of the elements of the combination has some inherent or natural variability, the causes of which cannot be isolated, plus unnatural variability, which can be isolated and therefore controlled to a certain irreducible economic minimum.

Industry views two sources of variation. First, the causes for material variation may be many, including inadequate purchased materials or quality assurance, poor material specifications, immediate need of materials regardless of quality, lowest purchase price rather than minimum cost delivered to the shop floor, reciprocity, or any of a number of causes. One frequent cause of poor quality of purchased materials, if such exists, results from the vendor's lack of knowledge of what the buyer really wants. There is often a double standard: (a) the material specification, and (b) what the buyer will take for the sake of expedience. An analogous situation exists with personnel in the machine shop, that is, (a) the so-called working drawings, and (b) what the supervisor will okay, again for the sake of expedience.

The second source of variation is the machine. Every process, precision or not, has a certain capability range within which it will operate. The limits of this range are known as the natural limits of the process. This natural range of variability is also often referred to as "process of machine capability." A process is defined to be any employment of equipment or personnel for the purpose of production, the products of which may be tangible or intangible. Contrasted to the natural limits are specification or drawing limits. These limits are most often arbitrary because the objectives of the design of the product determine what they will be. At least this is the way it should be. Very often, however, the design limits are arbitrary without proper consideration of the objectives of the design. This in turn leads to formation of the double standard, namely, what is desired and what will be accepted.

Many industries have shown that attempts to control the process to a range of variability narrower than its natural range is courting indecision, frustration, and unjustified expense. If the process is incapable of acceptable operation within design limits, there are only three alternative courses of action open to the decision maker: (a) separation of nonconforming from conforming product, (b) employment of a more precise process, and (c) change in the design of the product. The choice of which alternative to use is an economic one.

There were occasions when the first alternative was justified but there were many more occasions when poor production and experience were reasons for its use. The second alternative involves a substantial investment in new equipment, a different machine load, or a subcontract to more precise production processes. Quite often, through careful machine loading and scheduling, more precise equipment was released for use as needed. It was just as economically faulty to tie a highly precise process to an imprecise design as the reverse. The third choice, and one that was most difficult to achieve, was a change in design. Indiscriminate changes in design can wreak havoc in a planned production operation, but a justified relaxation in design requirements can mean the difference between profit and loss. The costs of screening inspection, scrap, and rework were viewed as opportunity costs, that is, unnecessary costs that can be reduced or eliminated through proper planning and control. Conversely, a merited tightening in design requirements meant increased demand for a quality product. In any case, the objective was optimum design at minimum total cost.

Specific QC/QA Procedures and Equipment. Current practice in the manufacturing industry is focused on providing as much in-line production sampling and testing as possible. This practice provides for real-time testing and early decision making. Most in-line sampling is applicable to manufacturing processes such as the automotive, clothing, computer, plastic, and steel industries. However, two in-line techniques may be applicable to this project. The polymer industry (DuPont) has developed an in-line sensor for controlling quality of polymer melts. This sensor measures dielectric properties and uses previously established correlations between dielectric properties, chemistry, and rheology to control the quality and consistency of the polymer melt.

Also, the aggregate industry in France through the LCPC have developed an in-line grading system termed the videograder. This device is capable of grading aggregates by measuring real dimensions of aggregates 1 to 60 mm in size. It utilizes an optical scanning approach using exact coordinates of aggregates to obtain size fractions. The grading curve and volume passing each size are obtained within minutes. The French use this approach routinely and are eliminating the sieve analysis procedure for QC purposes.

Controls Required for Product Manufacturing. Control of quality in a process involves the rationalization of many quality objectives to those that will return the best investment on the QC person-hours expended. The QC tools that do the job at optimum total quality cost are the ones that most manufacturing industries are using.

Some industries are using the “quality capability” analysis approach. Quality capability analysis is often called process or machine capability. The latter, of course is more confining and refers only to the capability of machinery where the term process includes machines and any other type of process used, including personnel. The purpose of capability analysis is to determine the “natural variation” of a process when the effects of all extraneous factors not contributing to the process have been minimized. Process capability is defined as the “minimum spread of a specific measurement variation which will include 99.7% of the measurements from a given process”—in other words, six standard deviations (6σ).

Other industries use percent defective, fraction defective, or number defective for control purposes. A unit of inspection can be 1 unit, 10 units, 100 units, or any quantity chosen. If the unit of inspection remains fairly constant from period to period, the expression may be in terms of defects with the unit being implied. A common method is to express the defects as a ratio; for example, number of paint imperfections per 100 in.^{2} of painted surface.

Various sampling schemes are used. These include single, double, and multiple sampling plans. Most are based on Military Standard 105 (MIL-STD 105), although some industries use sampling schemes derived from Military Standard 414 (MIL-STD 414).

Many industries are considering the adoption of a QC approach based on an underlying quadratic loss function. The approach is commonly referred to as the “Taguchi Methodology,” named after the Japanese QC expert Genichi Taguchi. The primary focus of the Taguchi approach is reduction of variability. Theoretically, the use of a loss function, rather than upper and lower specification limits, should provide a reduction in variability by providing a stronger impetus to have the product closer to the target.

QC/QA Manufacturing Specification Controls. The literature survey of related industries indicates a myriad of sampling approaches for QC/QA. As identified previously, the related industries use both MIL-STD 105 (attributes) and MIL-STD 414 (variables) approaches to QC. The term attribute, as used in QC, is the property a unit of product has of being good or bad—that is, the quality characteristic of the unit is either within specified requirements or it is not. Some industries are using the percent defective control chart associated with process QC of attributes. Normally, it is used to control product quality when the ideal percent defective should be less than 10 percent.

The term “variables” implies characteristics for inspection that can be measured on a variable scale. In sampling by variables, sample units are selected in accordance with good sampling practice, and measures of average and variability are computed. For QC purposes, the lot percent defective or PWL is used. The establishment of the QC limits depends on the process capability and customer specifications.

Frequency and Personnel Required for QC/QA (Costs and Benefits). The literature indicates that a “variables” QC procedure usually involves higher administrative cost. Also, more skilled help is required; more computations are required; more errors in calculations are made; and more expensive inspection equipment is required. However, some of the industries found that where destructive testing is involved, variables sampling is the most inexpensive.

Some industries use the following cost function to evaluate whether to adapt an attribute or variables approach to QC:

$$C = a + (b + c + d)\, n$$

The costs are classified as follows:

1. Overhead. These are independent of the sample size. They include the cost of administration and part of the recording and computation costs. For a plan with σ known the cost of maintaining up-to-date information concerning the value of σ must be included. This could be done by use of a control chart for ranges.
2. Sampling. These are the same per unit regardless of the plan.
3. Inspection. These will ordinarily be much more expensive per unit for variables, because measuring costs more than making an attributes decision.
4. Computation. This involves only the negligible cost of counting for an attribute plan, computing a mean for a variables plan with σ known, and a mean and standard deviation (or average range) for a variables plan with σ unknown.

From the standpoint of the economic factors of QC, the related industries consider two areas:

- Budgeting and control of quality costs, and
- Economic optimization in a particular quality situation.

The most common method used for budgeting for QC is to measure the cost of quality as a proportion of direct labor. For example, General Electric Company uses three comparison bases to measure the cost of quality—contributed quality, net sales billed, and operation labor. The first base is calculated by subtracting the cost of outside purchased materials and services from net sales billed. Thus, it is the value contributed by the departments that design, manufacture, and sell the product. The second base is the total amount billed for products sold during a given period, and the third base represents the actual input of money for all planned labor operations.

Beech Aircraft Corporation uses the ratio of QC costs to direct labor for several interesting and useful purposes. It predicts costs of QC for continuing and new projects by analyzing ratios of QC to direct labor for factors such as work mix, production phase, product flow, rate, and production phaseout. It has found that different ratios are required for different prime contractors even though the work for each is similar. Also, there is a learning curve pattern on quality costs from the new product through the regular product phase. In an example cited, the ratio for new projects was 21 percent and for production of several years' duration it was only 9 percent.

Manufacturing Industry Laboratory QC/QA Procedures and Problems. The literature survey indicates that the related industries have identified laboratory and equipment control problems. Most industries clearly identify that the quality of a product depends on the accuracy and reliability of the tools, gauges, and test equipment used in the manufacturing, inspecting, and testing operations. Tools and gauges provide the physical means of attaining volume production and, at the same time, facilitate the fabrication, inspection, and testing of parts, components, and assemblies to the required degree of uniformity. Suitable gauges and other inspecting, measuring, and testing devices necessary to check supplies for conformance to requirements should be provided and maintained. Only with proper design, application, and control will such equipment guarantee continued uniformity and interchangeability within specification requirements.

Because such equipment is subjected to constant wear and deterioration, it is essential that a system for tool and gauge control be established and maintained to ensure the required standards of quality of the product. The equipment should be checked with suitable measuring equipment at established periods to ensure continued accuracy. Records or other suitable conclusive evidence should be maintained to ensure that proper control is being provided.

Reliability has been identified as a problem area. Reliability is that aspect of QC that is concerned with the quality of product function over time. One definition of reliability is that it is "the probability of performing without failure a specified function under given conditions for a specified period of time." In contrasting it to traditional QC, reliability is associated with quality over the long term where QC is associated with the relatively short period of time required for manufacturing the product. The common statistical meaning of the term reliability is that quality that a test has of producing consistent or dependable results.

The causes of unreliability of product are many. One of the major causes is the increasing complexity of product. The multiplication law of probability illustrates this fact very simply. Given an assembly made up of five components, each of which has a reliability of function of 0.95, the reliability of function of the assembly is $(0.95)^5$ or about 0.78. For example, many assemblies, that are electronic in nature involve thousands of parts (a ballistic missile has upwards of 40,000). It does not take too much reflection to realize what the component reliabilities must be for such assemblies to have a reasonable chance of survival.

Implementation of New Software and Its Implications on QC/QA Procedures. The literature indicates that there are software packages available that have the potential of being used with the Superpave system for QC purposes. A few of these software packages are as follows:

- MINITAB,
- QI Analyst,
- STATVIEW 4.01, and
- SYSTAT for DOS/WINDOWS.

These software packages essentially integrate data management, statistical analysis (normality plots, etc.), Shewhart-type control charts ($\bar{x}$, R, σ), probability percent defects (C, P, μ, np, etc.), trend, run, moving average/range, Pareto analysis (causes, actions, defects, statistics), process capability analysis, and Cu sum charts. It is highly possible that such software could be combined with appropriate developed databases to form an automated personal computer (PC)-based quality information system at the plant and project site.

European Discussions and Surveys. Several European countries were surveyed about their QC/QA activities. The following is a brief summary:

Belgium. There are no plans in Belgium to adopt the Superpave mix design or to adopt more sophisticated equipment or parameters for QC/QA. The Belgians view good contractor-agency cooperation as essential to acceptable work.

France. No plans are being considered to bring new test methods or parameters to the QC/QA scene, except possibly to bring the gyratory and creep tests to the field for important jobs. The French very much believe that the contractor should be held to the recipe and that the mix design should identify the recipe. They have doubts about the adequacy of the U.S. gyratory compactor because it is not sufficiently stiff to hold the gyration angle under load. The French use a third party for job control. They believe their reliance on a third party is effective because the third party has the authority to shut down the job for poor QC.

Netherlands. The Dutch cited contractor-agency relations as a key to good work. They have no immediate plans to implement any of the SHRP research results, but a comprehensive program is under way to establish new fundamental test methods that can be used for QC/QA. They would like to move beyond Marshall-voids-mixture recipe conformance for acceptance but have not yet selected specific procedures. Repeated creep (e.g., NAT) and indirect tensile creep tests were offered as the most promising for field implementation.

Norway. The Norwegians are not interested in the traditional QC/QA activities but are more concerned with the uniformity of the construction. Specific details are followed to measure the uniformity of construction. Sections that show nonuniformity are repaired immediately at the contractor's expense.

Summary. The related industries generally specify quality in three broad areas—quality of design, quality of conformance to design, and quality of performance. These industries use many forms of QC techniques such as Shewhart control charts, percent defective charts, process capability charts, etc. The goals of the control processes are to isolate inherent or natural variability (chance causes) from unnatural variability (assignable causes).

The types of sampling in the related industries are quite varied. However, random sampling, systematic selection, and stratified sampling appear to be the most predominant. Both MIL-STD 105 (attribute) and MIL-STD 414 (variables) are used for QC. The establishment of QC limits generally depends on the production process capability and the customer specifications. However, the variables QC procedure usually involves higher administrative costs. The Taguchi loss function methodology or some modified procedure may be applicable to HMA QC.

The related industries are constantly striving for the development of real-time testing to aid in early decision-making related to QC. Two techniques may be applicable to this project—in-line sensors used by the polymer industry (possible used with binder QC) and the in-line aggregate grading system.

Several PC software packages are commercially available that could be integrated with the Superpave system and combined with databases to form an automated PC-based quality information system at the HMA plant and project site.

6.3.2 Phase II: Experiment Design and Field Experiments

The purpose of the Phase II research work was to develop and implement an experiment design plan related to Superpave field QC/QA activities. The results of the experiment would provide for establishment of the allowable tolerances and variations of the QC tests included in the final QC/QA procedures.

6.3.2.a Background

The original work plan developed in the research proposal identified that SPS-9 projects would provide the primary source of construction projects for the development of the field database for QC/QA related to the Superpave mix design method. This approach was based on initial SPS-9 documents submitted by SHRP to FHWA. Based on the pooled-fund equipment procurement, the initial thinking was that a number of states would have the SHRP mix design equipment in 1994 or 1995.

Subsequently, FHWA indicated that only a few states would have the SHRP mix design equipment by 1995 at the earliest. Also, FHWA began to restructure the SPS-9 experiment design and research plan. The experiment design was expected to be divided into two types of projects—SPS-9A and SPS-9B. The research experimental plan was initially designed to include 20 SPS-9 projects. Key to this design was the SHAs developing the SHRP mix design with the gyratory compactor and providing the gyratory for QC at the field sites.

Lacking a substantial program for SPS-9 construction, at a meeting on February 15, 1994, at NCHRP concerning the SPS-9 experiments, the Principal Investigator identified that the Asphalt Institute (AI) and Advanced Asphalt Technologies (AAT) had the Superpave binder and mix equipment necessary for developing the Superpave mix designs and for QC/QA field support. NCHRP decided that AI and AAT, as subcontractors to the project, would develop the Superpave mix designs and provide field QC/QA support with the gyratory compactor. Based on the NCHRP decision, a two-stage experimental design plan was developed for the field experiments.

6.3.2.b Some QC/QA Aspects To Be Considered

QC/QA essentially involves an examination of the variability associated with a process. In general, there are two main causes of variability:

1. *Common causes*, resulting purely at random from chance; and
2. *Assignment causes*, resulting from some specific changes in the process.

A process is said to be in control if, based on a suitable sample of observations from that process, there is no evidence of any assignable causes of variation present. The sampled observations are based on one or more tests conducted on the process.

For a QC/QA program to be effectively applied to paving projects, it must provide the necessary QC/QA information in time to determine whether there is a problem and, if so, to take appropriate corrective action before a partial "out of spec" job has resulted. Asphalt pavement results from a procession-type process (i.e., a series of sequential operations), involving binder, aggregate, plant mix, and site mix. Thus, there is a chance to identify or, better, prevent a problem "upstream" by applying QC/QA techniques at each stage of the process; that is, quality-monitoring tests can be conducted at the four control points in the overall process as indicated in Figure 6-7.

The underlying variability associated with each of the tests needs to be quantified so that, at each stage in the QC/QA monitoring process, the appropriate analysis is applied. In most cases, the usual assumptions are that observations from a test on an in-control process are independent and normally distributed with mean μ and standard deviation σ. However, it is possible that some of these assumptions are not valid for a particular test. For example, the observations may be correlated or from a nonnormal distribution.

Thus, observational test results are needed not only to estimate the corresponding mean and standard deviation but also to determine which assumptions are valid. In addition, the results are required to assess process capability, i.e., to estimate how well the process (overall or at any stage) can hold tolerances.

The usual measure of process capability (where it is assumed that the mean is the target value) is

$$C_p = (USL - LSL) / 6\sigma$$

where USL denotes the upper specification level and LSL denotes the lower specification level. (Analogous measures can be used if it is not assumed that the mean is the target value.)

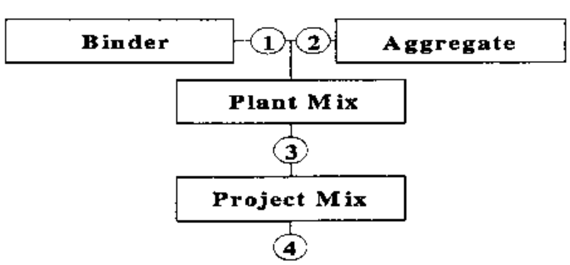


Figure 6-7. The four QC points considered in the overall experimental design process.

Of course, the larger the value of C_p (i.e., the smaller γ) the better is the quality that results from the process. It must be realized, however, that a process can be in control but not produce quality results because of low capability. Thus, it is not enough for a process just to be in control; it also must have relatively high capability.

6.3.2.c Multivariate Aspects of QC/QA

In addition to examining process capability, the multivariate nature of a quality asphalt pavement should be considered. For example, quality is controlled at one level by using the volumetric properties of percent air voids, VMA, and density; it is controlled at another level by using engineering properties related to shear and strain.

Consider the case where there are n independent characteristics used to control the quality of a process. Assume each of these n characteristics is controlled individually by using a probability of Type I error (i.e., the probability that the process is erroneously judged out of control when it is not) equal to α. The *overall* probability that the process is erroneously judged out of control is $1 - (1 - \alpha)^n$. For example, if a process were controlled by measurements of six independent characteristics using $\alpha = 0.05$ for each, then the probability that the process would be judged to be out of control is $1 - (0.95)^6 = 0.265$, over 5 times larger than the value of α. This is the problem of multitest bias that occurs with a number of tests made on the same process. It will affect both the probability of Type I error and the overall operating characteristics curve.

In reality, the characteristics used to measure the quality of asphalt pavement form a multivariate measurement. Furthermore, they are not statistically independent, which adds even more complexity to development of efficient QC/QA procedures. This means that attention must be paid to the correlations between the characteristics.

6.3.2.d QC/QA Procedures and Ease of Use

Although the topics discussed in the previous section need to be addressed in the development of the appropriate QC/QA procedures, it is realized that they may result in methodology that is relatively complex statistically. Even if the best QC/QA procedures should result, they will not be truly best if they are too cumbersome to use in applications.

One approach to developing optimal QC/QA procedures would be to accept techniques that strike a balance between statistical correctness and ease of use. However, such a compromise should not be necessary in today's environment of readily available PCs. A more promising approach would be to develop the most statistically appropriate QC/QA procedure, and then make them available in the form of easy-to-use PC software. It is envisioned that in the future such software could be combined with appropriately developed databases to form an automated PC-based quality information system.

The topics discussed previously impose a number of requirements on the experimental design. A major requirement is that the design must deal with the constraint that tests used to measure a quality characteristic must permit appropriate corrective action to be taken before a partial out-of-spec job can result. This means that rapid and reliable tests, particularly for measuring the mixture engineering properties in the plant and on the road, *need* to be developed and evaluated. Thus, several rapid tests were evaluated as possible surrogates for the most time-consuming Superpave mix design and analysis tests.

A Superpave mix design is determined by a number of factors. It is desirable that a surrogate test is not only highly correlated with the corresponding Superpave test, but also that it be insensitive to variations in material and mix properties. That is, the relationship between the surrogate and the Superpave test results does not depend on the factors (such as asphalt content, design traffic level, aggregate gradation, etc.) defining the mix design.

Experimental Objectives, Responses, and Factors. The experimental design addressed four primary objectives:

1. Obtain information on accuracy and variability (repeatability and reproducibility), as well as correlation structures, for use in development of the required QC/QA procedures.
2. Examine possible relationships between test results at the four points in the overall process as indicated in Figure 6-7.
3. Determine the degree and type of relationships between surrogate test results and Superpave test results.
4. Identify mix design factors that are important, i.e., ones that have a strong effect on those relationships.

The responses (dependent variables) in the experiment were as follows:

1. The observations obtained with the surrogate tests;
2. The observations obtained with the Superpave tests; and
3. The parameters defining the relationship between the results of each surrogate test and the corresponding Superpave test.

The factors (independent variables) such as binder type, binder content, aggregate gradation, aggregate type, and traffic volume defined each SHRP Superpave mix design used in the experiment.

The assumption is that all test candidates can be used for the test section constructed from a given mix design. In other words, all possible responses (surrogate test results) of interest can be measured for any given experimental run (cell).

Considerations.

1. NCHRP Project 9-7 had a maximum of 14 test sections constructed using the Superpave mix design.
2. Generally, only a single Superpave mix design can be used in any project.
3. Based on (1) and (2), there will be a maximum of 14 experimental runs or "cells" in the overall experiment.
4. There were several candidates for evaluation as possible "quick" test surrogates for the more time-consuming Superpave tests.
5. It was better to have an evolutionary experimental strategy; therefore, a two-stage experimental procedure was adopted.

6.3.2.e Statistically Based Experiment Design

The experiment design was established in two stages. Stage I included six projects constructed in 1994. The experiment design was viewed as a sequential-type design containing a partial factorial. The purpose of this design was to serve as a preliminary means of differentiating between the levels of control and test equipment based on analysis of the Stage I design.

The Stage II experiment design was used on eight projects constructed in 1995. This design was also a partial factorial using the QC parameters, the types of field equipment, and the levels of control recommended from Stage I. The adjusted parameters for QC/QA from the Stage II projects were then evaluated on one project constructed during 1996. This experiment was used to evaluate control sensitivity and to establish appropriate tolerance limits for the levels of control related to the Superpave mix design.

The objectives of the experimental design were to

- Examine Superpave mix design factors of importance (levels of control);
- Make observations using Superpave tests;
- Make observations using surrogate tests;
- Determine relationships between surrogate tests and Superpave tests;
- Investigate QC/QA relationships from data obtained at plant/project; and
- Analyze variability of measured quality characteristics.

A major requirement is that the experiment design must deal with the constraint that tests used to measure a quality characteristic must permit appropriate corrective action to be taken before a partial out-of-spec job can result. This means that rapid and reliable tests, particularly for measuring the mixture engineering properties in the plant and on the road, need to be developed and evaluated. Thus, a number of rapid tests were evaluated as possible surrogates for the more time-consuming Superpave tests. The rapid tests examined included the following:

1. Endura-Tec Systems prototype simple shear at constant height,
2. Industrial Process Controls MATTA (repeated-load creep and uniaxial loading),
3. EMACO VDG-40 video grader for aggregate, and
4. SGC.

All test candidates were used on the test section constructed from a given mix design. In other words, all possible responses, test results, and surrogate/Superpave test relationships of interest were measured for any given experimental run (cell). Therefore, the limited number of experimental runs did not pose an obstacle to examining a number of test candidates.

Table 6-3 provides the sampling scheme used in the Stage I and II experiments. Figure 6-8 illustrates schematically the sequence of events for sampling and subsequent testing.

6.3.2.f Superpave Mix Design and QC Sampling

Mix Design. AI or AAT developed a Superpave mix design for the SHA for each project. The SHA or contractor, whichever was applicable, supplied the following quantities of material to AI or AAT approximately 4 weeks before paving:

- Each aggregate stockpile, 400 lb; and
- Superpave performance-graded asphalt binder, 10 gal.

AI or AAT determined the appropriate asphalt binder performance grade to be used in the mix design through consideration of the climate and the traffic loading at the site of the paving project. The asphalt binder was selected in accordance with the AASHTO MP1 specifications. These laboratories evaluated the coarse and fine aggregate in relation to the Superpave mix specification requirements.

The volumetric mix design was developed in accordance with Superpave procedures. Once the volumetric design criteria were satisfied, additional specimens were prepared for engineering property analysis and determination of the optimum asphalt content in accordance with Superpave procedures. When the volumetric and engineering property criteria were met, the mix design process was considered complete.

At this juncture, four sets of duplicate specimens were prepared with the developed mix design and compacted with the SGC. These specimens were tested with the FST device, and they provided a basis for statistical evaluation with the Superpave mix design engineering properties for permanent deformation.

Asphalt Plant Sampling Design. Binder samples were obtained at the job site. The specific sampling plan used depended on the specific job, but multiple samples were obtained from the job-site storage plant or from the asphalt feed at the time of mixing. The samples were tested with the Superpave binder equipment and initially with the SDR. Results from these tests were compared with test results on the binder using the full Superpave testing protocol.

QC Sampling Design. Specimens obtained for aggregate QC purposes were taken from the aggregate cold feed or hot bins and recovered from the HMA. The asphalt content was monitored by the plant metering devices, nuclear gauge, ignition furnace, or extraction tests. The aggregate was controlled on the nominal maximum size, a midcontrol point, and the 75-

TABLE 6-3 Typical asphalt plant QC samples per sublot (experiment design)

Sample Type	Number of Samples/Sublot	
Raw Aggregate - Hot Bin/Cold Feed (Gradation Analysis)	1	
Ignition Furnace Asphalt Content, Gradation	2	
Extraction (Asphalt Content, Aggregate Gradation)	2	
Nuclear Asphalt Content Gauge	2	
Rice Specific Gravity	2	
Field Gyratory-Compacted Specimens	Volumetric Tests	2 (2 Reps x 1 Test)
	Surrogate Tests	2 (2 Reps x 1 Tests)
Field Gyratory-Compacted Specimens (test at design laboratory)	2 (2 Reps x 1 Test)	
Superpave Laboratory Gyratory-Compacted Specimen (Test at Design Laboratory)	Volumetric tests (Reheated)	2 (2 Reps x 1 Test)
	SHRP Tests (Reheated)	2 (2 Reps x 1 Test)
	Surrogate Tests	2 (2 Reps x 1 Test)
Total Number of Specimens for QC Analyses	21	

Lot was defined as a day's production. A lot was subdivided into four equal sublots.

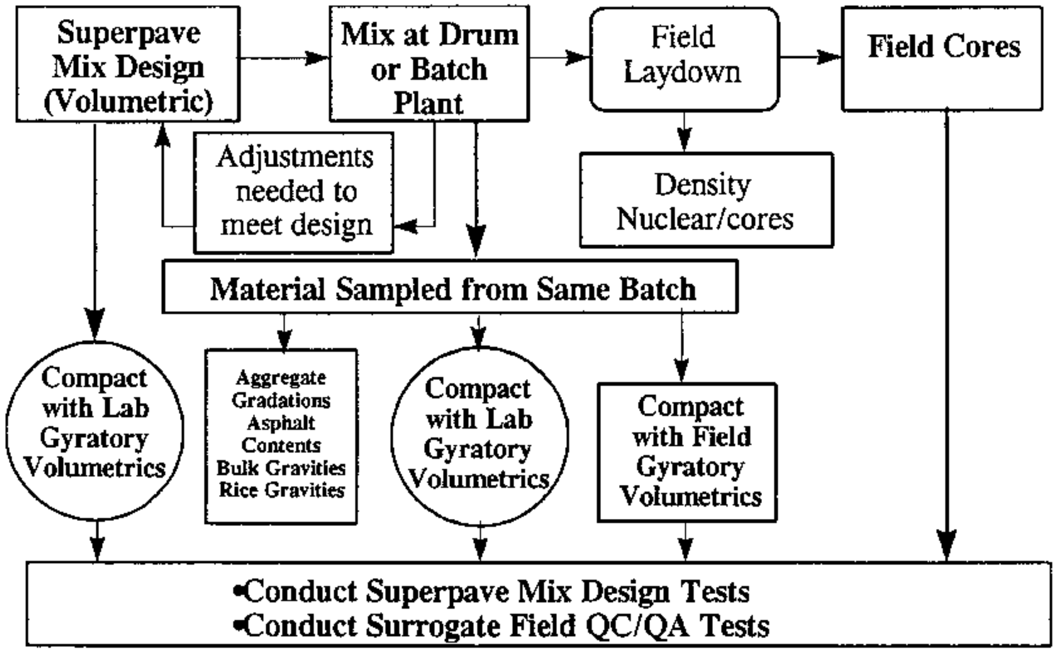


Figure 6-8. Project experiment design flow diagram.

µm (No. 200) sieve. The asphalt was controlled within ±0.5 percent of the mix design optimum value. QC specimens of the HMA were compacted in the field gyratory compactor to evaluate the volumetric properties. Specimens were evaluated in some cases after the volumetric determinations, with the surrogate field tests. A set of specimens was prepared using the field gyratory compactor for later testing at the laboratory (AI or AAT). HMA mixtures were sent to AI or AAT for compaction in the mix design gyratory compactor for volumetric analysis and then tested with the SST equipment. These specimens were tested with the SST equipment.

HMA samples were obtained from the hauling unit at the plant site. Figure 6-9 depicts the sampling scheme from the hauling unit. The samples were collected in 5-gal metal containers. Five 5-gal containers of HMA for each sublot were collected. For sampling purposes, a lot was considered as

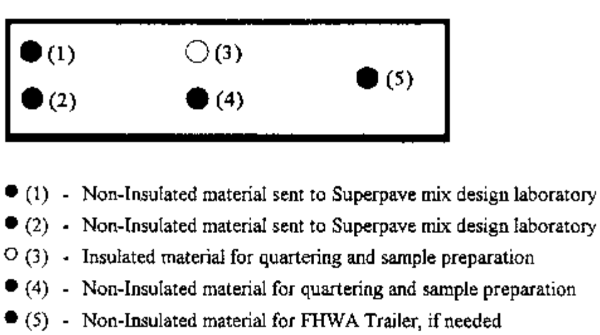


Figure 6-9. Typical truck sampling.

1 day's production. The day's production was divided into four equal sublots. The samples were obtained randomly from each sublot.

The five, 5-gallon containers of HMA per sublot contained the following:

- One insulated container with ~24 kg of HMA, and
- Four noninsulated containers with ~24 kg of HMA per container.

One noninsulated container was quartered immediately. Individual quarters were placed in pans in an oven operating at mix compaction temperature. Two specimens were compacted for determination of volumetric properties. These specimens were compacted to N_{max} based on the Superpave design traffic and 7-day maximum air temperature for which N_{des} was selected. The other two specimens were compacted to approximately 7 percent air voids and 115-mm height for the surrogate tests. Figure 6-10 illustrates schematically the gyratory and surrogate test samples produced by the quartering process.

The other two noninsulated containers were sealed and sent for future testing to the laboratory that performed the mix design. On several of the NCHRP 9-7 projects, FHWA assisted with part of the QC sampling and testing. FHWA provided its mobile-equipped trailer and support personnel. When the trailer was available, one additional noninsulated container was obtained for FHWA to perform support testing.

The insulated container with 24 kg of HMA was split after all the specimens from the first bucket were compacted. The

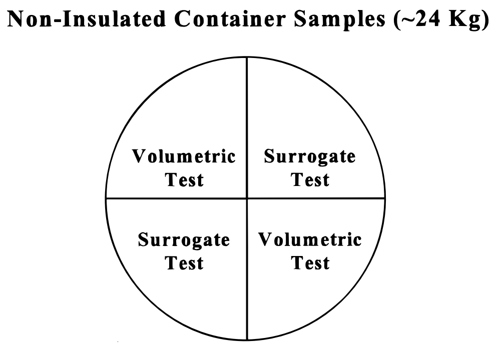


Figure 6-10. Sample quartering for volumetric and surrogate tests.

first split produced two specimens for performance-based tests (compacted to 140-mm height and 7 percent air voids). The remaining material was recombined and requartered. Two quarters were selected for nuclear asphalt content gauge testing or ignition furnace testing. The remaining material was recombined and requartered to provide two samples for determination of G_{mm}, and two samples for solvent extraction.

The two sealed containers returned to the laboratory were split to provide two reheated surrogate specimens, two reheated volumetric specimens, and two reheated performance-based specimens. Figure 6-11 illustrates schematically samples generated from the quartering procedures.

Raw aggregate was also sampled from the plant cold feed or hot bins, whichever was applicable. The raw aggregate sampled at the plant was placed in 5-gal containers or canvas-type sample bags for shipment to the mix design laboratory (AI or AAT).

6.3.2.g Stage I Projects

Six projects were constructed during the 1994 construction season. The experiment design used on these projects was discussed in Section 6.3.2.e. Table 6-4 identifies the projects by route, plant type, and other relevant characteristics.

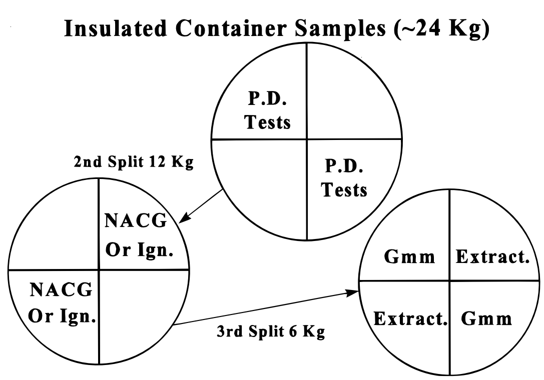


Figure 6-11. Samples produced by quartering HMA from insulated containers.

The initial levels of control in the field were those recommended by the SHRP researchers. The characteristics that were evaluated were asphalt content (extracted), aggregate gradation, and the volumetric properties. The aggregate cold feed was sampled on two projects (Mississippi and Virginia) for comparisons with the extracted aggregate gradations. Sampling safety considerations precluded sampling at the plant on other projects for cold aggregate gradation determinations.

The controls on the volumetric properties were air voids content (V_a), VMA, VFA, and density. The following volumetric limits were controlled:

- Air voids content (V_a), controlled between 3 and 5 percent;
- VMA, controlled as the design VMA as the minimum;
- VFA, controlled as the design VFA; and
- Density, evaluated at $N_{initial}$, N_{design}, and $N_{maximum}$.

The maximum theoretical gravity (G_{mm}) and the measured bulk specific gravity (G_{mb}) were recorded. In addition, the dust-to-asphalt ratios were recorded. Appendix D provides the Superpave mix design for each project and the data obtained during construction. Also shown are the pooled standard deviations by projects for the various parameters considered for the QC activities.

The formula for estimating the pooled variance, S_p^2, for K samples is

$$S_p^2 = \frac{(n_1)S_1^2 + (n_2)S_2^2 + \ldots + (n_k)S_k^2}{n_1 + n_2 + \ldots + n_k - k}$$

This S_p^2 is an unbiased estimate of σ^2 or the population standard deviation.

Table 6-5 presents the project and the pooled standard deviations derived from the 1994 projects. The pooled standard deviations were used in developing the Version No. 1 QC Plan and the QC limits.

The Version No. 1 QC Plan was developed from the 1994 field projects to fulfill the following characteristics in relation to process control:

- Be based on measurements that are timely and easy to perform;
- Be based on equipment that is appropriate for field use—considering both cost and skill of field technicians;
- Be simple and easy to apply—provide graphic pictures of state of process to allow opportunity for correction;
- Consider sampling and testing variability as well as variability in material;
- Consider hot-mix *production* versus hot-mix *construction*; and
- Be based on measured properties that are performance related and not simply based on historical ability of contractor to perform.

TABLE 6-4 State projects designed, constructed, and sampled by the NCHRP project (1994)

State	Route	City/ County	Plant Type	Mix Type	Nominal Max.	Binder
Florida	US 301 (SR 43)	Tampa	Drum Mixer	DG HMAC with RAP	12.5mm	PG64-28
Kentucky #1	IH 64/75	Lexington	Drum Mixer	DG HMAC	9.5mm	PG70-22
Mississippi	US Highway 61	Bolivar County	Batch	DG HMAC with RAP	12.5mm	PG64-22
Texas #1	FM 1604	San Antonio	Batch	DG HMAC	12.5mm	PG64-22
Texas #2	FM 1604	San Antonio	Batch	DG HMAC	12.5mm	PG64-22
Virginia	Route 7	Leesburg	Drum Mixer	DG HMAC	9.5mm	PG64-22

The Superpave system did not provide for any suggested ranges of variance associated with its recommended field QC testing plan. Therefore, it was necessary to identify the variances as shown in Table 6-5.

The Version No. 1 QC Plan attempted to provide testing and analysis that were *timely* or related to real-time operations and control as possible. This approach was included in the QC Plan to afford the contractor an opportunity for early process correction when deemed necessary without producing a large quantity of out-of-specification material. The following items were identified in the Version No. 1 QC Plan and were based on the pooled variances developed from the 1994 projects:

- Samples compacted in field with a gyratory compactor;
- Parameters from gyratory compaction process, essentially compactibility;
- Density properties G_{mm} and G_{mb} measured on gyratory-compacted samples;
- Asphalt content (extraction on possibly nuclear or ignition devices);
- Process control charts to include
  –Both mean and variability (dispersion), and
  –Sampling and testing error;
- When above items indicate control problems
  –Gradation analysis, extracted or cold feed,
  –Fines analysis—content and source,
  –VMA and reconsideration of mix design, and
  –Investigation of plant operating parameters and correction to changes in control charts.

The three QC approaches specifically developed for the Version No. 1 QC Plan were the following:

1. Bulk Specific Gravity Surface Saturated Dry. This approach is applicable for QC with the Superpave volumetric mix design method as well as the abbreviated and complete mix analysis methods. On the first sublot of the first day, the Contractor shall determine the following HMA properties:

- The asphalt content (AASHTO T 164 or equivalent);
- The percent of the combined aggregate passing the 4.25-mm (No. 4), 2.36-mm (No. 8), 600-μm (No. 30), and 75-μm (No. 200) sieves (AASHTO T 27);
- The maximum theoretical specific gravity, G_{mm}, of the Superpave mix (AASHTO T 209); and
- The bulk specific gravity, G_{mb}, of the SGC Superpave mix (AASHTO T 166).

The results of these tests are compared with the Superpave JMF.

If the results are within the JMF tolerances the production is in control and subsequent sampling and testing will be done using the bulk specific gravities (G_{mb}) as the control parameter. Otherwise, corrections must be made to the plant proportioning of asphalt binder and aggregate fractions to conform to the JMF. UCL and LCL shall be set at $\pm 2\sigma$ and $\pm 3\sigma$, defined as *warning* and *action* control limits, respectively. Typical standard deviation values used were those identified in Table 6-5.

2. Estimated Bulk Specific Gravity. The Contractor for QC may opt for the following simplified procedure. This approach is applicable for QC with the Superpave volumetric mix design method as well as the abbreviated and complete mix analysis methods.

- A sample is obtained. A known weight is measured into the heated mold.
- The specimen is compacted to $N_{maximum}$. Heights are recorded at each gyration.
- The operator performs a calculation to estimate G_{mb} at N_{design}.
- The estimated bulk specific gravity is corrected by the laboratory correction ratio.
- The predicted bulk specific gravity is compacted to a range of acceptable G_{mb}.

3. Mix Composition and Volumetric Approach. This approach is applicable for QC with the Superpave volumet-

TABLE 6-5 1994 project and pooled standard deviations

Table 6.5. a. Asphalt Content and Volumetric Standard Deviations

1994 Projects	# of Samples	Gmm	Gmb	Calculated Gse	Air Voids @ Ninit	Air Voids @ Ndes	Air Voids @ Nmax	VMA	VFA	Dust/AC Ratio	AC Absorption	%AC Extracted	%AC Nuc Gauge
FL	8	0.006	0.014	-	1.1	0.8	0.4	0.4	7.5	0.1	0.1	0.31	-
KY	90	0.009	0.016	-	1.2	0.8	0.6	0.6	6.4	0.1	0.1	0.15	0.22
MS	12	0.005	0.013	-	0.4	0.4	0.4	0.4	2.2	0.3	0.0	0.19	-
TX1	21	0.005	0.008	-	0.4	0.4	0.4	0.4	2.4	0.1	0.0	0.13	-
TX2	17	0.006	0.005	-	0.2	0.1	0.1	0.1	0.9	0.0	0.0	0.05	-
VA	39	0.016	0.029	-	1.5	1.5	1.4	1.4	8.6	0.1	0.0	0.34	-
Pooled Standard Deviation		0.010	0.018	0.000	1.1	0.9	0.8	0.8	6.3	0.1	0.1	0.21	0.22

Table 6.5. b. Cold Feed Aggregate Standard Deviations

1994 Projects	# of Samples	Cold Feed 19.0mm	Cold Feed 12.5mm	Cold Feed 9.5mm	Cold Feed 4.75mm	Cold Feed 2.36mm	Cold Feed 1.18mm	Cold Feed 0.600mm	Cold Feed 0.300mm	Cold Feed 0.150mm	Cold Feed 0.075mm
FL	8	-	-	-	-	-	-	-	-	-	-
KY	90	-	-	-	-	-	-	-	-	-	-
MS	12	0.2	1.8	3.1	3.2	2.6	1.9	1.0	0.6	0.4	0.3
TX1	21	-	-	-	-	-	-	-	-	-	-
TX2	17	-	-	-	-	-	-	-	-	-	-
VA	39	0.0	0.2	2.2	3.3	2.5	2.1	1.7	1.2	0.9	0.9
Pooled Standard Deviation		0.1	0.9	2.4	3.3	2.5	2.1	1.5	1.1	0.8	0.8

Table 6.5. c. Extracted Aggregate Standard Deviations

1994 Projects	# of Samples	Extracted 37.5mm	Extracted 25.0mm	Extracted 19.0mm	Extracted 12.5mm	Extracted 9.5mm	Extracted 4.75mm	Extracted 2.36mm	Extracted 1.18mm	Extracted 0.600mm	Extracted 0.300mm	Extracted 0.150mm	Extracted 0.075mm
FL	8	0.0	0.0	0.3	1.1	1.5	1.9	1.0	0.8	0.7	0.5	0.2	0.1
KY	90	0.0	0.0	0.0	0.0	1.7	7.2	2.9	2.0	2.7	1.4	0.9	0.6
MS	12	0.0	0.0	0.0	2.2	2.8	2.9	1.6	0.9	0.8	1.3	1.3	1.0
TX1	21	0.0	0.0	0.0	0.6	1.9	3.1	1.9	0.8	0.3	0.2	0.4	0.3
TX2	17	0.0	0.0	0.0	0.7	0.7	1.2	0.9	0.4	0.4	0.3	0.2	0.2
VA	39	0.0	0.0	0.0	0.3	2.4	2.7	2.5	2.0	1.6	1.2	0.9	0.7
Pooled Standard Deviation		0.0	0.0	0.1	0.7	1.9	5.4	2.5	1.7	2.0	1.2	0.8	0.6

ric mix design method as well as the abbreviated and complete mix analysis methods. The Contractor shall use the arithmetic means sample standard deviations of the test results to establish statistical control charts for the following HMA properties:

- The maximum specific gravity (G_{mm}) of the HMA (AASHTO T209);
- The asphalt content (AASHTO T164 or equivalent);
- The percent of the combined aggregate passing the 4.25-mm (No. 4), 236-mm (No. 8), 600-µm (No. 30), and 75-µm (No. 200) sieves (AASHTO T 27);
- The air voids content (percent V_a), the percent VMA, and the percent VFA at N_{design} gyrations (AASHTO Standard Method TP4); and
- The air voids content (percent V_a), N_{init}, and N_{max} gyrations (AASHTO Standard Method TP4).

The Contractor will use the statistical control charts to determine whether variability in the HMA production due to assignable causes that must be remedied has occurred.

Target values and UCL and LCL for the control charts may be determined from the HMA properties measured during the field verification process and the first week of production; at a minimum, measurements on samples taken from 15 sublots of HMA shall be required for preparation of control charts. The grand mean and average range of the test data shall be used to develop *x-bar (mean) and R (range)* control charts for each material property. UCL and LCL shall be set at $\pm 2\sigma$ and $\pm 3\sigma$, defined as *warning* and *action* control limits, respectively, where σ is the *sample standard deviation.* The measurements for HMA production shall be within the variances of the specified properties (Table 6-5). If the control limits are not within the allowable tolerance limits, the Contractor must modify the HMA production process to reduce the variability to bring the control limits within the specification limits.

The 1995 (Stage II) projects were constructed based on the pooled standard deviations or variances established from the 1994 projects and the Version No. 1 QC Plan approaches.

6.3.2.h Stage II Projects

The Stage II projects were constructed in 1995 to verify the approaches developed in the Version No. 1 QC Plan utilizing the 1994 project pooled variances. Table 6-6 provides a listing of the 1995 projects. Appendix E provides details on each project's Superpave mix design and the data obtained from each of the projects. Although a Superpave mix design was developed for the Nebraska project, this project was not constructed as part of the NCHRP 9-7 research effort.

As part of the field QC effort, the same parameters evaluated for the 1994 projects were collected. The Maryland 1 and 2 projects also provided nuclear gauge asphalt contents and the Maryland 2 project also provided asphalt contents by the ignition furnace method.

Table 6-7 identifies the 1995 project and pooled standard deviations. The last line in each subsection of this table is the pooled standard deviation combining the 1994 and 1995 project data.

Based on implementation of the Version No. 1 QC Plan on the 1995 projects, it was concluded that the mix composition and volumetric approach was not practical for QC activities. The testing involved (extraction asphalt content, aggregate gradation, and G_{mm}) was too time-consuming and the length of time to receive the test results did not afford the contractor the quick action required from QC activities.

It was concluded that the following approach would be the most practical for the Superpave QC activities.

The primary method of field QC will make use of the SGC and the volumetric properties of the mix. Within the first 100 tons of Superpave mix production shipped to the project, the Contractor shall determine the following Superpave mix properties:

- The asphalt content (AASHTO T 164 or equivalent);
- The percent of the combined aggregate passing the 4.25-mm (No. 4), 2.36-mm (No. 8), 600-µm (No. 30), and 75-µm (No. 200) sieves (AASHTO T 27);
- The maximum theoretical specific gravity (G_{mm}) of the mix (AASHTO T 209);

TABLE 6-6 State projects designed, constructed, and sampled by the NCHRP project (1995)

State	Route	City/ County	Plant Type	Mix Type	Nominal Max.	Binder
Alabama #1	SR 165	Russell	Drum	DG HMAC	37.5mm	PG76-22
Alabama #2	SR 165	Russell	Drum	DG HMAC	25mm	PG76-22
Georgia	---	Marietta	Drum	DG HMAC	12.5mm	PG64-22
Kansas	I-70	Salina	Drum	DG HMAC	9.5mm	PG70-28
Kentucky #2	SR 676	Frankfort	Drum	DG HMAC	19.0mm	PG70-22
Maryland #1	I-68	Hancock	Batch	SMA	12.5mm	PG70-22
Maryland #2	US Rt 40A	Grantsville	Drum	DG HMAC	12.5mm	PG64-22
WesTrack	---	Silver Springs, NV	Drum	DG HMAC	19.0mm	PG64-22

TABLE 6-7 Asphalt content and volumetric standard deviations and extracted aggregate standard deviations

Table 6.7. a. Asphalt Content and Volumetric Standard Deviations

1995 Projects	# of Samples	Gmm	Gmb	Calculated Gse	Air Voids @ Nini	Air Voids @ Ndes	Air Voids @ Nmax	VMA	VFA	Dust/AC Ratio	AC Absorption	%AC Extracted	%AC Nuc Gauge
AL1	28	0.015	0.015	0.011	1.1	0.8	0.8	0.7	5.9	0.1	0.2	0.40	-
AL2	26	0.017	0.016	0.018	1.0	0.9	0.9	0.6	6.1	0.1	0.3	0.39	-
GA	8	0.004	0.013	0.004	1.0	0.5	0.5	0.5	3.1	0.2	0.0	0.12	-
KS	12	0.009	0.008	-	1.2	0.4	0.3	0.3	3.2	0.1	-	0.20	-
KY2	22	0.006	0.012	-	0.7	0.7	0.7	0.4	4.4	0.1	-	0.16	-
MD1	30	0.009	0.034	0.012	0.7	1.0	1.0	0.5	5.3	0.2	0.1	0.22	0.10
MD2	30	0.006	0.043	0.007	1.0	0.9	0.8	1.0	5.0	0.2	0.1	0.21	0.09
TX3	16	0.011	0.016	0.012	0.8	0.9	0.8	0.5	6.0	0.1	0.2	0.08	-
Pooled Standard Deviation		0.011	0.025	0.012	1.0	0.9	0.8	0.6	5.3	0.1	0.2	0.27	0.10
94 & '95 Pooled Std. Dev.		0.011	0.022	0.012	1.0	0.9	0.8	0.6	5.8	0.1	0.1	0.24	0.18

Table 6.7. b Extracted Aggregate Standard Deviations

1995 Projects	# of Samples	Extracted 37.5mm	Extracted 25.0mm	Extracted 19.0mm	Extracted 12.5mm	Extracted 9.5mm	Extracted 4.75mm	Extracted 2.36mm	Extracted 1.18mm	Extracted 0.600mm	Extracted 0.300mm	Extracted 0.150mm	Extracted 0.075mm
AL1	28	0.0	1.3	3.2	2.5	2.7	3.2	2.6	2.0	1.6	1.3	1.0	0.8
AL2	26	0.0	0.0	0.4	2.0	3.0	3.5	2.2	1.5	1.1	0.7	0.5	0.4
GA	8	0.0	0.0	0.0	1.0	1.7	3.5	3.2	2.6	2.1	1.6	1.2	0.7
KS	12	0.0	0.0	0.0	0.2	0.6	1.5	1.1	0.7	0.4	0.3	0.2	0.2
KY2	22	0.0	0.0	0.0	0.0	1.3	2.3	1.7	1.1	0.9	0.4	0.2	0.2
MD1	30	0.0	0.0	1.1	2.4	2.3	1.3	1.0	1.0	1.0	1.1	1.1	1.6
MD2	30	0.0	0.0	0.0	1.2	2.0	2.8	1.6	1.1	0.9	0.9	0.9	0.9
TX3	16	0.0	0.0	0.0	1.0	1.7	2.8	1.7	0.9	0.5	0.4	0.3	0.2
Pooled Standard Deviation		0.0	0.5	1.4	1.7	2.2	2.7	1.9	1.4	1.1	0.9	0.8	0.9
94 & '95 Pooled Std. Dev.		0.0	0.4	1.0	1.3	2.1	4.3	2.2	1.6	1.7	1.1	0.8	0.7

- The bulk specific gravity, G_{mb}, of the Superpave gyratory-compacted mix (AASHTO T 166);
- The air voids content (percent V_a), the percent VMA, and the percent VFA at N_{design} gyrations (AASHTO Standard Method TP4).
- The air voids content (percent V_a), N_{init}, and N_{max} gyrations (AASHTO Standard Method TP4);
- G_{mb} estimated at N_{des}; and
- The slope of gyratory compaction curve.

These results are compared with the target values established and must not exceed the tolerances specified about the LTMF. If the results are within the LTMF tolerances, the production is in control, and subsequent sampling and testing will be performed using the estimated bulk specific gravities (G_{mb} est.) at design number of gyrations (N_{des}) obtained from the gyratory compactor by the following:

- A sample is randomly obtained. A known weight is measured into the heated mold.
- The specimen is compacted to $N_{maximum.}$ Heights are recorded at each gyration.
- The operator performs a calculation to determine the estimated G_{mb} at $N_{design.}$
- The estimated bulk specific gravity is corrected by the laboratory correction ratio

$$C = \frac{G_{measured}}{G_{estimated}}$$

- Calculate the slope of the gyratory compaction curve.

The compaction or densification curve is characterized by three parameters. Figure 6-12 illustrates these parameters. C_{init} is the percent maximum specific gravity after N_{init} gyrations; C_{max} is the percent maximum specific gravity after N_{max} gyrations. The slope of the densification curve, m, is calculated from the best-fit line of all data points assuming that the gyratory compaction curve is approximately linear. In situations where density begins to approach 100 percent, and the densification curve begins to bend downward, the slope is calculated from the straight line portion of the curve. The slope is calculated by the following equation:

$$\text{slope, } m = \frac{\log N_{max} - \log N_{init}}{C_{max} - C_{init}}$$

The Contractor will use statistical control charts for estimated G_{mb} and the slope of the gyratory compaction curve to determine whether the process target or variability in the Superpave mix production is due to random causes or assignable causes. Periodically, the Contractor will determine a measured G_{mb} for control comparison. Target values and UCL and LCL for the control charts are determined from the gyratory Superpave mix properties (estimated G_{mb} and compaction curve slope).

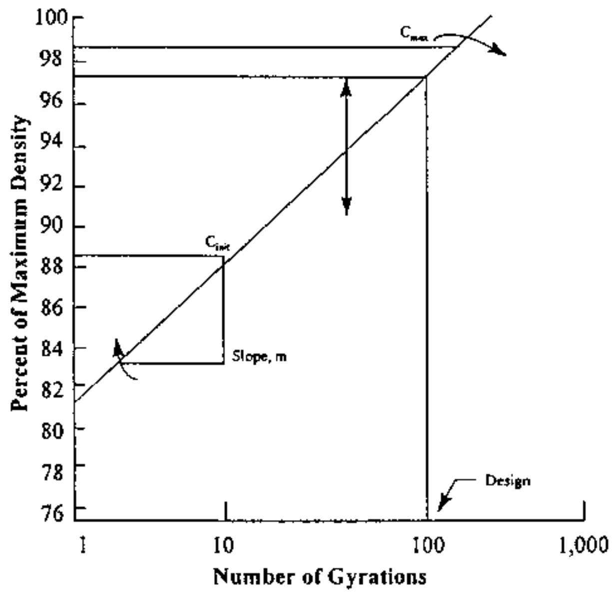


Figure 6-12. Typical compaction curve for gyratory-compacted specimen.

Table 6-8 provides the recommended Superpave LTMF tolerances based on the standard deviations developed from the 1995 projects (Table 6-7 and Appendix E). These are also the standard deviations recommended for QC purposes once the contractor establishes the LTMF as discussed in Chapter 2. The pooled variances were used in the development of the standard deviations. Therefore, the sample sizes reflected in Table 6-8 are individual samples or n = 1. If sample sizes other than n = 1 are to be used, the standard deviation values must be adjusted by using the following equation:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

where

σ_x = standard deviation of sample means of sample size n
σ = standard deviation from Table 6-8
n = sample size

6.3.2.i Other QC Studies and Considerations

1. Aggregate Gradation QC. Associated with the Stage II studies were two studies. The first was a very preliminary evaluation of the French video grader unit. The aggregate industry in France through LCPC has developed an in-line grading system termed the video grader. This device is capable of grading aggregates by measuring real dimensions of aggregates 1 mm to 60 mm in size. It utilizes an optical scanning approach using exact coordinates of aggregates to obtain size fractions. The grading curve and volume passing are obtained within minutes. The French use this approach

TABLE 6-8 Superpave LTMF tolerances (mixture composition and gyratory properties)

Mix Composition Property	Extraction	Nuclear Gauge	Ignition Furnace	Cold Feed
Asphalt Content	± 0.25	± 0.18	± 0.13	---
Gradation Passing 4.75mm (No. 4) and Larger Sieves	± 3	--	--	± 3
Passing 2.36mm (No. 8) to 150μm (No. 100) Sieve	± 2	--	--	± 2
Passing 75μm (No. 200) Sieve	± 0.7	--	--	± 0.7
Maximum Theoretical Specific Gravity (G_{mm})	± 0.015			
Gyratory Compacted Mix Property				
Air Voids (V_a)	± 1			
Voids in Mineral Aggregate (VMA)	± 1			
Voids Filled With Asphalt (VFA)	± 5			
Bulk Specific Gravity (G_{mb})	± 0.022			
Compaction Curve Slope (m)	± 0.40			

routinely and are eliminating the sieve-analysis procedure for QC purposes.

One set of replicate samples from the Alabama project was sent to the FHWA laboratories at the Turner-Fairbank Highway Research Center. The samples were graded using the traditional Gilson sieve analysis and the video grader. Figure 6-13 illustrates the test results. Comparison could be made only down to the 1-mm fraction, because the video grader does not include sizes smaller than 1 mm. It appears that this device has merit for quick determination of aggregate gradation for QC purposes. More research is recommended in this area.

2. Performance Testing and Data Evaluation. The second study involved performance testing with the SST device for use with the Superpave models. The concept was to predict the service life of the Superpave mix by using the performance test results (including both abbreviated and complete analysis) and the proposed models. It became apparent during evaluation of the testing data associated with the 1994 and 1995 construction projects that the quality of the performance test data using the SST devices was in many cases very poor. In addition, a number of problems associated with the Superpave prediction models surfaced.

The Superpave materials characterization program will not provide reliable material property estimates for use in the performance models when the SST data are of poor quality. Several data quality problems were identified during the NCHRP Project 9-7 data evaluation including the following:

1. Unstable loading and response due to sample rocking (i.e., unparallel faces);
2. Uncharacteristic measurement response (i.e., spikes in data or very "noisy" data);
3. Large differences between linear variable differential transformer (LVDT) responses on the same sample;
4. Loss of load control because of problems with measurement devices (i.e., bad LVDTs);
5. Not enough data points captured during testing; and
6. Unreasonable data (e.g.; stiffness does not follow logical pattern with temperature).

It is imperative that care be taken when setting up and running the SST tests so that good quality data are produced for input into the models. Testing engineers and technicians report that sample preparation plays a very important role in generating good quality data. Proper sawing, gluing to platens, and LVDT attachment on the specimen are extremely important when preparing a sample for testing in the SST. Also, proper care in adhering to the test protocols has been shown to help produce consistent test results.

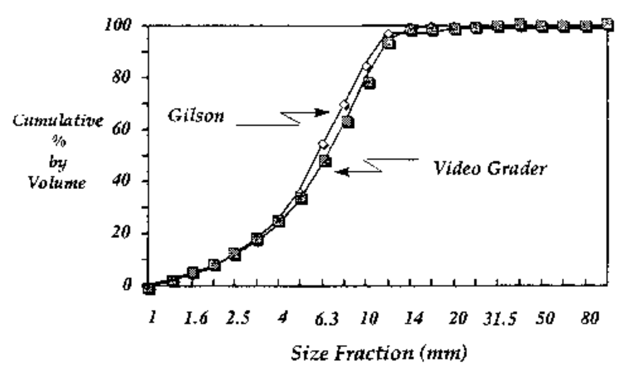


Figure 6-13. Aggregate gradation comparison between video grader and traditional sieve analysis.

Many of these recommendations were generated through the testing and evaluation that was conducted under the NCHRP 9-7 Project. This project was the first to make full use of the SST and produce results on a large scale. It was also identified through this project that changes to the SST testing protocols would need to be made. The project laboratories completing the testing for this project made every effort possible to produce good quality data but, as stated, they faced many complications that were beyond their control. Table 6-9 provides an overview of the SST testing and Figures 6-14 and 6-15 illustrate some of the data quality issues raised from the evaluation of the tests.

Another problem encountered by the project consisted of the difficulties associated with the Superpave performance models provided at the end of SHRP in 1993. These models were to be used by the NCHRP Project 9-7 to predict the rutting over the design life of the paving mixes designed and constructed under the project. However, it became apparent during the performance analysis (with those SST data files that were acceptable) that there were serious problems with the Superpave models.

FHWA Contract DTFH61-95-C-00100, *Superpave Support and Performance Models Management*, has completed an extensive evaluation of these models and concurs with the previous statement. In fact, much of the initial evaluation completed in the FHWA contract built on the work that was initiated in NCHRP Project 9-7. Because of the problems encountered with some of the test results and the performance model deficiencies, the performance-based test results from the SST were not further evaluated.

6.3.2.j Field Validation of Version No. 2 QC Plan

The field validation of the Version No. 2 QC Plan was implemented on I-10 in Louisiana in June 1996. The Superpave mix design was developed by the University of Texas Superpave Center located in Austin, Texas. The mix design is contained in Appendix F.

Also included in Appendix F are the gyratory compaction data and compaction curves obtained from the field QC sampling.

Table 6-10 depicts the data used for QC chart development. Figures 6-16 and 6-17 illustrate the QC charts developed with the data from Table 6-10. The estimated bulk gravity and the slope of the compaction curve are the two key control parameters as identified in the Version No. 2 QC Plan. These two parameters provide the contractor with very quick tests for QC purposes.

The UCL and LCL were based on the project standard deviations. As shown in both figures, the project was in control in relation to statistically reproducing the Superpave LTMF.

The QC/QA Plan presented in Chapter 2 of this report differs in several aspects from the Version No. 2 QC/QA Plan validated on the Louisiana I-10 project constructed in June 1996. The Version No. 2 QC/QA Plan had the following requirements:

The contractor and the SHA shall *each* randomly obtain one 200-lb sample of cold feed aggregate and plant-produced Superpave mix from each 60-ton sublot. The SHA and the Contractor shall split each sample into two sets of specimens to determine the arithmetic means and standard deviations of the following properties for each 100-ton sublot and for the minimum 500-ton production:

1. The gradation of the cold-feed aggregate;
2. The asphalt content and combined aggregate gradation (AASHTO T 165);
3. The maximum specific gravity of the HMA (AASHTO T 209);
4. The gyratory compaction curve for N_{max} (AASHTO Standard Method TP4);
5. The bulk specific gravity (AASHTO T 166, SSD method) at N_{design} gyrations (AASHTO Standard Method TP4);
6. The air voids content (percent V_a) at N_{init}, N_{design}, and N_{max} gyrations (AASHTO Standard Method TP4);
7. The percent VMA and the percent VFA at N_{design} gyrations (AASHTO Standard Method TP4); and
8. Slope of compaction curve.

The contractor and SHA shall statistically evaluate their independent sets of test results (e.g., with the Student t-test or using approaches in Appendix G) and compare them with those for the LTMF of the paving mix with due consideration to test type and variations associated with the applicable tests. The 500-ton lot of Superpave mix must meet an acceptable quality level of ninety percent within the LTMF limits for each of the following characteristics: asphalt content, aggregate gradation, and volumetric properties identified in Table 2-1 (see Chapter 2).

The VMA and the VFA were considered as acceptance criteria in the Version No. 2 QC/QA Plan. The NCHRP 9-7 panel decided to include these criteria as options for acceptance for the SHAs rather than specific requirements.

6.3.2.k Binder QC Equipment

The SHRP asphalt binder specification, which has been adopted by AASHTO in the form of AASHTO MP-1 "Specification for Performance-Graded Asphalt Binder," is based on fundamental rheological properties. These properties are measured at three temperatures—the maximum expected pavement temperature, the minimum expected pavement temperature plus ten degrees, and an intermediate pavement temperature. The dynamic shear rheometer (DSR) is used to obtain the measurements at the maximum and intermediate temperature, and the bending beam rheometer (BBR) is used

TABLE 6-9 **Performance testing completed by NCHRP Project 9-7 laboratories**

Superpave ID	Mix Design	Test Level	SST Testing						IDT Testing		Comments
			Freq.	Shear	Hydro.	Uniax.	RSCSR	RSCH	Creep	Stren.	
Florida Mix	Y	3	Y	Y	Y	Y	N	N	N	N	Bad Data - Uniaxial and Hydrostatic
Florida Field	Y	2	Y	Y	N	N	N	N	N	N	
Miss Mix	Y	3	Y	Y	Y	Y	N	N	N	N	Bad Data - Uniaxial and Hydrostatic
Miss Field	Y	2	Y	Y	N	N	N	N	N	N	
Kent I Mix	Y	3	Y	Y	Y	Y	N	Y	N	N	Bad Data - Uniaxial and Hydrostatic
Kent I Field	Y	2	Y	Y	N	N	N	N	N	N	
Virginia Mix	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Virginia Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Virginia Core	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas I Mix	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas I Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas I Core	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas II Mix	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas II Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas II Core	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Texas III Mix	Y	X	N	N	N	N	N	N	N	N	Tests Pending
Texas III Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Alabama Mix	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Alabama Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Alabama Core	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Georgia Mix	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Georgia Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Georgia Core	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Kansas Mix	Y	X	N	N	N	N	N	N	N	N	
Kansas Field	Y	X	N	N	N	N	N	N	N	N	
Mary SMA Mix	Y	X	N	N	N	N	N	N	N	N	
Mary SMA Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Mary HMAC Mix	Y	X	N	N	N	N	N	N	N	N	
Mary HMAC Field	Y	2	Y	Y	N	N	N	N	N	N	Not enough points on shear load/unload
Louisiana Mix	Y	X	N	N	N	N	N	N	N	N	
WesTrack	Y	2	Y	Y	N	N	N	N	N	N	Tests Pending (UNR)

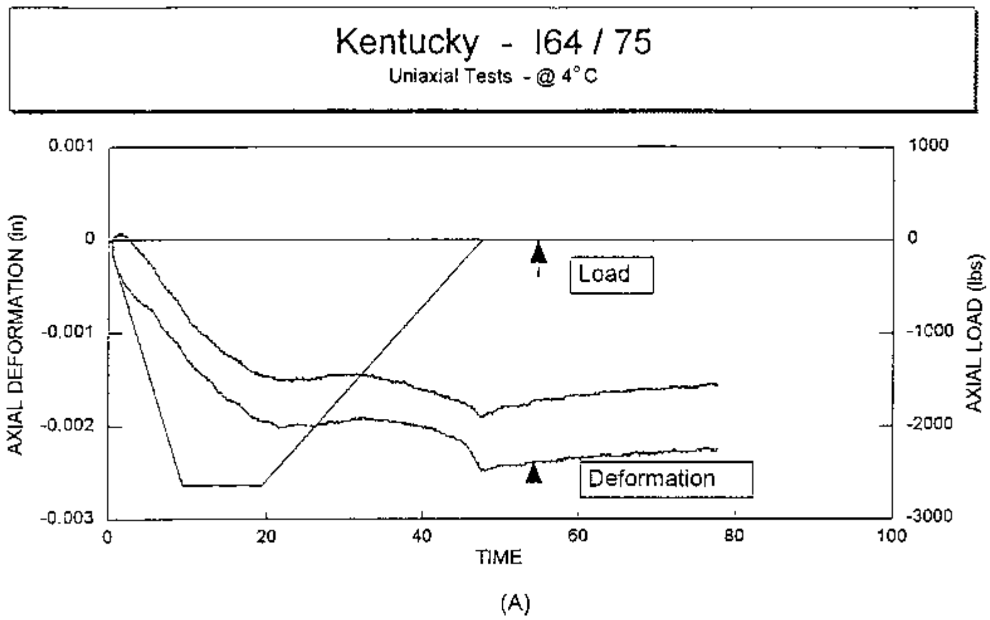


Figure 6-14. (A) Axial load and response.

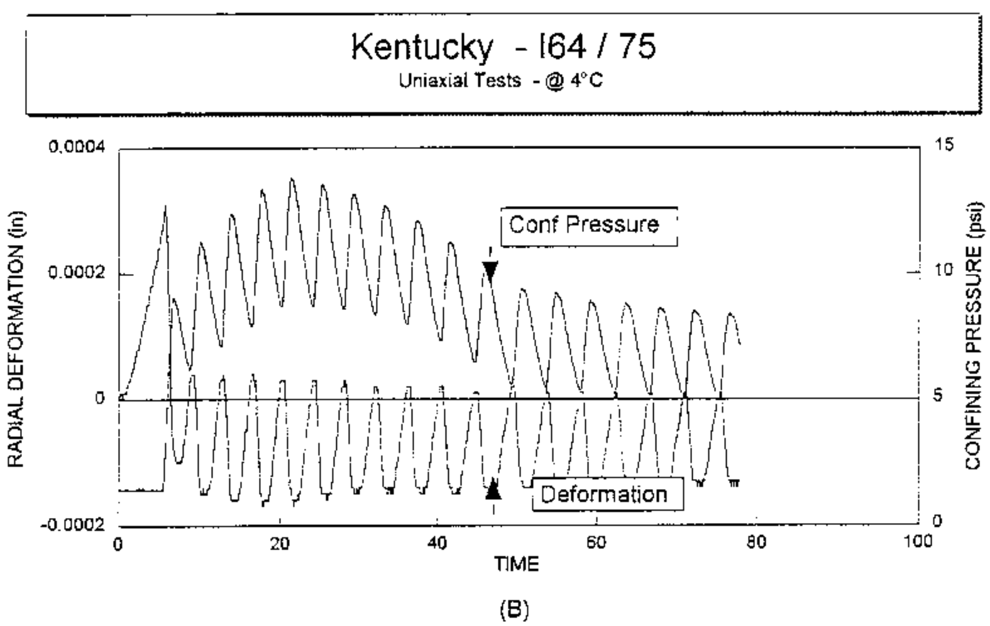
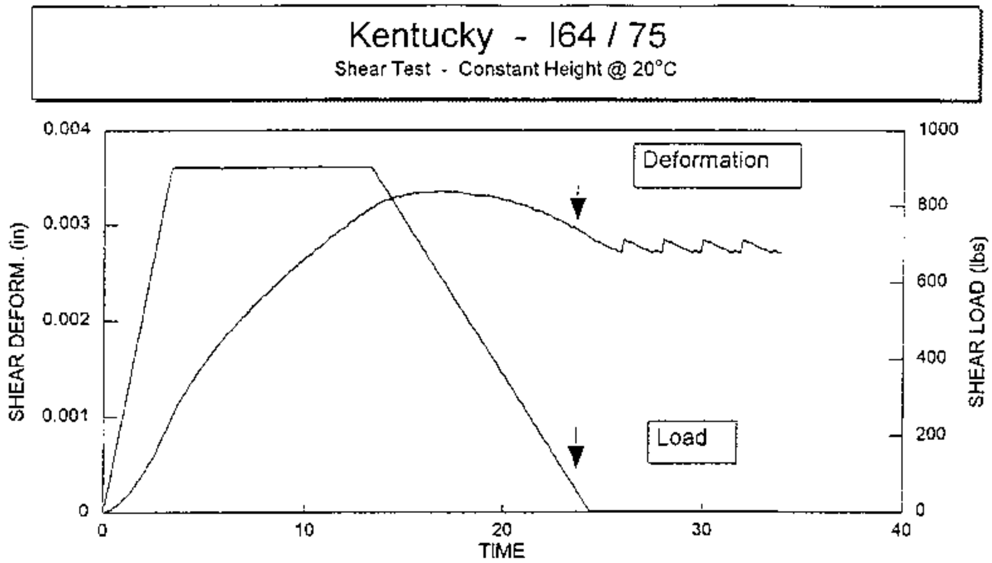


Figure 6-14. (B) Radial pressure and response.

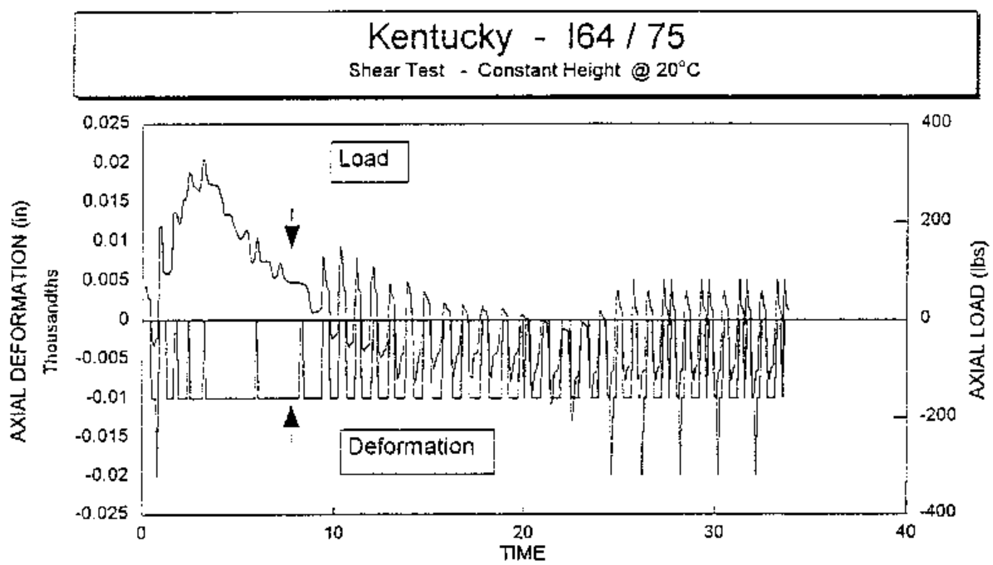
at the low temperature. At each temperature, two measurements are obtained, either the complex modulus and phase angle or the stiffness modulus and the m-value. The phase angle and the m-value describe the time dependency of their respective moduli. The phase angle and m-value also may be thought of as describing the relative proportion of the modulus that is either elastic or viscous in nature. Thus, both a modulus and either the phase angle or the m-value are needed to characterize the performance-related properties of asphalt binders.

To provide the required fundamental, performance-related properties the DSR and BBR were selected by the SHRP



(A)

Figure 6-15. (A) Shear load and response.



(B)

Figure 6-15. (B) Axial load and response.

researchers as the preferred specification and acceptance test procedures. These tests are considerably more sophisticated than the penetration and ductility tests they replace. To conduct the newly developed DSR and BBR tests, more sophisticated test equipment is needed, the skill level required of the test equipment operators is greater, and the time required to complete the tests is longer than for old test methods. These factors limit the amount of testing that can be done with current resources and personnel, neither of which can be expected to improve in the near future.

As a result of the SHRP research, AASHTO has adopted PP-26, a provisional QC practice for use with the new SHRP

TABLE 6-10 Data collected on Louisiana project 1996

IH10 - Baton Rouge, LA

Sample	Avg Gmm measured	Avg Gmb measured	Gmb meas Std dev.	Avg Correction Factor	Avg Gmb estimated	Avg Gmb Absolute Difference	Avg Gmb Difference	Avg Air Voids Measured	Air Voids Std Dev Measured	Avg AirVoids Estimated	Air Voids Std Dev Estimated	Avg Difference AVm-AVe	Avg comp curve slope meas	Stdv comp curve slope meas	Avg comp curve slope est	Stdv comp curve slope est
Truck#1	2.513	2.448	0.005	1.030	2.452	0.0059	-0.0041	4.14	0.211	3.69	0.207	0.450	9.75	0.102	9.80	0.081
Truck#2	2.496	2.449	0.004	1.031	2.468	0.0189	-0.0189	3.16	0.303	3.05	0.519	0.108	9.85	0.045	9.86	0.066
Truck#3	2.515	2.444	0.005	1.030	2.453	0.0090	-0.0090	4.43	0.320	3.69	0.549	0.741	9.64	0.226	9.72	0.207
Truck#4	2.489	2.473	0.002	1.019	2.514	0.0409	-0.0409	1.92	0.049	0.94	0.307	0.977	9.30	0.066	9.39	0.092
Truck#5	2.499	2.462	0.002	1.027	2.473	0.0112	-0.0112	3.02	0.100	2.83	0.080	0.198	9.57	0.238	9.59	0.236
Truck#6	2.508	2.468	0.003	1.028	2.470	0.0069	-0.0023	3.23	0.126	3.02	0.448	0.211	10.13	0.197	10.16	0.232
Truck#7	2.488	2.474	0.003	1.017	2.512	0.0383	-0.0383	1.91	0.134	1.07	0.215	0.838	9.34	0.193	9.42	0.184
Truck#8	2.511	2.467	0.007	1.023	2.485	0.0174	-0.0174	3.20	0.276	2.29	0.279	0.914	9.41	0.077	9.50	0.071
Truck#9	2.506	2.457	0.002	1.030	2.461	0.0040	-0.0040	3.41	0.099	3.22	0.000	0.196	9.50	0.054	9.52	0.051
Standard Deviation	0.010	0.012		0.005	0.022			0.900		0.963			0.270		0.247	
Average	2.501	2.460		1.026	2.476			3.116		2.613			9.656		9.705	

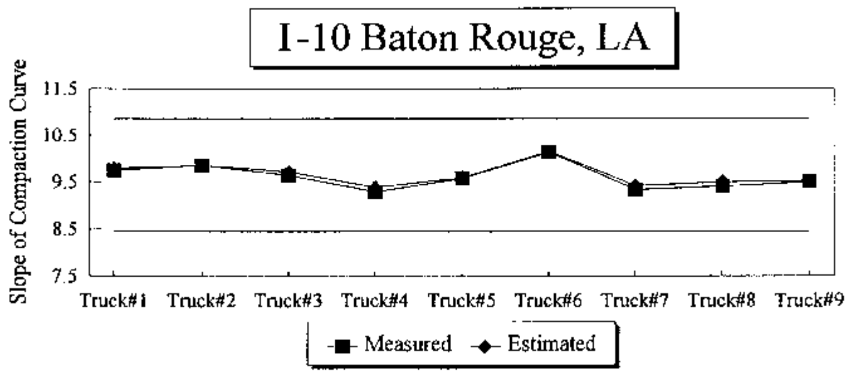


Figure 6-16. Control chart for slope of gyratory compaction slope.

performance-graded asphalt binder specifications. According to AASHTO PP-26, each refiner is required to develop a QC program and to certify that the asphalt binder is in conformance with the specifications (MP-1) before it is shipped. In addition, AASHTO PP-26 places the responsibility for the quality of the asphalt binder on the last contractual entity that handles the asphalt binder as it passes from the refiner to the hot-mix plant. It may be argued that certification will eliminate the need for extensive testing thereby minimizing the need for intermediate testing. This may be true if the asphalt is totally "manufactured" at the refinery (i.e., is a finished product as it leaves the refinery) and therefore no blending or on-site modification is used, in which case extensive on-site testing would be needed. The properties of the asphalt binder also may be seriously affected by factors outside the control of the refiner or the hot-mix plant owner. Refinery certification cannot ensure that the asphalt cement is shipped without contamination with other products (e.g., fuel oil) and without accidental cross-blending with other grades or sources of asphalt binders. Therefore, even if certification is adopted universally and if no on-site blending or modification is to occur, the issue of contamination and uniformity points to some sort of easy-to-conduct on-site testing procedure to monitor quality and to ensure that the material will ultimately be accepted by the user agency.

One proposal for refinery or on-site QC testing would be to simply measure viscosity at 60°C or, alternatively, at the maximum pavement temperature. A viscosity test at elevated temperatures cannot control the viscoelastic properties at pavement service temperatures and therefore a surrogate test is needed for the DSR and BBR. Having established the need for a low-cost, easy-to-perform, and rapid test that can be used on-site by relatively unskilled technicians, an appropriate test must be identified. Considerable work was done with a ball indentation test during the SHRP A-002A Project. Although the test was not adopted as one of the SHRP binder specification test procedures, accurate results were obtained with the test and it did show promise as a QC test. The results obtained during the SHRP program with the ball indentation test were considered sufficient to warrant and recommend further development of the ball indentation test by the A-002A researchers. Therefore, the ball indentation test was selected for use in NCHRP 9-7 for use as a potential QC test to supplement the BBR and DST test methods.

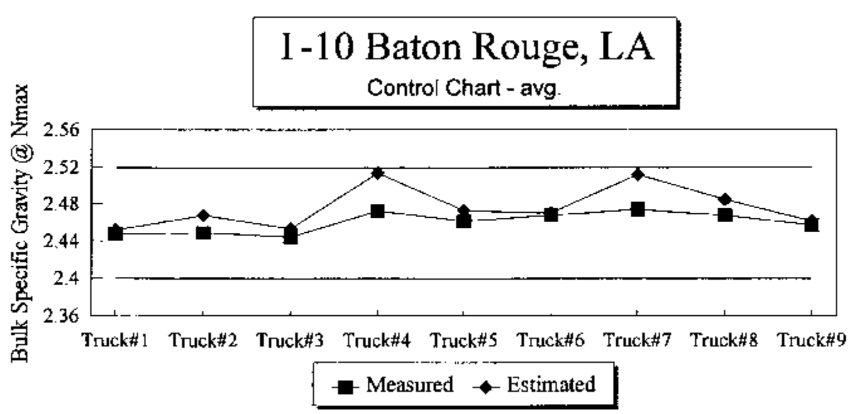


Figure 6-17. Control chart for bulk specific gravity.

As a result of the confusion raised by the name "ball indentation," and the association with the penetration test, the term SDR has been chosen to describe the ball indentation test. This is an appropriate acronym. The ball causes a shear displacement as it displaces the asphalt binder beneath the indenter or ball. In the SHRP project, the SDR test was used with a constant rate of deformation (screw) test machine. To conduct the test with the BBR, it was necessary to revise the equations used to calculate a modulus from the test measurements.

The SDR test is not an empirical test but is based on fundamental, theoretical principles and should in no way be confused with the standard penetration test. The standard penetration test is based on a needle that penetrates to a depth many times the diameter of the tip of the needle, producing strains that are very large and resulting in nonlinear response. The ball indentation test is based on a spherical indenter that penetrates only a fraction of the diameter of the ball. By keeping the depth of penetration of the ball less than the radius of the ball, the response of the asphalt closely approximates linear behavior. This allows the test results from the ball indentation test to be related in a fundamental manner to the creep compliance or dynamic shear modulus obtained from the BBR or DSR. In the ball indentation test the modulus of the asphalt binder is obtained by measuring the diameter of the ball, the applied load, and the resulting depth of indentation as a function of time. These values are then used, along with a model of the system, to calculate the modulus. The observed modulus decreases with time and the depth of indentation increases with time as follows:

$$G(t) = [\sigma(t)]^{3/2} \frac{16\sqrt{R}}{3P_o}$$

where

$G(t)$ = shear modulus, Pa
$\sigma(t)$ = indentation of ball, m
R = radius of ball, m
P_o = constant load, N

This equation has been developed for the linear quasi-static case where the load is a creep load. This is in contrast to the use of a constant rate of indentation device and the nonlinear case as was done during the SHRP research. As used in this project, the SDR was confined to the range of loads and indentations allowed by the BBR testing frame. This limitation, plus the use of the quasi-static solution, limited the accuracy of the results. Further application of the SDR should consider the development of a moving boundary value solution and different loads and indentations to extend the range of the device (see Appendix A). In spite of these limitations, the SDR does show promise as a rapid and easy-to-perform test device that could be used for QC purposes.

In practice, the SDR would be used in conjunction with either the Brookfield viscometer or a simple hand-held viscometer. SDR data in the range of the intermediate specification temperature would be obtained by the refiner and include a part of the certification a supplement to the current BBR and DSR specification test results. It is envisioned that the refiner would perform QC with frequent SDR measurements but certify on the basis of less frequent DSR and BBR measurements. During the path from the refiner to the hot-mix plant and at the hot-mix plant, the SDR would be used to monitor uniformity. If at any time the asphalt binder fails the SDR test, then a full slate of DSR and BBR testing would be required. In this manner, because of the relative rapidity and simplicity of the SDR, the frequency of testing and, hence, degree of QC would be greatly enhanced and the amount of nonconforming material would be greatly reduced. Appendix H provides a report of the SDR approach initially researched by NCHRP 9-7. Because of limited funds this portion of the research project was terminated.

6.3.2.1 Sensitivity of Superpave Mixture Tests to Changes in Mixture Components

NCHRP 9-7 was established to address the implementation of the asphalt products developed by SHRP from 1987 to 1992. The focus of this research was the development of procedures and equipment, if necessary, for QC and QA of Superpave asphalt mixtures. As part of the research program, a variety of tests were used in the field production of asphalt mixtures. NCHRP 9-7 focused research on mixtures that were designed and constructed with the Superpave mix design system on projects in Kentucky, Mississippi, Virginia, Florida, Texas, Kansas, Maryland, and Alabama. Testing on these projects provided data on mixture components, volumetric properties, and performance properties that were analyzed to determine the appropriate level of QC/QA for projects using the Superpave mix design system.

The goal of the research of NCHRP 9-7 is to recommend the appropriate tests, test procedures, and testing frequency to ensure that the produced mixture will perform satisfactorily as a part of the total pavement structure. The Superpave system uses a series of mixture tests that will yield the fundamental mechanical properties of a compacted mixture specimen. These test results may be analyzed to provide a determination of material properties. The original intent of many of these tests was that they would be input into performance models developed during SHRP that will output a prediction of various forms of pavement distress as a function of time or traffic. This level of prediction was formerly referred to as a Superpave Level 3 mix design.

Superpave performance tests utilize the SST and Indirect Tensile Tester for a complete characterization of material properties. Using the Superpave performance tests would involve an extensive testing program requiring much time and expense. The equipment alone may cost in excess of $250,000.

Because there is a substantial investment of time and money required to perform advanced performance testing in Superpave, it is not likely that these tests can be routinely used for QC/QA operations. Consequently, it was the goal of the research plan to identify those mixture tests and properties, that can be used to ensure adequate performance in lieu of the advanced performance tests. It is possible that the performance tests can be simplified for routine use. The question then remains "How sensitive are these mixture tests to changes in key mixture components?" In other words, if asphalt binder content were increased by 0.5 percent (within the normal production tolerance range established by some agencies), would the Superpave mixture tests detect the change and result in a change of material properties? If so, is it sufficient to specify *only* these tests as the basis for the assurance of performance of a mixture? Or, possibly can other tests be specified as "surrogate" performance tests or performance-related tests that will ensure adequate mixture behavior?

The purpose of this research was to analyze whether laboratory changes in mixture components will result in significant mixture property (volumetric and mechanical) changes. The tools used to execute this research were the SGC for volumetric properties and the SST for mechanical properties. Low-temperature testing with the indirect tensile tester was not considered in this research.

This experiment was designed to investigate changes in the following input variables:

- Asphalt binder content;
- Change in coarse aggregation gradation (material refined on the 4.75-mm sieve);
- Change in intermediate aggregate gradation (material passing the 4.75-mm sieve and retained on the 0.3-mm sieve);
- Change in fine aggregate gradation (material passing the 0.3-mm sieve); and
- Change in ratio of natural and crushed sands.

The SGC was used to evaluate the effects of changes in the input variables on the response variables indicated below:

- Percent of densification (percent G_{mm}) or air voids (V_a), at N_{design};
- Percent of densification (percent G_{mm}) at $N_{initial}$ and $N_{maximum}$; and
- Densification slope (percent G_{mm} as a function of number of gyrations).

The SST was used to evaluate the effects of changes in the input variables on the response variables indicated below:

- Complex shear modulus and shear loss modulus (frequency sweep);
- Maximum and final shear strain (simple shear);
- Permanent shear strain (repeated simple shear-constant height); and
- Rate of change in permanent shear strain with loading cycles.

Appendix I provides specific details of the findings of this research effort.

6.3.2.m Recommendations

Based on findings from the research data, the following recommendations are made:

- QC limits should be based on test variance;
- QA specification limits should be based on test variance;
- QC/QA should be based primarily on gyratory compaction;
- Plant QC should be based on estimated gyratory bulk gravity (G_{mb}); and
- Field shear devices may be used for validating mix design adjustment and additional QC.

APPENDIXES A–C

Appendixes A through C as submitted by the research agency are not published herein but are available for loan on request to the NCHRP.

APPENDIX A—Additional Training Modules

APPENDIX B—Field Shear Test Procedure in AASHTO Draft Format

APPENDIX C—Rapid Triaxial Test Procedure in AASHTO Draft Format

APPENDIX D

SUMMARY OF INFORMATION FOR PROJECTS CONSTRUCTED IN 1994

Appendix D is not published herein in its complete form as submitted by the research agency but is available for loan on request to the NCHRP.

The following sections have been selected from Appendix D for publication:

Project Data—1994 Projects

Project and Pooled Standard Deviations (1994)

PROJECT DATA

1994 PROJECTS

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
KY	1	1	20P	1	11-Jul-94	TAI	P	F	N	BATCH	20	S	PG70-22
KY	1	1	20P	2	11-Jul-94	TAI	P	F	N	BATCH	20	S	PG70-22
KY	1	1	20P	1	11-Jul-94	TAI	P	F	Y	BATCH	20	S	PG70-22
KY	1	1	20P	2	11-Jul-94	TAI	P	F	Y	BATCH	20	S	PG70-22
KY	1	1	20T	1	11-Jul-94	TAI	T	F	N	BATCH	20	S	PG70-22
KY	1	1	20T	2	11-Jul-94	TAI	T	F	N	BATCH	20	S	PG70-22
KY	1	2	68P	1	11-Jul-94	TAI	P	F	N	BATCH	685	S	PG70-22
KY	1	2	68P	2	11-Jul-94	TAI	P	F	N	BATCH	685	S	PG70-22
KY	1	2	68P	1	11-Jul-94	TAI	P	F	Y	BATCH	685	S	PG70-22
KY	1	2	68P	2	11-Jul-94	TAI	P	F	Y	BATCH	685	S	PG70-22
KY	1	2	68T	1	11-Jul-94	TAI	T	F	N	BATCH	685	S	PG70-22
KY	1	2	68T	2	11-Jul-94	TAI	T	F	N	BATCH	685	S	PG70-22
KY	1	3	13P	1	11-Jul-94	TAI	P	F	N	BATCH	1308	S	PG70-22
KY	1	3	13P	2	11-Jul-94	TAI	P	F	N	BATCH	1308	S	PG70-22
KY	1	3	13P	1	11-Jul-94	TAI	P	F	Y	BATCH	1308	S	PG70-22
KY	1	3	13P	2	11-Jul-94	TAI	P	F	Y	BATCH	1308	S	PG70-22
KY	1	3	13T	1	11-Jul-94	TAI	T	F	N	BATCH	1308	S	PG70-22
KY	1	3	13T	2	11-Jul-94	TAI	T	F	N	BATCH	1308	S	PG70-22
KY	2	1	18P	1	12-Jul-94	TAI	P	F	N	BATCH	1832	S	PG70-22
KY	2	1	18P	2	12-Jul-94	TAI	P	F	N	BATCH	1832	S	PG70-22
KY	2	1	18P	1	12-Jul-94	TAI	P	F	Y	BATCH	1832	S	PG70-22
KY	2	1	18P	2	12-Jul-94	TAI	P	F	Y	BATCH	1832	S	PG70-22
KY	2	1	18T	1	12-Jul-94	TAI	T	F	N	BATCH	1832	S	PG70-22
KY	2	1	18T	2	12-Jul-94	TAI	T	F	N	BATCH	1832	S	PG70-22
KY	2	2	19P	1	12-Jul-94	TAI	P	F	N	BATCH	1972	S	PG70-22
KY	2	2	19P	2	12-Jul-94	TAI	P	F	N	BATCH	1972	S	PG70-22
KY	2	2	19P	1	12-Jul-94	TAI	P	F	Y	BATCH	1972	S	PG70-22
KY	2	2	19P	2	12-Jul-94	TAI	P	F	Y	BATCH	1972	S	PG70-22
KY	2	2	19T	1	12-Jul-94	TAI	T	F	N	BATCH	1972	S	PG70-22
KY	2	2	19T	2	12-Jul-94	TAI	T	F	N	BATCH	1972	S	PG70-22
KY	2	3	22P	1	12-Jul-94	TAI	P	F	N	BATCH	2229	S	PG70-22
KY	2	3	22P	2	12-Jul-94	TAI	P	F	N	BATCH	2229	S	PG70-22
KY	2	3	22P	1	12-Jul-94	TAI	P	F	Y	BATCH	2229	S	PG70-22
KY	2	3	22P	2	12-Jul-94	TAI	P	F	Y	BATCH	2229	S	PG70-22
KY	2	3	22T	1	12-Jul-94	TAI	T	F	N	BATCH	2229	S	PG70-22
KY	2	3	22T	2	12-Jul-94	TAI	T	F	N	BATCH	2229	S	PG70-22
KY	3	1	30P	1	13-Jul-94	TAI	P	F	N	BATCH	3017	S	PG70-22
KY	3	1	30P	2	13-Jul-94	TAI	P	F	N	BATCH	3017	S	PG70-22
KY	3	1	30P	1	13-Jul-94	TAI	P	F	Y	BATCH	3017	S	PG70-22
KY	3	1	30P	2	13-Jul-94	TAI	P	F	Y	BATCH	3017	S	PG70-22
KY	3	1	30T	1	13-Jul-94	TAI	T	F	N	BATCH	3017	S	PG70-22
KY	3	1	30T	2	13-Jul-94	TAI	T	F	N	BATCH	3017	S	PG70-22
KY	3	2	35P	1	13-Jul-94	TAI	P	F	N	BATCH	3500	S	PG70-22
KY	3	2	35P	2	13-Jul-94	TAI	P	F	N	BATCH	3500	S	PG70-22
KY	3	2	35P	1	13-Jul-94	TAI	P	F	Y	BATCH	3500	S	PG70-22
KY	3	2	35P	2	13-Jul-94	TAI	P	F	Y	BATCH	3500	S	PG70-22
KY	3	2	35T	1	13-Jul-94	TAI	T	F	N	BATCH	3500	S	PG70-22
KY	3	2	35T	2	13-Jul-94	TAI	T	F	N	BATCH	3500	S	PG70-22
KY	3	3	40P	1	13-Jul-94	TAI	P	F	N	BATCH	4034	S	PG70-22
KY	3	3	40P	2	13-Jul-94	TAI	P	F	N	BATCH	4034	S	PG70-22
KY	3	3	40P	1	13-Jul-94	TAI	P	F	Y	BATCH	4034	S	PG70-22
KY	3	3	40P	2	13-Jul-94	TAI	P	F	Y	BATCH	4034	S	PG70-22
KY	3	3	40T	1	13-Jul-94	TAI	T	F	N	BATCH	4034	S	PG70-22
KY	3	3	40T	2	13-Jul-94	TAI	T	F	N	BATCH	4034	S	PG70-22
KY	3	4	45P	1	13-Jul-94	TAI	P	F	N	BATCH	4549	S	PG70-22

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PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
KY	3	4	45P	2	13-Jul-94	TAI	P	F	N	BATCH	4549	S	PG70-22
KY	3	4	45P	1	13-Jul-94	TAI	P	F	Y	BATCH	4549	S	PG70-22
KY	3	4	45P	2	13-Jul-94	TAI	P	F	Y	BATCH	4549	S	PG70-22
KY	3	4	45T	1	13-Jul-94	TAI	T	F	N	BATCH	4549	S	PG70-22
KY	3	4	45T	2	13-Jul-94	TAI	T	F	N	BATCH	4549	S	PG70-22
KY	4	1	49P	1	14-Jul-94	TAI	P	F	N	BATCH	4907	S	PG70-22
KY	4	1	49P	2	14-Jul-94	TAI	P	F	N	BATCH	4907	S	PG70-22
KY	4	1	49P	1	14-Jul-94	TAI	P	F	Y	BATCH	4907	S	PG70-22
KY	4	1	49P	2	14-Jul-94	TAI	P	F	Y	BATCH	4907	S	PG70-22
KY	4	1	49T	1	14-Jul-94	TAI	T	F	N	BATCH	4907	S	PG70-22
KY	4	1	49T	2	14-Jul-94	TAI	T	F	N	BATCH	4907	S	PG70-22
KY	4	2	54P	1	14-Jul-94	TAI	P	F	N	BATCH	5425	S	PG70-22
KY	4	2	54P	2	14-Jul-94	TAI	P	F	N	BATCH	5425	S	PG70-22
KY	4	2	54P	1	14-Jul-94	TAI	P	F	Y	BATCH	5425	S	PG70-22
KY	4	2	54P	2	14-Jul-94	TAI	P	F	Y	BATCH	5425	S	PG70-22
KY	4	2	54T	1	14-Jul-94	TAI	T	F	N	BATCH	5425	S	PG70-22
KY	4	2	54T	2	14-Jul-94	TAI	T	F	N	BATCH	5425	S	PG70-22
KY	4	3	62P	1	14-Jul-94	TAI	P	F	N	BATCH	6270	S	PG70-22
KY	4	3	62P	2	14-Jul-94	TAI	P	F	N	BATCH	6270	S	PG70-22
KY	4	3	62P	1	14-Jul-94	TAI	P	F	Y	BATCH	6270	S	PG70-22
KY	4	3	62P	2	14-Jul-94	TAI	P	F	Y	BATCH	6270	S	PG70-22
KY	4	3	62T	1	14-Jul-94	TAI	T	F	N	BATCH	6270	S	PG70-22
KY	4	3	62T	2	14-Jul-94	TAI	T	F	N	BATCH	6270	S	PG70-22
KY	5	1	69P	1	18-Jul-94	TAI	P	F	N	BATCH	6969	S	PG70-22
KY	5	1	69P	2	18-Jul-94	TAI	P	F	N	BATCH	6969	S	PG70-22
KY	5	1	69P	1	18-Jul-94	TAI	P	F	Y	BATCH	6969	S	PG70-22
KY	5	1	69P	2	18-Jul-94	TAI	P	F	Y	BATCH	6969	S	PG70-22
KY	5	1	69T	1	18-Jul-94	TAI	T	F	N	BATCH	6969	S	PG70-22
KY	5	1	69T	2	18-Jul-94	TAI	T	F	N	BATCH	6969	S	PG70-22
KY	5	2	76P	1	18-Jul-94	TAI	P	F	N	BATCH	7684	S	PG70-22
KY	5	2	76P	2	18-Jul-94	TAI	P	F	N	BATCH	7684	S	PG70-22
KY	5	2	76P	1	18-Jul-94	TAI	P	F	Y	BATCH	7684	S	PG70-22
KY	5	2	76P	2	18-Jul-94	TAI	P	F	Y	BATCH	7684	S	PG70-22
KY	5	2	76T	1	18-Jul-94	TAI	T	F	N	BATCH	7684	S	PG70-22
KY	5	2	76T	2	18-Jul-94	TAI	T	F	N	BATCH	7684	S	PG70-22
MS	1	1	TRUCK7	1	12-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	1	1	TRUCK7	2	12-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	1	2	TRUCK8	1	12-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	1	2	TRUCK8	2	12-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	2	1	TRUCK9	1	13-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	2	1	TRUCK9	2	13-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	2	2	TRUCK10	1	13-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	2	2	TRUCK10	2	13-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	2	3	TRUCK11	1	13-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	2	3	TRUCK11	2	13-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	3	1	TRUCK12	1	14-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
MS	3	1	TRUCK12	2	14-Sep-94	TAI	T	F	N	BATCH		S	PG64-22
VA	2	1	TRUCK1	1	20-Oct-94	AAT	F	F	N	DRUM	114	S	PG64-22
VA	2	1	TRUCK1	2	20-Oct-94	AAT	F	F	N	DRUM	114	S	PG64-22
VA	2	1	TRUCK1	3	20-Oct-94	AAT	F	F	N	DRUM	114	S	PG64-22
VA	2	2	TRUCK2	1	20-Oct-94	AAT	F	F	N	DRUM	742	S	PG64-22
VA	2	2	TRUCK2	2	20-Oct-94	AAT	F	F	N	DRUM	742	S	PG64-22
VA	2	2	TRUCK2	3	20-Oct-94	AAT	F	F	N	DRUM	742	S	PG64-22
VA	2	3	TRUCK5	1	21-Oct-94	AAT	F	F	N	DRUM	1642	S	PG64-22
VA	3	1	TRUCK3	1	21-Oct-94	AAT	F	F	N	DRUM	1121	S	PG64-22

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PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
VA	3	1	TRUCK3	2	21-Oct-94	AAT	F	F	N	DRUM	1121	S	PG64-22
VA	3	1	TRUCK3	3	21-Oct-94	AAT	F	F	N	DRUM	1121	S	PG64-22
VA	3	2	TRUCK4	1	21-Oct-94	AAT	F	F	N	DRUM	1478	S	PG64-22
VA	3	2	TRUCK4	2	21-Oct-94	AAT	F	F	N	DRUM	1478	S	PG64-22
VA	3	2	TRUCK4	3	21-Oct-94	AAT	F	F	N	DRUM	1478	S	PG64-22
VA	3	3	TRUCK5	2	21-Oct-94	AAT	F	F	N	DRUM	1642	S	PG64-22
VA	3	3	TRUCK5	3	21-Oct-94	AAT	F	F	N	DRUM	1642	S	PG64-22
VA	1	1	TRUCK7	1	17-Nov-94	AAT	F	F	Y	DRUM	2268	S	PG64-22
VA	1	1	TRUCK7	2	17-Nov-94	AAT	F	F	Y	DRUM	2268	S	PG64-22
VA	1	1	TRUCK7	3	17-Nov-94	AAT	F	F	Y	DRUM	2268	S	PG64-22
VA	1	2	TRUCK8	1	17-Nov-94	AAT	F	F	Y	DRUM	2406	S	PG64-22
VA	1	2	TRUCK8	2	17-Nov-94	AAT	F	F	Y	DRUM	2406	S	PG64-22
VA	1	2	TRUCK8	3	17-Nov-94	AAT	F	F	Y	DRUM	2406	S	PG64-22
VA	1	3	TRUCK9	1	17-Nov-94	AAT	F	F	Y	DRUM	2900	S	PG64-22
VA	1	3	TRUCK9	2	17-Nov-94	AAT	F	F	Y	DRUM	2900	S	PG64-22
VA	1	3	TRUCK9	3	17-Nov-94	AAT	F	F	Y	DRUM	2900	S	PG64-22
VA	4	1	TRUCK10	1	22-Nov-94	AAT	F	F	Y	DRUM	3533	S	PG64-22
VA	4	1	TRUCK10	2	22-Nov-94	AAT	F	F	Y	DRUM	3533	S	PG64-22
VA	4	1	TRUCK10	3	22-Nov-94	AAT	F	F	Y	DRUM	3533	S	PG64-22
VA	4	2	TRUCK11	1	22-Nov-94	AAT	F	F	Y	DRUM	3924	S	PG64-22
VA	4	2	TRUCK11	2	22-Nov-94	AAT	F	F	Y	DRUM	3924	S	PG64-22
VA	4	2	TRUCK11	3	22-Nov-94	AAT	F	F	Y	DRUM	3924	S	PG64-22
VA	5	1	TRUCK12	1	03-Dec-94	AAT	F	F	Y	DRUM	4561	S	PG64-22
VA	5	1	TRUCK12	2	03-Dec-94	AAT	F	F	Y	DRUM	4561	S	PG64-22
VA	5	1	TRUCK12	3	03-Dec-94	AAT	F	F	Y	DRUM	4561	S	PG64-22
VA	5	2	TRUCK13	1	03-Dec-94	AAT	F	F	Y	DRUM	4977	S	PG64-22
VA	5	2	TRUCK13	2	03-Dec-94	AAT	F	F	Y	DRUM	4977	S	PG64-22
VA	5	2	TRUCK13	3	03-Dec-94	AAT	F	F	Y	DRUM	4977	S	PG64-22
VA	5	3	TRUCK14	1	03-Dec-94	AAT	F	F	Y	DRUM	5261	S	PG64-22
VA	5	3	TRUCK14	2	03-Dec-94	AAT	F	F	Y	DRUM	5261	S	PG64-22
VA	5	3	TRUCK14	3	03-Dec-94	AAT	F	F	Y	DRUM	5261	S	PG64-22
FL	1	1	TRUCK1	1	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	1	TRUCK1	2	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	2	TRUCK2	1	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	2	TRUCK2	2	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	3	TRUCK3	1	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	3	TRUCK3	2	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	4	TRUCK4	1	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
FL	1	4	TRUCK4	2	24-Jan-95	TAI	T	F	N	DRUM		S	PG64-22
TX1	1	1	TRUCK1	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	1	TRUCK1	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	1	TRUCK1	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	2	TRUCK2	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	2	TRUCK2	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	2	TRUCK2	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	3	TRUCK3	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	3	TRUCK3	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	3	TRUCK3	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	4	TRUCK4	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	4	TRUCK4	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1	1	4	TRUCK4	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX1			CORE18	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE19	2	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE20	3	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE16	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22

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PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
TX1			CORE13	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE14	2	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE15	3	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE11	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX1			CORE12	2	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2	1	1	TRUCK1	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	1	TRUCK1	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	1	TRUCK1	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	2	TRUCK2	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	2	TRUCK2	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	2	TRUCK2	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	3	TRUCK3	1	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	3	TRUCK3	2	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2	1	3	TRUCK3	3	01-Feb-95	AAT	F	F	Y	BATCH		S	PG64-22
TX2			CORE1	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE2	2	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE3	3	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE4	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE7	2	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE8	1	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE9	2	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22
TX2			CORE10	3	01-Feb-95	AAT	F	C	N	BATCH		S	PG64-22

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDB	EN_NMA	MAX_HEIG
KY	1	1	2.487			2.435	12.5	2.1	0.8	11.8	82.3	1.2	1.4		87.5	97.9	99.2	117.8
KY	1	1	2.487			2.432	12.4	2.2	0.8	11.9	81.5	1.2	1.4		87.6	97.8	99.2	114.9
KY	1	1	2.487			2.425	12.6	2.5	1.1	12.2	79.3	1.2	1.4		87.4	97.5	98.9	118.4
KY	1	1	2.487			2.445	11.9	1.7	0.4	11.4	85.5	1.2	1.4		88.1	98.3	99.6	117.7
KY	1	1	2.487			2.410	12.9	3.1	1.8	12.7	75.7	1.2	1.4		87.1	96.9	98.2	118.0
KY	1	1	2.487			2.417	12.6	2.8	1.5	12.4	77.8	1.2	1.4		87.4	97.2	98.5	118.2
KY	1	2	2.481			2.434	12.2	1.9	0.6	11.8	84.3	1.3	1.3		87.8	98.1	99.4	113.8
KY	1	2	2.481			2.436	12.1	1.8	0.4	11.8	84.4	1.3	1.3		87.9	98.2	99.6	117.5
KY	1	2	2.481			2.431	12.2	2.0	0.7	11.9	83.5	1.3	1.3		87.8	98.0	99.3	114.3
KY	1	2	2.481			2.426	12.5	2.2	0.8	12.1	81.9	1.3	1.3		87.5	97.8	99.2	118.8
KY	1	2	2.481			2.404	12.9	3.1	1.7	12.9	76.1	1.3	1.3		87.1	96.9	98.3	115.8
KY	1	2	2.481			2.414	12.7	2.7	1.3	12.6	78.3	1.3	1.3		87.3	97.3	98.7	115.0
KY	1	3	2.474			2.442	11.3	1.3	0.2	11.6	88.4	1.2	1.2		88.7	98.7	99.8	115.4
KY	1	3	2.474			2.439	11.4	1.4	0.3	11.6	88.3	1.2	1.2		88.6	98.6	99.7	111.5
KY	1	3	2.474			2.424	11.9	2.0	0.6	12.2	83.5	1.2	1.2		88.1	98.0	99.4	118.7
KY	1	3	2.474			2.429	11.9	1.8	0.4	12.0	85.0	1.2	1.2		88.1	98.2	99.6	115.6
KY	1	3	2.474			2.424	11.8	2.0	0.8	12.2	83.5	1.2	1.2		88.2	98.0	99.2	111.9
KY	1	3	2.474			2.424	11.9	2.0	0.7	12.2	83.5	1.2	1.2		88.1	98.0	99.3	113.5
KY	2	1	2.475			2.435	12.0	1.6	0.2	12.0	86.5	1.2	1.4		88.0	98.4	99.8	113.3
KY	2	1	2.475			2.430	12.1	1.8	0.4	12.2	84.9	1.2	1.4		87.9	98.2	99.6	112.4
KY	2	1	2.475			2.433	12.0	1.7	0.5	12.1	85.6	1.2	1.4		88.0	98.3	99.5	117.9
KY	2	1	2.475			2.430	12.2	1.8	0.4	12.2	84.9	1.2	1.4		87.8	98.2	99.6	119.6
KY	2	1	2.475			2.418	12.8	2.3	0.9	12.6	81.8	1.2	1.4		87.2	97.7	99.1	118.2
KY	2	1	2.475			2.418	12.7	2.3	0.9	12.6	81.8	1.2	1.4		87.3	97.7	99.1	113.4
KY	2	2	2.478			2.441	11.5	1.5	0.4	11.6	87.0	1.2	1.3		88.5	98.5	99.6	113.5
KY	2	2	2.478			2.436	11.5	1.7	0.4	11.8	85.3	1.2	1.3		88.5	98.3	99.6	112.9
KY	2	2	2.478			2.448	11.2	1.2	0.1	11.3	89.6	1.2	1.3		88.8	98.8	99.9	114.2
KY	2	2	2.478			2.436	12.0	1.7	0.3	11.8	85.3	1.2	1.3		88.0	98.3	99.7	118.5
KY	2	2	2.478			2.423	12.1	2.2	0.9	12.2	82.1	1.2	1.3		87.9	97.8	99.1	116.7
KY	2	2	2.478			2.428	12.0	2.0	0.7	12.0	83.7	1.2	1.3		88.0	98.0	99.3	113.3
KY	2	3	2.482			2.445	11.5	1.5	0.4	11.4	87.3	1.4	1.4		88.5	98.5	99.6	115.0
KY	2	3	2.482			2.452	11.3	1.2	0.4	11.2	89.1	1.4	1.4		88.7	98.8	99.6	115.6
KY	2	3	2.482			2.462	10.5	0.8	0.3	10.8	92.8	1.4	1.4		89.5	99.2	99.7	114.8
KY	2	3	2.482			2.457	11.1	1.0	0.2	11.0	90.9	1.4	1.4		88.9	99.0	99.8	115.9
KY	2	3	2.482			2.437	11.8	1.8	0.6	11.7	84.8	1.4	1.4		88.2	98.2	99.4	114.9
KY	2	3	2.482			2.440	11.6	1.7	0.7	11.6	85.6	1.4	1.4		88.4	98.3	99.3	116.9
KY	3	1	2.483			2.458	10.8	1.0	0.1	10.8	90.5	1.4	1.3		89.2	99.0	99.9	116.7
KY	3	1	2.483			2.456	10.9	1.1	0.1	10.9	89.6	1.4	1.3		89.1	98.9	99.9	113.0
KY	3	1	2.483			2.453	11.0	1.2	0.1	11.0	88.7	1.4	1.3		89.0	98.8	99.9	115.9
KY	3	1	2.483			2.443	11.5	1.6	0.4	11.3	86.0	1.4	1.3		88.5	98.4	99.6	114.3
KY	3	1	2.483			2.448	10.9	1.4	0.3	11.1	87.7	1.4	1.3		89.1	98.6	99.7	115.1
KY	3	1	2.483			2.453	10.9	1.2	0.2	11.0	88.7	1.4	1.3		89.1	98.8	99.8	115.0
KY	3	2	2.478			2.458	10.9	0.8	0.1	10.8	92.4	1.0	1.2		89.1	99.2	99.9	113.0
KY	3	2	2.478			2.458	10.9	0.8	0.0	10.8	92.4	1.0	1.2		89.1	99.2	100.0	112.0
KY	3	2	2.478			2.466	10.2	0.5	0.0	10.5	95.3	1.0	1.2		89.8	99.5	100.0	117.8
KY	3	2	2.478			2.461	10.6	0.7	0.1	10.7	93.3	1.0	1.2		89.4	99.3	99.9	112.7
KY	3	2	2.478			2.451	11.1	1.1	0.2	11.0	90.4	1.0	1.2		88.9	98.9	99.8	116.6
KY	3	2	2.478			2.451	11.0	1.1	0.3	11.0	90.4	1.0	1.2		89.0	98.9	99.7	112.9
KY	3	3	2.481			2.451	11.3	1.2	0.1	11.0	89.3	1.4	1.2		88.7	98.8	99.9	117.2
KY	3	3	2.481			2.449	11.1	1.3	0.2	11.1	88.4	1.4	1.2		88.9	98.7	99.8	112.0
KY	3	3	2.481			2.459	10.9	0.9	-0.1	10.8	91.3	1.4	1.2		89.1	99.1	100.1	112.7
KY	3	3	2.481			2.459	10.4	0.9	0.0	10.8	91.3	1.4	1.2		89.6	99.1	100.0	114.4
KY	3	3	2.481			2.449	11.1	1.3	0.2	11.1	88.4	1.4	1.2		88.9	98.7	99.8	116.6
KY	3	3	2.481			2.444	11.4	1.5	0.3	11.3	86.7	1.4	1.2		88.6	98.5	99.7	116.6
KY	3	4	2.477			2.455	10.4	0.9	-0.1	10.9	91.7	1.2	1.1		89.6	99.1	100.1	114.2

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PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
KY	3	4	2.477			2.450	10.6	1.1	0.0	11.1	89.9	1.2	1.1		89.4	98.9	100.0	117.3
KY	3	4	2.477			2.460	9.9	0.7	-0.1	10.7	93.6	1.2	1.1		90.1	99.3	100.1	115.4
KY	3	4	2.477			2.462	10.0	0.6	-0.3	10.6	94.6	1.2	1.1		90.0	99.4	100.3	113.8
KY	3	4	2.477			2.450	10.6	1.1	0.1	11.1	89.9	1.2	1.1		89.4	98.9	99.9	117.0
KY	3	4	2.477			2.447	10.9	1.2	0.2	11.2	89.0	1.2	1.1		89.1	98.8	99.8	117.2
KY	4	1	2.508			2.445	11.6	2.5	1.3	11.1	77.9	1.3	1.6		88.4	97.5	98.7	115.2
KY	4	1	2.508			2.443	11.7	2.6	1.4	11.2	77.1	1.3	1.6		88.3	97.4	98.6	113.2
KY	4	1	2.508			2.395	13.4	4.5	3.3	13.0	65.2	1.3	1.6		86.6	95.5	96.7	113.7
KY	4	1	2.508			2.443	11.7	2.6	1.4	11.2	77.1	1.3	1.6		88.3	97.4	98.6	115.8
KY	4	1	2.508			2.435	11.7	2.9	1.8	11.5	74.9	1.3	1.6		88.3	97.1	98.2	111.8
KY	4	1	2.508			2.440	11.8	2.7	1.6	11.3	76.4	1.3	1.6		88.2	97.3	98.4	116.8
KY	4	2	2.477			2.437	11.4	1.6	0.7	11.8	86.5	1.1	1.3		88.6	98.4	99.3	117.4
KY	4	2	2.477			2.430	11.8	1.9	0.8	12.1	84.1	1.1	1.3		88.2	98.1	99.2	114.6
KY	4	2	2.477			2.432	12.1	1.8	0.5	12.0	84.9	1.1	1.3		87.9	98.2	99.5	113.9
KY	4	2	2.477			2.432	12.2	1.8	0.5	12.0	84.9	1.1	1.3		87.8	98.2	99.5	112.9
KY	4	2	2.477			2.418	12.2	2.4	1.3	12.5	81.0	1.1	1.3		87.8	97.6	98.7	114.5
KY	4	2	2.477			2.420	12.2	2.3	1.2	12.4	81.8	1.1	1.3		87.8	97.7	98.8	113.2
KY	4	3	2.476			2.446	10.9	1.2	0.2	11.2	89.3	1.2	1.1		89.1	98.8	99.8	116.7
KY	4	3	2.476			2.441	11.1	1.4	0.2	11.4	87.6	1.2	1.1		88.9	98.6	99.8	115.9
KY	4	3	2.476			2.441	11.5	1.4	0.3	11.4	87.6	1.2	1.1		88.5	98.6	99.7	110.2
KY	4	3	2.476			2.449	10.9	1.1	0.0	11.1	90.2	1.2	1.1		89.1	98.9	100.0	116.1
KY	4	3	2.476			2.434	11.3	1.7	0.5	11.7	85.1	1.2	1.1		88.7	98.3	99.5	117.6
KY	4	3	2.476			2.439	11.3	1.5	0.4	11.5	86.7	1.2	1.1		88.7	98.5	99.6	113.2
KY	5	1	2.473			2.471	8.8	0.1	-0.1	10.7	99.1	1.3	1.4		91.2	99.9	100.1	114.9
KY	5	1	2.473			2.471	9.2	0.1	-0.3	10.7	99.1	1.3	1.4		90.8	99.9	100.3	118.3
KY	5	1	2.473			2.471	7.4	0.1	-0.4	10.7	99.1	1.3	1.4		92.6	99.9	100.4	115.0
KY	5	1	2.473			2.473	8.9	0.0	-0.4	10.6	100.0	1.3	1.4		91.1	100.0	100.4	116.1
KY	5	1	2.473			2.458	9.6	0.6	0.2	11.2	94.2	1.3	1.4		90.4	99.4	99.8	116.7
KY	5	1	2.473			2.458	9.7	0.6	0.0	11.2	94.2	1.3	1.4		90.3	99.4	100.0	113.5
KY	5	2	2.469			2.459	8.3	0.4	0.1	10.7	96.6	1.5	1.0		91.7	99.6	99.9	117.5
KY	5	2	2.469			2.462	8.3	0.3	0.0	10.6	97.6	1.5	1.0		91.7	99.7	100.0	116.3
KY	5	2	2.469			2.466	8.5	0.1	-0.1	10.5	98.8	1.5	1.0		91.5	99.9	100.1	116.8
KY	5	2	2.469			2.469	8.6	-0.1	-0.4	10.4	100.0	1.5	1.0		91.4	100.1	100.4	113.9
KY	5	2	2.469			2.457	9.0	0.5	0.3	10.8	95.6	1.5	1.0		91.0	99.5	99.7	116.6
KY	5	2	2.469			2.459	8.9	0.4	0.2	10.7	96.6	1.5	1.0		91.1	99.6	99.8	117.3
MS	1	1	2.409			2.308	12.7	4.2	3.0	13.9	69.6	1.1	0.8		87.3	95.8	97.0	119.3
MS	1	1	2.409			2.320	12.1	3.7	2.5	13.4	72.6	1.1	0.8		87.9	96.3	97.5	119.4
MS	1	2	2.419			2.344	12.3	3.1	1.8	12.1	74.1	1.9	0.7		87.7	96.9	98.2	117.5
MS	1	2	2.419			2.349	12.2	2.9	1.7	11.9	75.5	1.9	0.7		87.8	97.1	98.3	117.6
MS	2	1	2.408			2.312	12.4	4.0	2.9	13.6	70.9	1.1	0.7		87.6	96.0	97.1	118.1
MS	2	1	2.408			2.314	12.5	3.9	2.7	13.6	71.0	1.1	0.7		87.5	96.1	97.3	118.5
MS	2	2	2.414			2.322	12.3	3.8	2.6	13.1	70.7	1.1	0.7		87.7	96.2	97.4	118.2
MS	2	2	2.414			2.320	12.2	3.9	2.6	13.2	70.1	1.1	0.7		87.8	96.1	97.4	118.1
MS	2	3	2.409			2.334	11.5	3.1	1.8	12.7	75.6	1.2	0.7		88.5	96.9	98.2	117.8
MS	2	3	2.409			2.313	12.7	4.0	2.7	13.5	70.5	1.2	0.7		87.3	96.0	97.3	119.5
MS	3	1	2.403			2.319	11.9	3.5	2.3	13.5	73.8	1.1	0.7		88.1	96.5	97.7	117.8
MS	3	1	2.403			2.321	11.7	3.4	2.1	13.4	74.4	1.1	0.7		88.3	96.6	97.9	117.7
VA	2	1	2.657			2.614	11.5	1.6	0.4	15.5	89.7	1.1	0.5	2.908	88.5	98.4	99.6	101.4
VA	2	1	2.657			2.614	11.6	1.6	0.3	15.5	89.7	1.1	0.5	2.908	88.4	98.4	99.7	101.8
VA	2	1	2.657			2.609	12.1	1.8	0.4	15.7	88.5	1.1	0.5	2.908	87.9	98.2	99.6	101.0
VA	2	2	2.682			2.639	11.0	1.6	0.6	14.4	88.9	1.4	0.6	2.910	89.0	98.4	99.4	100.6
VA	2	2	2.682			2.639	11.2	1.6	0.4	14.4	88.9	1.4	0.6	2.910	88.8	98.4	99.6	100.6
VA	2	2	2.682			2.631	11.4	1.9	0.7	14.6	87.0	1.4	0.6	2.910	88.6	98.1	99.3	100.4
VA	2	3	2.703			2.622	12.8	3.0	1.7	14.6	79.4	1.5	0.7	2.910	87.2	97.0	98.3	102.0
VA	3	1	2.699			2.599	13.0	3.7	2.5	15.4	76.0	1.3	0.6	2.910	87.0	96.3	97.5	102.7

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
VA	3	1	2.699			2.602	12.9	3.6	2.3	15.3	76.5	1.3	0.6	2.910	87.1	96.4	97.7	102.6
VA	3	1	2.699			2.596	13.2	3.8	2.5	15.5	75.5	1.3	0.6	2.910	86.8	96.2	97.5	103.2
VA	3	2	2.697			2.619	12.7	2.9	1.5	14.7	80.3	1.4	0.7	2.907	87.3	97.1	98.5	102.7
VA	3	2	2.697			2.616	12.9	3.0	1.5	14.8	79.7	1.4	0.7	2.907	87.1	97.0	98.5	102.6
VA	3	2	2.697			2.616	12.7	3.0	1.6	14.8	79.7	1.4	0.7	2.907	87.3	97.0	98.4	102.7
VA	3	3	2.703			2.611	13.6	3.4	2.0	14.9	77.2	1.5	0.7	2.910	86.4	96.6	98.0	102.0
VA	3	3	2.703			2.619	12.7	3.1	1.7	14.7	78.9	1.5	0.7	2.910	87.3	96.9	98.3	102.0
VA	1	1	2.712			2.568	14.8	5.3	3.9	16.0	66.9	1.2	0.6	2.908	85.2	94.7	96.1	105.2
VA	1	1	2.712			2.560	15.1	5.6	4.2	16.3	65.6	1.2	0.6	2.908	84.9	94.4	95.8	104.8
VA	1	1	2.712			2.576	14.4	5.0	3.6	15.7	68.2	1.2	0.6	2.908	85.6	95.0	96.4	104.0
VA	1	2	2.718			2.571	15.0	5.4	4.1	15.8	65.9	1.2	0.6	2.908	85.0	94.6	95.9	104.2
VA	1	2	2.718			2.558	15.5	5.9	4.5	16.3	63.7	1.2	0.6	2.908	84.5	94.1	95.5	104.6
VA	1	2	2.718			2.555	15.3	6.0	4.7	16.4	63.3	1.2	0.6	2.908	84.7	94.0	95.3	105.4
VA	1	3	2.703			2.576	14.5	4.7	3.1	15.9	70.5	1.2	0.6	2.908	85.5	95.3	96.9	103.4
VA	1	3	2.703			2.576	14.5	4.7	3.2	15.9	70.5	1.2	0.6	2.908	85.5	95.3	96.8	104.2
VA	1	3	2.703			2.573	14.6	4.8	3.4	16.0	70.0	1.2	0.6	2.908	85.4	95.2	96.6	104.1
VA	4	1	2.700			2.630	11.9	2.6	1.3	14.1	81.5	1.4	0.6	2.908	88.1	97.4	98.7	101.5
VA	4	1	2.700			2.635	11.8	2.4	1.2	13.9	82.7	1.4	0.6	2.908	88.2	97.6	98.8	101.6
VA	4	1	2.700			2.633	11.9	2.5	1.2	14.0	82.1	1.4	0.6	2.908	88.1	97.5	98.8	101.8
VA	4	2	2.688			2.618	12.5	2.6	1.4	14.8	82.5	1.1	0.6	2.908	87.5	97.4	98.6	102.0
VA	4	2	2.688			2.618	12.4	2.6	1.3	14.8	82.5	1.1	0.6	2.908	87.6	97.4	98.7	101.8
VA	4	2	2.688			2.621	12.0	2.5	1.2	14.7	83.0	1.1	0.6	2.908	88.0	97.5	98.8	101.6
VA	5	1	2.713			2.591	14.1	4.5	3.6	15.3	70.5	1.2	0.6	2.908	85.9	95.5	96.4	103.4
VA	5	1	2.713			2.607	13.8	3.9	2.5	14.7	73.5	1.2	0.6	2.908	86.2	96.1	97.5	103.0
VA	5	1	2.713			2.588	14.1	4.6	3.2	15.4	70.0	1.2	0.6	2.908	85.9	95.4	96.8	104.1
VA	5	2	2.707			2.564	14.9	5.3	3.9	16.3	67.4	1.3	0.6	2.908	85.1	94.7	96.1	104.6
VA	5	2	2.707			2.572	14.9	5.0	3.5	16.0	68.7	1.3	0.6	2.908	85.1	95.0	96.5	104.4
VA	5	2	2.707			2.569	14.9	5.1	3.6	16.1	68.3	1.3	0.6	2.908	85.1	94.9	96.4	104.8
VA	5	3	2.716			2.548	15.8	6.2	4.8	16.6	62.6	1.2	0.6	2.908	84.2	93.8	95.2	104.9
VA	5	3	2.716			2.548	16.0	6.2	4.7	16.6	62.6	1.2	0.6	2.908	84.0	93.8	95.3	105.2
VA	5	3	2.716			2.550	15.7	6.1	4.6	16.5	63.1	1.2	0.6	2.908	84.3	93.9	95.4	105.5
FL	1	1	2.300			2.279	11.7	0.9	0.1	9.5	90.3	1.8	2.3		88.3	99.1	99.9	112.2
FL	1	1	2.300			2.279	12.0	0.9	-0.1	9.5	90.3	1.8	2.3		88.0	99.1	100.1	111.9
FL	1	2	2.314			2.252	13.9	2.7	1.0	9.9	72.9	2.0	2.1		86.1	97.3	99.0	114.4
FL	1	2	2.314			2.249	14.3	2.8	1.0	10.0	72.1	2.0	2.1		85.7	97.2	99.0	113.4
FL	1	3	2.306			2.285	11.5	0.9	0.2	8.7	89.3	2.0	2.0		88.5	99.1	99.8	112.1
FL	1	3	2.306			2.267	12.8	1.7	0.6	9.4	82.0	2.0	2.0		87.2	98.3	99.4	112.5
FL	1	4	2.310			2.280	11.8	1.3	0.4	8.8	85.0	2.0	2.0		88.2	98.7	99.6	112.2
FL	1	4	2.310			2.261	12.9	2.1	0.7	9.5	78.1	2.0	2.0		87.1	97.9	99.3	114.3
TX1	1	1	2.446			2.378	13.4	2.8	1.5	13.6	79.4	1.6	0.7	2.606	86.6	97.2	98.5	111.8
TX1	1	1	2.446			2.392	12.5	2.2	1.0	13.1	83.2	1.6	0.7	2.606	87.5	97.8	99.0	111.7
TX1	1	1	2.446			2.390	12.4	2.3	0.9	13.2	82.5	1.6	0.7	2.606	87.6	97.7	99.1	112.1
TX1	1	2	2.445			2.399	12.4	1.9	0.6	12.7	85.0	1.8	0.7	2.606	87.6	98.1	99.4	110.9
TX1	1	2	2.445			2.396	12.5	2.0	0.7	12.7	84.3	1.8	0.7	2.606	87.5	98.0	99.3	111.1
TX1	1	2	2.445			2.408	12.2	1.5	0.3	12.3	87.8	1.8	0.7	2.606	87.8	98.5	99.7	111.0
TX1	1	3	2.441			2.402	12.0	1.6	0.2	12.4	87.1	1.9	0.7	2.606	88.0	98.4	99.8	110.4
TX1	1	3	2.441			2.397	12.2	1.8	0.5	12.6	85.7	1.9	0.7	2.606	87.8	98.2	99.5	110.6
TX1	1	3	2.441			2.402	12.0	1.6	0.3	12.4	87.1	1.9	0.7	2.606	88.0	98.4	99.7	109.6
TX1	1	4	2.453			2.401	12.5	2.1	1.0	12.5	83.1	1.9	0.7	2.606	87.5	97.9	99.0	110.4
TX1	1	4	2.453			2.401	12.6	2.1	1.0	12.5	83.1	1.9	0.7	2.606	87.4	97.9	99.0	110.2
TX1	1	4	2.453			2.409	12.2	1.8	0.7	12.2	85.2	1.9	0.7	2.606	87.8	98.2	99.3	112.0
TX1																		
TX1																		
TX1																		
TX1																		

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
TX1																		
TX1																		
TX1																		
TX1																		
TX1																		
TX2	1	1	2.425			2.396	10.6	1.2	0.4	8.5	85.9	2.2	2.1	2.482	89.4	98.8	99.6	111.7
TX2	1	1	2.425			2.393	11.0	1.3	0.3	8.6	84.9	2.2	2.1	2.482	89.0	98.7	99.7	101.2
TX2	1	1	2.425			2.393	10.2	1.3	0.3	8.6	84.9	2.2	2.1	2.482	89.8	98.7	99.7	111.2
TX2	1	2	2.416			2.387	10.5	1.2	0.1	8.7	86.3	2.2	2.1	2.482	89.5	98.8	99.9	111.4
TX2	1	2	2.416			2.389	10.6	1.1	0.1	8.6	87.3	2.2	2.1	2.482	89.4	98.9	99.9	111.5
TX2	1	2	2.416			2.389	10.6	1.1	0.1	8.6	87.3	2.2	2.1	2.482	89.4	98.9	99.9	111.2
TX2	1	3	2.411			2.382	10.8	1.2	0.1	8.9	86.5	2.1	2.1	2.482	89.2	98.8	99.9	111.2
TX2	1	3	2.411			2.382	10.9	1.2	0.1	8.9	86.5	2.1	2.1	2.482	89.1	98.8	99.9	111.6
TX2	1	3	2.411			2.382	10.9	1.2	0.1	8.9	86.5	2.1	2.1	2.482	89.1	98.8	99.9	111.4
TX2																		
TX2																		
TX2																		
TX2																		
TX2																		
TX2																		
TX2																		
TX2																		

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
KY	1	1	5.5	5.5			5.4	
KY	1	1	5.5	5.5			5.4	
KY	1	1	5.5	5.5			5.4	
KY	1	1	5.5	5.5			5.4	
KY	1	1	5.5	5.5			5.4	
KY	1	1	5.5	5.5			5.4	
KY	1	2	5.5	5.5			5.5	
KY	1	2	5.5	5.5			5.5	
KY	1	2	5.5	5.5			5.5	
KY	1	2	5.5	5.5			5.5	
KY	1	2	5.5	5.5			5.5	
KY	1	2	5.5	5.5			5.5	
KY	1	3	5.5	5.5			5.6	
KY	1	3	5.5	5.5			5.6	
KY	1	3	5.5	5.5			5.6	
KY	1	3	5.5	5.5			5.6	
KY	1	3	5.5	5.5			5.6	
KY	1	3	5.5	5.5			5.6	
KY	2	1	5.5	5.7			5.4	
KY	2	1	5.5	5.7			5.4	
KY	2	1	5.5	5.7			5.4	
KY	2	1	5.5	5.7			5.4	
KY	2	1	5.5	5.7			5.4	
KY	2	1	5.5	5.7			5.4	
KY	2	2	5.5	5.5			5.7	
KY	2	2	5.5	5.5			5.7	
KY	2	2	5.5	5.5			5.7	
KY	2	2	5.5	5.5			5.7	
KY	2	2	5.5	5.5			5.7	
KY	2	2	5.5	5.5			5.7	
KY	2	3	5.5	5.5			5.7	
KY	2	3	5.5	5.5			5.7	
KY	2	3	5.5	5.5			5.7	
KY	2	3	5.5	5.5			5.7	
KY	2	3	5.5	5.5			5.7	
KY	2	3	5.5	5.5			5.7	
KY	3	1	5.5	5.3			5.5	
KY	3	1	5.5	5.3			5.5	
KY	3	1	5.5	5.3			5.5	
KY	3	1	5.5	5.3			5.5	
KY	3	1	5.5	5.3			5.5	
KY	3	1	5.5	5.3			5.5	
KY	3	2	5.5	5.3			5.1	
KY	3	2	5.5	5.3			5.1	
KY	3	2	5.5	5.3			5.1	
KY	3	2	5.5	5.3			5.1	
KY	3	2	5.5	5.3			5.1	
KY	3	2	5.5	5.3			5.1	
KY	3	3	5.5	5.3			5.6	
KY	3	3	5.5	5.3			5.6	
KY	3	3	5.5	5.3			5.6	
KY	3	3	5.5	5.3			5.6	
KY	3	3	5.5	5.3			5.6	
KY	3	3	5.5	5.3			5.6	
KY	3	4	5.5	5.3			5.8	

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
KY	3	4	5.5	5.3			5.8	
KY	3	4	5.5	5.3			5.8	
KY	3	4	5.5	5.3			5.8	
KY	3	4	5.5	5.3			5.8	
KY	3	4	5.5	5.3			5.8	
KY	4	1	5.5	5.2			5.0	
KY	4	1	5.5	5.2			5.0	
KY	4	1	5.5	5.2			5.0	
KY	4	1	5.5	5.2			5.0	
KY	4	1	5.5	5.2			5.0	
KY	4	1	5.5	5.2			5.0	
KY	4	2	5.5	5.6			5.8	
KY	4	2	5.5	5.6			5.8	
KY	4	2	5.5	5.6			5.8	
KY	4	2	5.5	5.6			5.8	
KY	4	2	5.5	5.6			5.8	
KY	4	2	5.5	5.6			5.8	
KY	4	3	5.5	5.3			5.6	
KY	4	3	5.5	5.3			5.6	
KY	4	3	5.5	5.3			5.6	
KY	4	3	5.5	5.3			5.6	
KY	4	3	5.5	5.3			5.6	
KY	4	3	5.5	5.3			5.6	
KY	5	1	5.5	5.7			5.6	
KY	5	1	5.5	5.7			5.6	
KY	5	1	5.5	5.7			5.6	
KY	5	1	5.5	5.7			5.6	
KY	5	1	5.5	5.7			5.6	
KY	5	1	5.5	5.7			5.6	
KY	5	2	5.5	5.3			5.5	
KY	5	2	5.5	5.3			5.5	
KY	5	2	5.5	5.3			5.5	
KY	5	2	5.5	5.3			5.5	
KY	5	2	5.5	5.3			5.5	
KY	5	2	5.5	5.3			5.5	
MS	1	1	5.1	5.1				
MS	1	1	5.1	5.1				
MS	1	2	5.1	4.6				
MS	1	2	5.1	4.6				
MS	2	1	5.1	5.0				
MS	2	1	5.1	5.0				
MS	2	2	5.1	4.8				
MS	2	2	5.1	4.8				
MS	2	3	5.1	4.9				
MS	2	3	5.1	4.9				
MS	3	1	5.1	5.1				
MS	3	1	5.1	5.1				
VA	2	1	5.7	6.0				
VA	2	1	5.7	6.0				
VA	2	1	5.7	6.0				
VA	2	2	5.7	5.6				
VA	2	2	5.7	5.6				
VA	2	2	5.7	5.6				
VA	2	3	5.5	5.2				
VA	3	1	5.5	5.3				

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PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
VA	3	1	5.5	5.3				
VA	3	1	5.5	5.3				
VA	3	2	5.5	5.3				
VA	3	2	5.5	5.3				
VA	3	2	5.5	5.3				
VA	3	3	5.5	5.2				
VA	3	3	5.5	5.2				
VA	1	1	5.5	4.9				
VA	1	1	5.5	4.9				
VA	1	1	5.5	4.9				
VA	1	2	5.5	4.8				
VA	1	2	5.5	4.8				
VA	1	2	5.5	4.8				
VA	1	3	5.5	5.1				
VA	1	3	5.5	5.1				
VA	1	3	5.5	5.1				
VA	4	1	5.5	5.0				
VA	4	1	5.5	5.0				
VA	4	1	5.5	5.0				
VA	4	2	5.5	5.4				
VA	4	2	5.5	5.4				
VA	4	2	5.5	5.4				
VA	5	1	5.5	4.9				
VA	5	1	5.5	4.9				
VA	5	1	5.5	4.9				
VA	5	2	5.5	5.0				
VA	5	2	5.5	5.0				
VA	5	2	5.5	5.0				
VA	5	3	5.5	4.8				
VA	5	3	5.5	4.8				
VA	5	3	5.5	4.8				
FL	1	1	5.9	6.0				
FL	1	1	5.9	6.0				
FL	1	2	5.9	5.3				
FL	1	2	5.9	5.3				
FL	1	3	5.9	5.4				
FL	1	3	5.9	5.4				
FL	1	4	5.9	5.3				
FL	1	4	5.9	5.3				
TX1	1	1	5.2	5.3				
TX1	1	1	5.2	5.3				
TX1	1	1	5.2	5.3				
TX1	1	2	5.2	5.1				
TX1	1	2	5.2	5.1				
TX1	1	2	5.2	5.1				
TX1	1	3	5.2	5.0				
TX1	1	3	5.2	5.0				
TX1	1	3	5.2	5.0				
TX1	1	4	5.2	5.0				
TX1	1	4	5.2	5.0				
TX1	1	4	5.2	5.0				
TX1			5.2					
TX1			5.2					
TX1			5.2					
TX1			5.2					

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	AC_DBS	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
TX1			5.2					
TX1			5.2					
TX1			5.2					
TX1			5.2					
TX1			5.2					
TX2	1	1	5.4	5.2				
TX2	1	1	5.4	5.2				
TX2	1	1	5.4	5.2				
TX2	1	2	5.4	5.1				
TX2	1	2	5.4	5.1				
TX2	1	2	5.4	5.1				
TX2	1	3	5.4	5.1				
TX2	1	3	5.4	5.1				
TX2	1	3	5.4	5.1				
TX2			5.4					
TX2			5.4					
TX2			5.4					
TX2			5.4					
TX2			5.4					
TX2			5.4					
TX2			5.4					
TX2			5.4					

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PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	2										
KY	1	2										
KY	1	2										
KY	1	2										
KY	1	2										
KY	1	2										
KY	1	3										
KY	1	3										
KY	1	3										
KY	1	3										
KY	1	3										
KY	1	3										
KY	2	1										
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KY	3	3										
KY	3	3										
KY	3	4										

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
KY	3	4										
KY	3	4										
KY	3	4										
KY	3	4										
KY	3	4										
KY	4	1										
KY	4	1										
KY	4	1										
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KY	5	2										
KY	5	2										
KY	5	2										
KY	5	2										
KY	5	2										
KY	5	2										
MS	1	1										
MS	1	1										
MS	1	2	100.0	92.0	81.3	41.5	26.3	18.3	12.3	6.2	4.5	3.5
MS	1	2	100.0	92.0	81.3	41.5	26.3	18.3	12.3	6.2	4.5	3.5
MS	2	1	100.0	94.5	86.1	47.9	32.0	22.5	14.5	7.5	5.3	4.1
MS	2	1	100.0	94.5	86.1	47.9	32.0	22.5	14.5	7.5	5.3	4.1
MS	2	2										
MS	2	2										
MS	2	3										
MS	2	3										
MS	3	1	99.6	90.4	79.5	41.8	28.3	20.6	13.7	7.0	5.1	4.0
MS	3	1	99.6	90.4	79.5	41.8	28.3	20.6	13.7	7.0	5.1	4.0
VA	2	1	100.0	99.6	90.4	46.2	30.2	22.5	17.0	11.3	7.5	5.2
VA	2	1	100.0	99.6	90.4	46.2	30.2	22.5	17.0	11.3	7.5	5.2
VA	2	1	100.0	99.6	90.4	46.2	30.2	22.5	17.0	11.3	7.5	5.2
VA	2	2	100.0	99.7	93.1	57.1	40.5	30.7	22.8	14.7	9.7	6.8
VA	2	2	100.0	99.7	93.1	57.1	40.5	30.7	22.8	14.7	9.7	6.8
VA	2	2	100.0	99.7	93.1	57.1	40.5	30.7	22.8	14.7	9.7	6.8
VA	2	3	100.0	99.7	90.2	49.6	35.1	27.3	21.0	13.7	8.7	6.0
VA	3	1										

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
VA	3	1										
VA	3	1										
VA	3	2	100.0	99.1	90.5	51.1	33.8	25.1	18.7	12.4	8.2	5.7
VA	3	2	100.0	99.1	90.5	51.1	33.8	25.1	18.7	12.4	8.2	5.7
VA	3	2	100.0	99.1	90.5	51.1	33.8	25.1	18.7	12.4	8.2	5.7
VA	3	3	100.0	99.7	90.2	49.6	35.1	27.3	21.0	13.7	8.7	6.0
VA	3	3	100.0	99.7	90.2	49.6	35.1	27.3	21.0	13.7	8.7	6.0
VA	1	1	100.0	99.2	87.6	48.0	32.0	23.8	17.5	11.3	7.3	4.8
VA	1	1	100.0	99.2	87.6	48.0	32.0	23.8	17.5	11.3	7.3	4.8
VA	1	1	100.0	99.2	87.6	48.0	32.0	23.8	17.5	11.3	7.3	4.8
VA	1	2										
VA	1	2										
VA	1	2										
VA	1	3	100.0	99.6	89.5	53.5	34.3	25.6	18.9	11.4	6.9	4.4
VA	1	3	100.0	99.6	89.5	53.5	34.3	25.6	18.9	11.4	6.9	4.4
VA	1	3	100.0	99.6	89.5	53.5	34.3	25.6	18.9	11.4	6.9	4.4
VA	4	1	100.0	99.3	84.2	46.6	35.5	27.4	20.4	12.8	7.8	4.8
VA	4	1	100.0	99.3	84.2	46.6	35.5	27.4	20.4	12.8	7.8	4.8
VA	4	1	100.0	99.3	84.2	46.6	35.5	27.4	20.4	12.8	7.8	4.8
VA	4	2	100.0	99.3	88.9	51.0	33.6	25.4	18.8	11.4	6.9	4.1
VA	4	2	100.0	99.3	88.9	51.0	33.6	25.4	18.8	11.4	6.9	4.1
VA	4	2	100.0	99.3	88.9	51.0	33.6	25.4	18.8	11.4	6.9	4.1
VA	5	1	100.0	99.3	88.1	48.9	32.5	24.2	17.5	10.3	6.3	4.1
VA	5	1	100.0	99.3	88.1	48.9	32.5	24.2	17.5	10.3	6.3	4.1
VA	5	1	100.0	99.3	88.1	48.9	32.5	24.2	17.5	10.3	6.3	4.1
VA	5	2	100.0	99.7	91.0	54.9	34.3	25.4	18.7	11.5	7.2	4.6
VA	5	2	100.0	99.7	91.0	54.9	34.3	25.4	18.7	11.5	7.2	4.6
VA	5	2	100.0	99.7	91.0	54.9	34.3	25.4	18.7	11.5	7.2	4.6
VA	5	3	100.0	99.3	88.9	51.0	33.6	25.4	18.8	11.4	6.9	4.1
VA	5	3	100.0	99.3	88.9	51.0	33.6	25.4	18.8	11.4	6.9	4.1
VA	5	3	100.0	99.3	88.9	51.0	33.6	25.4	18.8	11.4	6.9	4.1
FL	1	1										
FL	1	1										
FL	1	2										
FL	1	2										
FL	1	3										
FL	1	3										
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TX1	1	1										
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NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
TX1												
TX1												
TX1												
TX1												
TX1												
TX2	1	1										
TX2	1	1										
TX2	1	1										
TX2	1	2										
TX2	1	2										
TX2	1	2										
TX2	1	3										
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TX2												
TX2												
TX2												
TX2												
TX2												

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	1										
KY	1	2										
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KY	3	3										
KY	3	3										
KY	3	4										

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
KY	3	4										
KY	3	4										
KY	3	4										
KY	3	4										
KY	3	4										
KY	4	1										
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MS	2	3										
MS	3	1										
MS	3	1										
VA	2	1										
VA	2	1										
VA	2	1										
VA	2	2										
VA	2	2										
VA	2	2										
VA	2	3										
VA	3	1										

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
VA	3	1										
VA	3	1										
VA	3	2										
VA	3	2										
VA	3	2										
VA	3	3										
VA	3	3										
VA	1	1										
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VA	5	3										
FL	1	1										
FL	1	1										
FL	1	2										
FL	1	2										
FL	1	3										
FL	1	3										
FL	1	4										
FL	1	4										
TX1	1	1	99.7	89.2	78.9	53.6	37.3	29.6	26.5	24.2	20.5	16.9
TX1	1	1	99.7	89.2	78.9	53.6	37.3	29.6	26.5	24.2	20.5	16.9
TX1	1	1	99.7	89.2	78.9	53.6	37.3	29.6	26.5	24.2	20.5	16.9
TX1	1	2										
TX1	1	2										
TX1	1	2										
TX1	1	3										
TX1	1	3										
TX1	1	3										
TX1	1	4										
TX1	1	4										
TX1	1	4										
TX1												
TX1												
TX1												
TX1												

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
TX1												
TX1												
TX1												
TX1												
TX1												
TX2	1	1	100.0	93.3	78.7	55.9	37.4	27.1	21.2	14.8	8.5	5.8
TX2	1	1	100.0	93.3	78.7	55.9	37.4	27.1	21.2	14.8	8.5	5.8
TX2	1	1	100.0	93.3	78.7	55.9	37.4	27.1	21.2	14.8	8.5	5.8
TX2	1	2										
TX2	1	2										
TX2	1	2										
TX2	1	3										
TX2	1	3										
TX2	1	3										
TX2												
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TX2												
TX2												
TX2												
TX2												

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
KY	1	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	24.0	15.0	8.0	6.0	4.9
KY	1	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	24.0	15.0	8.0	6.0	4.9
KY	1	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	24.0	15.0	8.0	6.0	4.9
KY	1	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	24.0	15.0	8.0	6.0	4.9
KY	1	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	24.0	15.0	8.0	6.0	4.9
KY	1	1	100.0	100.0	100.0	100.0	94.0	6.0	38.0	24.0	15.0	8.0	6.0	4.9
KY	1	2	100.0	100.0	100.0	100.0	95.0	62.0	39.0	24.0	15.0	9.0	6.0	5.4
KY	1	2	100.0	100.0	100.0	100.0	95.0	62.0	39.0	24.0	15.0	9.0	6.0	5.4
KY	1	2	100.0	100.0	100.0	100.0	95.0	62.0	39.0	24.0	15.0	9.0	6.0	5.4
KY	1	2	100.0	100.0	100.0	100.0	95.0	62.0	39.0	24.0	15.0	9.0	6.0	5.4
KY	1	2	100.0	100.0	100.0	100.0	95.0	62.0	39.0	24.0	15.0	9.0	6.0	5.4
KY	1	2	100.0	100.0	100.0	100.0	95.0	62.0	39.0	24.0	15.0	9.0	6.0	5.4
KY	1	3	100.0	100.0	100.0	100.0	94.0	61.0	37.0	25.0	17.0	9.0	6.0	5.0
KY	1	3	100.0	100.0	100.0	100.0	94.0	61.0	37.0	25.0	17.0	9.0	6.0	5.0
KY	1	3	100.0	100.0	100.0	100.0	94.0	61.0	37.0	25.0	17.0	9.0	6.0	5.0
KY	1	3	100.0	100.0	100.0	100.0	94.0	61.0	37.0	25.0	17.0	9.0	6.0	5.0
KY	1	3	100.0	100.0	100.0	100.0	94.0	61.0	37.0	25.0	17.0	9.0	6.0	5.0
KY	1	3	100.0	100.0	100.0	100.0	94.0	61.0	37.0	25.0	17.0	9.0	6.0	5.0
KY	2	1	100.0	100.0	100.0	100.0	95.0	63.0	37.0	24.0	15.0	9.0	6.0	5.3
KY	2	1	100.0	100.0	100.0	100.0	95.0	63.0	37.0	24.0	15.0	9.0	6.0	5.3
KY	2	1	100.0	100.0	100.0	100.0	95.0	63.0	37.0	24.0	15.0	9.0	6.0	5.3
KY	2	1	100.0	100.0	100.0	100.0	95.0	63.0	37.0	24.0	15.0	9.0	6.0	5.3
KY	2	1	100.0	100.0	100.0	100.0	95.0	63.0	37.0	24.0	15.0	9.0	6.0	5.3
KY	2	1	100.0	100.0	100.0	100.0	95.0	63.0	37.0	24.0	15.0	9.0	6.0	5.3
KY	2	2	100.0	100.0	100.0	100.0	94.0	59.0	36.0	24.0	16.0	9.0	6.0	4.9
KY	2	2	100.0	100.0	100.0	100.0	94.0	59.0	36.0	24.0	16.0	9.0	6.0	4.9
KY	2	2	100.0	100.0	100.0	100.0	94.0	59.0	36.0	24.0	16.0	9.0	6.0	4.9
KY	2	2	100.0	100.0	100.0	100.0	94.0	59.0	36.0	24.0	16.0	9.0	6.0	4.9
KY	2	2	100.0	100.0	100.0	100.0	94.0	59.0	36.0	24.0	16.0	9.0	6.0	4.9
KY	2	2	100.0	100.0	100.0	100.0	94.0	59.0	36.0	24.0	16.0	9.0	6.0	4.9
KY	2	3	100.0	100.0	100.0	100.0	95.0	63.0	38.0	26.0	18.0	10.0	7.0	6.1
KY	2	3	100.0	100.0	100.0	100.0	95.0	63.0	38.0	26.0	18.0	10.0	7.0	6.1
KY	2	3	100.0	100.0	100.0	100.0	95.0	63.0	38.0	26.0	18.0	10.0	7.0	6.1
KY	2	3	100.0	100.0	100.0	100.0	95.0	63.0	38.0	26.0	18.0	10.0	7.0	6.1
KY	2	3	100.0	100.0	100.0	100.0	95.0	63.0	38.0	26.0	18.0	10.0	7.0	6.1
KY	2	3	100.0	100.0	100.0	100.0	95.0	63.0	38.0	26.0	18.0	10.0	7.0	6.1
KY	3	1	100.0	100.0	100.0	100.0	93.0	59.0	37.0	26.0	18.0	10.0	7.0	5.7
KY	3	1	100.0	100.0	100.0	100.0	93.0	59.0	37.0	26.0	18.0	10.0	7.0	5.7
KY	3	1	100.0	100.0	100.0	100.0	93.0	59.0	37.0	26.0	18.0	10.0	7.0	5.7
KY	3	1	100.0	100.0	100.0	100.0	93.0	59.0	37.0	26.0	18.0	10.0	7.0	5.7
KY	3	1	100.0	100.0	100.0	100.0	93.0	59.0	37.0	26.0	18.0	10.0	7.0	5.7
KY	3	1	100.0	100.0	100.0	100.0	93.0	59.0	37.0	26.0	18.0	10.0	7.0	5.7
KY	3	2	100.0	100.0	100.0	100.0	89.0	50.0	29.0	22.0	16.0	9.0	6.0	4.3
KY	3	2	100.0	100.0	100.0	100.0	89.0	50.0	29.0	22.0	16.0	9.0	6.0	4.3
KY	3	2	100.0	100.0	100.0	100.0	89.0	50.0	29.0	22.0	16.0	9.0	6.0	4.3
KY	3	2	100.0	100.0	100.0	100.0	89.0	50.0	29.0	22.0	16.0	9.0	6.0	4.3
KY	3	2	100.0	100.0	100.0	100.0	89.0	50.0	29.0	22.0	16.0	9.0	6.0	4.3
KY	3	2	100.0	100.0	100.0	100.0	89.0	50.0	29.0	22.0	16.0	9.0	6.0	4.3
KY	3	3	100.0	100.0	100.0	100.0	94.0	57.0	35.0	25.0	18.0	11.0	7.0	5.8
KY	3	3	100.0	100.0	100.0	100.0	94.0	57.0	35.0	25.0	18.0	11.0	7.0	5.8
KY	3	3	100.0	100.0	100.0	100.0	94.0	57.0	35.0	25.0	18.0	11.0	7.0	5.8
KY	3	3	100.0	100.0	100.0	100.0	94.0	57.0	35.0	25.0	18.0	11.0	7.0	5.8
KY	3	3	100.0	100.0	100.0	100.0	94.0	57.0	35.0	25.0	18.0	11.0	7.0	5.8
KY	3	3	100.0	100.0	100.0	100.0	94.0	57.0	35.0	25.0	18.0	11.0	7.0	5.8
KY	3	4	100.0	100.0	100.0	100.0	91.0	56.0	36.0	26.0	19.0	10.0	7.0	5.1

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
KY	3	4	100.0	100.0	100.0	100.0	91.0	56.0	36.0	26.0	19.0	10.0	7.0	5.1
KY	3	4	100.0	100.0	100.0	100.0	91.0	56.0	36.0	26.0	19.0	10.0	7.0	5.1
KY	3	4	100.0	100.0	100.0	100.0	91.0	56.0	36.0	26.0	19.0	10.0	7.0	5.1
KY	3	4	100.0	100.0	100.0	100.0	91.0	56.0	36.0	26.0	19.0	10.0	7.0	5.1
KY	3	4	100.0	100.0	100.0	100.0	91.0	56.0	36.0	26.0	19.0	10.0	7.0	5.1
KY	4	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	28.0	20.0	11.0	6.0	4.8
KY	4	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	28.0	20.0	11.0	6.0	4.8
KY	4	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	28.0	20.0	11.0	6.0	4.8
KY	4	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	28.0	20.0	11.0	6.0	4.8
KY	4	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	28.0	20.0	11.0	6.0	4.8
KY	4	1	100.0	100.0	100.0	100.0	94.0	60.0	38.0	28.0	2.0	11.0	6.0	4.8
KY	4	2	100.0	100.0	100.0	100.0	95.0	66.0	37.0	25.0	17.0	10.0	6.0	4.9
KY	4	2	100.0	100.0	100.0	100.0	95.0	66.0	37.0	25.0	17.0	10.0	6.0	4.9
KY	4	2	100.0	100.0	100.0	100.0	95.0	66.0	37.0	25.0	17.0	10.0	6.0	4.9
KY	4	2	100.0	100.0	100.0	100.0	95.0	66.0	37.0	25.0	17.0	10.0	6.0	4.9
KY	4	2	100.0	100.0	100.0	100.0	95.0	66.0	37.0	25.0	17.0	10.0	6.0	4.9
KY	4	2	100.0	100.0	100.0	100.0	95.0	66.0	37.0	25.0	17.0	10.0	6.0	4.9
KY	4	3	100.0	100.0	100.0	100.0	93.0	57.0	36.0	26.0	17.0	10.0	6.0	5.1
KY	4	3	100.0	100.0	100.0	100.0	93.0	57.0	36.0	26.0	17.0	10.0	6.0	5.1
KY	4	3	100.0	100.0	100.0	100.0	93.0	57.0	36.0	26.0	17.0	10.0	6.0	5.1
KY	4	3	100.0	100.0	100.0	100.0	93.0	57.0	36.0	26.0	17.0	10.0	6.0	5.1
KY	4	3	100.0	100.0	100.0	100.0	93.0	57.0	36.0	26.0	17.0	10.0	6.0	5.1
KY	4	3	100.0	100.0	100.0	100.0	93.0	57.0	36.0	26.0	17.0	10.0	6.0	5.1
KY	5	1	100.0	100.0	100.0	100.0	96.0	69.0	43.0	30.0	22.0	13.0	8.0	5.8
KY	5	1	100.0	100.0	100.0	100.0	96.0	69.0	43.0	30.0	22.0	13.0	8.0	5.8
KY	5	1	100.0	100.0	100.0	100.0	96.0	69.0	43.0	30.0	22.0	13.0	8.0	5.8
KY	5	1	100.0	100.0	100.0	100.0	96.0	69.0	43.0	30.0	22.0	13.0	8.0	5.8
KY	5	1	100.0	100.0	100.0	100.0	96.0	69.0	43.0	30.0	22.0	13.0	8.0	5.8
KY	5	1	100.0	100.0	100.0	100.0	96.0	69.0	43.0	30.0	22.0	13.0	8.0	5.8
KY	5	2	100.0	100.0	100.0	100.0	94.0	62.0	40.0	29.0	21.0	13.0	9.0	6.6
KY	5	2	100.0	100.0	100.0	100.0	94.0	62.0	40.0	29.0	21.0	13.0	9.0	6.6
KY	5	2	100.0	100.0	100.0	100.0	94.0	62.0	40.0	29.0	21.0	13.0	9.0	6.6
KY	5	2	100.0	100.0	100.0	100.0	94.0	62.0	40.0	29.0	21.0	13.0	9.0	6.6
KY	5	2	100.0	100.0	100.0	100.0	94.0	62.0	40.0	29.0	21.0	13.0	9.0	6.6
KY	5	2	100.0	100.0	100.0	100.0	94.0	62.0	40.0	29.0	21.0	13.0	9.0	6.6
MS	1	1	100.0	100.0	100.0	91.9	76.8	42.8	30.6	24.0	16.8	8.5	6.2	4.9
MS	1	1	100.0	100.0	100.0	91.9	76.8	42.8	30.6	24.0	16.8	8.5	6.2	4.9
MS	1	2	100.0	100.0	100.0	93.2	82.4	50.8	34.4	25.2	17.8	11.7	9.4	7.5
MS	1	2	100.0	100.0	100.0	93.2	82.4	50.8	34.4	25.2	17.8	11.7	9.4	7.5
MS	2	1	100.0	100.0	100.0	90.6	79.5	45.5	31.5	23.5	15.7	8.2	6.0	4.7
MS	2	1	100.0	100.0	100.0	90.6	79.5	45.5	31.5	23.5	15.7	8.2	6.0	4.7
MS	2	2	100.0	100.0	100.0	86.4	73.8	42.3	29.4	22.6	15.8	8.1	5.9	4.6
MS	2	2	100.0	100.0	100.0	86.4	73.8	42.3	29.4	22.6	15.8	8.1	5.9	4.6
MS	2	3	100.0	100.0	100.0	90.8	79.6	45.2	30.4	23.0	15.8	8.6	6.5	5.1
MS	2	3	100.0	100.0	100.0	90.8	79.6	45.2	30.4	23.0	15.8	8.6	6.5	5.1
MS	3	1	100.0	100.0	100.0	90.2	77.8	44.4	30.6	23.5	16.6	8.6	6.3	4.9
MS	3	1	100.0	100.0	100.0	90.2	77.8	44.4	30.6	23.5	16.6	8.6	6.3	4.9
VA	2	1	100.0	100.0	100.0	99.6	90.8	53.1	35.8	26.4	19.8	13.5	9.1	6.3
VA	2	1	100.0	100.0	100.0	99.6	90.8	53.1	35.8	26.4	19.8	13.5	9.1	6.3
VA	2	1	100.0	100.0	100.0	99.6	90.8	53.1	35.8	26.4	19.8	13.5	9.1	6.3
VA	2	2	100.0	100.0	100.0	99.6	93.8	55.3	39.8	30.5	23.0	15.4	10.3	7.0
VA	2	2	100.0	100.0	100.0	99.6	93.8	55.3	39.8	30.5	23.0	15.4	10.3	7.0
VA	2	2	100.0	100.0	100.0	99.6	93.8	55.3	39.8	30.5	23.0	15.4	10.3	7.0
VA	2	3	100.0	100.0	100.0	99.7	92.0	50.7	34.3	26.3	20.5	14.2	9.6	6.6
VA	3	1	100.0	100.0	100.0	99.9	92.1	50.5	35.2	26.9	20.6	14.0	9.3	6.3

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
VA	3	1	100.0	100.0	100.0	99.9	92.1	50.5	35.2	26.9	20.6	14.0	9.3	6.3
VA	3	1	100.0	100.0	100.0	99.9	92.1	50.5	35.2	26.9	20.6	14.0	9.3	6.3
VA	3	2	100.0	100.0	100.0	99.8	92.3	53.8	36.5	27.1	20.5	13.9	9.4	6.5
VA	3	2	100.0	100.0	100.0	99.8	92.3	53.8	36.5	27.1	20.5	13.9	9.4	6.5
VA	3	2	100.0	100.0	100.0	99.8	92.3	53.8	36.5	27.1	20.5	13.9	9.4	6.5
VA	3	3	100.0	100.0	100.0	99.7	92.0	50.7	34.3	26.3	20.5	14.2	9.6	6.6
VA	3	3	100.0	100.0	100.0	99.7	92.0	50.7	34.3	26.3	20.5	14.2	9.6	6.6
VA	1	1	100.0	100.0	100.0	99.5	88.6	49.1	33.0	24.7	18.3	11.9	7.7	5.0
VA	1	1	100.0	100.0	100.0	99.5	88.6	49.1	33.0	24.7	18.3	11.9	7.7	5.0
VA	1	1	100.0	100.0	100.0	99.5	88.6	49.1	33.0	24.7	18.3	11.9	7.7	5.0
VA	1	2	100.0	100.0	100.0	99.6	88.2	48.9	32.0	24.1	18.1	11.7	7.6	5.0
VA	1	2	100.0	100.0	100.0	99.6	88.2	48.9	32.0	24.1	18.1	11.7	7.6	5.0
VA	1	2	100.0	100.0	100.0	99.6	88.2	48.9	32.0	24.1	18.1	11.7	7.6	5.0
VA	1	3	100.0	100.0	100.0	99.6	90.3	51.8	33.8	25.2	19.0	12.6	8.3	5.5
VA	1	3	100.0	100.0	100.0	99.6	90.3	51.8	33.8	25.2	19.0	12.6	8.3	5.5
VA	1	3	100.0	100.0	100.0	99.6	90.3	51.8	33.8	25.2	19.0	12.6	8.3	5.5
VA	4	1	100.0	100.0	100.0	98.9	86.6	49.4	35.8	27.5	20.9	13.9	9.1	6.0
VA	4	1	100.0	100.0	100.0	98.9	86.6	49.4	35.8	27.5	20.9	13.9	9.1	6.0
VA	4	1	100.0	100.0	100.0	98.9	86.6	49.4	35.8	27.5	20.9	13.9	9.1	6.0
VA	4	2	100.0	100.0	100.0	99.9	88.3	48.1	33.3	25.9	19.7	12.8	8.1	5.3
VA	4	2	100.0	100.0	100.0	99.9	88.3	48.1	33.3	25.9	19.7	12.8	8.1	5.3
VA	4	2	100.0	100.0	100.0	99.9	88.3	48.1	33.3	25.9	19.7	12.8	8.1	5.3
VA	5	1	100.0	100.0	100.0	99.8	85.0	45.6	31.2	23.6	17.9	11.7	7.7	5.1
VA	5	1	100.0	100.0	100.0	99.8	85.0	45.6	31.2	23.6	17.9	11.7	7.7	5.1
VA	5	1	100.0	100.0	100.0	99.8	85.0	45.6	31.2	23.6	17.9	11.7	7.7	5.1
VA	5	2	100.0	100.0	100.0	99.9	89.5	50.2	32.5	24.2	18.3	12.2	8.2	5.6
VA	5	2	100.0	100.0	100.0	99.9	89.5	50.2	32.5	24.2	18.3	12.2	8.2	5.6
VA	5	2	100.0	100.0	100.0	99.9	89.5	50.2	32.5	24.2	18.3	12.2	8.2	5.6
VA	5	3	100.0	100.0	100.0	99.2	89.0	46.7	29.7	22.6	17.1	11.4	7.6	5.2
VA	5	3	100.0	100.0	100.0	99.2	89.0	46.7	29.7	22.6	17.1	11.4	7.6	5.2
VA	5	3	100.0	100.0	100.0	99.2	89.0	46.7	29.7	22.6	17.1	11.4	7.6	5.2
FL	1	1	100.0	100.0	99.5	94.9	85.2	48.7	32.3	25.4	20.5	16.1	10.1	6.8
FL	1	1	100.0	100.0	99.5	94.9	85.2	48.7	32.3	25.4	20.5	16.1	10.1	6.8
FL	1	2	100.0	100.0	99.3	92.4	81.4	43.7	29.6	23.3	18.8	14.9	9.6	6.6
FL	1	2	100.0	100.0	99.3	92.4	81.4	43.7	29.6	23.3	18.8	14.9	9.6	6.6
FL	1	3	100.0	100.0	99.4	92.3	82.1	46.8	31.3	24.6	19.8	15.7	10.2	6.9
FL	1	3	100.0	100.0	99.4	92.3	82.1	46.8	31.3	24.6	19.8	15.7	10.2	6.9
FL	1	4	100.0	100.0	100.0	92.6	83.0	46.6	30.7	24.1	19.5	15.4	10.0	6.8
FL	1	4	100.0	100.0	100.0	92.6	83.0	46.6	30.7	24.1	19.5	15.4	10.0	6.8
TX1	1	1	100.0	100.0	100.0	93.4	85.9	61.9	39.2	24.6	17.2	12.4	9.5	7.5
TX1	1	1	100.0	100.0	100.0	93.4	85.9	61.9	39.2	24.6	17.2	12.4	9.5	7.5
TX1	1	1	100.0	100.0	100.0	93.4	85.9	61.9	39.2	24.6	17.2	12.4	9.5	7.5
TX1	1	2	100.0	100.0	100.0	92.0	81.7	54.5	34.6	22.9	16.8	12.9	10.4	8.1
TX1	1	2	100.0	100.0	100.0	92.0	81.7	54.5	34.6	22.9	16.8	12.9	10.4	8.1
TX1	1	2	100.0	100.0	100.0	92.0	81.7	54.5	34.6	22.9	16.8	12.9	10.4	8.1
TX1	1	3	100.0	100.0	100.0	93.1	82.7	55.8	35.4	23.1	16.8	12.7	10.1	8.2
TX1	1	3	100.0	100.0	100.0	93.1	82.7	55.8	35.4	23.1	16.8	12.7	10.1	8.2
TX1	1	3	100.0	100.0	100.0	93.1	82.7	55.8	35.4	23.1	16.8	12.7	10.1	8.2
TX1	1	4	100.0	100.0	100.0	92.1	81.4	55.1	34.9	22.8	16.5	12.4	9.8	8.0
TX1	1	4	100.0	100.0	100.0	92.1	81.4	55.1	34.9	22.8	16.5	12.4	9.8	8.0
TX1	1	4	100.0	100.0	100.0	92.1	81.4	55.1	34.9	22.8	16.5	12.4	9.8	8.0
TX1														
TX1														
TX1														
TX1														

NCHRP Project 9-7: Field Data for Projects Constructed in 1994

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
TX1														
TX1														
TX1														
TX1														
TX1														
TX2	1	1	100.0	100.0	100.0	93.9	79.9	54.9	35.1	25.0	19.9	14.6	9.5	6.9
TX2	1	1	100.0	100.0	100.0	93.9	79.9	54.9	35.1	25.0	19.9	14.6	9.5	6.9
TX2	1	1	100.0	100.0	100.0	93.9	79.9	54.9	35.1	25.0	19.9	14.6	9.5	6.9
TX2	1	2	100.0	100.0	100.0	92.5	78.2	54.6	34.6	24.7	19.6	14.2	9.1	6.6
TX2	1	2	100.0	100.0	100.0	92.5	78.2	54.6	34.6	24.7	19.6	14.2	9.1	6.6
TX2	1	2	100.0	100.0	100.0	92.5	78.2	54.6	34.6	24.7	19.6	14.2	9.1	6.6
TX2	1	3	100.0	100.0	100.0	92.5	78.8	52.3	33.2	24.0	19.1	13.9	9.0	6.4
TX2	1	3	100.0	100.0	100.0	92.5	78.8	52.3	33.2	24.0	19.1	13.9	9.0	6.4
TX2	1	3	100.0	100.0	100.0	92.5	78.8	52.3	33.2	24.0	19.1	13.9	9.0	6.4
TX2														
TX2														
TX2														
TX2														
TX2														
TX2														
TX2														
TX2														

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Mix Design Laboratory Samples - Low Asphalt Content

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi

No Samples Molded With Low Asphalt Content

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi

No Samples Molded With Low Asphalt Content

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi

No Samples Molded With Low Asphalt Content

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi

No Samples Molded With Low Asphalt Content

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi

No Samples Molded With Low Asphalt Content

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi

No Samples Molded With Low Asphalt Content

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Mix Design Laboratory Samples - Medium Asphalt Content

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	50.09	0.000083	600187	14.64	580689	151739
5	100	44.36	0.000081	549192	13.76	533422	130663
2	20	40.48	0.000083	487969	15.25	470783	128362
1	20	39.18	0.000091	428759	17.68	408510	130207
0.5	10	36.82	0.000096	381785	18.94	361118	123909
0.2	10	30.67	0.000098	313596	22.45	289823	119771
0.1	7	25.68	0.000097	265321	25.21	240057	112996
0.05	4	21.04	0.000096	218903	28.64	192111	104938
0.02	4	15.48	0.000095	163399	33.2	136728	89470
0.01	4	12.04	0.000094	128440	36.79	102864	76914

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	30.82	0.000045	687117	16.01	660478	189470
5	100	58.16	0.000088	660788	12.16	645963	139186
2	20	46.93	0.000084	561193	15	542071	145246
1	20	44.11	0.00009	490776	18.01	466731	151734
0.5	10	40.15	0.000095	421430	18.69	399212	135029
0.2	10	33.58	0.000095	351849	22.01	326207	131860
0.1	7	28.31	0.000095	297658	24.84	270114	125054
0.05	4	23.22	0.000095	244576	27.58	216775	113253
0.02	4	17.61	0.000094	186528	30.79	160230	95494
0.01	4	14.4	0.000095	151452	33.84	125796	84339

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	11.04	0.000064	172319	39.64	132689	109943
5	100	9.4	0.000074	126733	41.99	94194	84786
2	20	7.97	0.000093	85319	45.03	60294	60365
1	20	5.93	0.000095	62110	47.76	41752	45982
0.5	10	4.1	0.000093	43870	49.52	28480	33369
0.2	10	2.55	0.000093	27253	50.95	17171	21163
0.1	7	1.82	0.000094	19397	51.51	12072	15183
0.05	4	1.2	0.000094	12773	50.43	8137	9845
0.02	4	0.8	0.000092	8695	48.48	5764	6510
0.01	4	0.66	0.000092	7204	41.26	5415	4751

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	16.62	0.000047	357140	27.15	317782	162984
5	100	21.75	0.000077	284177	28.41	249943	135221
2	20	18.11	0.000085	212716	32.12	180162	113091
1	20	15.79	0.000095	166321	34.78	136602	94883
0.5	10	12.46	0.000098	127388	37.93	100483	78301
0.2	10	8.57	0.000097	88248	41.32	66273	58271
0.1	7	6.09	0.000094	64605	44.02	46456	44895
0.05	4	4.46	0.000096	46423	46.18	32141	33496
0.02	4	2.78	0.000096	29012	46.98	19793	21212
0.01	4	1.95	0.000095	20593	48.6	13619	15447

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	7.37	0.000102	72457	57.8	38615	61309
5	100	5.14	0.000098	52457	58.79	27184	44864
2	20	3.5	0.000099	35230	52.1	21640	27800
1	20	2.47	0.000096	25803	53.43	15373	20724
0.5	10	1.76	0.000091	19320	48.86	12709	14551
0.2	10	1.05	0.000082	12764	43.41	9273	8771
0.1	7	0.89	0.000084	10605	38.53	8296	6606
0.05	4	0.77	0.000083	9287	32.29	7851	4961
0.02	4	0.93	0.000083	11220	24.42	10216	4638
0.01	4	0.9	0.000086	10531	24.8	9560	4418

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	6.29	0.000099	63751	55.77	35858	52710
5	100	4.47	0.000097	46184	56	25826	38289
2	20	2.93	0.000092	31863	57.77	16994	26953
1	20	2.06	0.000084	24595	57.01	13390	20630
0.5	10	1.51	0.000088	17274	50.79	10921	13384
0.2	10	0.93	0.000083	11300	43.36	8215	7759
0.1	7	0.75	0.000081	9225	38	7269	5680
0.05	4	0.69	0.000083	8294	33.89	6885	4625
0.02	4	0.56	0.00008	6944	31.46	5924	3624
0.01	4	0.54	0.000076	7077	21.82	6570	2631

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Mix Design Laboratory Samples - High Asphalt Content

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	26.69	0.000045	590714	19.3	557532	195194
5	100	43.27	0.000082	528090	18.72	500154	169484
2	20	36.66	0.000082	448236	20.93	418674	160086
1	20	34.84	0.00009	386972	23.24	355584	152667
0.5	10	31.45	0.000097	325517	25.42	293998	139738
0.2	10	24.61	0.000098	252127	30.27	217757	127083
0.1	7	19.39	0.000096	201418	33.85	167281	112190
0.05	4	15.03	0.000097	155344	37.82	122714	95252
0.02	4	10.11	0.000094	107282	42.35	79285	72273
0.01	4	7.72	0.000094	82167	46.1	56973	59207

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	22.96	0.000042	542425	13.94	526459	130638
5	100	41.48	0.000082	506135	13.13	492912	114933
2	20	38.14	0.000084	451536	12.98	439996	101432
1	20	36.89	0.000089	412776	14.47	399681	103147
0.5	10	36.2	0.000096	376667	15.12	363619	98281
0.2	10	31.58	0.000097	326861	17.05	312490	95856
0.1	7	27.95	0.000097	289253	19.18	273195	95035
0.05	4	24.28	0.000096	251738	21.84	233666	93660
0.02	4	19.44	0.000096	202983	24.42	184824	83919
0.01	4	16.11	0.000095	169384	26.52	151562	75630

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	13.16	0.000042	312164	35.52	254087	181345
5	100	17.42	0.000074	236938	36.9	189473	142266
2	20	13.71	0.000085	160677	39.64	123729	102510
1	20	10.67	0.000092	116547	44.53	83084	81733
0.5	10	8.07	0.000097	83087	48.49	55071	62215
0.2	10	4.85	0.000093	52319	51.85	32317	41145
0.1	7	3.34	0.000095	35289	53.86	20813	28498
0.05	4	2.24	0.000095	23515	55.98	13157	19489
0.02	4	1.3	0.000094	13810	56.29	7664	11488
0.01	4	0.9	0.000095	9565	58.04	5063	8115

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	10.87	0.00003	362114	23.27	332664	143043
5	100	22.71	0.000076	297977	24.63	270874	124169
2	20	19.28	0.000081	236800	27.27	210489	108482
1	20	18.17	0.000093	194901	28.82	170758	93958
0.5	10	15.44	0.000098	158112	31.68	134549	83043
0.2	10	11.06	0.000096	115079	36.09	92995	67788
0.1	7	8.34	0.000096	86762	38.71	67707	54254
0.05	4	6.12	0.000095	64396	41.77	48026	42900
0.02	4	4.01	0.000096	41890	45.34	29447	29794
0.01	4	2.81	0.000094	29929	46.13	20743	21575

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	6.04	0.000103	58679	57.71	31343	49607
5	100	4.14	0.0001	41453	56.35	22970	34507
2	20	2.89	0.000096	30083	54.38	17518	24455
1	20	2.11	0.00009	23334	54.53	13541	19003
0.5	10	1.61	0.000089	18193	52.02	11195	14340
0.2	10	1.11	0.000087	12832	40.62	9740	8354
0.1	7	1.01	0.000086	11688	33.02	9800	6370
0.05	4	0.96	0.000087	11119	29.51	9677	5477
0.02	4	1.02	0.000086	11980	15.09	11567	3119
0.01	4	0.94	0.000079	11854	26.48	10611	5285

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	4.5	0.000084	53651	60.6	26337	46742
5	100	2.78	0.000072	38532	55.39	21888	31712
2	20	1.91	0.000062	30924	64.54	13296	27920
1	20	1.02	0.000039	26325	52.42	16053	20864
0.5	10	1.17	0.000089	13127	73.96	3627	12615
0.2	10	1.06	0.000091	11652	53.9	6866	9414
0.1	7	1	0.000095	10487	54.39	6106	8526
0.05	4	0.95	0.000095	9970	45.44	6995	7104
0.02	4	0.91	0.000091	10075	33.38	8413	5543
0.01	4	0.98	0.00009	10839	30.53	9336	5507

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Plant Field Samples - Truck #1 Mix #1

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	24.8	0.000036	690454	18.15	656089	215114
5	100	63.46	0.000093	681877	14.08	661379	165935
2	20	51.46	0.000088	588017	11.07	577067	112952
1	20	44.24	0.00009	493182	17.08	471426	144865
0.5	10	40.36	0.000095	425205	19.97	399643	145207
0.2	10	33.45	0.000096	348607	23.25	320288	137633
0.1	7	28.49	0.000096	296949	25.72	267522	128884
0.05	4	23.37	0.000095	246153	27.64	218069	114180
0.02	4	17.73	0.000094	187761	30.87	161163	96337
0.01	4	14.3	0.000093	153395	33.07	128552	83692

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	22.8	0.00008	285830	31.2	244477	148087
5	100	16.58	0.000071	233603	31.45	199283	121889
2	20	14.78	0.000086	171924	35.32	140287	99385
1	20	12.52	0.000096	130269	38.2	102375	80557
0.5	10	9.59	0.000097	99117	41.46	74276	65631
0.2	10	6.57	0.000098	67141	44.77	47665	47285
0.1	7	4.58	0.000092	49582	46.61	34062	36030
0.05	4	3.37	0.000095	35633	47.64	24007	26332
0.02	4	2.17	0.000095	22951	47.83	15406	17011
0.01	4	1.57	0.000094	16687	46.72	11441	12148

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	22.8	0.00008	285830	31.2	244477	148087
5	100	16.58	0.000071	233603	31.45	199283	121889
2	20	14.78	0.000086	171924	35.32	140287	99385
1	20	12.52	0.000096	130269	38.2	102375	80557
0.5	10	9.59	0.000097	99117	41.46	74276	65631
0.2	10	6.57	0.000098	67141	44.77	47665	47285
0.1	7	4.58	0.000092	49582	46.61	34062	36030
0.05	4	3.37	0.000095	35633	47.64	24007	26332
0.02	4	2.17	0.000095	22951	47.83	15406	17011
0.01	4	1.57	0.000094	16687	46.72	11441	12148

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	19.66	0.00008	246050	31.26	210330	127679
5	100	14.2	0.00007	201972	31.87	171532	106628
2	20	12.66	0.000085	148998	34.54	122729	84488
1	20	10.93	0.000095	115093	37.09	91812	69405
0.5	10	8.7	0.000097	89439	40.2	68311	57732
0.2	10	5.91	0.000097	61083	43.88	44029	42340
0.1	7	4.28	0.000093	46018	45.15	32454	32625
0.05	4	3.16	0.000096	33041	46.67	22671	24036
0.02	4	2.1	0.000095	22145	46.63	15208	16097
0.01	4	1.56	0.000094	16533	47.28	11216	12147

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	4.86	0.000098	49352	54.98	28322	40416
5	100	3.57	0.000098	36431	55.64	20561	30075
2	20	2.26	0.000097	23353	53.72	13820	18824
1	20	1.66	0.000098	17023	49.17	11130	12881
0.5	10	1.27	0.000097	13066	44.6	9304	9174
0.2	10	0.92	0.000095	9614	36.41	7737	5707
0.1	7	0.78	0.000096	8142	35.83	6601	4766
0.05	4	0.71	0.000096	7378	28.72	6470	3546
0.02	4	0.69	0.000096	7124	31.2	6094	3691
0.01	4	0.62	0.000095	6516	28.69	5716	3129

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	4.18	0.000099	42220	55.44	23947	34772
5	100	3.21	0.0001	32027	54.12	18773	25948
2	20	1.98	0.000099	20119	50.99	12665	15632
1	20	1.45	0.000097	14865	48.46	9857	11127
0.5	10	1.09	0.000095	11458	43.36	8331	7867
0.2	10	0.82	0.000096	8549	39.97	6552	5492
0.1	7	0.64	0.000095	6703	36.76	5370	4011
0.05	4	0.51	0.000096	5328	23.89	4872	2158
0.02	4	0.52	0.000095	5503	24.74	4998	2303
0.01	4	0.51	0.000095	5369	22.34	4966	2040

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Plant Field Samples - Truck #2 Mix #1

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	30.14	0.000043	703658	14.92	679933	181177
5	100	60.32	0.000087	693322	11.43	679561	137447
2	20	52.29	0.000085	616526	10.01	607144	107148
1	20	51.26	0.000091	560880	12.48	547626	121214
0.5	10	47.03	0.000095	497226	15.02	480244	128837
0.2	10	41.13	0.000097	423485	18.22	402264	132376
0.1	7	35.66	0.000096	371011	19.98	348675	126788
0.05	4	30.17	0.000096	314457	22.71	290083	121388
0.02	4	23.88	0.000096	249809	25.39	225688	107096
0.01	4	19.48	0.000095	205888	27.41	182779	94771

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	31.42	0.000041	763623	15.89	734451	209051
5	100	70.98	0.000092	773860	16.28	742847	216882
2	20	60.32	0.000087	690645	12.75	673612	152437
1	20	55.33	0.000089	620346	12.02	606749	129170
0.5	10	49.99	0.000094	532317	17	509061	155625
0.2	10	42.08	0.000097	434756	20.42	407434	151691
0.1	7	35.82	0.000096	373397	23.18	343255	146972
0.05	4	29.69	0.000095	312728	25.34	282628	133867
0.02	4	22.63	0.000095	239294	28.74	209814	115065
0.01	4	18.11	0.000094	191812	31.06	164314	98958

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	20.81	0.000076	275536	30.61	237133	140314
5	100	15.54	0.000069	223735	31.86	190036	118083
2	20	14.72	0.000092	160725	35.97	130078	94404
1	20	12.16	0.000098	124542	38.31	97724	77205
0.5	10	9.41	0.000099	95433	41.85	71085	63674
0.2	10	6.34	0.000098	64894	44.79	46057	45717
0.1	7	4.56	0.000096	47295	46.35	32645	34221
0.05	4	3.27	0.000095	34493	47.23	23421	25323
0.02	4	2.15	0.000096	22341	47.3	15152	16418
0.01	4	1.59	0.000095	16779	44.26	12018	11709

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	21.61	0.000075	289988	29.25	253020	141683
5	100	16.14	0.000067	239891	31.35	204875	124797
2	20	15.31	0.000088	173635	34.55	143007	98479
1	20	13.3	0.000098	135982	37.18	108342	82177
0.5	10	10.17	0.000097	105098	40.64	79749	68451
0.2	10	6.93	0.000097	71127	44.75	50516	50072
0.1	7	5.03	0.000097	51942	47.22	35279	38123
0.05	4	3.53	0.000096	36645	49.11	23988	27702
0.02	4	2.27	0.000095	24006	50.31	15330	18473
0.01	4	1.63	0.000094	17292	48.31	11500	12914

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	4.21	0.000096	43971	53.94	25882	35547
5	100	2.92	0.000094	30909	53.66	18314	24899
2	20	1.93	0.000098	19819	49.58	12851	15088
1	20	1.5	0.000097	15483	45.64	10825	11070
0.5	10	1.2	0.000097	12358	42.03	9179	8274
0.2	10	0.97	0.000095	10166	36.81	8139	6092
0.1	7	0.8	0.000097	8237	33.16	6896	4506
0.05	4	0.7	0.000096	7239	31.4	6179	3772
0.02	4	0.65	0.000095	6818	28.32	6002	3235
0.01	4	0.61	0.000096	6374	26.58	5700	2852

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	4.7	0.000099	47530	59.42	24180	40920
5	100	3.43	0.000099	34766	55.69	19595	28718
2	20	2.08	0.000097	21397	52.34	13072	16940
1	20	1.59	0.000098	16273	48.78	10723	12241
0.5	10	1.23	0.000097	12735	44.35	9107	8902
0.2	10	0.92	0.000097	9568	36.66	7675	5713
0.1	7	0.81	0.000097	8394	35.58	6827	4884
0.05	4	0.71	0.000096	7401	30.19	6397	3722
0.02	4	0.65	0.000095	6820	30.15	5897	3426
0.01	4	0.6	0.000094	6344	28.96	5551	3072

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Plant Field Samples - Truck #3 Mix #1

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	32.55	0.00004	821410	14.42	795517	204614
5	100	77.57	0.000089	872941	16.54	836803	248571
2	20	71.16	0.000089	802405	13.16	781320	182736
1	20	64.01	0.00009	709628	10.17	698486	125261
0.5	10	61.27	0.000093	660684	7.15	655547	82229
0.2	10	52.44	0.000097	538995	12.37	526490	115432
0.1	7	45.05	0.000097	464706	15.71	447357	125790
0.05	4	38.65	0.000097	400054	18.45	379494	126598
0.02	4	31.13	0.000096	325656	20.89	304254	116112
0.01	4	26.39	0.000095	277546	23.17	255167	109186

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	9.73	0.000013	721278	17.35	688472	215056
5	100	46.28	0.000081	570696	15.71	549373	154542
2	20	43.24	0.000084	516005	15.56	497099	138399
1	20	42.49	0.00009	474606	16.5	455064	134787
0.5	10	40.66	0.000095	428358	17.27	409057	127135
0.2	10	35.37	0.000097	366142	19.43	345300	121770
0.1	7	31.08	0.000097	320611	21.64	298006	118253
0.05	4	26.51	0.000096	277295	23.95	253417	112573
0.02	4	21.02	0.000094	222636	26.95	198460	100899
0.01	4	17.71	0.000095	186918	28.76	163859	89936

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	30.4	0.000079	384394	26.1	345206	169091
5	100	24.3	0.000073	332091	26.52	297145	148287
2	20	22.73	0.000089	255843	28.92	223934	123730
1	20	19.84	0.000097	205040	31.07	175620	105825
0.5	10	16.06	0.000098	163648	33.28	136802	89810
0.2	10	11.67	0.000098	118951	36.37	95780	70538
0.1	7	8.84	0.000096	91693	38.16	72098	56652
0.05	4	6.66	0.000096	69578	39.18	53932	43960
0.02	4	4.62	0.000094	48895	40.9	36956	32016
0.01	4	3.55	0.000095	37220	42.05	27638	24929

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	30.01	0.000081	369252	24.21	336778	151419
5	100	23.83	0.000076	315460	24.83	286292	132483
2	20	21.75	0.000087	249981	26.75	223235	112501
1	20	19.02	0.000093	204027	29.52	177543	100526
0.5	10	15.84	0.000096	165122	32.21	139706	88019
0.2	10	11.47	0.000096	119799	35.87	97085	70188
0.1	7	8.68	0.000093	92939	38.43	72810	57762
0.05	4	6.82	0.000097	70187	40.18	53627	45281
0.02	4	4.62	0.000095	48721	41.98	36217	32590
0.01	4	3.52	0.000095	36899	40.59	28021	24007

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	10.97	0.000094	116818	46.52	80390	84759
5	100	8.91	0.000099	89900	47.67	60538	66462
2	20	5.81	0.000097	59759	51.11	37521	46511
1	20	4.33	0.000099	43652	52.32	26682	34549
0.5	10	3.13	0.000099	31718	52.67	19232	25222
0.2	10	2.06	0.000097	21271	51.58	13220	16665
0.1	7	1.56	0.000097	16026	49.16	10481	12123
0.05	4	1.16	0.000097	11928	48.8	7857	8975
0.02	4	0.88	0.000097	9118	45.56	6384	6510
0.01	4	0.71	0.000096	7472	46.33	5159	5405

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	8.85	0.0001	88086	51.25	55130	68701
5	100	6.4	0.000098	65101	52.76	39395	51828
2	20	4.24	0.000098	43048	54.39	25064	34998
1	20	3.06	0.000099	31044	54.64	17965	25318
0.5	10	2.2	0.000098	22533	53.64	13359	18146
0.2	10	1.53	0.000096	15858	49.65	10267	12085
0.1	7	1.15	0.000097	11875	47.24	8063	8718
0.05	4	0.98	0.000097	10116	43.13	7383	6916
0.02	4	0.81	0.000097	8339	36.07	6740	4910
0.01	4	0.74	0.000096	7678	34.37	6337	4334

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Plant Field Samples - Truck #4 Mix #1

TX11FLD1
4C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	28.51	0.000037	768467	15.87	739170	210163
5	100	64.61	0.000093	696731	14.23	675346	171295
2	20	60.1	0.000092	652879	14.38	632429	162123
1	20	54.32	0.000094	580444	15.24	560038	152554
0.5	10	48.6	0.000096	508316	17.25	485440	150775
0.2	10	41.15	0.000097	424394	20.77	396817	150487
0.1	7	35.08	0.000097	360527	23.6	330365	144356
0.05	4	28.95	0.000096	301803	26.41	270305	134239
0.02	4	21.87	0.000093	234128	29.95	202868	116878
0.01	4	17.94	0.000094	190732	32.54	160782	102606

TX11FLD2
4C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	31.18	0.000044	711320	14.36	689110	176362
5	100	66.82	0.000092	729873	13.73	709011	173255
2	20	58.96	0.000089	659747	10.52	648651	120490
1	20	53.95	0.000092	586037	11.04	575198	112188
0.5	10	48.96	0.000094	522276	13.1	508693	118337
0.2	10	43.02	0.000098	440712	16.82	421863	127510
0.1	7	36.62	0.000095	385785	18.71	365405	123732
0.05	4	32	0.000096	332358	21.16	309947	119976
0.02	4	25.5	0.000095	267627	24.2	244115	109692
0.01	4	21.45	0.000095	225205	26.51	201528	100518

TX11FLE1
20C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	34.43	0.000081	427176	24.4	389025	176464
5	100	27.94	0.000075	373159	24.81	338722	156573
2	20	27.28	0.000092	295801	27.04	263470	134468
1	20	24.15	0.000099	244380	30.22	211158	123020
0.5	10	19.13	0.000098	194923	34.12	161374	109331
0.2	10	13.87	0.000098	141300	38.67	110315	88296
0.1	7	10.18	0.000096	105973	42.61	77998	71740
0.05	4	7.47	0.000097	76634	45.42	53788	54585
0.02	4	4.75	0.000097	49101	49.27	32041	37205
0.01	4	3.19	0.000094	33808	49.13	22124	25564

TX11FLE2
20C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	25.56	0.000079	323264	27.4	286999	148765
5	100	19.99	0.000073	273121	28.69	239589	131119
2	20	18.21	0.000089	205349	31.28	175502	106616
1	20	15.98	0.000098	163396	34.17	135188	91775
0.5	10	12.66	0.000099	127258	37.81	100545	78007
0.2	10	8.61	0.000097	88482	42.21	65536	59449
0.1	7	6.33	0.000097	65414	45.43	45905	46601
0.05	4	4.56	0.000097	46804	48.05	31285	34811
0.02	4	2.93	0.000097	30214	50.17	19351	23204
0.01	4	2.04	0.000094	21630	50.88	13647	16781

TX11FLF1
40C - Replicate #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	7	0.0001	69875	45.6	48885	49928
5	100	5.35	0.000099	53800	46.44	37076	38984
2	20	3.84	0.000099	38790	46.43	26735	28106
1	20	2.88	0.000099	29110	47.54	19652	21475
0.5	10	2.18	0.000098	22154	46.09	15365	15960
0.2	10	1.55	0.000098	15812	42.58	11642	10699
0.1	7	1.21	0.000098	12373	39.88	9496	7933
0.05	4	1.02	0.000097	10561	37.49	8380	6428
0.02	4	0.84	0.000097	8682	33.52	7239	4794
0.01	4	0.76	0.000096	7982	28.08	7043	3757

TX11FLF2
40C - Replicate #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	6.71	0.0001	67264	51.63	41755	52735
5	100	4.84	0.000099	49050	51.8	30332	38547
2	20	3.3	0.000099	33375	51.25	20889	26029
1	20	2.39	0.000099	24164	49.95	15549	18497
0.5	10	1.81	0.000098	18465	47.47	12482	13607
0.2	10	1.31	0.000097	13452	42.19	9968	9033
0.1	7	1.04	0.000096	10836	40.1	8288	6981
0.05	4	0.87	0.000096	9113	36.03	7370	5361
0.02	4	0.78	0.000095	8135	29.69	7067	4029
0.01	4	0.71	0.000095	7484	27.77	6622	3487

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Extracted Roadway Cores - Cores 1 & 2

TX11FLD1
4C - Core #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	42.53	0.000079	537227	16.35	515502	151229
5	100	40.14	0.000079	507058	15	489785	131219
2	20	37.88	0.000084	452759	15.72	435819	122688
1	20	36.5	0.000088	412579	16.57	395443	117672
0.5	10	34.34	0.000092	371275	18.52	352053	117913
0.2	10	29.51	0.000095	311235	21.63	289320	114724
0.1	7	25.01	0.000094	266453	24.7	242068	111356
0.05	4	20.66	0.000094	220461	28.14	194406	103968
0.02	4	15.28	0.000092	165543	32.82	139117	89728
0.01	4	11.69	0.000092	126861	36.91	101432	76193

TX11FLD2
4C - Core #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	41.53	0.000081	513416	11.74	502668	104502
5	100	36.73	0.000076	480282	13.73	466565	113967
2	20	33.58	0.000081	413224	16.93	395323	120307
1	20	32.63	0.00009	363651	17.04	347687	106563
0.5	10	31	0.000092	335194	18.1	318615	104112
0.2	10	27.24	0.000094	288795	21.15	269342	104199
0.1	7	23.01	0.000092	251317	24.03	229531	102352
0.05	4	19.82	0.000093	212653	27.73	188231	98947
0.02	4	14.87	0.000091	163027	32.59	137351	87821
0.01	4	11.9	0.000092	130011	35.32	106086	75158

TX11FLB1
20C - Core #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	16.94	0.000078	216999	33.98	179944	121279
5	100	12.8	0.000073	174695	35.46	142287	101356
2	20	10.69	0.000088	120847	40.34	92118	78219
1	20	8.39	0.000092	91202	44.06	65538	63423
0.5	10	5.93	0.000091	65269	48.11	43580	48588
0.2	10	3.68	0.000094	39311	52.97	23676	31381
0.1	7	2.43	0.000092	26517	55.41	15053	21830
0.05	4	1.57	0.000092	17158	56.6	9444	14325
0.02	4	0.93	0.000092	10168	57.29	5494	8556
0.01	4	0.61	0.00009	6723	50.92	4238	5220

TX11FLB2
20C - Core #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	16.74	0.000073	228775	35.9	185319	134145
5	100	14.96	0.000085	175003	37.1	139576	105568
2	20	11.33	0.000092	123050	41.86	91641	82117
1	20	8.13	0.000091	89383	44.88	63335	63071
0.5	10	5.82	0.000092	63586	47.07	43312	46554
0.2	10	3.64	0.000091	39982	47.76	26875	29602
0.1	7	2.61	0.000092	28462	47.76	19134	21071
0.05	4	1.92	0.000092	20859	46.69	14308	15179
0.02	4	1.27	0.000091	13883	41.78	10353	9250
0.01	4	0.97	0.00009	10701	36.72	8577	6399

TX11FLF1
40C - Core #1

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	3.19	0.00009	35405	60.31	17534	30758
5	100	2.29	0.000092	24739	56.65	13600	20665
2	20	1.58	0.000093	16895	49.52	10968	12851
1	20	1.25	0.000094	13288	44.83	9424	9368
0.5	10	1.02	0.000092	11143	39.03	8657	7017
0.2	10	0.85	0.000093	9136	32.73	7685	4940
0.1	7	0.76	0.000092	8254	31.04	7072	4256
0.05	4	0.71	0.000092	7690	29.25	6710	3757
0.02	4	0.64	0.000092	6921	24.95	6275	2920
0.01	4	0.63	0.00009	6997	24.14	6385	2861

TX11FLF2
40C - Core #2

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	2.81	0.000091	31020	58.59	16165	26474
5	100	1.97	0.000092	21395	55.38	12154	17607
2	20	1.23	0.000092	13420	50.07	8614	10291
1	20	0.96	0.00009	10625	42.96	7775	7241
0.5	10	0.77	0.000091	8539	37.12	6809	5153
0.2	10	0.63	0.000089	7021	33.44	5859	3869
0.1	7	0.58	0.00009	6437	30	5575	3218
0.05	4	0.51	0.000089	5714	28.04	5044	2686
0.02	4	0.49	0.00009	5510	25.9	4957	2407
0.01	4	0.5	0.00009	5599	25.98	5033	2453

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Extracted Roadway Cores - Cores 3 & 4

TX11FLD1
4C - Core #3

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	29.13	0.000078	374128	16.24	359204	104614
5	100	25.63	0.000071	363281	15.62	349871	97795
2	20	25.47	0.000079	323372	14.82	312609	82735
1	20	27.05	0.000089	303281	14.78	293243	77381
0.5	10	25.52	0.000091	280437	15.56	270164	75208
0.2	10	22.59	0.000093	243855	18.05	231850	75571
0.1	7	19.89	0.000092	215532	20.1	202403	74075
0.05	4	17.07	0.000092	184930	23.33	169809	73240
0.02	4	13.36	0.000091	147082	27.58	130371	68093
0.01	4	10.95	0.000092	119127	31.07	102035	61484

TX11FLD2
4C - Core #4

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	32.68	0.000079	412232	14.14	399739	100718
5	100	27.91	0.000072	387990	14.18	376167	95050
2	20	28.22	0.000081	349028	14.52	337881	87504
1	20	28.87	0.000088	327422	14.47	317031	81833
0.5	10	27.81	0.000092	301762	16.32	289606	84786
0.2	10	24.49	0.000094	260677	19.16	246239	85550
0.1	7	21.3	0.000093	229205	21.83	212764	85243
0.05	4	17.88	0.000092	194017	24.79	176133	81361
0.02	4	13.89	0.000093	150049	30.34	129502	75789
0.01	4	11.03	0.000092	120474	33.63	100306	66728

TX11FLE1
20C - Core #3

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	12.07	0.000074	163123	29.71	141686	80834
5	100	11.06	0.000084	131814	31.93	111875	69705
2	20	9.61	0.000094	102463	36.05	82846	60293
1	20	7.33	0.000092	79695	39.96	61087	51183
0.5	10	5.47	0.000093	58762	44.07	42219	40872
0.2	10	3.5	0.000093	37602	48.38	24978	28108
0.1	7	2.38	0.000092	25937	50.78	16400	20094
0.05	4	1.67	0.000091	18305	51.29	11447	14284
0.02	4	1	0.000091	10963	50.16	7024	8417
0.01	4	0.73	0.000091	8028	46.73	5503	5846

TX11FLE2
20C - Core #4

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	14.5	0.000082	177223	32.22	149939	94479
5	100	9.79	0.000069	141213	33.79	117358	78538
2	20	8.65	0.000086	101062	37.06	80648	60904
1	20	6.65	0.00009	74117	44.38	52971	51840
0.5	10	5.04	0.000093	54350	47.46	36746	40046
0.2	10	3.07	0.000092	33264	52.8	20111	26496
0.1	7	2.05	0.000092	22211	54.66	12847	18119
0.05	4	1.36	0.000093	14614	56.08	8155	12127
0.02	4	0.83	0.000093	8925	53.84	5266	7206
0.01	4	0.49	0.000092	5292	52.26	3239	4185

TX11FLF1
40C - Core #3

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	2.49	0.000086	29084	61.47	13890	25553
5	100	1.93	0.000092	21002	55.38	11931	17284
2	20	1.28	0.000093	13761	51.79	8512	10813
1	20	0.99	0.000094	10576	44.9	7491	7465
0.5	10	0.81	0.000091	8885	40.56	6750	5777
0.2	10	0.67	0.00009	7385	35.18	6036	4255
0.1	7	0.61	0.000092	6636	30.11	5740	3330
0.05	4	0.54	0.000092	5894	27.37	5235	2709
0.02	4	0.5	0.000089	5581	27.47	4952	2575
0.01	4	0.5	0.00009	5524	25.78	4975	2402

TX11FLF2
40C - Core #4

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	2.61	0.000095	27400	61.26	13173	24026
5	100	1.65	0.000093	17825	59.12	9148	15298
2	20	1	0.000094	10672	55.82	5995	8829
1	20	0.69	0.000093	7446	51.74	4611	5847
0.5	10	0.49	0.000091	5411	47.08	3685	3962
0.2	10	0.39	0.000089	4338	44.54	3092	3043
0.1	7	0.38	0.000091	4128	37.32	3283	2502
0.05	4	0.33	0.000093	3589	33.48	2993	1980
0.02	4	0.3	0.000092	3233	27.02	2880	1469
0.01	4	0.3	0.000091	3315	26.72	2961	1491

NCHRP Project 9-7
Project: FM 1604 Texas
Performance Data: Complex Modulus from the SST Frequency Sweep at Constant Height Test
Extracted Roadway Cores - Cores 5 & 6

TX11FLD1
4C - Core #5

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	30.91	0.00008	388619	14.53	376192	97493
5	100	26.11	0.000073	359297	13.99	348633	86890
2	20	26.82	0.000082	326257	14.27	316196	80395
1	20	27.43	0.000091	301459	14.13	292341	73580
0.5	10	26.41	0.000096	275770	15.76	265403	74903
0.2	10	22.7	0.000096	236106	18.04	224495	73130
0.1	7	20.1	0.000097	206611	20.63	193358	72806
0.05	4	16.98	0.000096	177686	23.46	163004	70726
0.02	4	13.15	0.000094	139849	27.38	124184	64314
0.01	4	10.66	0.000094	113778	29.88	98651	56687

TX11FLD2
4C - Core #6

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	25.71	0.000078	329274	15.76	316897	89431
5	100	23.11	0.000076	304014	13.39	295753	70387
2	20	21.73	0.00008	271843	14.83	262785	69591
1	20	21.61	0.000087	247182	15.79	237851	67275
0.5	10	20.74	0.000094	221493	16.98	211843	64666
0.2	10	17.95	0.000095	187957	19.98	176641	64231
0.1	7	15.38	0.000095	161740	22.65	149261	62298
0.05	4	12.63	0.000093	136281	25.42	123083	58507
0.02	4	9.69	0.000093	104531	29.5	90981	51471
0.01	4	7.78	0.000094	82752	32.54	69759	44515

TX11FLE1
20C - Core #5

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	12.21	0.000066	185502	31.42	158296	96712
5	100	10.72	0.000072	148673	33.46	124029	81977
2	20	9.11	0.000086	106416	37	84983	64048
1	20	7.33	0.000091	80736	41.23	60723	53207
0.5	10	5.6	0.000096	58203	43.97	41891	40408
0.2	10	3.55	0.000094	37684	46.93	25733	27529
0.1	7	2.53	0.000095	26476	47.76	17797	19603
0.05	4	1.8	0.000095	19008	47.57	12825	14030
0.02	4	1.21	0.000094	12824	45.84	8933	9201
0.01	4	0.89	0.000093	9644	44.28	6905	6734

TX11FLE2
20C - Core #6

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	12.09	0.000073	164774	34.67	135509	93743
5	100	8.99	0.000069	129477	35.79	105027	75722
2	20	7.94	0.000089	89287	42.23	66115	60009
1	20	5.84	0.00009	64594	44.73	45886	45463
0.5	10	4.29	0.000093	46225	47.44	31266	34047
0.2	10	2.68	0.000093	28823	49.29	18797	21850
0.1	7	1.84	0.000092	20073	49.62	13004	15291
0.05	4	1.29	0.000093	13938	47.6	9399	10292
0.02	4	0.8	0.000091	8782	46.91	5999	6413
0.01	4	0.61	0.000092	6627	43.24	4828	4540

TX11FLF1
40C - Core #5

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	2.46	0.000096	25590	59.38	13033	22023
5	100	1.78	0.000098	18262	55.98	10218	15136
2	20	1.11	0.000098	11314	52.3	6919	8951
1	20	0.83	0.000098	8452	48.61	5589	6341
0.5	10	0.63	0.000097	6535	44.03	4698	4542
0.2	10	0.51	0.000095	5340	39.4	4126	3390
0.1	7	0.43	0.000095	4508	33.63	3754	2497
0.05	4	0.37	0.000095	3827	32.11	3242	2034
0.02	4	0.34	0.000094	3621	27.71	3206	1684
0.01	4	0.33	0.000094	3474	29.95	3010	1735

TX11FLF2
40C - Core #6

Frequency	Period	Amp._shr._stress	Amp._shear_strain	Comp._shr._mod.	Shr._phase_angle	Stor._shr._mod.	Loss_shear_mod.
Hz	none	psi	none	psi	none	psi	psi
10	100	1.85	0.000094	19699	59.82	9902	17030
5	100	1.19	0.000089	13389	58.16	7064	11374
2	20	0.81	0.000093	8728	50.85	5510	6769
1	20	0.62	0.000092	6686	46.92	4567	4883
0.5	10	0.5	0.000094	5367	41.52	4019	3558
0.2	10	0.39	0.000092	4218	36.62	3385	2516
0.1	7	0.31	0.00009	3498	34.82	2871	1997
0.05	4	0.29	0.000091	3196	31.36	2729	1663
0.02	4	0.29	0.000091	3152	26.07	2831	1385
0.01	4	0.27	0.00009	2943	26.4	2636	1309

PROJECT AND POOLED STANDARD DEVIATIONS

(1994)

NCHRP Project 9-7: Standard Deviations Computed from Projects Constructed in 1994

1994 Projects	# of Samples	Gmm	Gmb	Calculated Gse	Air Voids @ Nini	Air Voids @ Ndes	Air Voids @ Nmax	VMA	VFA	Dust/AC Ratio	AC Absorption	%AC Extracted	%AC Nuc Gauge	%AC Ignition
FL	8	0.006	0.014	-	1.1	0.8	0.4	0.4	7.5	0.1	0.1	0.31	-	-
KY	90	0.009	0.016	-	1.2	0.8	0.6	0.6	6.4	0.1	0.1	0.15	0.22	-
MS	12	0.005	0.013	-	0.4	0.4	0.4	0.4	2.2	0.3	0.0	0.19	-	-
TX1	21	0.005	0.008	-	0.4	0.4	0.4	0.4	2.4	0.1	0.0	0.13	-	-
TX2	17	0.006	0.005	-	0.2	0.1	0.1	0.1	0.9	0.0	0.0	0.05	-	-
VA	39	0.016	0.029	-	1.5	1.5	1.4	1.4	8.6	0.1	0.0	0.34	-	-
Pooled Standard Deviation		0.010	0.018	0.000	1.1	0.9	0.8	0.8	6.3	0.1	0.1	0.21	0.22	0.00

1994 Projects	# of Samples	Cold Feed 19.0mm	Cold Feed 12.5mm	Cold Feed 9.5mm	Cold Feed 4.75mm	Cold Feed 2.36mm	Cold Feed 1.18mm	Cold Feed 0.600mm	Cold Feed 0.300mm	Cold Feed 0.150mm	Cold Feed 0.075mm
FL	8	-	-	-	-	-	-	-	-	-	-
KY	90	-	-	-	-	-	-	-	-	-	-
MS	12	0.2	1.8	3.1	3.2	2.6	1.9	1.0	0.6	0.4	0.3
TX1	21	-	-	-	-	-	-	-	-	-	-
TX2	17	-	-	-	-	-	-	-	-	-	-
VA	39	0.0	0.2	2.2	3.3	2.5	2.1	1.7	1.2	0.9	0.9
Pooled Standard Deviation		0.1	0.9	2.4	3.3	2.5	2.1	1.5	1.1	0.8	0.8

1994 Projects	# of Samples	Hot Bin 19.0mm	Hot Bin 12.5mm	Hot Bin 9.5mm	Hot Bin 4.75mm	Hot Bin 2.36mm	Hot Bin 1.18mm	Hot Bin 0.600mm	Hot Bin 0.300mm	Hot Bin 0.150mm	Hot Bin 0.075mm
FL	8	-	-	-	-	-	-	-	-	-	-
KY	90	-	-	-	-	-	-	-	-	-	-
MS	12	-	-	-	-	-	-	-	-	-	-
TX1	21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TX2	17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VA	39										
Pooled Standard Deviation		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1994 Projects	# of Samples	Extracted 37.5mm	Extracted 25.0mm	Extracted 19.0mm	Extracted 12.5mm	Extracted 9.5mm	Extracted 4.75mm	Extracted 2.36mm	Extracted 1.18mm	Extracted 0.600mm	Extracted 0.300mm	Extracted 0.150mm	Extracted 0.075mm
FL	8	0.0	0.0	0.3	1.1	1.5	1.9	1.0	0.8	0.7	0.5	0.2	0.1
KY	90	0.0	0.0	0.0	0.0	1.7	7.2	2.9	2.0	2.7	1.4	0.9	0.6
MS	12	0.0	0.0	0.0	2.2	2.8	2.9	1.6	0.9	0.8	1.3	1.3	1.0
TX1	21	0.0	0.0	0.0	0.6	1.9	3.1	1.9	0.8	0.3	0.2	0.4	0.3
TX2	17	0.0	0.0	0.0	0.7	0.7	1.2	0.9	0.4	0.4	0.3	0.2	0.2
VA	39	0.0	0.0	0.0	0.3	2.4	2.7	2.5	2.0	1.6	1.2	0.9	0.7
Pooled Standard Deviation		0.0	0.0	0.1	0.7	1.9	5.4	2.5	1.7	2.0	1.2	0.8	0.6

APPENDIX E

SUMMARY OF INFORMATION FOR PROJECTS CONSTRUCTED IN 1995

Appendix E is not published herein in its complete form as submitted by the research agency but is available for loan on request to the NCHRP.

The following sections have been selected from Appendix E for publication:

Project Data—1995 Projects

Project and Pooled Standard Deviations (1995)

PROJECT DATA

1995 PROJECTS

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
KS	1	1	1	1	25-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	1	1	2	25-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	2	2	1	25-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	2	2	2	25-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	3	3	1	25-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	3	3	2	25-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	1	4	1	26-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	1	4	2	26-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	1	5	1	27-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	1	5	2	27-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	2	6	1	27-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
KS	1	2	6	2	27-Apr-95	TAI	P	F	N	DRUM		S	PG76-28
MD1	1	1	1	1	11-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	1	1	1	2	11-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	1	2	2	1	11-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	1	2	2	2	11-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	1	3	3	1	11-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	1	3	3	2	11-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	1	4	1	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	1	4	2	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	1	1	1	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	1	1	2	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	2	5	1	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	2	5	2	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	2	2	1	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	2	2	2	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	3	6	1	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	3	6	2	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	3	3	1	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	3	3	2	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	4	7	1	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	4	7	2	12-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	2	4	4	1	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	2	4	4	2	12-Jul-95	AAT	F	F	N	BATCH		S	PG70-22
MD1	3	1	8	1	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	1	8	2	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	2	9	1	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	2	9	2	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	3	10	1	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	3	10	2	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	4	11	1	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
MD1	3	4	11	2	13-Jul-95	TAI	P	F	N	BATCH		S	PG70-22
AL1	1	1	1	1	19-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	1	1	1	2	19-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	1	2	2	1	19-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	1	2	2	2	19-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	2	1	3	1	24-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	2	1	3	2	24-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	2	2	4	1	24-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	2	2	4	2	24-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	2	3	5	1	24-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	2	3	5	2	24-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	3	1	6	1	25-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	3	1	6	2	25-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	3	2	7	1	25-Jul-95	AAT	F	F	N	DRUM		B	PG76-22

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
AL1	3	2	7	2	25-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	3	3	8	1	25-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	3	3	8	2	25-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	4	1	9	1	26-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	4	1	9	2	26-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	4	2	10	1	26-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	4	2	10	2	26-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	4	3	11	1	26-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	4	3	11	2	26-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	5	1	12	1	27-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	5	1	12	2	27-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	5	2	13	1	27-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	5	2	13	2	27-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	5	3	14	1	27-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL1	5	3	14	2	27-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	6	1	15	1	28-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	6	1	15	2	28-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	6	2	16	1	28-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	6	2	16	2	28-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	6	3	17	1	28-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	6	3	17	2	28-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	7	1	18	1	31-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	7	1	18	2	31-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	7	2	19	1	31-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	7	2	19	2	31-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	7	3	20	1	31-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	7	3	20	2	31-Jul-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	1	21	1	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	1	21	2	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	2	22	1	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	2	22	2	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	3	23	1	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	3	23	2	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	4	24	1	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	8	4	24	2	01-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	9	1	25	1	02-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	9	1	25	2	02-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	9	2	26	1	02-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	9	2	26	2	02-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	10	1	27	1	03-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
AL2	10	1	27	2	03-Aug-95	AAT	F	F	N	DRUM		B	PG76-22
GA	1	1	1	1	18-Aug-95	AAT	F	F	N	DRUM		S	PG64-22
GA	1	1	1	2	18-Aug-95	AAT	F	F	N	DRUM		S	PG64-22
GA	1	2	2	1	18-Aug-95	AAT	F	F	N	DRUM		S	PG64-22
GA	1	2	2	2	18-Aug-95	AAT	F	F	N	DRUM		S	PG64-22
GA	1	3	3	1	18-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
GA	1	3	3	2	18-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
GA	1	4	4	1	18-Aug-95	AAT	F	F	N	DRUM		S	PG64-22
GA	1	4	4	2	18-Aug-95	AAT	F	F	N	DRUM		S	PG64-22
MD2	1	1	1	1	22-Aug-95	TAI	P	F	Y	DRUM		S	PG64-22
MD2	1	1	1	2	22-Aug-95	TAI	P	F	Y	DRUM		S	PG64-22
MD2	1	1	1*	1	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	1	1	1	2	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	2	1	2	1	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	2	1	2	2	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22

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PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
MD2	2	2	3	1	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	2	2	3	2	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	2	2	2	1	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	2	2	2	2	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	2	3	4	1	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	2	3	4	2	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	2	4	5	1	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	2	4	5	2	23-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	3	3	1	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	3	3	3	2	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	4	4	4	1	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	4	4	4	2	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	5	5	5	1	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	5	5	5	2	23-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	3	1	6	1	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	1	6	2	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	2	7	1	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	2	7	2	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	3	8	1	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	3	8	2	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	4	9	1	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	3	4	9	2	24-Aug-95	TAI	P	F	N	DRUM		S	PG64-22
MD2	6	6	6	1	24-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
MD2	6	6	6	2	24-Aug-95	AAT	F	F	Y	DRUM		S	PG64-22
KY2	1	1	1	1	25-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	1	1	1	2	25-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	1	2	2	1	25-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	1	2	2	2	25-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	1	3	3	1	25-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	1	3	3	2	25-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	2	1	4	1	26-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	2	1	4	2	26-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	2	2	5	1	26-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	2	2	5	2	26-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	2	3	6	1	26-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	2	3	6	2	26-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	3	1	7	1	30-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	3	1	7	2	30-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	3	2	8	1	30-Oct-95	TAI	T	F	Y	DRUM		S	PG70-22
KY2	3	2	8	2	30-Oct-95	TAI	T	F	Y	DRUM		S	PG70-22
KY2	4	1	9	1	31-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	4	1	9	2	31-Oct-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	5	1	10	1	01-Nov-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	5	1	10	2	01-Nov-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	5	2	11	1	01-Nov-95	TAI	T	F	N	DRUM		S	PG70-22
KY2	5	2	11	2	01-Nov-95	TAI	T	F	N	DRUM		S	PG70-22
TX3	1	1	1	1	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	1	1	2	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	2	2	1	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	2	2	2	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	3	3	1	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	3	3	2	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	4	4	1	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	1	4	4	2	26-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	1	5	1	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22

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PROJ	LOT	SUBLOT	SAMPLEN	REPLICAT	PAVDATE	LAB	YRATOR	MIX	REHEATE	PLANT	TONNAGE	URF_BIN	BINDER
TX3	2	1	5	2	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	2	6	1	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	2	6	2	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	3	7	1	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	3	7	2	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	4	8	1	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22
TX3	2	4	8	2	27-Dec-95	AAT	F	F	Y	NA		S	PG70-22

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PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
KS	1	1	2.362			2.373	9.5	0.1	-0.3	13.4	99.3	1.0			90.5	99.9	100.3	113.0
KS	1	1	2.372			2.380	9.7	-0.2	-0.5	13.1	101.5				90.3	100.2	100.5	112.5
KS	1	2	2.379			2.380	11.8	0.4	0.0	13.1	97.3	0.9			88.2	99.6	100.0	113.2
KS	1	2	2.381			2.380	11.4	0.4	0.0	13.2	96.7				88.6	99.6	100.0	112.9
KS	1	3	2.382			2.391	11.8	0.1	-0.3	12.8	99.2	1.0			88.2	99.9	100.3	112.9
KS	1	3	2.384			2.378	11.5	0.6	0.2	13.2	95.8				88.5	99.4	99.8	113.3
KS	1	1	2.385			2.401	11.9	-0.1	-0.6	12.6	100.8	1.0			88.1	100.1	100.6	112.8
KS	1	1	2.388			2.393	12.4	0.3	-0.3	13.0	97.5				87.6	99.7	100.3	112.8
KS	1	1	2.389			2.395	13.3	1.0	-0.2	13.1	92.2	1.1			86.7	99.0	100.2	112.5
KS	1	1	2.391			2.385	12.7	1.1	0.2	13.2	91.8				87.3	98.9	99.8	113.0
KS	1	2	2.390			2.393	12.5	0.6	0.0	12.6	95.4	1.1			87.5	99.4	100.0	112.7
KS	1	2	2.394			2.391	12.9	0.8	0.0	12.8	93.5				87.1	99.2	100.0	113.0
MD1	1	1	2.643			2.559	14.6	4.4	3.2	18.1	75.9	1.5			85.4	95.6	96.8	112.1
MD1	1	1				2.551	15.0	4.8	3.5	18.5	74.3				85.0	95.2	96.5	112.4
MD1	1	2	2.635			2.588	13.9	3.0	1.8	18.2	83.6				86.1	97.0	98.2	113.0
MD1	1	2				2.584	13.7	3.1	1.9	18.4	82.9				86.3	96.9	98.1	113.2
MD1	1	3	2.649			2.587	14.3	3.6	2.3	18.2	80.0				85.7	96.4	97.7	112.1
MD1	1	3				2.582	14.3	3.7	2.5	18.2	79.7				85.7	96.3	97.5	113.8
MD1	2	1	2.632			2.567	15.0	3.9	2.5	17.9	78.3				85.0	96.1	97.5	114.3
MD1	2	1				2.576	14.3	3.4	2.1	17.5	80.5				85.7	96.6	97.9	113.0
MD1	2	1	2.652	2.635	2.668	2.475	16.0	6.7	5.4	18.8	64.6	1.2	0.4	2.883	84.0	93.3	94.6	112.0
MD1	2	1	2.652	2.635	2.668	2.473	16.1	6.8	5.5	18.9	64.2	1.2	0.4	2.883	83.9	93.2	94.5	114.2
MD1	2	2	2.635			2.586	14.0	3.1	1.9	17.1	81.7	1.7			86.0	96.9	98.1	113.9
MD1	2	2				2.572	13.9	3.6	2.4	17.5	79.2				86.1	96.4	97.6	114.9
MD1	2	2	2.625	2.612	2.638	2.510	13.8	4.4	3.2	17.9	75.5	1.3	0.2	2.883	86.2	95.6	96.8	111.8
MD1	2	2	2.625	2.612	2.638	2.510	14.2	4.4	3.1	17.9	75.5	1.3	0.2	2.883	85.8	95.6	96.9	111.4
MD1	2	3	2.639			2.550	15.1	4.6	3.4	18.3	74.9	1.5			84.9	95.4	96.6	116.7
MD1	2	3				2.538	14.9	5.0	3.8	18.7	73.0				85.1	95.0	96.2	116.9
MD1	2	3	2.637	2.630	2.643	2.524	13.6	4.3	2.9	17.6	75.8	1.3	0.5	2.883	86.4	95.7	97.1	111.0
MD1	2	3	2.637	2.630	2.643	2.526	13.6	4.2	2.9	17.6	76.1	1.5	0.5	2.883	86.4	95.8	97.1	111.8
MD1	2	4	2.640			2.592	14.0	3.1	1.8	17.7	82.5	1.5			86.0	96.9	98.2	113.1
MD1	2	4				2.591	13.7	3.2	1.9	17.8	81.9				86.3	96.8	98.1	112.6
MD1	2	4	2.652	2.654	2.650	2.534	14.1	4.4	3.2	17.0	73.9	1.3	0.6	2.883	85.9	95.6	96.8	111.0
MD1	2	4	2.652	2.654	2.650	2.520	14.4	5.0	3.5	17.5	71.5	0.8	0.6	2.883	85.6	95.0	96.5	110.8
MD1	3	1				2.531												117.7
MD1	3	1				2.548												116.3
MD1	3	2				2.584						1.6						113.7
MD1	3	2				2.584												114.0
MD1	3	3				2.554												115.4
MD1	3	3				2.533												116.3
MD1	3	4				2.578						1.5						113.5
MD1	3	4				2.573												114.6
AL1	1	1	2.502	2.497	2.507	2.398	11.3	4.1	3.2	15.7	73.5	1.0	0.5	2.692	88.7	95.9	96.8	112.4
AL1	1	1	2.502	2.497	2.507	2.433	10.0	2.8	1.7	14.5	80.9	1.3	0.5	2.692	90.0	97.2	98.3	111.2
AL1	1	2	2.484	2.488	2.480	2.460	8.2	1.0	0.2	13.9	93.1	1.2	0.5	2.692	91.8	99.0	99.8	110.0
AL1	1	2	2.484	2.488	2.480	2.457	7.1	1.1	0.7	14.0	92.2	1.2	0.5	2.692	92.9	98.9	99.3	110.7
AL1	2	1	2.539	2.539	2.539	2.445	11.4	3.7	2.8	13.6	72.8	1.1	0.8	2.692	88.6	96.3	97.2	111.3
AL1	2	1	2.539	2.539	2.539	2.419	12.9	4.7	3.6	14.5	67.5	1.3	0.8	2.692	87.1	95.3	96.4	113.8
AL1	2	2	2.524	2.517	2.531	2.450	10.4	2.9	1.9	13.4	78.1	0.8	0.5	2.692	89.6	97.1	98.1	111.1
AL1	2	2	2.524	2.517	2.531	2.449	10.2	3.0	2.0	13.4	77.8	1.2	0.5	2.692	89.8	97.0	98.0	111.5
AL1	2	3	2.509	2.508	2.51	2.435	11.2	2.9	1.7	14.5	79.6	1.1	0.7	2.692	88.8	97.1	98.3	113.7
AL1	2	3	2.509	2.508	2.51	2.424	10.9	3.4	2.3	14.9	77.2	1.0	0.7	2.692	89.1	96.6	97.7	111.3
AL1	3	1	2.537	2.534	2.539	2.423	11.9	4.5	3.5	13.8	67.5	0.9	0.3	2.692	88.1	95.5	96.5	111.3
AL1	3	1	2.537	2.534	2.539	2.434	11.7	4.1	2.9	13.4	69.8	1.0	0.3	2.692	88.3	95.9	97.1	112.1
AL1	3	2	2.510	2.517	2.502	2.437	10.3	2.9	1.9	14.0	79.4	1.2	0.4	2.692	89.7	97.1	98.1	112.0

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PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
AL1	3	2	2.510	2.517	2.502	2.438	10.3	2.9	1.8	14.0	79.7	1.3	0.4	2.692	89.7	97.1	98.2	111.1
AL1	3	3	2.524	2.522	2.525	2.454	10.0	2.8	1.8	13.3	79.3	1.1	0.6	2.692	90.0	97.2	98.2	110.6
AL1	3	3	2.524	2.522	2.525	2.457	10.0	2.6	1.6	13.2	80.0	1.1	0.6	2.692	90.0	97.4	98.4	110.6
AL1	4	1	2.521	2.523	2.519	2.448	10.8	2.9	1.8	13.3	78.3	1.0	0.4	2.692	89.2	97.1	98.2	112.2
AL1	4	1	2.521	2.523	2.519	2.449	10.3	2.8	1.7	13.3	78.5	1.0	0.4	2.692	89.7	97.2	98.3	111.0
AL1	4	2	2.516	2.514	2.518	2.439	10.4	3.1	2.1	14.0	78.2	1.3	0.6	2.692	89.6	96.9	97.9	111.5
AL1	4	2	2.516	2.514	2.518	2.451	10.1	2.6	1.5	13.6	81.0	1.3	0.6	2.692	89.9	97.4	98.5	111.7
AL1	4	3	2.531	2.523	2.539	2.436	10.8	3.8	2.8	13.7	72.5	1.3	0.5	2.692	89.2	96.2	97.2	111.4
AL1	4	3	2.531	2.523	2.539	2.457	10.1	2.9	2.0	12.9	77.4	1.4	0.5	2.692	89.9	97.1	98.0	110.9
AL1	5	1	2.527	2.505	2.549	2.429	11.5	3.9	2.8	14.1	72.5	1.0	0.5	2.692	88.5	96.1	97.2	111.8
AL1	5	1	2.527	2.505	2.549	2.441	11.1	3.4	2.3	13.7	75.1	1.0	0.5	2.692	88.9	96.6	97.7	112.1
AL1	5	2	2.543	2.550	2.535	2.457	11.2	3.4	2.2	13.0	74.2	0.9	0.7	2.692	88.8	96.6	97.8	111.3
AL1	5	2	2.543	2.550	2.535	2.461	11.1	3.2	2.1	12.9	75.1	1.2	0.7	2.692	88.9	96.8	97.9	111.8
AL1	5	3	2.516	2.529	2.503	2.461	9.7	2.2	1.2	12.8	83.0	0.9	0.3	2.692	90.3	97.8	98.8	110.9
AL1	5	3	2.516	2.529	2.503	2.462	9.7	2.2	1.2	12.8	83.2	1.0	0.3	2.692	90.3	97.8	98.8	110.6
AL2	6	1	2.478	2.473	2.482	2.402	11.0	3.0	1.9	15.4	80.3	0.6	0.3	2.683	89.0	97.0	98.1	112.8
AL2	6	1	2.478	2.473	2.482	2.403	11.4	3.0	1.9	15.4	80.5	0.6	0.3	2.683	88.6	97.0	98.1	112.6
AL2	6	2	2.495	2.493	2.496	2.440	10.0	2.2	1.2	14.4	84.9	0.7	0.9	2.683	90.0	97.8	98.8	110.5
AL2	6	2	2.495	2.493	2.496	2.443	10.7	2.5	1.4	14.0	85.2	0.7	0.6	2.683	89.3	97.5	98.6	112.1
AL2	6	3	2.491	2.487	2.494	2.406	11.2	3.4	2.3	15.1	77.6	0.6	0.4	2.683	88.8	96.6	97.7	112.7
AL2	6	3	2.491	2.487	2.494	2.394	12.2	3.9	2.8	15.6	75.1	0.7	0.4	2.683	87.8	96.1	97.2	112.3
AL2	7	1	2.481	2.479	2.483	2.413	9.1	2.7	1.7	15.1	81.8	0.7	0.4	2.683	90.9	97.3	98.3	112.0
AL2	7	1	2.481	2.479	2.483	2.418	10.5	2.5	1.4	14.9	83.0	0.7	0.4	2.683	89.5	97.5	98.6	111.9
AL2	7	2	2.493	2.503	2.482	2.428	9.8	2.6	1.8	14.6	82.2	0.8	0.6	2.683	90.2	97.4	98.2	111.6
AL2	7	2	2.493	2.503	2.482	2.424	10.7	2.8	1.7	14.7	81.3	0.7	0.6	2.683	89.3	97.2	98.3	111.9
AL2	7	3	2.481	2.486	2.475	2.421	9.9	2.4	1.4	14.7	83.7	0.6	0.3	2.683	90.1	97.6	98.6	111.5
AL2	7	3	2.481	2.486	2.475	2.424	10.3	2.3	1.2	14.6	84.4	0.6	0.3	2.683	89.7	97.7	98.8	112.3
AL2	8	1	2.483	2.492	2.474	2.427	9.6	2.2	1.4	14.7	84.6	0.8	0.5	2.683	90.4	97.8	98.6	111.4
AL2	8	1	2.483	2.492	2.474	2.426	10.0	2.9	1.3	14.7	84.4	0.8	0.5	2.683	90.0	97.1	98.7	111.9
AL2	8	2	2.509	2.507	2.511	2.422	10.9	3.5	2.4	14.3	75.8	0.8	0.6	2.683	89.1	96.5	97.6	112.0
AL2	8	2	2.509	2.507	2.511	2.418	11.5	3.6	2.5	14.5	75.0	0.8	0.6	2.683	88.5	96.4	97.5	112.3
AL2	8	3	2.513	2.507	2.519	2.443	10.2	2.8	1.9	13.3	79.1	0.9	0.5	2.683	89.8	97.2	98.1	111.6
AL2	8	3	2.513	2.507	2.519	2.435	10.4	3.1	2.2	13.6	77.2	0.9	0.5	2.683	89.6	96.9	97.8	111.2
AL2	8	4	2.502	2.499	2.505	2.426	10.2	3.0	2.2	13.7	77.8	0.9	0.0	2.683	89.8	97.0	97.8	112.0
AL2	8	4	2.502	2.499	2.505	2.429	10.3	2.9	2.0	13.6	78.5	0.7	0.0	2.683	89.7	97.1	98.0	111.6
AL2	9	1	2.530	2.523	2.537	2.404	12.5	5.0	3.9	14.8	66.4	0.7	0.8	2.683	87.5	95.0	96.1	112.8
AL2	9	1	2.530	2.523	2.537	2.406	12.7	4.9	3.8	14.8	66.8	0.7	0.8	2.683	87.3	95.1	96.2	112.4
AL2	9	2	2.522	2.520	2.523	2.387	12.9	5.4	4.4	15.3	65.2	0.9	0.6	2.683	87.1	94.6	95.6	114.2
AL2	9	2	2.522	2.520	2.523	2.388	12.9	5.3	4.3	15.3	65.4	0.9	0.6	2.683	87.1	94.7	95.7	114.1
AL2	10	1	2.519	2.515	2.523	2.419	11.0	3.5	2.4	14.8	76.4	0.8	1.0	2.683	89.0	96.5	97.6	112.5
AL2	10	1	2.519	2.515	2.523	2.424	11.0	3.3	2.3	14.7	77.5	0.6	1.0	2.683	89.0	96.7	97.7	111.9
GA	1	1	2.589	2.580	2.598	2.489	14.0	3.9	2.4	15.0	74.2	1.3	0.3	2.787	86.0	96.1	97.6	108.0
GA	1	1	2.589	2.580	2.598	2.494	13.9	3.7	2.2	14.8	75.2	1.3	0.3	2.787	86.1	96.3	97.8	107.6
GA	1	2	2.592	2.600	2.583	2.514	11.7	3.0	1.8	13.9	78.5	1.6	0.1	2.787	88.3	97.0	98.2	106.3
GA	1	2	2.592	2.600	2.583	2.527	11.4	2.5	1.3	13.5	81.5	1.5	0.1	2.787	88.6	97.5	98.7	105.9
GA	1	3	2.595	2.595	2.595	2.501	12.9	3.6	2.3	14.3	74.7	1.7	0.2	2.787	87.1	96.4	97.7	106.8
GA	1	3	2.595	2.595	2.595	2.511	12.5	3.2	1.9	14.0	76.9	1.7	0.2	2.787	87.5	96.8	98.1	106.8
GA	1	4	2.586	2.578	2.594	2.517	11.7	2.7	1.4	14.0	80.9	1.6	0.2	2.787	88.3	97.3	98.6	105.9
GA	1	4	2.586	2.578	2.594	2.520	11.9	2.6	1.3	13.9	81.6	1.6	0.2	2.787	88.1	97.4	98.7	106.8
MD2	1	1	2.475															
MD2	1	1																
MD2	1	1	2.467	2.471	2.462	2.382	14.2	3.4	1.7	15.9	78.5	1.2	0.2	2.678	85.8	96.6	98.3	111.2
MD2	1	1	2.467	2.471	2.462	2.398	14.2	2.8	1.2	15.4	81.9	1.1	0.2	2.678	85.8	97.2	98.8	111.2
MD2	2	1	2.477			2.449	15.1	2.8	1.1	14.6	81.1	1.4			84.9	97.2	98.9	113.1
MD2	2	1				2.446	15.2	3.0	1.3	14.8	79.9				84.8	97.0	98.7	112.7

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
MD2	2	2	2.476			2.463	14.0	1.7	0.5	13.8	87.5				86.0	98.3	99.5	115.0
MD2	2	2				2.464	14.2	1.9	0.5	14.0	86.1				85.8	98.1	99.5	114.1
MD2	2	2	2.475	2.473	2.476	2.373	15.3	4.1	2.4	16.2	74.6	1.2	0.2	2.678	84.7	95.9	97.6	117.1
MD2	2	2	2.475	2.473	2.476	2.369	15.1	4.1	2.8	16.3	73.9	1.2	0.2	2.678	84.9	95.9	97.2	114.1
MD2	2	3	2.480			2.469	13.8	1.5	0.4	13.8	89.3	1.4			86.2	98.5	99.6	114.7
MD2	2	3				2.461	14.1	2.0	0.8	14.2	86.1	1.5			85.9	98.0	99.2	114.4
MD2	2	4	2.481			2.468	14.2	2.0	0.5	13.9	85.8	1.5			85.8	98.0	99.5	114.6
MD2	2	4				2.466	14.5	2.1	0.6	14.0	85.2	1.5			85.5	97.9	99.4	113.9
MD2	3	3	2.476	2.477	2.475	2.364	15.3	4.5	2.9	16.5	72.6	1.2	0.3	2.678	84.7	95.5	97.1	115.2
MD2	3	3	2.476	2.477	2.475	2.375	15.7	4.1	2.4	16.1	74.7	1.2	0.3	2.678	84.3	95.9	97.6	112.2
MD2	4	4	2.468	2.461	2.474	2.389	19.3	3.2	1.6	15.4	79.3	1.0	0.0	2.678	80.7	96.8	98.4	111.2
MD2	4	4	2.468	2.461	2.474	2.366	14.9	4.1	2.4	16.2	74.7	1.1	0.0	2.678	85.1	95.9	97.6	112.9
MD2	5	5	2.466	2.462	2.469	2.374	15.9	3.7	2.1	16.3	77.3	1.0	0.2	2.678	84.1	96.3	97.9	111.8
MD2	5	5	2.466	2.462	2.469	2.367	15.0	4.0	2.4	16.6	75.9	1.0	0.2	2.678	85.0	96.0	97.6	113.8
MD2	3	1	2.480			2.457	14.3	2.0	0.9	14.4	85.9				85.7	98.0	99.1	115.1
MD2	3	1				2.459	14.6	2.1	0.8	14.5	85.3	1.4			85.4	97.9	99.2	115.3
MD2	3	2	2.478			2.464	14.0	1.6	0.6	13.8	88.4				86.0	98.4	99.4	113.3
MD2	3	2				2.459	14.2	1.7	0.8	13.9	87.7				85.8	98.3	99.2	114.4
MD2	3	3	2.480			2.453	15.2	2.7	1.1	14.8	81.8				84.8	97.3	98.9	115.2
MD2	3	3				2.446	15.4	3.1	1.4	15.2	79.4				84.6	96.9	98.6	115.6
MD2	3	4	2.476			2.452	14.7	2.6	1.0	14.6	82.3	1.3			85.3	97.4	99.0	115.2
MD2	3	4				2.455	14.8	2.5	0.8	14.5	83.0	1.3			85.2	97.5	99.2	115.0
MD2	6	6	2.467	2.479	2.454	2.377	15.7	3.6	1.8	16.2	77.6	1.0	0.2	2.678	84.3	96.4	98.2	111.7
MD2	6	6	2.467	2.479	2.454	2.371	15.1	3.9	2.4	16.4	76.4	1.0	0.2	2.678	84.9	96.1	97.6	112.4
KY2	1	1	2.512			2.429	15.0	4.8	3.2	14.6	67.5	1.2			85.0	95.2	96.8	112.4
KY2	1	1	2.511			2.428	15.4	4.9	3.3	14.7	66.9				84.6	95.1	96.7	112.7
KY2	1	2	2.503			2.455	13.4	3.3	1.8	13.7	76.1	1.3			86.6	96.7	98.2	114.3
KY2	1	2	2.501			2.455	13.7	3.4	1.8	13.8	75.6				86.3	96.6	98.2	114.0
KY2	1	3	2.494			2.456	13.0	2.8	1.4	13.8	79.4	1.2			87.0	97.2	98.6	115.0
KY2	1	3	2.492			2.462	13.1	2.7	1.2	13.7	80.3				86.9	97.3	98.8	114.4
KY2	2	1	2.492			2.443	13.3	3.5	2.1	14.3	75.5	1.2			86.7	96.5	97.9	115.5
KY2	2	1	2.498			2.451	13.2	3.2	1.8	14.0	77.2				86.8	96.8	98.2	114.8
KY2	2	2	2.494			2.448	13.7	3.5	2.0	14.4	75.7				86.3	96.5	98.0	115.4
KY2	2	2	2.503			2.461	13.2	2.9	1.5	13.9	78.9				86.8	97.1	98.5	114.4
KY2	2	3	2.492			2.449	12.7	3.1	1.8	14.2	78.1				87.3	96.9	98.2	114.4
KY2	2	3	2.494			2.454	12.6	2.9	1.6	14.1	79.2				87.4	97.1	98.4	114.1
KY2	3	1	2.493			2.441	13.2	3.6	2.2	14.4	75.1	1.2			86.8	96.4	97.8	116.2
KY2	3	1	2.497			2.448	13.1	3.3	1.9	14.1	76.6				86.9	96.7	98.1	115.7
KY2	3	2																
KY2	3	2																
KY2	4	1	2.505			2.425	13.1	4.7	3.3	14.6	68.0	1.3			86.9	95.3	96.7	116.3
KY2	4	1	2.509			2.436	14.3	4.3	2.8	14.3	69.8				85.7	95.7	97.2	116.2
KY2	5	1	2.504			2.427	14.3	4.4	3.0	14.6	69.9	1.3			85.7	95.6	97.0	116.5
KY2	5	1	2.501			2.427	14.3	4.5	3.0	14.7	69.5				85.7	95.5	97.0	116.2
KY2	5	2	2.504			2.434	14.0	4.3	2.8	14.9	71.3				86.0	95.7	97.2	116.1
KY2	5	2	2.503			2.433	14.0	4.3	2.8	14.9	71.1				86.0	95.7	97.2	116.0
TX3	1	1	2.460	2.457	2.462	2.373	12.6	3.6	2.2	12.7	72.3	0.7	0.5	2.599	87.4	96.4	97.8	113.9
TX3	1	1	2.460	2.457	2.462	2.371	12.6	3.6	2.2	12.8	71.9	0.7	0.5	2.599	87.4	96.4	97.8	113.9
TX3	1	2	2.460	2.460	2.459	2.387	12.8	3.0	1.6	12.3	74.7	0.7	0.4	2.599	87.21	97.04	98.41	113.25
TX3	1	2	2.460	2.460	2.459	2.388	12.7	2.9	1.5	12.2	74.9	0.6	0.4	2.599	87.27	97.08	98.5	113.05
TX3	1	3	2.462	2.460	2.463	2.370	13.3	3.7	2.3	12.7	70.8	0.7	0.5	2.599	86.7	96.3	97.7	114.2
TX3	1	3	2.462	2.460	2.463	2.367	13.4	3.9	2.5	12.9	70.1	0.7	0.5	2.599	86.6	96.1	97.6	114.2
TX3	1	4	2.469	2.467	2.471	2.351	13.8	4.8	3.4	13.4	64.3	0.6	0.6	2.599	86.2	95.2	96.6	115.4
TX3	1	4	2.469	2.467	2.471	2.348	14.2	4.9	3.5	13.5	63.7	0.6	0.6	2.599	85.8	95.1	96.5	115.1
TX3	2	1	2.465	2.467	2.463	2.383	13.2	3.3	2.0	12.2	72.7	0.7	0.5	2.599	86.9	96.7	98.0	113.3

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	GMM	GMM1	GMM2	GMB	AV Ninit	AV Ndes	AV Nmax	VMA	VFA	DUST	AC_ABS	AGGMB	DEN_NINI	DEN_NDE	EN_NMA	MAX_HEIG
TX3	2	1	2.465	2.467	2.463	2.384	13.2	3.3	1.9	12.2	73.0	0.6	0.5	2.599	86.8	96.7	98.1	113.5
TX3	2	2	2.454	2.453	2.454	2.373	13.2	3.3	1.8	12.5	73.8	0.6	0.2	2.599	86.8	96.7	98.2	113.9
TX3	2	2	2.454	2.453	2.454	2.375	13.0	3.2	1.8	12.4	74.3	0.6	0.2	2.599	87.0	96.8	98.2	113.1
TX3	2	3	2.461	2.459	2.462	2.344	14.7	4.8	2.4	13.6	65.2	0.5	0.4	2.599	85.3	95.2	97.6	115.7
TX3	2	3	2.461	2.459	2.462	2.344	14.7	4.8	3.3	13.6	65.2	0.5	0.4	2.599	85.3	95.2	96.7	115.6
TX3	2	4	2.432	2.433	2.431	2.383	11.9	2.0	0.6	12.3	83.7	0.5	0.0	2.599	88.1	98.0	99.4	113.3
TX3	2	4	2.432	2.433	2.431	2.385	12.0	1.9	0.6	12.3	84.2	0.5	0.0	2.599	88.0	98.1	99.4	113.0

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
KS	1	1	6.2	6.2				
KS	1	1	6.2					
KS	1	2	6.2	6.2				
KS	1	2	6.2					
KS	1	3	6.2	6.2				
KS	1	3	6.2					
KS	1	1	6.2	6.3				
KS	1	1	6.2					
KS	1	1	6.2	5.9				
KS	1	1	6.2					
KS	1	2	6.2	5.8				
KS	1	2	6.2					
MD1	1	1	6.3	5.6			6.6	
MD1	1	1	6.3					
MD1	1	2	6.3	6.2			6.5	
MD1	1	2	6.3					
MD1	1	3	6.3	5.9			6.3	
MD1	1	3	6.3					
MD1	2	1	6.3	5.7			6.4	
MD1	2	1	6.3					
MD1	2	1	6.3	5.4	5.4	5.4		
MD1	2	1	6.3	5.4	5.4	5.4		
MD1	2	2	6.3	5.6			6.4	
MD1	2	2	6.3					
MD1	2	2	6.3	5.7	5.8	5.6		
MD1	2	2	6.3	5.7	5.8	5.6		
MD1	2	3	6.3	5.6			6.5	
MD1	2	3	6.3					
MD1	2	3	6.3	5.9	5.7	6.1		
MD1	2	3	6.3	5.9	5.7	6.1		
MD1	2	4	6.3	5.9			6.5	
MD1	2	4	6.3					
MD1	2	4	6.3	5.6	5.7	5.5		
MD1	2	4	6.3	5.6	5.7	5.5		
MD1	3	1	6.3	5.6				
MD1	3	1	6.3					
MD1	3	2	6.3	6.0				
MD1	3	2	6.3					
MD1	3	3	6.3	5.8				
MD1	3	3	6.3					
MD1	3	4	6.3	6.1				
MD1	3	4	6.3					
AL1	1	1	4.2	5.4	4.8	5.9		
AL1	1	1	4.2	5.4	4.8	5.9		
AL1	1	2	4.2	5.8	5.9	5.7		
AL1	1	2	4.2	5.8	5.9	5.7		
AL1	2	1	4.2	4.9	4.4	5.4		
AL1	2	1	4.2	4.9	4.4	5.4		
AL1	2	2	4.2	4.8	5.1	4.5		
AL1	2	2	4.2	4.8	5.1	4.5		
AL1	2	3	4.2	5.5	5.0	5.9		
AL1	2	3	4.2	5.5	5.0	5.9		
AL1	3	1	4.2	4.2	3.9	4.5		
AL1	3	1	4.2	4.2	3.9	4.5		
AL1	3	2	4.2	5.1	5.1	5.0		

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
AL1	3	2	4.2	5.1	5.1	5.0		
AL1	3	3	4.2	4.9	4.9	4.9		
AL1	3	3	4.2	4.9	4.9	4.9		
AL1	4	1	4.2	4.7	4.7	4.7		
AL1	4	1	4.2	4.7	4.7	4.7		
AL1	4	2	4.2	5.1	5.3	4.9		
AL1	4	2	4.2	5.1	5.3	4.9		
AL1	4	3	4.2	4.6	4.6	4.6		
AL1	4	3	4.2	4.6	4.6	4.6		
AL1	5	1	4.2	4.8	4.8	4.8		
AL1	5	1	4.2	4.8	4.8	4.8		
AL1	5	2	4.2	4.7	4.8	4.6		
AL1	5	2	4.2	4.7	4.8	4.6		
AL1	5	3	4.2	4.7	4.9	4.4		
AL1	5	3	4.2	4.7	4.9	4.4		
AL2	6	1	5.8	5.5	5.5	5.5		
AL2	6	1	5.8	5.5	5.5	5.5		
AL2	6	2	5.8	5.9	5.8	6.1		
AL2	6	2	5.8	5.5	5.5	5.5		
AL2	6	3	5.8	5.4	5.2	5.5		
AL2	6	3	5.8	5.4	5.2	5.5		
AL2	7	1	5.8	5.6	5.4	5.8		
AL2	7	1	5.8	5.6	5.4	5.8		
AL2	7	2	5.8	5.6	5.0	6.2		
AL2	7	2	5.8	5.6	5.0	6.2		
AL2	7	3	5.8	5.5	4.9	6.1		
AL2	7	3	5.8	5.5	4.9	6.1		
AL2	8	1	5.8	5.7	5.7	5.7		
AL2	8	1	5.8	5.7	5.7	5.7		
AL2	8	2	5.8	5.1	5.0	5.2		
AL2	8	2	5.8	5.1	5.0	5.2		
AL2	8	3	5.8	4.8	4.3	5.3		
AL2	8	3	5.8	4.8	4.3	5.3		
AL2	8	4	5.8	4.5	4.1	4.9		
AL2	8	4	5.8	4.5	4.1	4.9		
AL2	9	1	5.8	5.0	5.0	4.9		
AL2	9	1	5.8	5.0	5.0	4.9		
AL2	9	2	5.8	4.9	5.0	4.7		
AL2	9	2	5.8	4.9	5.0	4.7		
AL2	10	1	5.8	5.5	5.4	5.7		
AL2	10	1	5.8	5.5	5.4	5.7		
GA	1	1	4.8	4.8	4.7	4.9		
GA	1	1	4.8	4.8	4.7	4.9		
GA	1	2	4.8	4.6	4.7	4.4		
GA	1	2	4.8	4.6	4.7	4.4		
GA	1	3	4.8	4.6	4.5	4.6		
GA	1	3	4.8	4.6	4.5	4.6		
GA	1	4	4.8	4.8	4.8	4.7		
GA	1	4	4.8	4.8	4.8	4.7		
MD2	1	1	5.5				5.7	5.4
MD2	1	1	5.5					
MD2	1	1	5.5	5.5	5.6	5.4		
MD2	1	1	5.5	5.5	5.6	5.4		
MD2	2	1	5.5	5.3			5.6	5.6
MD2	2	1	5.5					

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
MD2	2	2	5.5	5.3			5.6	5.3
MD2	2	2	5.5	5.4				
MD2	2	2	5.5	5.4	NA	NA		
MD2	2	2	5.5	5.4	NA	NA		
MD2	2	3	5.5	5.6			5.6	5.5
MD2	2	3	5.5	5.9				
MD2	2	4	5.5	5.5			5.4	5.2
MD2	2	4	5.5	5.3				
MD2	3	3	5.5	5.4	NA	NA		
MD2	3	3	5.5	5.4	NA	NA		
MD2	4	4	5.5	5.2	5.1	5.4		
MD2	4	4	5.5	5.2	5.1	5.4		
MD2	5	5	5.5	5.6				
MD2	5	5	5.5	5.6				
MD2	3	1	5.5	5.8			5.7	5.4
MD2	3	1	5.5	6.0				
MD2	3	2	5.5	5.8			5.7	
MD2	3	2	5.5	5.4				
MD2	3	3	5.5	5.5			5.6	5.5
MD2	3	3	5.5	5.9				
MD2	3	4	5.5	5.4			5.6	5.5
MD2	3	4	5.5	5.4				
MD2	6	6	5.5	5.6	5.6	5.7		
MD2	6	6	5.5	5.6	5.6	5.7		
KY2	1	1	5.4	4.9				
KY2	1	1	5.4					
KY2	1	2	5.4	5.0				
KY2	1	2	5.4					
KY2	1	3	5.6	5.1				
KY2	1	3	5.6					
KY2	2	1	5.6	5.2				
KY2	2	1	5.6					
KY2	2	2	5.6					
KY2	2	2	5.6					
KY2	2	3	5.6					
KY2	2	3	5.6					
KY2	3	1	5.6	5.2				
KY2	3	1	5.6					
KY2	3	2	5.6					
KY2	3	2	5.6					
KY2	4	1	5.4	4.8				
KY2	4	1	5.4					
KY2	5	1	5.4	4.9				
KY2	5	1	5.4					
KY2	5	2	5.4					
KY2	5	2	5.4					
TX3	1	1	5.0	4.4	4.4	4.4		
TX3	1	1	5.0	4.4	4.4	4.4		
TX3	1	2	5.0	4.3	4.3	4.4		
TX3	1	2	5.0	4.3	4.3	4.4		
TX3	1	3	5.0	4.3	4.3	4.4		
TX3	1	3	5.0	4.3	4.3	4.4		
TX3	1	4	5.0	4.3	4.2	4.3		
TX3	1	4	5.0	4.3	4.2	4.3		
TX3	2	1	5.0	4.2	4.3	4.2		

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	AC_DES	AC_EXT	AC_EXT1	AC_EXT2	AC_NUC	AC_IGN
TX3	2	1	5.0	4.2	4.3	4.2		
TX3	2	2	5.0	4.2	4.3	4.1		
TX3	2	2	5.0	4.2	4.3	4.1		
TX3	2	3	5.0	4.2	4.2	4.2		
TX3	2	3	5.0	4.2	4.2	4.2		
TX3	2	4	5.0	4.4	4.4	4.4		
TX3	2	4	5.0	4.4	4.4	4.4		

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
KS	1	1										
KS	1	1										
KS	1	2										
KS	1	2										
KS	1	3										
KS	1	3										
KS	1	1										
KS	1	1										
KS	1	1										
KS	1	1										
KS	1	2										
KS	1	2										
MD1	1	1										
MD1	1	1										
MD1	1	2										
MD1	1	2										
MD1	1	3										
MD1	1	3										
MD1	2	1										
MD1	2	1										
MD1	2	1										
MD1	2	1										
MD1	2	2										
MD1	2	2										
MD1	2	2										
MD1	2	2										
MD1	2	3										
MD1	2	3										
MD1	2	3										
MD1	2	3										
MD1	2	4										
MD1	2	4										
MD1	2	4										
MD1	2	4										
MD1	3	1										
MD1	3	1										
MD1	3	2										
MD1	3	2										
MD1	3	3										
MD1	3	3										
MD1	3	4										
MD1	3	4										
AL1	1	1										
AL1	1	1										
AL1	1	2										
AL1	1	2										
AL1	2	1										
AL1	2	1										
AL1	2	2										
AL1	2	2										
AL1	2	3										
AL1	2	3										
AL1	3	1										
AL1	3	1										
AL1	3	2										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
AL1	3	2										
AL1	3	3										
AL1	3	3										
AL1	4	1										
AL1	4	1										
AL1	4	2										
AL1	4	2										
AL1	4	3										
AL1	4	3										
AL1	5	1										
AL1	5	1										
AL1	5	2										
AL1	5	2										
AL1	5	3										
AL1	5	3										
AL2	6	1										
AL2	6	1										
AL2	6	2										
AL2	6	2										
AL2	6	3										
AL2	6	3										
AL2	7	1										
AL2	7	1										
AL2	7	2										
AL2	7	2										
AL2	7	3										
AL2	7	3										
AL2	8	1										
AL2	8	1										
AL2	8	2										
AL2	8	2										
AL2	8	3										
AL2	8	3										
AL2	8	4										
AL2	8	4										
AL2	9	1										
AL2	9	1										
AL2	9	2										
AL2	9	2										
AL2	10	1										
AL2	10	1										
GA	1	1										
GA	1	1										
GA	1	2										
GA	1	2										
GA	1	3										
GA	1	3										
GA	1	4										
GA	1	4										
MD2	1	1										
MD2	1	1										
MD2	1	1										
MD2	1	1										
MD2	2	1										
MD2	2	1										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
MD2	2	2										
MD2	2	2										
MD2	2	2										
MD2	2	2										
MD2	2	3										
MD2	2	3										
MD2	2	4										
MD2	2	4										
MD2	3	3										
MD2	3	3										
MD2	4	4										
MD2	4	4										
MD2	5	5										
MD2	5	5										
MD2	3	1										
MD2	3	1										
MD2	3	2										
MD2	3	2										
MD2	3	3										
MD2	3	3										
MD2	3	4										
MD2	3	4										
MD2	6	6										
MD2	6	6										
KY2	1	1										
KY2	1	1										
KY2	1	2										
KY2	1	2										
KY2	1	3										
KY2	1	3										
KY2	2	1										
KY2	2	1										
KY2	2	2										
KY2	2	2										
KY2	2	3										
KY2	2	3										
KY2	3	1										
KY2	3	1										
KY2	3	2										
KY2	3	2										
KY2	4	1										
KY2	4	1										
KY2	5	1										
KY2	5	1										
KY2	5	2										
KY2	5	2										
TX3	1	1										
TX3	1	1										
TX3	1	2										
TX3	1	2										
TX3	1	3										
TX3	1	3										
TX3	1	4										
TX3	1	4										
TX3	2	1										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	COLD19	COLD12_5	COLD9_5	COLD4_75	COLD2_36	COLD1_18	COLD0_6	COLD0_3	COLD0_15	COLD0_07
TX3	2	1										
TX3	2	2										
TX3	2	2										
TX3	2	3										
TX3	2	3										
TX3	2	4										
TX3	2	4										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
KS	1	1										
KS	1	1										
KS	1	2										
KS	1	2										
KS	1	3										
KS	1	3										
KS	1	1										
KS	1	1										
KS	1	1										
KS	1	1										
KS	1	2										
KS	1	2										
MD1	1	1										
MD1	1	1										
MD1	1	2										
MD1	1	2										
MD1	1	3										
MD1	1	3										
MD1	2	1										
MD1	2	1										
MD1	2	1										
MD1	2	1										
MD1	2	2										
MD1	2	2										
MD1	2	2										
MD1	2	2										
MD1	2	3										
MD1	2	3										
MD1	2	3										
MD1	2	3										
MD1	2	4										
MD1	2	4										
MD1	2	4										
MD1	2	4										
MD1	3	1										
MD1	3	1										
MD1	3	2										
MD1	3	2										
MD1	3	3										
MD1	3	3										
MD1	3	4										
MD1	3	4										
AL1	1	1										
AL1	1	1										
AL1	1	2										
AL1	1	2										
AL1	2	1										
AL1	2	1										
AL1	2	2										
AL1	2	2										
AL1	2	3										
AL1	2	3										
AL1	3	1										
AL1	3	1										
AL1	3	2										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
AL1	3	2										
AL1	3	3										
AL1	3	3										
AL1	4	1										
AL1	4	1										
AL1	4	2										
AL1	4	2										
AL1	4	3										
AL1	4	3										
AL1	5	1										
AL1	5	1										
AL1	5	2										
AL1	5	2										
AL1	5	3										
AL1	5	3										
AL2	6	1										
AL2	6	1										
AL2	6	2										
AL2	6	2										
AL2	6	3										
AL2	6	3										
AL2	7	1										
AL2	7	1										
AL2	7	2										
AL2	7	2										
AL2	7	3										
AL2	7	3										
AL2	8	1										
AL2	8	1										
AL2	8	2										
AL2	8	2										
AL2	8	3										
AL2	8	3										
AL2	8	4										
AL2	8	4										
AL2	9	1										
AL2	9	1										
AL2	9	2										
AL2	9	2										
AL2	10	1										
AL2	10	1										
GA	1	1										
GA	1	1										
GA	1	2										
GA	1	2										
GA	1	3										
GA	1	3										
GA	1	4										
GA	1	4										
MD2	1	1										
MD2	1	1										
MD2	1	1										
MD2	1	1										
MD2	2	1										
MD2	2	1										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
MD2	2	2										
MD2	2	2										
MD2	2	2										
MD2	2	2										
MD2	2	3										
MD2	2	3										
MD2	2	4										
MD2	2	4										
MD2	3	3										
MD2	3	3										
MD2	4	4										
MD2	4	4										
MD2	5	5										
MD2	5	5										
MD2	3	1										
MD2	3	1										
MD2	3	2										
MD2	3	2										
MD2	3	3										
MD2	3	3										
MD2	3	4										
MD2	3	4										
MD2	6	6										
MD2	6	6										
KY2	1	1										
KY2	1	1										
KY2	1	2										
KY2	1	2										
KY2	1	3										
KY2	1	3										
KY2	2	1										
KY2	2	1										
KY2	2	2										
KY2	2	2										
KY2	2	3										
KY2	2	3										
KY2	3	1										
KY2	3	1										
KY2	3	2										
KY2	3	2										
KY2	4	1										
KY2	4	1										
KY2	5	1										
KY2	5	1										
KY2	5	2										
KY2	5	2										
TX3	1	1										
TX3	1	1										
TX3	1	2										
TX3	1	2										
TX3	1	3										
TX3	1	3										
TX3	1	4										
TX3	1	4										
TX3	2	1										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	HOT19	HOT12_5	HOT9_5	HOT4_75	HOT2_36	HOT1_18	HOT0_6	HOT0_3	HOT0_15	HOT0_075
TX3	2	1										
TX3	2	2										
TX3	2	2										
TX3	2	3										
TX3	2	3										
TX3	2	4										
TX3	2	4										

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
KS	1	1	100.0	100.0	100.0	100.0	90.7	48.7	33.2	23.1	15.3	10.5	7.4	5.7
KS	1	1												
KS	1	2	100.0	100.0	100.0	99.6	90.5	46.6	31.0	21.5	14.5	9.9	6.9	5.3
KS	1	2												
KS	1	3	100.0	100.0	100.0	99.4	92.0	50.8	32.6	22.7	15.5	10.6	7.3	5.5
KS	1	3												
KS	1	1	100.0	100.0	100.0	99.8	91.2	48.9	32.1	22.2	15.3	10.6	7.3	5.5
KS	1	1												
KS	1	1	100.0	100.0	100.0	99.8	90.8	48.1	31.2	22.1	15.3	10.7	7.5	5.8
KS	1	1												
KS	1	2	100.0	100.0	100.0	100.0	91.4	47.1	30.2	21.3	14.8	10.5	7.5	5.8
KS	1	2												
MD1	1	1	100.0	100.0	99.4	79.4	56.1	22.6	14.5	12.8	12.0	11.5	10.6	8.6
MD1	1	1												
MD1	1	2												
MD1	1	2												
MD1	1	3												
MD1	1	3												
MD1	2	1												
MD1	2	1												
MD1	2	1	100.0	100.0	97.7	77.3	54.0	20.6	13.0	10.9	9.8	9.1	8.1	5.8
MD1	2	1	100.0	100.0	97.9	76.2	53.5	20.1	13.2	11.1	10.0	9.3	8.2	5.9
MD1	2	2	100.0	100.0	99.4	80.2	57.9	24.4	16.0	14.2	13.3	12.7	11.7	9.6
MD1	2	2												
MD1	2	2	100.0	100.0	98.5	82.2	60.2	23.3	15.0	12.9	12.0	11.3	10.2	7.4
MD1	2	2	100.0	100.0	99.2	81.3	58.8	22.8	14.6	12.6	11.7	11.1	10.1	7.2
MD1	2	3	100.0	100.0	97.4	78.9	57.6	23.2	15.3	13.1	12.1	11.4	10.5	8.6
MD1	2	3												
MD1	2	3	100.0	100.0	100.0	73.0	51.5	21.5	14.7	12.8	11.8	11.1	9.9	7.0
MD1	2	3	100.0	100.0	98.2	79.9	57.9	23.5	15.9	13.8	12.7	12.0	10.8	7.8
MD1	2	4	100.0	100.0	98.2	77.5	55.8	23.8	16.0	13.6	12.4	11.7	10.6	8.7
MD1	2	4												
MD1	2	4	100.0	100.0	100.0	76.9	57.6	22.6	14.9	12.8	11.7	10.9	9.7	6.7
MD1	2	4	100.0	100.0	98.1	77.3	55.3	22.4	14.8	12.3	11.1	10.2	8.9	4.2
MD1	3	1												
MD1	3	1												
MD1	3	2			96.6	78.2	56.2	24.2	15.9	13.9	12.9	12.3	11.4	9.3
MD1	3	2												
MD1	3	3												
MD1	3	3												
MD1	3	4			97.2	75.8	55.0	23.8	15.6	13.7	12.8	12.2	11.3	9.4
MD1	3	4												
AL1	1	1	100.0	100.0	85.7	78.9	65.6	38.6	29.6	24.2	19.7	14.0	8.7	4.8
AL1	1	1	100.0	96.7	90.5	79.5	65.1	37.7	29.2	24.2	19.7	14.1	8.9	5.1
AL1	1	2	100.0	100.0	91.7	83.3	68.2	44.4	34.1	27.6	22.6	16.5	10.8	6.4
AL1	1	2	100.0	100.0	94.2	86	70.1	42.3	32.8	26.9	22.0	16.1	10.5	6.2
AL1	2	1	100.0	100.0	99.0	80.9	66.6	41.5	29.7	23.7	19.3	14.1	9.0	4.3
AL1	2	1	100.0	100.0	99.5	85.6	72.8	47.8	34.4	27.1	21.7	15.8	10.1	5.3
AL1	2	2	100.0	100.0	91.1	83.3	72.3	49.7	36.7	28.8	22.7	16.2	10.1	3.6
AL1	2	2	100.0	100.0	90.1	79.6	68.1	42.6	31.2	25.0	20.3	14.7	9.4	5.3
AL1	2	3	100.0	100.0	95.5	87.9	74.3	45.2	32.3	26.1	21.1	15.1	9.5	5.2
AL1	2	3	100.0	100.0	88.9	82.6	69	40.2	28.0	22.1	18.0	13.2	8.3	4.6
AL1	3	1	100.0	100.0	88.0	78.9	63.7	34.6	24.6	19.7	15.8	11.3	6.9	3.7
AL1	3	1	100.0	100.0	91.9	84.4	72.4	42.3	29.6	23.1	18.2	12.8	7.8	4.0
AL1	3	2	100.0	100.0	89.2	82.5	71.1	43.7	32.2	25.9	21.0	15.3	9.9	5.7

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
AL1	3	2	100.0	98.4	88.6	79.2	69.8	44.9	33.5	26.7	21.5	15.6	10.1	5.8
AL1	3	3	100.0	100.0	88.8	83.1	70.1	41.4	29.9	24.0	19.3	13.8	8.6	4.7
AL1	3	3	100.0	98.1	88.7	80.9	69.5	42.9	30.8	24.5	19.8	14.2	8.8	4.8
AL1	4	1	100.0	100.0	89.2	78.1	65.5	37.4	26.5	21.5	17.6	12.7	8.0	4.5
AL1	4	1	100.0	98.9	87.5	78.4	63.8	37.5	27.0	21.9	17.8	12.8	8.1	4.4
AL1	4	2	100.0	97.7	91.1	84	72.4	45.4	32.8	26.3	21.3	15.5	10.1	5.8
AL1	4	2	100.0	94.3	89.4	81.3	67.6	41.3	29.8	24.1	19.7	14.6	9.7	5.9
AL1	4	3	100.0	98.8	88.9	80.3	68.3	42.9	32.0	25.9	21.1	15.4	9.8	5.4
AL1	4	3	100.0	100.0	90.0	79.9	69.8	43.2	31.9	25.9	21.1	15.4	10.0	5.7
AL1	5	1	100.0	98.6	89.5	82.8	68.9	41.1	29.7	24.0	19.4	14.0	8.7	4.4
AL1	5	1	100.0	100.0	89.5	82.2	70.9	42.8	30.7	24.7	19.9	14.2	8.7	4.3
AL1	5	2	100.0	99.0	87.8	80.8	69.4	40.4	28.9	23.0	18.5	13.0	7.7	3.7
AL1	5	2	100.0	98.7	92.8	83.8	71	40.6	29.3	23.6	19.2	13.8	8.5	4.6
AL1	5	3	100.0	99.0	87.9	80.9	69.5	40.5	29.1	23.2	18.7	13.2	7.8	3.8
AL1	5	3	100.0	98.7	92.7	83.9	71.1	40.6	29.2	23.4	19.0	13.5	8.2	4.2
AL2	6	1	100.0	100.0	99.2	89.0	74.7	43.3	26.2	20.0	15.3	9.7	5.2	2.9
AL2	6	1	100.0	100.0	99.6	90.2	76.2	43.6	26.6	20.4	15.6	9.8	5.3	2.9
AL2	6	2	100.0	100.0	100.0	87.0	73.7	43.8	28.0	21.5	16.7	10.7	5.9	3.3
AL2	6	2	100.0	100.0	100.0	90.5	79.8	49.5	30.8	23.5	17.8	11.4	6.3	3.5
AL2	6	3	100.0	100.0	100.0	86.1	73.0	41.4	26.1	20.2	15.5	10.0	5.6	3.2
AL2	6	3	100.0	100.0	100.0	88.7	75.6	43.3	27.3	20.9	16.0	10.3	5.8	3.3
AL2	7	1	100.0	100.0	99.0	88.5	74.1	45.5	28.8	21.5	16.2	10.3	5.8	3.4
AL2	7	1	100.0	100.0	100.0	89.4	79.7	50.0	30.8	22.8	17.0	10.7	5.9	3.5
AL2	7	2	100.0	100.0	99.0	85.6	73.8	43.1	28.7	22.5	17.6	11.8	6.7	3.8
AL2	7	2	100.0	100.0	99.5	88.0	75.2	43.0	28.8	22.6	17.6	11.6	6.6	3.7
AL2	7	3	100.0	100.0	98.7	82.2	67.7	40.9	27.0	21.0	16.2	10.3	5.6	3.2
AL2	7	3	100.0	100.0	99.4	87.5	71.5	44.7	29.0	21.9	16.5	10.3	5.4	2.9
AL2	8	1	100.0	100.0	100.0	88.5	75.5	44.2	30.2	23.7	18.5	12.1	6.9	4.0
AL2	8	1	100.0	100.0	99.5	87.9	73.7	43.4	29.8	23.5	18.4	12.0	6.8	4.0
AL2	8	2	100.0	100.0	98.9	87.5	72.1	41.0	28.5	22.2	17.2	11.3	6.4	3.7
AL2	8	2	100.0	100.0	99.3	87.2	73.2	41.6	28.8	22.4	17.2	11.1	6.2	3.5
AL2	8	3	100.0	100.0	99.5	85.7	71.4	39.8	27.4	21.8	17.1	11.3	6.6	3.8
AL2	8	3	100.0	100.0	99.8	86.1	71.6	40.1	27.6	21.9	17.1	11.3	6.5	3.8
AL2	8	4	100.0	100.0	99.4	84.1	68.5	36.3	25.2	20.4	16.3	10.9	6.3	3.8
AL2	8	4	100.0	100.0	99.6	87.6	69.4	33.7	22.7	18.8	15.1	10.1	5.7	3.3
AL2	9	1	100.0	100.0	100.0	90.4	73.3	42.2	28.5	21.8	16.2	10.0	5.3	2.8
AL2	9	1	100.0	100.0	100.0	87.5	73.0	40.8	26.8	20.7	15.8	9.9	5.3	2.8
AL2	9	2	100.0	100.0	100.0	89.7	77.1	47.4	32.8	25.2	18.9	11.9	6.6	3.8
AL2	9	2	100.0	100.0	99.7	90.5	76.5	45.8	31.4	24.3	18.4	11.6	6.5	3.8
AL2	10	1	100.0	100.0	100.0	86.6	71.8	43.7	30.2	23.5	17.9	11.4	6.3	3.6
AL2	10	1	100.0	100.0	100.0	89.6	77.6	46.3	31.9	24.4	18.2	11.1	5.6	2.8
GA	1	1	100.0	100.0	100.0	95.2	76.5	39.4	26.2	20.0	16.4	13.0	9.3	5.9
GA	1	1	100.0	100.0	100.0	96.6	78.0	41.1	26.6	20.2	16.5	13.0	9.3	5.8
GA	1	2	100.0	100.0	100.0	96.7	80.5	48.3	33.9	26.0	21.2	16.6	11.7	6.9
GA	1	2	100.0	100.0	100.0	95.3	78.5	46	32.2	24.9	20.4	16.0	11.3	6.5
GA	1	3	100.0	100.0	100.0	97.2	80.6	47.4	33.3	25.9	21.3	16.7	12.0	7.4
GA	1	3	100.0	100.0	100.0	96.2	81.5	47.9	34.0	26.4	21.6	16.9	12.1	7.4
GA	1	4	100.0	100.0	100.0	96.5	80.4	48.7	32.9	25.3	20.8	16.3	11.8	7.3
GA	1	4	100.0	100.0	100.0	94.3	79.1	47.0	32.3	24.9	20.5	16.1	11.6	7.3
MD2	1	1												
MD2	1	1												
MD2	1	1	100.0	100.0	100.0	95.2	85.5	58.2	38.0	24.5	17.3	12.3	9.3	6.4
MD2	1	1	100.0	100.0	100.0	93.5	83.1	56.3	37.6	24.2	17.2	12.2	9.1	6.4
MD2	2	1	100.0	100.0	100.0	94.3	84.6	60.0	37.8	23.3	16.2	11.9	9.2	6.9
MD2	2	1												

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
MD2	2	2												
MD2	2	2												
MD2	2	2	100.0	100.0	100.0	94.0	83.8	57.8	37.4	23.3	16.4	11.8	9.0	6.1
MD2	2	2	100.0	100.0	100.0	94.0	83.8	57.8	37.4	23.3	16.4	11.8	9.0	6.1
MD2	2	3	100.0	100.0	100.0	93.3	84.5	58.8	38.8	24.5	17.1	12.6	9.7	7.0
MD2	2	3	100.0	100.0	100.0	96.6	87.7	64.2	42.2	26.3	18.3	13.6	10.6	7.8
MD2	2	4	100.0	100.0	100.0	95.9	87.0	61.9	40.1	25.9	18.3	13.6	10.5	7.7
MD2	2	4	100.0	100.0	100.0	95.6	86.8	61.2	39.4	25.6	18.0	13.3	10.2	7.5
MD2	3	3	100.0	100.0	100.0	95.4	85.9	57.5	40.1	25.2	17.6	12.4	9.2	6.4
MD2	3	3	100.0	100.0	100.0	95.4	85.9	57.5	40.1	25.2	17.6	12.4	9.2	6.4
MD2	4	4	100.0	100.0	100.0	93.2	79.7	53.7	35.3	22.3	15.3	10.6	7.6	5.1
MD2	4	4	100.0	100.0	100.0	93.8	85.4	61.0	38.9	23.9	16.3	11.3	8.2	5.5
MD2	5	5	100.0	100.0	100.0	94.5	86.3	61.1	39.0	23.8	16.3	11.3	8.2	5.3
MD2	5	5	100.0	100.0	100.0	94.5	84.2	58.2	37.7	23.2	16.0	11.1	8.2	5.3
MD2	3	1												
MD2	3	1	100.0	100.0	100.0	95.5	87.4	63.3	40.7	25.6	17.7	13.1	10.1	7.3
MD2	3	2												
MD2	3	2												
MD2	3	3												
MD2	3	3												
MD2	3	4	100.0	100.0	100.0	96.5	87.4	63.4	40.2	25.7	17.7	12.6	9.4	6.9
MD2	3	4	100.0	100.0	100.0	96.0	86.1	62.6	39.6	25.5	17.5	12.5	9.3	6.8
MD2	6	6	100.0	100.0	100.0	96.3	86.5	60.6	39.2	23.4	15.7	10.9	8.0	5.4
MD2	6	6	100.0	100.0	100.0	97.5	88.6	63.9	40.4	23.7	15.9	11.0	8.0	5.3
KY2	1	1	100.0	100.0	100.0	100.0	92.6	55.2	33.0	22.5	16.0	9.4	6.4	5.3
KY2	1	1												
KY2	1	2	100.0	100.0	100.0	100.0	96.4	61.2	37.0	25.1	18.0	10.5	7.0	5.7
KY2	1	2												
KY2	1	3	100.0	100.0	100.0	100.0	94.0	58.9	36.6	24.9	17.7	10.6	7.1	5.8
KY2	1	3												
KY2	2	1	100.0	100.0	100.0	100.0	94.7	60.4	37.6	25.3	17.9	10.6	7.0	5.7
KY2	2	1												
KY2	2	2												
KY2	2	2												
KY2	2	3												
KY2	2	3												
KY2	3	1	100.0	100.0	100.0	100.0	94.4	61.3	37.9	25.3	17.9	10.3	6.8	5.5
KY2	3	1												
KY2	3	2												
KY2	3	2												
KY2	4	1	100.0	100.0	100.0	100.0	93.0	58.2	35.8	23.7	16.2	10.1	6.9	5.5
KY2	4	1												
KY2	5	1	100.0	100.0	100.0	99.9	93.0	57.0	35.4	23.7	16.5	10.0	6.9	5.8
KY2	5	1												
KY2	5	2												
KY2	5	2												
TX3	1	1	100.0	100.0	100.0	97.7	90.2	63.1	30.4	21.3	16.2	8.6	3.9	2.7
TX3	1	1	100.0	100.0	100.0	96.9	89.4	60.9	30.2	21.3	16.1	8.5	4.0	2.8
TX3	1	2	100.0	100.0	100.0	97.2	88.8	60.8	29.0	20.4	15.6	8.3	3.9	2.8
TX3	1	2	100.0	100.0	100.0	97.2	88.2	61.6	30.1	20.8	15.7	8.2	3.7	2.5
TX3	1	3	100.0	100.0	100.0	96.5	86.9	61.0	29.5	20.7	15.8	8.4	3.8	2.6
TX3	1	3	100.0	100.0	100.0	98.5	91.0	64.5	30.4	21.1	16.1	8.6	3.9	2.6
TX3	1	4	100.0	100.0	100.0	98.0	87.5	57.4	27.5	19.7	15.3	8.2	3.6	2.4
TX3	1	4	100.0	100.0	100.0	95.6	86.2	59.2	28.3	20.0	15.4	8.2	3.5	2.3
TX3	2	1	100.0	100.0	100.0	97.5	90.1	60.0	28.3	20.4	16.1	9.0	3.8	2.6

NCHRP Project 9-7: Field Data for Projects Constructed in 1995

PROJ	LOT	SUBLOT	EXT37.5	EXT25	EXT19	EXT12_5	EXT9_5	EXT4_75	EXT2_36	EXT1_18	EXT0_6	EXT0_3	EXT0_15	EXT0_075
TX3	2	1	100.0	100.0	100.0	96.3	86.9	57.3	27.2	19.7	15.6	8.7	3.6	2.4
TX3	2	2	100.0	100.0	100.0	98.4	90.9	61.5	29.3	20.4	15.9	8.8	3.6	2.5
TX3	2	2	100.0	100.0	100.0	97.0	86.2	56.1	26.9	19.4	15.3	8.4	3.6	2.5
TX3	2	3	100.0	100.0	100.0	97.3	88.7	59.3	26.1	18.5	14.5	7.7	2.9	2.0
TX3	2	3	100.0	100.0	100.0	97.6	86.4	55.7	25.2	18.1	14.3	7.5	2.8	2.0
TX3	2	4	100.0	100.0	100.0	96.7	86.3	54.2	26.2	19.5	15.5	8.3	3.2	2.2
TX3	2	4	100.0	100.0	100.0	99.9	88.7	57.3	27.2	19.7	15.6	8.7	3.6	2.4

PROJECT AND POOLED STANDARD DEVIATIONS

(1995)

NCHRP Project 9-7: Standard Deviations Computed from Projects Constructed in 1995

1995 Projects	# of Samples	Gmm	Gmb	Calculated Gse	Air Voids @ Nini	Air Voids @ Ndes	Air Voids @ Nmax	VMA	VFA	Dust/AC Ratio	AC Absorption	%AC Extracted	%AC Nuc Gauge	%AC Ignition
AL1	28	0.015	0.015	0.011	1.1	0.8	0.8	0.7	5.9	0.1	0.2	0.40	-	-
AL2	26	0.017	0.016	0.018	1.0	0.9	0.9	0.6	6.1	0.1	0.3	0.39	-	-
GA	8	0.004	0.013	0.004	1.0	0.5	0.5	0.5	3.1	0.2	0.0	0.12	-	-
KS	12	0.009	0.008	-	1.2	0.4	0.3	0.3	3.2	0.1	-	0.20	-	-
KY2	22	0.006	0.012	-	0.7	0.7	0.7	0.4	4.4	0.1	-	0.16	-	-
MD1	30	0.009	0.034	0.012	0.7	1.0	1.0	0.5	5.3	0.2	0.1	0.22	0.10	-
MD2	30	0.006	0.043	0.007	1.0	0.9	0.8	1.0	5.0	0.2	0.1	0.21	0.09	0.13
TX3	16	0.011	0.016	0.012	0.8	0.9	0.8	0.5	6.0	0.1	0.2	0.08	-	-
Pooled Standard Deviation		0.011	0.025	0.012	1.0	0.9	0.8	0.6	5.3	0.1	0.2	0.27	0.10	0.13
94 & '95 Pooled Std. Dev.		0.011	0.022	0.012	1.0	0.9	0.8	0.6	5.8	0.1	0.1	0.24	0.18	0.13

1995 Projects	# of Samples	Cold Feed 19.0mm	Cold Feed 12.5mm	Cold Feed 9.5mm	Cold Feed 4.75mm	Cold Feed 2.36mm	Cold Feed 1.18mm	Cold Feed 0.600mm	Cold Feed 0.300mm	Cold Feed 0.150mm	Cold Feed 0.075mm
AL1	28	-	-	-	-	-	-	-	-	-	-
AL2	26	-	-	-	-	-	-	-	-	-	-
GA	8	-	-	-	-	-	-	-	-	-	-
KS	12	-	-	-	-	-	-	-	-	-	-
KY2	22	-	-	-	-	-	-	-	-	-	-
MD1	30	-	-	-	-	-	-	-	-	-	-
MD2	30	-	-	-	-	-	-	-	-	-	-
TX3	16	-	-	-	-	-	-	-	-	-	-
Pooled Standard Deviation		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94 & '95 Pooled Std. Dev.		0.1	0.9	2.4	3.3	2.5	2.1	1.5	1.1	0.8	0.8

1995 Projects	# of Samples	Hot Bin 19.0mm	Hot Bin 12.5mm	Hot Bin 9.5mm	Hot Bin 4.75mm	Hot Bin 2.36mm	Hot Bin 1.18mm	Hot Bin 0.600mm	Hot Bin 0.300mm	Hot Bin 0.150mm	Hot Bin 0.075mm
AL1	28	-	-	-	-	-	-	-	-	-	-
AL2	26	-	-	-	-	-	-	-	-	-	-
GA	8	-	-	-	-	-	-	-	-	-	-
KS	12	-	-	-	-	-	-	-	-	-	-
KY2	22	-	-	-	-	-	-	-	-	-	-
MD1	30	-	-	-	-	-	-	-	-	-	-
MD2	30	-	-	-	-	-	-	-	-	-	-
TX3	16	-	-	-	-	-	-	-	-	-	-
Pooled Standard Deviation		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94 & '95 Pooled Std. Dev.		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1995 Projects	# of Samples	Extracted 37.5mm	Extracted 25.0mm	Extracted 19.0mm	Extracted 12.5mm	Extracted 9.5mm	Extracted 4.75mm	Extracted 2.36mm	Extracted 1.18mm	Extracted 0.600mm	Extracted 0.300mm	Extracted 0.150mm	Extracted 0.075mm
AL1	28	0.0	1.3	3.2	2.5	2.7	3.2	2.6	2.0	1.6	1.3	1.0	0.8
AL2	26	0.0	0.0	0.4	2.0	3.0	3.5	2.2	1.5	1.1	0.7	0.5	0.4
GA	8	0.0	0.0	0.0	1.0	1.7	3.5	3.2	2.6	2.1	1.6	1.2	0.7
KS	12	0.0	0.0	0.0	0.2	0.6	1.5	1.1	0.7	0.4	0.3	0.2	0.2
KY2	22	0.0	0.0	0.0	0.0	1.3	2.3	1.7	1.1	0.9	0.4	0.2	0.2
MD1	30	0.0	0.0	1.1	2.4	2.3	1.3	1.0	1.0	1.0	1.1	1.1	1.6
MD2	30	0.0	0.0	0.0	1.2	2.0	2.8	1.6	1.1	0.9	0.9	0.9	0.9
TX3	16	0.0	0.0	0.0	1.0	1.7	2.8	1.7	0.9	0.5	0.4	0.3	0.2
Pooled Standard Deviation		0.0	0.5	1.4	1.7	2.2	2.7	1.9	1.4	1.1	0.9	0.8	0.9
94 & '95 Pooled Std. Dev.		0.0	0.4	1.0	1.3	2.1	4.3	2.2	1.6	1.7	1.1	0.8	0.7

APPENDIX F

SUMMARY OF INFORMATION FOR VERIFICATION OF VERSION 2.0 QC/QA PLAN

Appendix F as submitted by the research agency is not published herein but is available for loan on request to the NCHRP.

APPENDIX G

COMPARISON OF QUALITY CONTROL AND ACCEPTANCE TESTS

INTRODUCTION

In many state specifications, quality assurance procedures require contractors to perform quality control (QC) tests and the state to perform acceptance tests. Frequently, these tests measure the same engineering properties, e.g., gradation and asphalt content. However, it is known that these results vary, even when taken from the same population. Thus, the contractor's results should not be expected to be identical to those of the state. When they differ, the question becomes "How different can they be and still be considered to have come from the same population?" Another factor entering into the issue is the fact that the sample sizes are usually different for the state and the contractor test results. The number of QC tests is often larger than the number of acceptance tests.

It is therefore advantageous to have a method for comparing the sample statistics, mean, and standard deviation (or variance), of the QC data with those of the acceptance data. This type of analysis may be done in an effort to verify that the two sets of test results were from the same materials or that the sampling and testing are being performed correctly. If the results allow, the two sets of test results might be combined to provide a better estimate of the population that was produced. The statistical test used to make the comparisons of the two data sets are called hypothesis tests and they are described in the following paragraphs.

ANALYSIS

To compare two populations that are assumed normally distributed, it is necessary to compare their centers (means) and their variabilities (standard deviations or variances). A different hypothesis test is used for each of these properties. The F-test provides a method for comparing variability by comparing the variances of two sets of data. Possible differences in means are assessed by a t-test.

The F-test is based on the ratio of the variances of two sets of data. In this case, the F-test is based on the ratio of the variances of the QC test results, S^2_c, and the acceptance test results, S^2_a. The t-test compares sample means, and in this case, is based on the means of the QC test results, $\bar{x}_c$, and the acceptance test results, $\bar{x}_a$.

Hypothesis tests, i.e., the F-test and the t-test, are conducted at a selected level of significance, α. The level of significance is the probability of incorrectly deciding the data sets are different when they actually come from the same population. The value of α is typically selected as either 0.05 or 0.01. The following analysis is based on an α of 0.01 so as to minimize the likelihood of incorrectly concluding that the test results are different when they are not.

For the analysis to be meaningful, all the samples must be obtained in a random manner, the two sets of test results must have been sampled over the same time period, and the same sampling and testing procedures must have been used for both QC and acceptance tests. If it is determined that a significant difference is likely between either the mean or the variance, the source of the difference should be identified. Although it is beyond the scope of the analysis presented here, a computer program could be developed that could identify the existence of significant differences once the test results are input.

If the analysis indicates that there is no reason to believe the results came from different populations, then the mean and variance (or standard deviation) could be determined from the combined set of test results to provide a better estimate of the population's parameters than would be obtained from either of the sets individually.

PROCEDURE

F-Test for the Sample Variances

Since the values used in the t-test depend on whether the variances are equal for the two sets of data, it is necessary to test the variances of the test results before the means. The intent is to determine whether the difference in the variability of the contractor's QC tests and that of the state's acceptance tests is larger than might be expected from chance if they came from the same population. In this case, it does not matter which variance is larger. After comparing the test results, one of the following will be concluded.

- The two sets of data have different variances because the difference between the two sets of test results is greater than is likely to occur from chance if their variances are actually equal.
- There is no reason to believe the variances are different because the difference is not so great as to be unlikely to have occurred from chance if the variances are actually equal.

First, compute the variance (the standard deviation squared) for the QC tests, S^2_c, and the acceptance tests, S^2_a.

Next, compute F, where $F = S^2_c/S^2_a$ or $F = S^2_a/S^2_c$. *Always use the larger of the two variances in the numerator*. Now, choose α, the level of significance for the test. As mentioned previously, the recommended α is 0.01. Next, a critical F value is determined from Table 1 using the degrees of freedom associated with each set of test results. The degrees of freedom for each set of results is the number of test results in the set, less one. If the number of QC tests is n_c and the number of acceptance tests is n_a, then the degrees of freedom associated with S^2_c is $(n_c - 1)$ and the degrees of freedom associated with S^2_a is $(n_a - 1)$. The values in Table 1 are tabulated to test if there is a difference (either larger or smaller) between two variance estimates. This is known as a two-sided or two-tailed test. Care must be taken when using other tables of the F distribution, because they are usually based on a one-tailed test, i.e., testing specifically whether one variance is larger than another.

Once the value for F_{crit} is determined from Table 1 (be sure the appropriate degrees of freedom for the numerator and denominator are used when obtaining the value from Table 1), if $F \geq F_{crit}$ then decide that the two sets of tests have significantly different variabilities. If $F < F_{crit}$, then decide that there is no reason to believe the variabilities are significantly different.

T-Test for Sample Means

Once the variances have been tested and assumed to be either equal or not equal, the means of the test results can be tested to determine whether they differ from one another or can be assumed equal. The desire is to determine whether it is reasonable to assume that the QC tests came from the same population as the acceptance tests. A t-test is used to compare the sample means. Two approaches for the t-test are necessary. If the sample variances are assumed equal, then the t-test is conducted based on the two samples using a pooled estimate for the variance and the pooled degrees of freedom. This approach is Case 1 described below. If the sample variances are assumed to be different, then the t-test is conducted using the individual sample variances, the individual sample sizes, and the effective degrees of freedom (estimated from the sample variances and sample sizes). This approach is Case 2 presented below.

In either of the two cases discussed in the previous paragraph, one of the following decisions is made:

TABLE 1 Critical values, F_{crit}, for the F-test for a level of significance, $\alpha = 0.01$

DEGREES OF FREEDOM FOR DENOMINATOR	DEGREES OF FREEDOM FOR NUMERATOR: 1	2	3	4	5	6	7	8	9	10	11	12
1	16 200	20 000	21 600	22 500	23 100	23 400	23 700	23 900	24 100	24 200	24 300	24 400
2	198	199	199	199	199	199	199	199	199	199	199	199
3	55.6	49.8	47.5	46.2	45.4	44.8	44.4	44.1	43.9	43.7	43.5	43.4
4	31.3	26.3	24.3	23.2	22.5	22.0	21.6	21.4	21.1	21.0	20.8	20.7
5	22.8	18.3	16.5	15.6	14.9	14.5	14.2	14.0	13.8	13.6	13.5	13.4
6	18.6	14.5	12.9	12.0	11.5	11.1	10.8	10.6	10.4	10.2	10.1	10.0
7	16.2	12.4	10.9	10.0	9.52	9.16	8.89	8.68	8.51	8.38	8.27	8.18
8	14.7	11.0	9.60	8.81	8.30	7.95	7.69	7.50	7.34	7.21	7.10	7.01
9	13.6	10.1	8.72	7.96	7.47	7.13	6.88	6.69	6.54	6.42	6.31	6.23
10	12.8	9.43	8.08	7.34	6.87	6.54	6.30	6.12	5.97	5.85	5.75	5.66
11	12.2	8.91	7.60	6.88	6.42	6.10	5.86	5.68	5.54	5.42	5.32	5.24
12	11.8	8.51	7.23	6.52	6.07	5.76	5.52	5.35	5.20	5.09	4.99	4.91
15	10.8	7.70	6.48	5.80	5.37	5.07	4.85	4.67	4.54	4.42	4.33	4.25
20	9.94	6.99	5.82	5.17	4.76	4.47	4.26	4.09	3.96	3.85	3.76	3.68
24	9.55	6.66	5.52	4.89	4.49	4.20	3.99	3.83	3.69	3.59	3.50	3.42
30	9.18	6.35	5.24	4.62	4.23	3.95	3.74	3.58	3.45	3.34	3.25	3.18
40	8.83	6.07	4.98	4.37	3.99	3.71	3.51	3.35	3.22	3.12	3.03	2.95
60	8.49	5.80	4.73	4.14	3.76	3.49	3.29	3.13	3.01	2.90	2.82	2.74
120	8.18	5.54	4.50	3.92	3.55	3.28	3.09	2.93	2.81	2.71	2.62	2.54
∞	7.88	5.30	4.28	3.72	3.35	3.09	2.90	2.74	2.62	2.52	2.43	2.36

Note: This is for a two-tailed test with null and alternate hypotheses shown below:

$H_o: S^2_c = S^2_a$

$H_a: S^2_c \neq S^2_a$

- The two sets of data have different means because the difference in the sample means is greater than is likely to occur from chance if their means are actually equal.
- There is no reason to believe the means are different because the difference in the sample means is not so great as to be unlikely to have occurred from chance if the means are actually equal.

Case 1: Sample Variances Assumed To Be Equal

To conduct the t-test when the sample variances are assumed equal, equation 1 is used to calculate the t value from which the decision is reached.

$$t = \frac{|\bar{x}_c - \bar{x}_a|}{\sqrt{\frac{s_p^2}{n_c} + \frac{s_p^2}{n_a}}} \qquad (1)$$

where

$\bar{x}_c$ = mean of QC tests
$\bar{x}_a$ = mean of acceptance tests
s_p^2 = pooled estimate for the variance (described below)
n_c = number of QC tests
n_a = number of acceptance tests

The pooled variance, which is the weighted average, using the degrees of freedom for each sample as the weighting factor, is computed from the sample variances using equation 2.

$$s_p^2 = \frac{s_c^2(n_c - 1) + s_a^2(n_a - 1)}{n_c + n_a - 2} \qquad (2)$$

where

s^2_p = pooled estimate for the variance
n_c = number of QC tests
n_a = number of acceptance tests
s^2_c = variance of QC tests
s^2_a = variance of acceptance tests

Once the pooled variance is estimated, the value of t is computed using equation 1.

To determine the critical t value against which to compare the computed t value, it is necessary to select the level of significance, α. As discussed above, a value of $\alpha = 0.01$ is recommended. Next, determine the critical t value, t_{crit}, from Table 2 for the pooled degrees of freedom. The pooled degrees of freedom for the case where the sample variances are assumed equal is $(n_c + n_a - 2)$. If $t \geq t_{crit}$, then decide that the two sets of tests have significantly different means. If $t < t_{crit}$ then decide that there is no reason to believe that the means are significantly different.

Case 2: Sample Variances Assumed To Be Not Equal

If the sample variances are not assumed to be equal, then the individual sample variances, rather than the pooled variance, are used to calculate t, and the degrees of freedom used are an estimated effective degrees of freedom rather than the pooled degrees of freedom.

To conduct the t-test when the sample variances are assumed not equal, equation 3 is used to calculate the t value from which the decision is reached.

$$t = \frac{|\bar{x}_c - \bar{x}_a|}{\sqrt{\frac{s_c^2}{n_c} + \frac{s_a^2}{n_a}}} \qquad (3)$$

where

$\bar{x}_c$ = mean of QC tests
$\bar{x}_a$ = mean of acceptance tests
s^2_c = variance of QC tests
s^2_a = variance of acceptance tests
n_c = number of QC tests
n_a = number of acceptance tests

To determine the critical t value against which to compare the computed t value, it is necessary to select the level of significance, α. As discussed above, a value of $\alpha = 0.01$ is recommended. Next, determine the critical t value t_{crit}, from Table 2 for the effective degrees of freedom. The effective degrees of freedom, f, for the case where the sample variances are assumed not equal is determined from equation 4.

$$f = \frac{\left(\frac{s_c^2 + s_a^2}{n_c n_a}\right)^2}{\left(\frac{\left(\frac{s_c^2}{n_c}\right)^2}{n_c + 1} + \frac{\left(\frac{s_a^2}{n_a}\right)^2}{n_a + 1}\right)} - 2 \qquad (4)$$

Where all the symbols are as described previously.

If $t \geq t_{crit}$ then decide that the two sets of tests have significantly different means. If $t < t_{crit}$ then decide that there is no reason to believe that the means are significantly different.

Example Problem: Case 1

A Contractor has run 21 QC tests for asphalt content and the State Highway Agency (SHA) has run eight acceptance tests over the same period of time for the same material property. The results are shown below. Is it likely that the tests came from the same population?

TABLE 2 Critical values, t_{crit}, for the t-test for various levels of significance

Degrees of Freedom	α=0.01	α=0.05	α=0.10
1	63.657	12.706	6.314
2	9.925	4.303	2.920
3	5.841	3.182	2.363
4	4.604	2.776	2.12
5	4.032	2.571	2.015
6	3.707	2.447	1.943
7	3.499	2.365	1.895
8	3.355	2.306	1.860
9	3.250	2.262	1.833
10	3.169	2.228	1.812
11	3.106	2.201	1.796
12	3.055	2.179	1.782
13	3.012	2.160	1.771
14	2.977	2.145	1.761
15	2.947	2.131	1.753
16	2.921	2.120	1.746
17	2.898	2.110	1.740
18	2.878	2.101	1.734
19	2.861	2.093	1.729
20	2.845	2.086	1.725
21	2.831	2.080	1.721
22	2.819	2.074	1.717
23	2.807	2.069	1.714
24	2.797	2.064	1.711
25	2.787	2.060	1.708
26	2.779	2.056	1.706
27	2.771	2.052	1.703
28	2.763	2.048	1.701
29	2.756	2.045	1.699
30	2.750	2.042	1.697
40	2.704	2.021	1.684
60	2.660	2.000	1.671
120	2.617	1.980	1.658
∞	2.576	1.960	1.645

Note: This is for a two-tailed test with the null and alternate hypotheses shown below:

$H_o: \bar{x}_c = \bar{x}_s$

$H_a: \bar{x}_c \neq \bar{x}_s$

QC Test Results	Acceptance Test Results
6.4	5.4
6.2	5.8
6.0	6.2
6.6	5.4
6.1	5.4
6.0	5.8
6.3	5.7
6.1	5.4
5.9	
5.8	
6.0	
5.7	
6.3	
6.5	
6.4	
6.0	
6.2	
6.5	
6.0	
5.9	
6.3	

First, use the F-test to determine whether to assume the variances of the QC tests differ from the acceptance tests.

Step 1. Compute the variance, s^2, for each set of tests

$$s^2_c = 0.0606 \qquad s^2_a = 0.0855$$

Step 2. Compute F, using the largest s^2 in the numerator.

$$F = \frac{s_a^{\ 2}}{s_c^{\ 2}} = \frac{0.0855}{0.0606} = 1.41$$

Step 3. Determine F_{crit} from Table 1 being sure to use the correct degrees of freedom for the numerator ($n_a - 1 = 8 - 1 = 7$) and the denominator ($n_c - 1 = 21 - 1 = 20$). From Table 1, $F_{crit} = 4.26$.

Conclusion: Since $F < F_{crit}$ (i.e., $1.41 < 4.26$), there is no reason to believe that the two sets of tests have different variabilities. That is, they could have come from the same population. Since we can assume that the variances are equal, we can use the pooled variance to calculate the t-test statistic and the pooled degrees of freedom to determine the critical t value, t_{crit}

Step 4. Compute the mean, $\bar{x}$, for each set of tests.

$$\bar{x}_c = 6.15 \qquad \bar{x}_a = 5.64$$

Step 5. Compute the pooled variance, s^2_p, using the sample variances from above.

$$s_p^{\ 2} = \frac{s_c^{\ 2}(n_c - 1) + s_a^{\ 2}(n_a - 1)}{n_c + n_a - 2}$$

$$s_p^{\ 2} = \frac{(0.0606)(20) + (0.0855)(7)}{21 + 8 - 2} = 0.067$$

Step 6. Compute the t-test statistic, t.

$$t = \frac{|\bar{x}_c - \bar{x}_a|}{\sqrt{\dfrac{s_p^{\ 2}}{n_c} + \dfrac{s_p^{\ 2}}{n_a}}}$$

$$t = \frac{|6.15 - 5.64|}{\sqrt{\dfrac{0.067}{21} + \dfrac{0.067}{8}}} = \frac{0.51}{\sqrt{0.0116}} = 4.735$$

Step 7. Determine the critical t value, t_{crit}, for the pooled degrees of freedom.

$$\text{degrees of freedom} = (n_c + n_a - 2) = (21 + 8 - 2) = 27$$

From Table 2, for $\alpha = 0.01$ and 27 degrees of freedom, $t_{crit} = 2.771$.

Conclusion: Since $4.735 > 2.771$, we assume that the sample means are not equal. It is therefore probable that the two sets of tests did not come from the same population.

Example Problem: Case 2

A Contractor has run 25 QC tests and the SHA has run 10 acceptance tests over the same period of time for the same material property. The results are shown below. Is it likely that the test came from the same population?

QC Test Results	Acceptance Test Results
21.4	34.7
20.2	16.8
24.5	16.2
24.2	27.7
23.1	20.3
22.7	16.8
23.5	20.0
15.5	19.0
17.9	11.3
24.1	22.3
18.6	
15.9	
17.0	
20.0	
24.2	

QC Test Results

14.6
19.7
16.0
23.1
20.8
14.6
16.4
22.0
18.7
24.2

First, use the F-test to determine whether to assume the variances of the QC tests differ from the acceptance tests.

Step 1. Compute the variance, s^2, for each set of tests.

$$s^2_c = 11.50 \qquad s^2_a = 43.30$$

Step 2. Compute F, using the largest s^2 in the numerator.

$$F = \frac{s_a^{\,2}}{s_c^{\,2}} = \frac{43.30}{11.50} = 3.76$$

Step 3. Determine F_{crit} from Table 1 being sure to use the correct degrees of freedom for the numerator ($n_a - 1 = 10 - 1 = 9$) and the denominator ($n_c - 1 = 25 - 1 = 24$).

Conclusion: Since $F > F_{crit}$ (i.e., $3.76 > 3.69$), there is reason to believe that the two sets of tests have different variabilities. That is, it is likely that they came from populations with different variances. Since we assume that the variances are not equal, we use the individual sample variances to calculate the t-test statistic and the approximate degrees of freedom to determine the critical t-value, t_{crit}.

Step 4. Compute the mean, $\bar{x}$, for each set of tests.

$$\bar{x}_c = 20.1 \qquad \bar{x}_a = 20.5$$

Step 5. Compute the t-test statistic, t.

$$t = \frac{|\bar{x}_c - \bar{x}_a|}{\sqrt{\dfrac{s_c^{\,2}}{n_c} + \dfrac{s_a^{\,2}}{n_a}}}$$

$$t = \frac{|20.1 - 20.5|}{\sqrt{\dfrac{11.50}{25} + \dfrac{43.30}{10}}} = \frac{0.4}{\sqrt{4.79}} = 0.183$$

Step 6. Determine the critical t value, t_{crit}, for the approximate degrees of freedom, f. Remember that the calculated effective degrees of freedom is rounded down to a whole number.

$$f = \frac{\left(\dfrac{s_c^{\,2} + s_a^{\,2}}{n_c n_a}\right)^2}{\left(\dfrac{\left(\dfrac{s_c^{\,2}}{n_c}\right)^2}{n_c + 1} + \dfrac{\left(\dfrac{s_a^{\,2}}{n_a}\right)^2}{n_a + 1}\right)}$$

$$f = \frac{\left(\dfrac{11.50}{25} + \dfrac{43.30}{10}\right)^2}{\left(\dfrac{\left(\dfrac{11.50}{25}\right)^2}{26} + \dfrac{\left(\dfrac{43.30}{10}\right)^2}{11}\right)} - 2 = \frac{(4.79)^2}{1.713} - 2 = 11$$

From Table 2, for $\alpha = 0.01$ and 11 degrees of freedom, $t_{crit} = 3.106$.

Conclusion: Since $t < t_{crit}$, (i.e., $0.183 < 3.106$), there is no reason to assume that the sample means are not equal. It is therefore reasonable to assume that the sets of test results came from populations that had the same mean.

APPENDIX H

QUALITY CONTROL TESTING OF ASPHALT BINDERS

Appendix H as submitted by the research agency is not published herein but is available for loan on request to the NCHRP.

APPENDIX I

SENSITIVITY OF SUPERPAVE MIXTURE TESTS TO CHANGES IN MIXTURE COMPONENTS

OBJECTIVE

NCHRP 9-7 was established to address the implementation of the asphalt products developed by SHRP from 1987 to 1992. The focus of this research was the development of procedures and equipment, if necessary, for quality control (QC) and quality assurance (QA) of Superpave asphalt mixtures. As part of the research program, a variety of tests were utilized in the field production of asphalt mixtures. NCHRP 9-7 focused research on mixtures that were designed and constructed using the Superpave mix design system on 11 projects in Kentucky, Mississippi, Virginia, Florida, Texas, Kansas, Maryland, and Alabama. Testing on these projects will provide data on mixture components, volumetric properties, and performance properties that will be analyzed to determine the appropriate level of QC/QA for projects using the Superpave mix design system.

The goal of the research of NCHRP 9-7 is to recommend the appropriate tests, test procedures, and testing frequency to assure that the produced mixture will perform satisfactorily as a part of the total pavement structure. The Superpave system uses a series of mixture tests that will yield the fundamental mechanical properties of a compacted mixture specimen. These test results may be analyzed to provide a determination of material properties. The original intent of many of these tests was that they would be input into performance models developed during SHRP that will output a prediction of various forms of pavement distress as a function of time or traffic. This level of prediction was formerly referred to as a Superpave Level 3 mix design.

Superpave performance tests utilize the Superpave Shear Tester (SST) and Indirect Tensile Tester (IDT). A complete characterization of material properties using the Superpave performance tests would involve an extensive testing program requiring much time and expense. The equipment alone may cost a laboratory in excess of $250,000.

Since there is a substantial investment of time and money required to perform advanced performance testing in Superpave, it is not likely that these tests can be routinely used for QC/QA operations. Consequently, it is the goal of the research plan to identify those mixture tests, and properties, which can be used to assure adequate performance in lieu of the advanced performance tests. It is possible that the performance tests can be simplified for routine use. The question then remains “How sensitive are these mixture tests to changes in key mixture components?” In other words, if asphalt binder content was increased by 0.5 percent (within the normal production tolerance range established by some agencies), will the Superpave mixture tests detect the change and result in a change in material properties? If so, is it sufficient to specify *only* these tests as the basis for the assurance of performance of a mixture? Or, possibly can other tests be specified as “surrogate” performance tests or performance-related tests that will assure adequate mixture behavior?

The purpose of this research is to analyze whether laboratory changes in mixture components will result in significant mixture property (volumetric and mechanical) changes. The tools used to execute this research will be the Superpave Gyratory Compactor (SGC) for volumetric properties, and the SST for mechanical properties. Low-temperature testing using the IDT will not be considered in this research.

This experiment is designed to investigate changes in the following input variables:

- Asphalt binder content;
- Change in coarse aggregate gradation (material retained on the 4.75-mm sieve);
- Change in intermediate aggregate gradation (material passing the 4.75-mm sieve and retained on the 0.3-mm sieve);
- Change in fine aggregate gradation (material passing the 0.3-mm sieve); and
- Change in ratio of natural and crushed sands.

The SGC will be used to evaluate the effects of changes in the input variables on the response variables indicated below:

- Percent of densification (G_{mm}) or air voids (V_a), at N_{design};
- Percent of densification (G_{mm}) at $N_{initial}$ and $N_{maximum}$; and
- Densification slope (G_{mm} as a function of number of gyrations).

The SST will be used to evaluate the effects of changes in the input variables on the response variables indicated below:

- Complex shear modulus and shear loss modulus (frequency sweep);
- Maximum and final shear strain (simple shear);
- Permanent shear strain (repeated simple shear-constant height); and
- Rate of change in permanent shear strain with loading cycles.

TABLE 1 Controlled variables in field sensitivity experiment

Controlled Variable	Number of Levels
Asphalt Binder Content	2
Coarse Aggregate Gradation	2
Intermediate Aggregate Gradation	2
Fine Aggregate Gradation	2
Ratio of Natural and Crushed Sands	2

EXPERIMENT DESIGN

The experiment consisted of compaction of several variations of one asphalt-aggregate combination. The number of controlled variables and levels are shown in Table 1. A brief description of each variable and level follows.

Baseline Mixture Design

One mixture design was used as the control. Properties of the selected mix design were the medium (baseline) value for each variable listed in Table 1.

The baseline mixture design selected for this study was a 19.0-mm nominal mix consisting of crushed limestone (coarse and fine) and natural sand. This mixture is representative of one that might be used in Kentucky. Two fine aggregates were used in this mixture, one natural, the other manufactured. Gradation of the control mixture is shown in Figure 1.

Asphalt Binder Content

The design asphalt binder content of the control mixture is 4.7 percent. Mixtures in the field sensitivity experiment have two asphalt content levels: high and low as shown in Table 2. These levels are representative of normal, acceptable production tolerances.

TABLE 2 Definition of asphalt content levels

Level	Value
1. Low	4.2%, (Design minus 0.5%)
2. High	5.2%, (Design plus 0.5%)

Coarse Aggregate Gradation

The control mixture has a high percentage of coarse aggregate: 30 percent limestone no. 57s and 38 percent limestone no. 8s. As a result, the percent passing the 2.36-mm sieve is near the minimum control point for a 19.0-mm mixture. During production, it would be possible that the coarse aggregate gradation would change. Production tolerances on the coarse sieve set (2.36-mm sieve and greater) are typically ±6 percent. Table 3 shows the two levels used in this experiment for coarse gradation. The gradation on the 19.0-, 12.5-, 9.5-, and 4.75-mm sieves was adjusted above and below the design values.

Intermediate Aggregate Gradation

Production tolerances on the intermediate sieve set (2.36-, 1.18-, and 0.6-mm sieves) are typically anywhere from ±4 percent to ±6 percent. Two levels were used in the experiment. The gradation on the 2.36-, 1.18-, and 0.6-mm sieves was adjusted above and below the design values (Table 4).

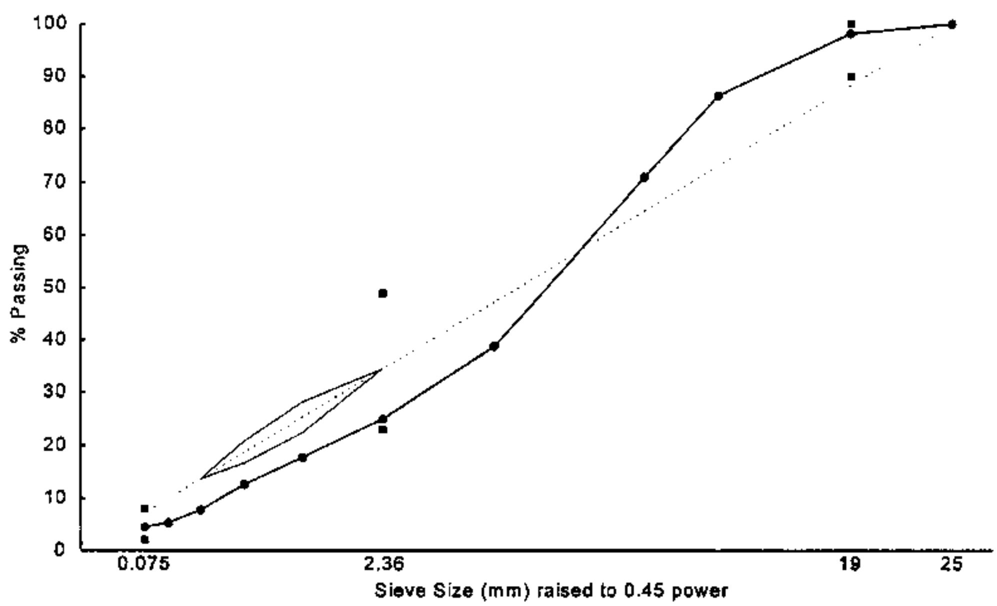


Figure 1. Gradation of control mixture for field sensitivity experiment.

TABLE 3 Definition of levels for coarse aggregate gradation

Level	Gradation, % Passing			
	19.0 mm	12.5 mm	9.5 mm	4.75 mm
1. Low	92.2	80.4	65.0	32.8
2. High	100.0	92.4	77.0	44.8

TABLE 4 Definition of levels for intermediate aggregate gradation

Level	Gradation, % Passing		
	2.36 mm	1.18 mm	0.6 mm
1. Low	19.1	13.7	8.6
2. High	31.1	21.7	16.6

TABLE 5 Definition of levels for fine aggregate gradation

Level	Gradation, % Passing		
	0.3 mm	0.15 mm	0.075 mm
1. Low	4.8	3.3	2.6
2. High	10.8	7.3	6.6

Fine Aggregate Gradation

Fine aggregate gradation comprises the fine sieve set (0.3-, 0.15-, and 0.075-mm sieves) as shown in Table 5. Specification control points for the 0.075-mm sieve in a 19.0-mm nominal maximum gradation are 2 percent to 8 percent. Normally, an increase in the dust content of a mixture (material finer than 0.075-mm) results in similar increases in the percents passing the 0.3- and 0.15-mm sieves. Two levels were used for the experiment to represent normal, acceptable production tolerances for the fine set of sieves.

Ratio of Natural and Crushed Sand

Table 6 shows that the proportion of fine aggregate (smaller than 2.36-mm sieve) was varied between natural and manufactured sand while maintaining the same design percentage of total fine aggregate (32 percent). Two levels of natural sand/manufactured sand were used for the experiment.

Replicates

Three replicate specimens were produced for testing the volumetric and mechanical properties of the mixture. For each cell of the partial factorial experiment, the following were produced:

TABLE 6 Definition of levels for ratio of natural and crushed sand

Level	Value
1. Low	0%/32%, (Lower proportion of natural sand than design mixture)
2. High	20%/12%, (Higher proportion of natural sand than design mixture)

- Three SGC specimens compacted to $N_{maximum}$ (volumetric properties);
- Two G_{mm} specimens (volumetric properties); and
- Five SGC specimens compacted to 7 percent air voids and 140-mm height (materials tests).

The SGC compacted specimens for performance testing (140-mm height) were sawed into two test specimens (50-mm height).

Experimental Design

The experiment was designed as a quarter factorial of a 2^5 design; a 2_{III}^{5-2} fractional factorial with a center point (control). A full factorial 2^5 design required a total of 256 compacted specimens (32 cells, plus one center point, with a minimum of eight compacted specimens per cell). The 2_{III}^{5-2} fractional factorial design reduced the number of compacted specimens to 72. Table 7 indicates the experimental design. Gradations for each of the 9 blends are indicated in the appendix.

High and low levels of each of these variables were described previously. The center point (Blend 1) is not shown in the testing matrix. Table 8 describes the experimental design with alias structure.

If all third-order and higher interactions are considered negligible, then the 2_{III}^{5-2} experimental design provides data on main effects aliased with second-order interactions involving variable A (asphalt content).

Specimen Preparation and Testing

Specimens prepared with the SGC for determination of mixture volumetric and densification properties had dimensions of 150-mm diameter and 115-mm height. Specimens were compacted to $N_{maximum}$. The Superpave compaction protocol (AASHTO TP4) was used.

Mixing temperature was selected at a viscosity of the unaged asphalt binder of 0.17 ± 0.02 Pascal-seconds. Compaction temperature was selected at a viscosity of 0.28 ± 0.03 Pascal-seconds. The asphalt binder used in this experiment was a PG 64-22. The mixing and compaction temperature ranges for this asphalt binder were 155 to 161°C and 143 to 148°C respectively. All mixtures were subjected to short-term oven aging for 4 h in a forced draft oven at 135°C.

Densification curves were generated for each specimen from $N_{initial}$ (8 gyrations) to $N_{maximum}$ (152 gyrations). The design number of gyrations was 96 gyrations. The densification slope was calculated as the change in percent G_{mm} as a function of the change in number of gyrations from $N_{initial}$ to N_{design}.

Three compacted specimens and two G_{mm} specimens were produced for determination of mixture volumetric and densification properties for each of the nine cells in the experiment.

TABLE 7 Field sensitivity experiment: Experimental matrix

		A_0				A_1			
		B_0		B_1		B_0		B_1	
		C_0	C_1	C_0	C_1	C_0	C_1	C_0	C_1
D_0	E_0				B8	B3			
	E_1			B4			B7		
D_1	E_0		B6					B5	
	E_1	B2							B9

Where: A_0 is the low level of variable A, B_1 is the high level of variable B, etc. B3 is Blend 3, etc.

Variable A is asphalt binder content.
Variable B is fine aggregate gradation.
Variable C is coarse aggregate gradation.
Variable D is intermediate aggregate gradation.
Variable E is ratio of natural and crushed sands.

Specimens prepared with the SGC for determination of mixture mechanical properties had dimensions of 150-mm diameter and 140-mm height. The mass of the mixture was varied to produce specimens with 7 percent air voids.

A minimum of five compacted specimens were produced at approximately 7 percent air voids for each of the nine cells in the experiment. These specimens were cut to produce specimens with dimensions of 150-mm diameter and 50-mm height. The percent air voids of each specimen was determined in accordance with AASHTO T 166.

Although AASHTO TP7 does not have any tolerances on the percent of air voids, it was desired to produce specimens with air voids between 6.5 and 7.5 percent. This range was selected to reasonably minimize variations in mechanical properties due to changes in air voids. During production of the specimens it was discovered that maintaining a 0.5 percent tolerance on air voids resulted in approximately 50 percent of the produced test specimens being discarded as out of tolerance. Consequently, the number of compacted specimens required to complete the 9 cells of the experiment increased from 72 to 90. In addition, during testing some specimens, approximately 10 to 20 percent, were destroyed or provided unusable data. This necessitated further test specimens. As a result of these difficulties, the tolerance was generally increased to allow a 1.0 percent tolerance from the 7 percent air voids target.

For each blend, three specimens were tested using the procedures described in AASHTO TP7 for Simple Shear at Constant Height (SSCH) and Frequency Sweep at Constant Height (FSCH) at two test temperatures (26°C and 41°C). The output of the SSCH test is a measurement of shear deformation as a shear load is increased, held, and decreased. The maximum and final shear strains will be analyzed. The output of the FSCH test is a determination of the response of the complex shear modulus, G*, and phase angle to frequency of loading.

Three specimens were also tested using the procedures described in AASHTO TP7 for Repeated Simple Shear at Constant Height (RSST-CH) at 54°C. The output of the RSST-CH is a determination of the permanent shear strain after a number of load cycles. The slope (m_{RSST}) of the curve (permanent shear strain as a function of load cycles) was also evaluated for each test specimen.

The recommended procedure for performing the RSST-CH (SHRP A-698) requires specimen air voids to be approx-

TABLE 8 Experimental design and alias structure

Variable							
A	B	C	D=AB	E=AC	Treatment	Blend	Effect
L	L	L	H	H	(1) (de)	2	-
H	L	L	L	L	a	3	l_A = A+BD+CE+ABCDE
L	H	L	L	H	b (e)	4	l_B = B+AD+CDE+ABCE
H	H	L	H	L	ab (d)	5	l_{AB} = AB+D+BCE+ACDE
L	L	H	H	L	c (d)	6	l_C = C+AE+BDE+ABCD
H	L	H	L	H	ac (e)	7	l_{AC} = AC+E+BCD+ABDE
L	H	H	L	L	bc	8	l_{BC} = BC+DE+ACD+ABE
H	H	H	H	H	abc (de)	9	l_{ABC} = BE+CD+ABC+ADE

The alias structure is determined from the defining relation I = ABD = ACE = BCDE:

A = BD	= CE	= ABCDE
B = AD	= ABCE	= CDE
C = ABCD	= AE	= BDE
D = AB	= ACDE	= BCE
E = ABDE	= AC	= BCD
BC = ACD	= ABE	= DE
BE = ADE	= ABC	= CD

imately 3 percent. For practical reasons described later, RSST-CH specimens had the same air voids as the other performance specimens (approximately 7 percent).

EXPERIMENTAL RESULTS

Phase 1: Volumetric and Densification Properties

Phase 1 testing examined the response of mixture volumetric and densification properties for the 2_{III}^{5-2} fractional factorial. Table 9 indicates the test values for the average volumetric and densification properties for the nine mixtures in the experiment.

Table 9 indicates that the percent air voids at N_{design} varied from 0.0 percent to 8.6 percent. If asphalt binder content alone affected the percentage of air voids at N_{design}, the range would have been from approximately 3.0 percent to 5.4 percent. These expected values come from the Superpave equation for estimating the design asphalt content from trial specimens

$$P_b = P_{bi} - [0.4*(4 - V_a)]$$

where

P_b = estimated design asphalt content;
P_{bi} = trial asphalt content; and
V_a = trial specimen air voids.

Solving for the percent of air voids, V_a, and substituting the actual design asphalt content (4.7 percent) and design air voids (4.2 percent) yields

$$V_a = [2.5*(4.7 - P_{bi})] + 4.2$$

where

P_{bi} = trial asphalt content (4.2 percent or 5.2 percent).

Since the percentage of air voids was less than 3.0 percent for two mixtures and greater than 5.4 percent for three mixtures, it is likely that some of the other variables contributed to the mixture volumetric properties.

TABLE 9 Mixture volumetric and densification properties

Blend	%G_{mm} N_{ini}	%G_{mm} N_{des}	%G_{mm} N_{max}	Slope	%Air Voids	%VMA
1	85.1	95.8	97.4	9.93	4.2	13.7
2	88.4	96.3	97.5	7.34	3.7	12.6
3	83.2	94.6	96.3	10.52	5.4	15.5
4	83.4	94.0	95.6	9.76	6.0	14.2
5	89.9	100.0	100.2	9.35	0.0	10.8
6	84.2	94.2	95.8	9.26	5.8	13.9
7	81.4	91.4	92.9	9.31	8.6	18.3
8	80.8	91.8	93.5	10.24	8.2	15.9
9	89.4	99.6	99.9	9.43	0.4	11.5

Percent G_{mm} at N_{design}

An analysis was performed on the set of eight mixtures in the fractional factorial experiment to determine if any of the five experimental variables had a significant effect on the densification at the design number of gyrations, percent G_{mm} at N_{design}. The ninth mixture, Blend 1, was the center point or the control mixture and provides a reference for the analysis.

An estimate of the effect of the variables can be determined by combining the data in Tables 8 and 9 and ignoring third-order and higher interactions

$$l_A = A+BD+CE = 0.083*(-96.3 + 94.6 - 94.0 + 100.0 - 94.2 + 91.4 - 91.8 + 99.6) = 0.775$$
$$l_B = B+AD = 0.083*(-96.3 - 94.6 + 94.0 + 100.0 - 94.2 - 91.4 + 91.8 + 99.6) = 0.742$$
$$l_{AB} = AB+D = 0.083*(96.3 - 94.6 - 94.0 + 100.0 + 94.2 - 91.4 - 91.8 + 99.6) = 1.525$$
$$l_C = C+AE = 0.083*(-96.3 - 94.6 - 94.0 - 100.0 + 94.2 + 91.4 + 91.8 + 99.6) = -0.658$$
$$l_{AC} = AC+E = 0.083*(96.3 - 94.6 + 94.0 - 100.0 - 94.2 + 91.4 - 91.8 + 99.6) = 0.058$$
$$l_{BC} = BC+DE = 0.083*(96.3 + 94.6 - 94.0 - 100.0 - 94.2 - 91.4 + 91.8 + 99.6) = 0.225$$
$$l_{ABC} = CD+BE = 0.083*(-96.3 + 94.6 + 94.0 - 100.0 + 94.2 - 91.4 - 91.8 + 99.6) = 0.242$$

The estimate of effects determined above indicate that the significant effects appear to be as follows (ranking from highest significant effect to lowest):

1. Variable **D** (intermediate gradation) aliased with the **interaction of A** (asphalt content) **and B** (fine gradation).
2. Variable **A** (asphalt content) aliased with the **interactions of B** (fine gradation) **and D** (intermediate gradation), ***and* C** (coarse gradation) **and E** (ratio of natural/crushed sand).
3. Variable **B** (fine gradation) aliased with the **interaction of A** (asphalt content) **and D** (intermediate gradation).
4. Variable **C** (coarse gradation) aliased with the **interaction of A** (asphalt content) **and E** (ratio of angular/natural sand).

As can be seen from the estimate of effects, the 2_{III}^{5-2} fractional factorial results in every main variable being aliased with at least one second-order interaction. From this analysis, it appears that the main effects of variables A, B, C, and D are significant, as well as most of the interactions involving variable A (asphalt binder content). The greatest value occurs with the D+AB effect. This is a mixed effect of variable D (intermediate aggregate gradation) and the interaction of variables A and B (asphalt binder content and fine aggregate gradation). The only nonsignificant effect apparently comes from variable E (ratio of natural/crushed sands). Since

TABLE 10 Experimental design and alias structure for complementary fraction

Variable							
A	B	C	D=-AB	E=-AC	Treatment	Blend	Effect
L	L	L	L	L	(1)	11	-
H	L	L	H	H	a (de)	10	l'_A = A-BD-CE+ABCDE
L	H	L	H	L	b (d)	13	l'_B = B-AD+CDE-ABCE
H	H	L	L	H	ab (e)	12	l'_{AB} = -AB+D+BCE-ACDE
L	L	H	L	H	c (e)	15	l'_C = C-AE+BDE-ABCD
H	L	H	H	L	ac (d)	14	l'_{AC} = -AC+E+BCD-ABDE
L	H	H	H	H	bc (de)	17	l'_{BC} = BC+DE-ACD-ABE
H	H	H	L	L	abc	16	l'_{ABC} = BE+CD-ABC-ADE

The alias structre is determined from the defining relation I = -ABD = -ACE = BCDE:

$$
\begin{aligned}
A &= BD &&= -CE &&= ABCDE\\
B &= AD &&= -ABCE &&= CDE\\
C &= ABCD &&= -AE &&= BDE\\
D &= AB &&= -ACDE &&= BCE\\
E &= ABDE &&= -AC &&= BCD\\
BC &= ACD &&= -ABE &&= DE\\
BE &= ADE &&= -ABC &&= CD
\end{aligned}
$$

all the main effects are aliased with a second-order interaction, it is virtually impossible to separate the significant variables contributing to the percent G_{mm} at N_{design} using only the data from the 2_{III}^{5-2} fractional factorial.

Rather than continuing the analysis, it was desired to perform testing on a complementary fractional factorial. The combination of the two fractions would allow the main variables to be isolated along with some second-order interactions. By reversing the levels of variable A in Table 8, and testing a second set of eight mixtures, the analysis would isolate all the main variables as well as the second-order interactions involving variable A (asphalt content). The resulting experimental matrix is indicated in Table 10.

Test results for the complementary fraction (Blends 10 to 17) are indicated in Table 11.

Table 11 indicates that the percent air voids at N_{design} varied from 1.2 to 9.4 percent. As noted previously, if asphalt binder content alone affected the percent of air voids at N_{design}, the range would have been from approximately 3.0 to 5.4 percent. Again, since the percentage of air voids was less than 3.0 percent for three mixtures and greater than 5.4 percent for three mixtures, it is an indication that some of the other variables contributed to the mixture volumetric properties.

An analysis was performed on the second set of eight mixtures in the complementary fraction to determine if any of the five experimental variables had a significant effect on the densification at the design number of gyrations, percent G_{mm} at N_{design}.

An estimate of the effect of the variables can be determined by combining the data in Tables 10 and 11, and ignoring third-order and higher interactions.

$$
\begin{aligned}
l'_A &= A-BD-CE = 0.083*(-96.3 + 94.6 - 94.0 + 100.0 - 94.2 + 91.4 - 91.8 + 99.6) = 0.542\\
l'_B &= B-AD = 0.083*(-96.3 - 94.6 + 94.0 + 100.0 - 94.2 - 91.4 + 91.8 + 99.6) = 0.608\\
l'_{AB} &= -AB+D = 0.083*(96.3 - 94.6 - 94.0 + 100.0 + 94.2 - 91.4 - 91.8 + 99.6) = 1.525\\
l'_C &= C-AE = 0.083*(-96.3 - 94.6 - 94.0 - 100.0 + 94.2 + 91.4 + 91.8 + 99.6) = -0.542\\
l'_{AC} &= -AC+E = 0.083*(96.3 - 94.6 + 94.0 - 100.0 - 94.2 + 91.4 - 91.8 + 99.6) = 0.208\\
l'_{BC} &= BC+DE = 0.083*(96.3 + 94.6 - 94.0 - 100.0 - 94.2 - 91.4 + 91.8 + 99.6) = 0.092\\
l'_{ABC} &= CD+BE = 0.083*(-96.3 + 94.6 + 94.0 - 100.0 + 94.2 - 91.4 - 91.8 + 99.6) = -0.208
\end{aligned}
$$

TABLE 11 Mixture volumetric and densification properties for complementary fraction

	%G_{mm}					
Blend	N_{ini}	N_{des}	N_{max}	Slope	%Air Voids	%VMA
10	89.9	98.8	99.8	8.27	1.2	12.3
11	82.3	92.6	94.1	9.48	7.4	15.2
12	85.8	96.4	98.0	9.81	3.6	14.3
13	86.8	98.1	99.6	10.50	1.9	10.2
14	86.2	96.9	98.5	9.90	3.1	13.5
15	81.2	90.6	92.1	8.72	9.4	17.6
16	82.9	93.8	95.4	10.15	6.2	16.3
17	87.9	98.0	99.4	9.41	2.0	11.0

Continuing the analysis of the complementary fraction of the experiment allows the complementary fractions to be analyzed together to isolate main effects. The data are indicated in Table 12.

By ignoring third-order interactions, Table 12 isolates all main variables and all second-order interactions including variable A (asphalt content). The estimate of effects determined above indicate that the significant effects appear to be as follows (ranking from highest significant effect to lowest):

1. The **interaction of** variable **A** (asphalt content) **and** variable **B** (fine gradation).
2. Variable **B** (fine gradation).
3. Variable **A** (asphalt content).
4. Variable **C** (coarse gradation).

From this analysis, it appears that the main effects of variables A, B, and C are significant, as well as the interaction of variables A and B. The greatest value occurs with this AB interaction. There appear to be two distinct groups of effects. The estimate of effect for the AB interaction is twice the value of the next highest estimates (B, A, and C). The B, A, and C variables likewise have estimates of effects that are three times greater than the next highest effect (CD + BE). It appears that all other variables and interactions, including the main variables of D (intermediate gradation) and E (ratio of natural/crushed sands), either do not have a significant effect on the percent G_{mm} at N_{design}, or affect percent G_{mm} at N_{design}, but not as much as the other effects (AB, B, A, and C). Of the two possibilities, the latter is the most likely—that the other variables and interactions have an effect on percent G_{mm} at N_{design}, but not as important an effect.

Examining the blends as being composed of three variables (A, B, and C) and ignoring the D and E variables can prove this theory. In this instance there are pairs of blends that have the same levels for the A, B, and C variables. The data are indicated in Table 13.

As indicated in Table 13, paired blends with the same asphalt content, coarse gradation and fine gradation, but different intermediate gradation and ratio of natural-to-crushed fine aggregate can result in values for percent G_{mm} at N_{design} varying by approximately 3 to 6 percent. The data in Table 13 indicate that both intermediate gradation and the ratio of natural-to-crushed fine aggregate appear to affect the percent air voids, or the percent G_{mm} at N_{design}. If variables D and E had an insignificant effect on the percent G_{mm} at N_{design}, the paired blends in Table 13 would have similar values. The fact that the paired blends have very different values indicates that variables D (intermediate gradation) and E (ratio of natural/crushed sands) have a potentially strong effect on the percent G_{mm} at N_{design}. With this conclusion, it appears that the assumption of ignoring all third-order and higher interactions is incorrect.

TABLE 12 Analysis of percent G_{mm} at N_{design}: Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	**0.658**	**A** + ABCDE	0.116	BD + CE
B	**0.675**	**B** + CDE	0.067	AD + ABCE
AB	**1.525**	**AB** + ACDE	0.000	D + BCE
C	**-0.600**	**C** + BDE	-0.058	AE + ABCD
AC	0.133	AC + ABDE	-0.075	E + BCD
BC	0.158	BC + DE	0.066	ACD + ABE
ABC	0.017	ABC + ADE	0.225	CD + BE

TABLE 13 Comparison of blends with variables D and E eliminated

Variable			Paired Blends	$\%G_{mm}$ at N_{design}	
A	B	C	(x,y)	Blend x	Blend y
L	L	L	(2,11)	96.3	92.6
H	L	L	(3,10)	94.6	98.8
L	H	L	(4,13)	94.0	98.1
H	H	L	(5,12)	100.0	96.4
L	L	H	(6,15)	94.2	90.6
H	L	H	(7,14)	91.4	96.9
L	H	H	(8,17)	91.8	98.0
H	H	H	(9,16)	99.6	93.8

The analysis of the data (indicated in Table 12) does not change with the change of assumption regarding all third-order and higher interactions. However, if all interactions are included, the significant effects change slightly for the data. The estimate of effects determined in Table 12 indicates that the significant effects appear to be as follows (ranking from highest significant effect to lowest):

1. The **interaction of A** (asphalt content) **and B** (fine gradation) ***aliased*** with the fourth-order **interaction of A**, **C** (coarse gradation), **D** (intermediate gradation), and **E** (ratio of natural/angular sand).
2. Variable **B** (fine gradation) ***aliased*** with the third-order **interaction of C** (coarse gradation), **D** (intermediate gradation), **and E** (ratio of natural/crushed sand).
3. Variable **A** (asphalt content) ***aliased*** with the fifth-order **interaction of all five variables—A, B, C, D,** and **E**.
4. Variable **C** (coarse gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **D** (intermediate gradation) **and E** (ratio of natural/crushed sand).

As can be seen, the D and E variables are apparent in each of these four "significant effects" as part of third-order or higher interactions. Based on this information, it appears that all interactions are potentially significant and cannot be ignored. Consequently, to isolate all the variables, a full factorial would be necessary. Since the experiment had already doubled in effort to add a complementary fraction, it was decided to analyze the existing data without completing the remaining two fractions of the full 2^5 factorial.

By selecting variable A as the main factor for analysis, the selection of the complementary fraction (with levels of A

TABLE 14 Comparison of complementary paired blends: Percent G_{mm} at N_{design}

Complementary Paired Blends (x,y)[1]	%G_{mm} at N_{design} Blend x	Blend y	Difference
(2,10)	96.3	98.8	2.5
(11,3)	92.6	94.6	2.0
(4,12)	94.0	96.4	2.4
(13,5)	98.1	100.0	1.9
(6,14)	94.2	96.9	2.7
(15,7)	90.6	91.4	0.8
(8,16)	91.8	93.8	2.0
(17,9)	98.0	99.6	1.6

[1] Blend with low level of variable A listed first.

reversed) resulted in variable A being isolated, with only one alias—the fifth-order interaction among all five variables, ABCDE. There are paired, complementary blends with the same levels of variables B, C, D, and E, but with the asphalt content, variable A, at different levels. Table 14 indicates the data for the percent G_{mm} at N_{design} for the complementary paired blends.

As indicated in Table 14, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand, but asphalt contents different by 1.0 percent show differences in percent G_{mm} at N_{design} of 0.8 to 2.7 percent. In all cases the low level of asphalt content produces values of percent G_{mm} at N_{design} lower than the high level of asphalt content. The values in Table 14 are consistent with the equations used in a Superpave volumetric mix design (1.0 percent change in asphalt content is approximately equal to 2.5 percent change in air voids).

Percent G_{mm} at $N_{initial}$

A similar analysis was performed on the set of 17 mixtures in the fractional factorial experiment to estimate the effects of changes in the five experimental variables on the percent G_{mm} at $N_{initial}$. The analysis of the data is indicated in Table 15.

The estimate of effects determined in Table 15 indicates results similar to those obtained in the analysis of the percent G_{mm} at N_{design}. The significant effects appear to be as follows (ranking from highest significant effect to lowest):

1. The **interaction of A** (asphalt content) **and B** (fine gradation) ***aliased*** with the fourth-order ***interaction of A***, **C** (coarse gradation), **D** (intermediate gradation), and **E** (ratio of natural/angular sand).
2. Variable **C** (coarse gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **D** (intermediate gradation) **and E** (ratio of natural/crushed sand).
3. Variable **A** (asphalt content) ***aliased*** with the fifth-order **interaction of all five variables—A, B, C, D,** and **E**.
4. The **interaction of A** (asphalt content) **and C** (coarse gradation) ***aliased*** with the fourth-order **interaction of A**, **B** (fine gradation), **D** (intermediate gradation), and **E** (ratio of natural/crushed sands).
5. Variable **B** (fine gradation) ***aliased*** with the third-order **interaction of C** (coarse gradation), **D** (intermediate gradation), **and E** (ratio of natural/crushed sand).

Once again, the AB interaction aliased with the ACDE interaction appears to be the most significant effect. The effect of variable C aliased with the BDE interaction appears to have more of an effect on the percent G_{mm} at $N_{initial}$ than it did at N_{design}. This is consistent with expectations as coarse asphalt mixtures typically have lower values of percent G_{mm} at $N_{initial}$ than fine mixtures.

Table 16 indicates the data for the percent G_{mm} at $N_{initial}$ for the complementary paired blends.

As indicated in Table 16, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand, but asphalt contents different by 1.0 percent show differences in percent G_{mm} at $N_{initial}$ of 0.2 to 3.1 percent. In all cases the low level of asphalt content produces values of percent G_{mm} at $N_{initial}$ lower than the high level of asphalt content.

Percent G_{mm} at $N_{maximum}$

The analysis was continued on the set of 17 mixtures in the fractional factorial experiment to estimate the effects of changes in the five experimental variables on the percent G_{mm} at $N_{maximum}$. The analysis of the data is indicated in Table 17.

TABLE 15 Analysis of percent G_{mm} at $N_{initial}$: Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	0.560	**A + ABCDE**	0.035	BD + CE
B	0.419	**B + CDE**	0.122	AD + ABCE
AB	1.738	**AB + ACDE**	0.190	D + BCE
C	-0.658	**C + BDE**	-0.106	AE + ABCD
AC	0.468	**AC + ABDE**	-0.096	E + BCD
BC	0.233	BC + DE	0.003	ACD + ABE
ABC	-0.060	ABC + ADE	0.043	CD + BE

TABLE 16 Comparison of complementary paired blends: Percent G_{mm} at $N_{initial}$

Complementary Paired Blends (x,y)[1]	%G_{mm} at $N_{initial}$ Blend x	Blend y	Difference
(2,10)	88.4	89.9	1.5
(11,3)	82.3	83.2	0.9
(4,12)	83.4	85.8	2.4
(13,5)	86.8	89.9	3.1
(6,14)	84.2	86.2	2.0
(15,7)	81.2	81.4	0.2
(8,16)	80.8	82.9	2.1
(17,9)	87.9	89.4	1.5

[1] Blend with low level of variable A listed first.

TABLE 17 Analysis of percent G_{mm} at $N_{maximum}$: Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	0.561	**A + ABCDE**	0.022	BD + CE
B	0.608	**B + CDE**	-0.053	AD + ABCE
AB	1.364	**AB + ACDE**	-0.108	D + BCE
C	-0.558	**C + BDE**	-0.058	AE + ABCD
AC	0.081	AC + ABDE	-0.064	E + BCD
BC	0.122	BC + DE	0.089	ACD + ABE
ABC	0.011	ABC + ADE	0.278	**CD + BE**

The estimate of effects determined in Table 17 indicate results identical to those obtained in the analysis of the percent G_{mm} at N_{design}. The significant effects appear to be as follows (ranking from highest significant effect to lowest):

1. The **interaction of A** (asphalt content) **and B** (fine gradation) ***aliased*** with the fourth-order **interaction of A, C** (coarse gradation), **D** (intermediate gradation), and **E** (ratio of natural/angular sand).
2. Variable **B** (fine gradation) ***aliased*** with the third-order **interaction of C** (coarse gradation), **D** (intermediate gradation), **and E** (ratio of natural/crushed sand).
3. Variable **A** (asphalt content) ***aliased*** with the fifth-order **interaction of all five variables—A, B, C, D,** and **E**.
4. Variable **C** (coarse gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **D** (intermediate gradation) **and E** (ratio of natural/crushed sand).

Once again, the AB interaction aliased with the ACDE interaction appears to be the most significant effect. Table 18 indicates the data for the percent G_{mm} at N_{design} for the complementary paired blends.

As indicated in Table 18, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand, but asphalt contents different by 1.0 percent show differences in percent G_{mm} at $N_{maximum}$ of 0.5 to 2.7 percent. In all cases the low level of asphalt content produces values of percent G_{mm} at $N_{maximum}$ lower than the high level of asphalt content.

TABLE 18 Comparison of complementary paired blends: Percent G_{mm} at $N_{maximum}$

Complementary Paired Blends (x,y)[1]	%G_{mm} at $N_{maximum}$ Blend x	Blend y	Difference
(2,10)	97.5	99.8	2.3
(11,3)	94.1	96.3	2.2
(4,12)	95.6	98.0	2.4
(13,5)	99.6	100.2	0.6
(6,14)	95.8	98.5	2.7
(15,7)	92.1	92.9	0.8
(8,16)	93.5	95.4	1.9
(17,9)	99.4	99.9	0.5

[1] Blend with low level of variable A listed first.

Densification Slope

The analysis was continued on the set of 17 mixtures in the fractional factorial experiment to estimate the effects of changes in the five experimental variables on the densification slope (m_{SGC}). This slope is calculated as the rate of change of percent G_{mm} versus the log of the number of gyrations from $N_{initial}$ to N_{design}. The analysis of the data is indicated in Table 19.

The estimate of effects determined in Table 19 indicate some different results than those obtained in the previous analyses. The significant effects appear to be as follows (ranking from highest significant effect to lowest):

1. The **interaction of A** (asphalt content) **and C** (coarse gradation) ***aliased*** with the fourth-order **interaction of A**, **B** (fine gradation), **D** (intermediate gradation), and **E** (ratio of natural/crushed sands).
2. Variable **B** (fine gradation) ***aliased*** with the third-order **interaction of C** (coarse gradation), **D** (intermediate gradation), **and E** (ratio of natural/crushed sand).
3. The **interaction of A** (asphalt content) **and B** (fine gradation) ***aliased*** with the fourth-order **interaction of A**, **C** (coarse gradation), **D** (intermediate gradation), and **E** (ratio of natural/angular sand).
4. Variable **D** (intermediate gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **C** (coarse gradation) **and E** (ratio of natural/crushed sand).
5. The **interaction of C** (coarse gradation) **and D** (intermediate gradation) ***aliased*** with the **interaction of B** (fine gradation) and **E** (ratio of natural/crushed sands).

This analysis provided several interesting bits of information. Although the AB interaction aliased with the ACDE interaction appeared to be the most significant effect for the densification parameters (percent G_{mm} at $N_{initial}$, N_{design}, and $N_{maximum}$), it was not as significant in affecting the densification slope (m_{SGC}). Also, while variable A (asphalt content) appeared to have a significant effect on all the densification parameters, it appeared that it did not significantly affect the densification slope. Once again, this is consistent with expectations in Superpave mix design, as densification slope is more strongly affected by changes in aggregate structure than by changes in asphalt content. The presence of variable D aliased

TABLE 19 Analysis of densification slope: Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	0.090	A + ABCDE	0.077	BD + CE
B	0.245	**B + CDE**	-0.049	AD + ABCE
AB	-0.188	**AB + ACDE**	-0.183	**D + BCE**
C	0.057	C + BDE	0.049	AE + ABCD
AC	-0.307	**AC + ABDE**	0.013	E + BCD
BC	-0.069	BC + DE	0.055	ACD + ABE
ABC	0.069	ABC + ADE	0.159	**CD + BE**

TABLE 20 Comparison of complementary paired blends: Densification slope

Complementary Paired Blends	Densification Slope		
(x,y)[1]	Blend x	Blend y	Difference
(2,10)	7.34	8.27	0.93
(11,3)	9.48	10.52	1.04
(4,12)	9.76	9.81	0.05
(13,5)	10.5	9.35	-1.15
(6,14)	9.26	9.90	0.64
(15,7)	8.72	9.31	0.59
(8,16)	10.24	10.15	-0.09
(17,9)	9.41	9.43	0.02

[1] Blend with low level of variable A listed first.

with the BCE interaction as a potentially significant effect is also interesting. For the first time, the intermediate gradation appears to have an effect on asphalt mixture densification properties. Since this effect is aliased with the BCE interaction it is difficult to tell which effect is more significant.

Table 20 indicates the data for the densification slope for the complementary paired blends.

As indicated in Table 20, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand, but asphalt contents different by 1.0 percent show differences in m_{SGC} of 0.02 to 1.15. Unlike the other comparisons, the low level of asphalt content did not always produce densification slope values lower than the high level of asphalt content.

Phase 2: Mechanical Property Testing

Phase 2 testing examined the response of mixture mechanical properties for complementary fractions of the 2_{III}^{5-2} fractional factorial. Tables 21 and 22 indicate the test values for the average mechanical properties for the 17 mixtures in the experiment.

TABLE 21 Mixture mechanical properties: Repeated and simple shear

	RSST-CH[1]		SS-CH[2]	
Blend	γ_{5000}, %	m_{RSST}	γ_{max}[3]	γ_{final}[3]
1	4.28	0.2589	2712	2082
2	7.47	0.3372	4751	3810
3	6.65	0.2914	4726	3838
4	5.53	0.2857	3045	2366
5	6.48	0.2475	6060	4958
6	4.14	0.2379	2095	1541
7	4.41	0.2544	4319	3524
8	4.15	0.2528	1272	918
9	10.90	0.3250	3580	2795
10	9.05	0.4178	4746	3699
11	3.32	0.2177	2251	1702
12	7.80	0.3832	4294	3524
13	4.22	0.2950	2363	1813
14	4.03	0.2642	1828	1418
15	3.60	0.2286	1601	1240
16	3.54	0.2573	3201	2487
17	6.16	0.3435	1998	1478

1 RSST-CH test executed at 54°C.
2 SS-CH test executed at 26°C.
3 Strain values reported as microstrain.

TABLE 22 Mixture mechanical properties: Frequency sweep

	10 Hz[1]		0.1 Hz[1]	
Blend	G*, kPa	G'', kPa	G*, kPa	G'', kPa
1	1,069,907	570,088	177,164	126,830
2	847,796	454,459	141,356	97,087
3	816,905	480,590	109,563	82,236
4	907,350	502,838	139,996	102,022
5	747,098	470,102	85,583	66,510
6	1,120,624	554,996	204,707	140,259
7	876,484	473,121	132,676	97,614
8	1,607,628	767,588	295,872	211,062
9	933,193	504,376	138,012	100,765
10	746,226	449,143	99,567	73,636
11	1,280,180	626,638	226,672	160,251
12	861,886	506,223	113,267	88,626
13	1,316,647	714,379	192,942	146,473
14	1,296,443	618,575	199,134	156,007
15	1,569,446	697,442	270,987	208,473
16	1,018,974	562,826	151,542	112,215
17	1,303,125	663,907	214,238	156,160

[1] FS-CH test executed at 26°C.

Repeated Shear Test: Constant Height (RSST-CH)

The 17 mixtures in the fractional factorial experiment were analyzed to estimate the effects of changes in the five experimental variables on the permanent shear strain at 5000 cycles (γ_{5000}) and the slope of the shear strain curve (m_{RSST}). The analysis of the data is indicated in Tables 23 and 24. A graphical representation of the data is illustrated in Figures 2 and 3.

TABLE 23 Analysis of γ_{5000} from RSST-CH: Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	0.595	**A + ABCDE**	0.001	BD + CE
B	0.254	B + CDE	0.111	AD + ABCE
AB	0.561	**AB + ACDE**	0.127	D + BCE
C	-0.400	**C + BDE**	0.189	AE + ABCD
AC	0.766	**AC + ABDE**	-0.192	E + BCD
BC	0.459	**BC + DE**	0.259	ACD + ABE
ABC	0.159	ABC + ADE	0.234	CD + BE

TABLE 24 Analysis of m_{RSST} from RSST-CH: Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	0.0101	**A + ABCDE**	-0.0097	**BD + CE**
B	0.0059	B + CDE	-0.0067	AD + ABCE
AB	0.0124	**AB + ACDE**	-0.0071	D + BCE
C	-0.0130	**C + BDE**	0.0053	AE + ABCD
AC	0.0213	**AC + ABDE**	-0.0069	E + BCD
BC	0.0103	**BC + DE**	0.0048	ACD + ABE
ABC	0.0016	ABC + ADE	0.0024	CD + BE

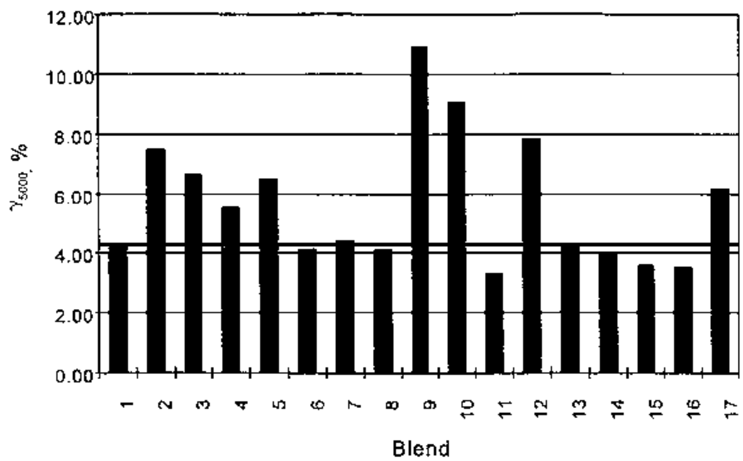


Figure 2. Permanent shear strain from repeated shear test.

The estimate of effects determined in Tables 23 and 24 indicates similar results. The significant effects appear to be as follows for the γ_{5000} (ranking from highest significant effect to lowest):

1. The **interaction of A** (asphalt content) **and C** (coarse gradation) ***aliased*** with the fourth-order **interaction of A, B** (fine gradation), **D** (intermediate gradation), and **E** (ratio of natural/angular sand).
2. Variable **A** (asphalt content) ***aliased*** with the fifth-order **interaction of all five variables—A, B, C, D,** and **E**.
3. The **interaction of A** (asphalt content) **and B** (fine gradation) ***aliased*** with the fourth-order **interaction of A**, **C** (coarse gradation), **D** (intermediate gradation), and **E** (ratio of natural/crushed sands).
4. The **interaction of B** (asphalt content) **and C** (coarse gradation) ***aliased*** with the **interaction of D** (intermediate gradation), and **E** (ratio of natural/crushed sands).
5. Variable **C** (coarse gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **D** (intermediate gradation) **and E** (ratio of natural/crushed sand).

The significant effects remain the same for the analysis of the m_{RSST}. The ranking changes only slightly with the A+ABCDE effect switching ranking position with the C+BDE effect.

There are two observations that can be made regarding the results of the repeated shear test. First, the most significant effect appears to be the interaction of asphalt content and coarse aggregate gradation. This effect is relatively insignificant in the analysis of the volumetric and densification properties. However, the AC interaction is the most significant effect in the analysis of the densification slope, m_{SGC}. The second observation is that, like the volumetric analysis, the D and E variables either are insignificant or do not have as great an effect on the results of the RSST-CH as the other main variables. Again, this hypothesis may be tested follow-

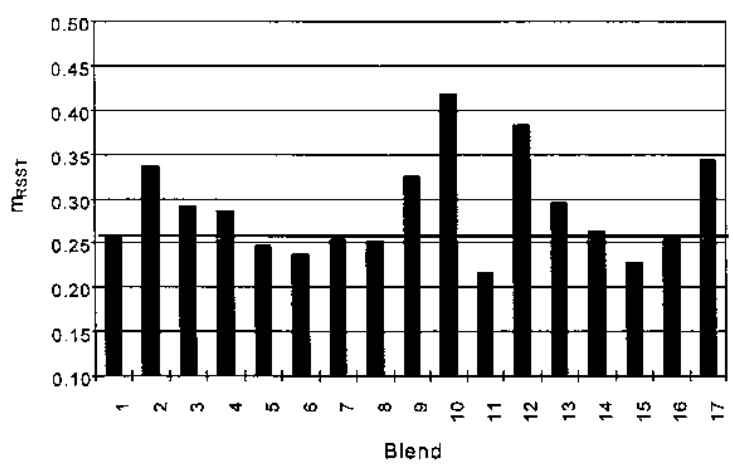


Figure 3. Shear strain slope from repeated shear test.

TABLE 25 Comparison of blends with variables D and E eliminated

Variable			Paired Blends	RSST-CH: γ_{5000}	
A	B	C	(x,y)	Blend x	Blend y
L	L	L	(2,11)	7.47	3.32
H	L	L	(3,10)	6.65	9.05
L	H	L	(4,13)	5.53	4.22
H	H	L	(5,12)	6.48	7.80
L	L	H	(6,15)	4.14	3.60
H	L	H	(7,14)	4.41	4.03
L	H	H	(8,17)	4.15	6.16
H	H	H	(9,16)	10.90	3.54

ing the analysis performed in Table 13. Examining the blends as being composed of three variables (A, B, and C) and ignoring the D and E variables completes the analysis. In this instance there are pairs of blends that have the same levels for the A, B, and C variables. The data are indicated in Tables 25 and 26.

As indicated in Tables 25 and 26, paired blends with the same asphalt content, coarse gradation, and fine gradation but different intermediate gradation and ratio of natural-to-angular fine aggregate can result in values for γ_{5000} varying by 0.38 to 7.36 percent. From Table 26, paired blends had results for m_{RSST} varying by 0.0093 to 0.1357. The data in Tables 25 and 26 indicate that both intermediate gradation and the ratio of natural-to-crushed sand appear to have some effect on the permanent shear strain (γ_{5000}) and slope (m_{RSST}). However, some of the paired blends, such as the 7,14 pair, indicate very little difference in the γ_{5000} and m_{RSST} results. This indicates that the D (intermediate gradation) and E (ratio of natural-to-angular fine aggregate) variables may not always have a significant effect on the RSST-CH results for some asphalt mixtures.

As noted before, the interaction of asphalt content and coarse aggregate gradation appears to be a significant effect in the densification slope (m_{SGC}) and the RSST-CH results (γ_{5000} and m_{RSST} results). This is a potentially significant result. The SGC is a shear compactor that operates by imparting a constant vertical pressure (600 kPa) at a specified angle (1.25 degrees) and speed of rotation (30 rpm) to create densification in the asphalt mixture specimen. The vertical pressure and angle create both normal and shear stresses in the asphalt mixture. The speed of rotation relates to the frequency of loading. This process is very similar to the repeated shear test, which imparts a shear stress at a specified frequency, along with a corresponding normal stress to maintain a constant specimen height. It is reasonable to assume that the rate of densification in the SGC (m_{SGC}) may be related to the shear resistance of a mixture, which in turn could relate to some parameter in the RSST-CH. Figures 4 to 6 illustrate the relationships between the densification slope, permanent shear strain, and shear strain slope from the RSST-CH.

TABLE 26 Comparison of blends with variables D and E eliminated

Variable			Paired Blends	RSST-CH: m_{RSST}	
A	B	C	(x,y)	Blend x	Blend y
L	L	L	(2,11)	0.3372	0.2177
H	L	L	(3,10)	0.2914	0.4178
L	H	L	(4,13)	0.2857	0.2950
H	H	L	(5,12)	0.2475	0.3832
L	L	H	(6,15)	0.2379	0.2286
H	L	H	(7,14)	0.2544	0.2642
L	H	H	(8,17)	0.2528	0.3435
H	H	H	(9,16)	0.3250	0.2573

Figure 4 indicates that there is some relationship between the permanent shear strain and the shear strain slope from the RSST-CH. This is an expected relationship since the permanent shear strain at 5000 cycles is typically included in the regression to determine shear strain slope. Figures 5 and 6

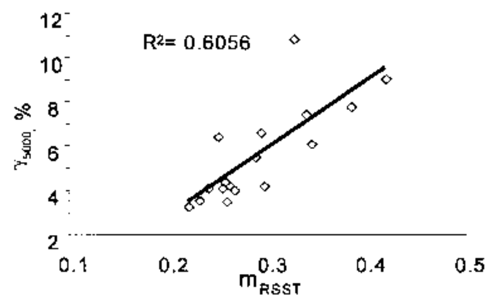


Figure 4. Relationship of permanent shear strain to shear slope.

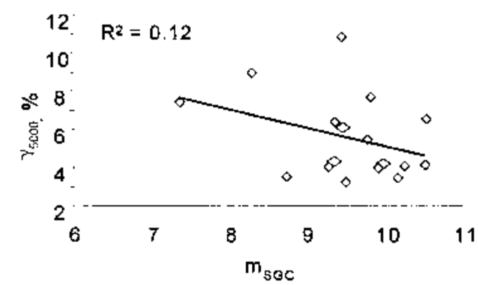


Figure 5. Relationship of permanent shear strain to densification slope.

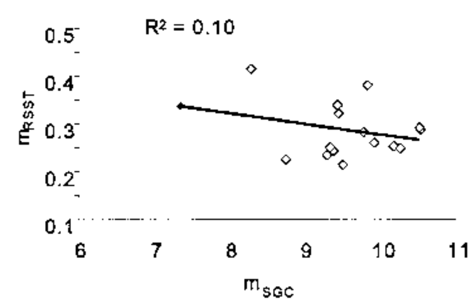


Figure 6. Relationship of shear slope to densification slope.

indicate no relationship between results of the RSST-CH (γ_{5000} and m_{RSST}) and the densification slope (m_{SGC}) from the SGC for the mixtures in this research.

There are several possible reasons for the lack of relationship between the densification slope and the results of the RSST-CH that could be explored. First, the RSST-CH as developed by the A-003A SHRP contract, was intended to be performed on specimens with approximately 3 percent air voids. Research during SHRP indicated that the permanent shear strain increased as the percentage of air voids in a specimen increased. Because the 17 blends in the research had significantly different air voids at N_{design} (0 to 9 percent), production of specimens at 3 percent air voids for all blends would be difficult. Consequently, to eliminate the effect of air voids as a variable, all mixtures were compacted to approximately 7 percent air voids. It is possible that a more apparent relationship will exist between the RSST-CH results and the densification slope at a lower air void level. Some internal research at the Asphalt Institute has indicated this effect (i.e., no relationship at 7 percent air voids, good relationship at 3 percent air voids).

A second possible reason that no relationship exists may be because of the effect of asphalt content (A+ABCDE) on the densification slope and the RSST-CH test results. As indicated in Table 19, asphalt content does not have a strong effect on the densification slope. As noted in the text following Table 19, this result corresponds well with the concepts in the Superpave volumetric mix design procedures. However, asphalt content appears to have an important effect on the permanent shear strain and shear strain slope from the RSST-CH. Tables 27 and 28 indicate the data for γ_{5000} and m_{RSST} for the complementary paired blends (blends with all variables the same except for asphalt content).

As indicated in Table 27, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand but asphalt contents different by 1.0 percent show differences in permanent shear strain from 0.11 to 4.74 percent. In six of the eight pairs, the low level of asphalt content produces values of γ_{5000} lower than the high level of asphalt content. Increasing asphalt content appears

TABLE 27 Comparison of complementary paired blends: Permanent shear strain

Complementary Paired Blends (x,y)[1]	γ_{5000} Blend x	Blend y	Difference
(2,10)	7.47	9.05	1.58
(11,3)	3.32	6.65	3.33
(4,12)	5.53	7.80	2.27
(13,5)	4.22	6.48	2.26
(6,14)	4.14	4.03	0.11
(15,7)	3.60	4.41	0.81
(8,16)	4.15	3.54	0.61
(17,9)	6.16	10.90	4.74

[1] Blend with low level of variable A listed first.

TABLE 28 Comparison of complementary paired blends: Shear strain slope

Complementary Paired Blends (x,y)[1]	m_{RSST} Blend x	Blend y	Difference
(2,10)	0.3372	0.4178	0.0806
(11,3)	0.2177	0.2914	0.0737
(4,12)	0.2857	0.3832	0.0975
(13,5)	0.2950	0.2475	0.0475
(6,14)	0.2379	0.2642	0.0263
(15,7)	0.2286	0.2544	0.0258
(8,16)	0.2528	0.2573	0.0045
(17,9)	0.3435	0.3250	0.0185

[1] Blend with low level of variable A listed first.

to increase the permanent shear strain. This result matches expectations. For two pairs (6,14 and 8,16) the high level of asphalt content has a lower permanent shear strain than the low level. However, the differences between the high and low asphalt contents for these pairs are small. Testing error may have resulted in the differences.

Data in Table 28 indicate a similar response as Table 27. Complementary paired blends show differences in shear strain slope from 0.0045 to 0.0975. Again, in six of the eight pairs, the low level of asphalt content produces values of m_{RSST} lower than the high level of asphalt content. Increasing asphalt content appears to increase the rate of accumulation of permanent shear strain. This result matches expectations. For two pairs (13,5 and 17,9) the high level of asphalt content has a lower shear strain slope than the low level. Once again, testing error may have resulted in the differences.

Finally, many of the apparent anomalies in the analysis of the data from the RSST-CH may be explained by testing error. Coefficients of variation (CV) for permanent shear strain (γ_{5000}) averaged 30 percent for all 17 mixtures. The median CV for all mixtures was 29 percent. The single mixture CV varied from 7 to 78 percent. These differences are substantial when attempting a statistical analysis. The CVs for shear strain slope were not as high as those for the permanent shear strain. Coefficients of variation for shear strain slope (m_{RSST}) averaged 14 percent for all 17 mixtures. The median CV for all mixtures was 10 percent. The single mixture CV varied from 2 to 45 percent.

Simple Shear (Constant Height)

The 17 mixtures in the fractional factorial experiment were analyzed to estimate the effects of changes in the five experimental variables on the results of the simple shear test at constant height (SS-CH)—maximum shear strain (γ_{max}) and final shear strain (γ_{final}). The data are indicated in Table 21 for the 17 mixtures at 26°C only. Values range from 1272 to 6060 µstrain for the 17 mixtures. An analysis of the data is indicated in Tables 29 and 30. A graphical representation of the data is illustrated in Figures 7 and 8.

TABLE 29 Analysis of γ_{max} from SS-CH (26°C): Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	557	**A + ABCDE**	69	BD + CE
B	-21	B + CDE	-140	AD + ABCE
AB	113	AB + ACDE	147	D + BCE
C	**-514**	**C + BDE**	-95	AE + ABCD
AC	189	AC + ABDE	-61	E + BCD
BC	38	BC + DE	-137	ACD + ABE
ABC	-59	ABC + ADE	-187	CD + BE

TABLE 30 Analysis of γ_{final} from SS-CH (26°C): Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	474	**A + ABCDE**	66	BD + CE
B	-18	B + CDE	-122	AD + ABCE
AB	80	AB + ACDE	125	D + BCE
C	**-430**	**C + BDE**	-87	AE + ABCD
AC	157	AC + ABDE	-53	E + BCD
BC	14	BC + DE	-100	ACD + ABE
ABC	-65	ABC + ADE	-158	CD + BE

The estimate of effects determined in Tables 29 and 30 indicates identical results. The significant effects appear to be as follows for the γ_{max} and γ_{final} (ranking from highest significant effect to lowest):

1. Variable **A** (asphalt content) ***aliased*** with the fifth-order **interaction of all five variables—A, B, C, D,** and **E**.
2. Variable **C** (coarse gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **D** (intermediate gradation), **and E** (ratio of natural/crushed sand).

The A+ABCDE and C+BDE effects appear to be much more significant than the other effects. Other potentially significant effects include the interaction of asphalt content and coarse gradation (AC+ABDE). Intermediate gradation (D+BCE) may have some effect on the shear strain values but not as much effect as the asphalt content and coarse gradation.

The results from the SS-CH tests at 26°C match the results from the RSST-CH at 54°C. In each case, the effects including asphalt content (A+ABCDE), coarse gradation (C+BDE), and their interaction (AC+ABDE) appear to affect the shear strain developed in the mixture.

Asphalt content appears to have an important effect on the maximum shear strain and final shear strain from the SS-CH. Tables 31 and 32 indicate the data for γ_{max} and γ_{final} for the complementary paired blends (blends with all variables the same except for asphalt content).

As indicated in Table 31, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand but asphalt contents different by 1.0 percent show differences in maximum shear strain from 5 to 3,697 µstrains. In six of the eight pairs, the low level of asphalt content produces values of γ_{max} lower than the high level of asphalt content. Increasing asphalt content appears to increase the maximum shear strain. This result matches expectations. For two pairs (2,10 and 6,14) the high level of asphalt content has a lower maximum shear strain than the low level. However, the differences between the high and low asphalt contents for these pairs are small (5 and 267 µstrains, respectively). Testing error may have resulted in the differences. It should be noted that the 6,14 pair also exhibited anomalous behavior in the RSST-CH. For this complementary pair, the permanent shear strain decreased slightly as the asphalt content increased.

Data in Table 32 indicate a similar response as Table 31. Complementary paired blends show differences in final

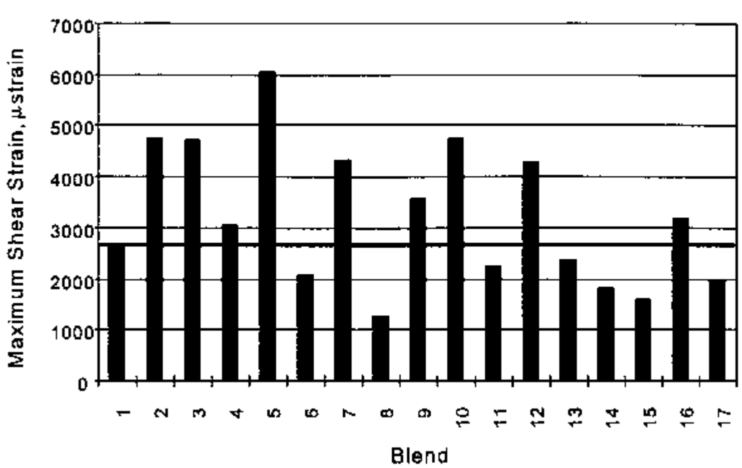


Figure 7. Maximum shear strain from simple shear test (26°C).

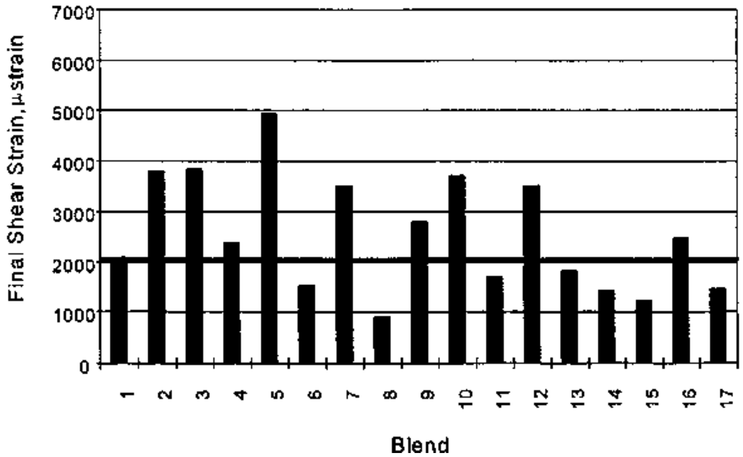


Figure 8. Final shear strain from simple shear test (26°C).

shear strain from 111 to 3,145 µstrains. Again, in six of the eight pairs, the low level of asphalt content produces values of γ_{final} lower than the high level of asphalt content. Increasing asphalt content appears to increase the final shear strain. This result matches expectations. The same two pairs (2,10 and 6,14) exhibit behavior where the high level of asphalt content has a lower final shear strain than the low level. Once again, testing error may have resulted in the differences.

CVs for maximum shear strain (γ_{max}) averaged 22 percent for all 17 mixtures. The median CV for all mixtures was 18 percent. The single mixture CV varied from 3 to 66 percent. The CVs for final shear strain were virtually identical to those for the maximum shear strain. CVs for final shear strain (γ_{final}) averaged 24 percent for all 17 mixtures. The median CV for all mixtures was 18 percent. The single mixture CV varied from 4 to 76 percent.

Although it was intended, a statistical analysis could not be performed on results of the SS-CH test at 41°C. Despite repeated attempts, several mixtures could not be accurately tested. These mixtures typically were destroyed during testing as LVDTs went out of range or the applied shear load sheared the specimen during the test. Table 33 indicates the results of the SS-CH tests at 26°C and 41°C. Despite the lack of statistical analysis, the effect of test temperature on a given mixture can be noted. This is illustrated in Figure 9.

Frequency Sweep (Constant Height)

The 17 mixtures in the fractional factorial experiment were analyzed to estimate the effects of changes in the five experimental variables on the complex shear modulus (G*) and phase angle (δ) of the mixtures. The product of G* and the sine of the phase angle yields the loss modulus (G*sin δ or G″). The data are indicated in Table 22 for the 17 mixtures at 26°C only. Values for G* at 10 Hz range from 746,226 to 1,607,628 kPa for the 17 mixtures. The analysis of the data is indicated in Tables 34 to 37. A graphical representation of the data is illustrated in Figures 10 to 13.

The estimate of effects determined in Tables 34 to 37 indicate virtually identical results. The significant effects appear to be as follows for the G* and G″ at 10 and 0.1 Hz (ranking from highest significant effect to lowest):

TABLE 31 Comparison of complementary paired blends: Maximum shear strain

Complementary Paired Blends (x,y)[1]	Blend x	γ_{max} Blend y	Difference
(2,10)	4751	4746	5
(11,3)	2251	4726	2475
(4,12)	3045	4294	1249
(13,5)	2363	6060	3697
(6,14)	2095	1828	267
(15,7)	1601	4319	2718
(8,16)	1272	3201	1929
(17,9)	1998	3580	1582

[1] Blend with low level of variable A listed first.

TABLE 32 Comparison of complementary paired blends: Final shear strain

Complementary Paired Blends (x,y)[1]	Blend x	γ_{final} Blend y	Difference
(2,10)	3810	3699	111
(11,3)	1702	3838	2136
(4,12)	2366	3524	1158
(13,5)	1813	4958	3145
(6,14)	1541	1418	123
(15,7)	1240	3524	2284
(8,16)	918	2487	1569
(17,9)	1478	2795	1317

[1] Blend with low level of variable A listed first.

TABLE 33 Simple shear test results at 26°C and 41°C

	γ_{max} (μstrains)	
Blend	26°C	41°C
1	2712	n/a
2	4751	5649
3	4726	n/a
4	3045	4577
5	6060	7990
6	2095	3688
7	4319	12975
8	1272	2700
9	3580	n/a
10	4746	n/a
11	2251	3561
12	4294	n/a
13	2363	3814
14	1828	6505
15	1601	4980
16	3201	4986
17	1998	3179

1. Variable **A** (asphalt content) ***aliased*** with the fifth-order **interaction of all five variables—A, B, C, D,** and **E**.
2. Variable **C** (coarse gradation) ***aliased*** with the third-order **interaction of B** (fine gradation), **D** (intermediate gradation) **and E** (ratio of natural/crushed sand).

The A+ABCDE and C+BDE effects appear to be much more significant than the other effects. Other potentially significant effects include the interaction of asphalt content and coarse gradation (AC+ABDE) and the mixed third-order interaction of ACD+ABE. Much like the results of the simple shear test, the fine gradation (B+CDE) appears to have little effect on the test results.

The results from the FS−CH tests at 26°C match the results from the RSST−CH at 54°C and the SS−CH tests at

TABLE 34 Analysis of G^*_{10Hz} from FS-CH (26°C): Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	-16036	**A + ABCDE**	2634	BD + CE
B	856	B + CDE	5586	AD + ABCE
AB	-3790	AB + ACDE	-2969	D + BCE
C	13296	**C + BDE**	1423	AE + ABCD
AC	-6999	AC + ABDE	-1787	E + BCD
B	-857	BC + DE	7548	ACD + ABE
ABC	-2363	ABC + ADE	-1272	CD + BE

TABLE 35 Analysis of $G^*_{0.1Hz}$ from FS-CH (26°C): Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	-3970	**A + ABCDE**	152	BD + CE
B	-321	B + CDE	1181	AD + ABCE
AB	-997	AB + ACDE	-313	D + BCE
C	3009	**C + BDE**	551	AE + ABCD
AC	-1304	AC + ABDE	-431	E + BCD
BC	227	BC + DE	1245	ACD + ABE
ABC	-613	ABC + ADE	-151	CD + BE

TABLE 36 Analysis of G''_{10Hz} from FS-CH (26°C): Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	-5539	**A + ABCDE**	1292	BD + CE
B	2037	B + CDE	1366	AD + ABCE
AB	-1131	AB + ACDE	-1770	D + BCE
C	3855	**C + BDE**	880	AE + ABCD
AC	-3286	**AC + ABDE**	-802	E + BCD
BC	-170	BC + DE	2657	**ACD + ABE**
ABC	-689	ABC + ADE	-791	CD + BE

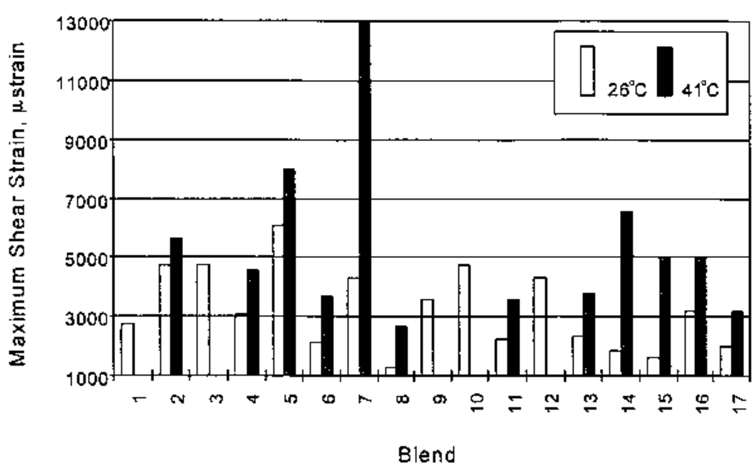


Figure 9. Effect of test temperature on simple shear test.

TABLE 37 Analysis of $G''_{0.1Hz}$ from FS-CH (26°C): Blends 1 to 17

i	Estimate of Effect	Effect	Estimate of Effect	Effect
A	-2682	**A + ABCDE**	227	BD + CE
B	-192	B + CDE	954	**AD + ABCE**
AB	-758	AB + ACDE	-308	D + BCE
C	2208	**C + BDE**	229	AE + ABCD
AC	-910	**AC + ABDE**	-329	E + BCD
BC	-76	BC + DE	1099	**ACD + ABE**
ABC	-406	ABC + ADE	-162	CD + BE

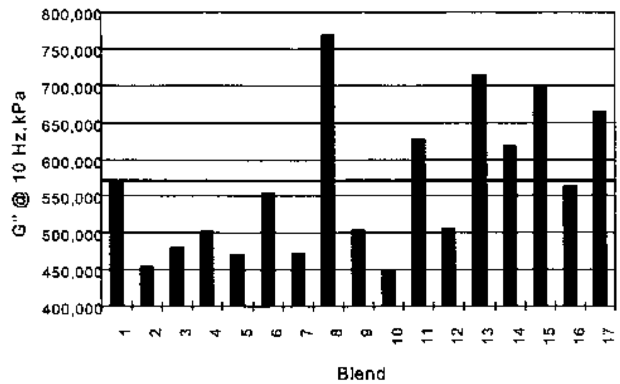


Figure 12. Shear loss modulus (G″) at 10 Hz from frequency sweep test (26°C).

26°C. In each case, the effects including asphalt content (A+ABCDE), coarse gradation (C+BDE), and their interaction (AC+ABDE) appear to affect the complex shear modulus (G*) and shear loss modulus (G″) developed in the mixture.

Asphalt content appears to have an important effect on the complex shear modulus and shear loss modulus from the FS-CH. Tables 38 and 39 indicate the data for G* and G″ at 10 Hz for the complementary paired blends (blends with all variables the same except for asphalt content).

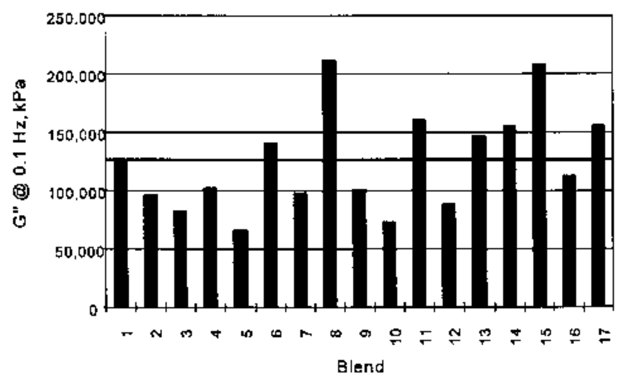


Figure 13. Shear loss modulus (G″) at 0.1 Hz from frequency sweep test (26°C).

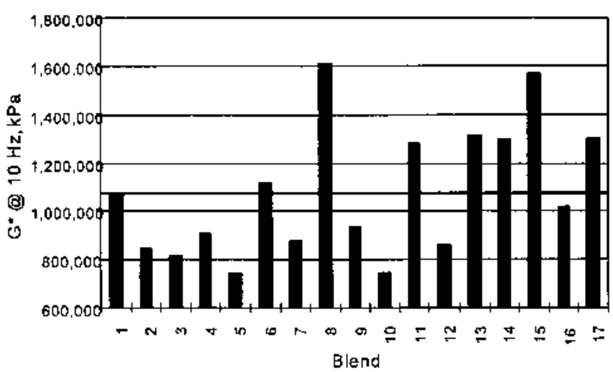


Figure 10. Complex shear modulus (G) at 10 Hz from frequency sweep test (26°C).*

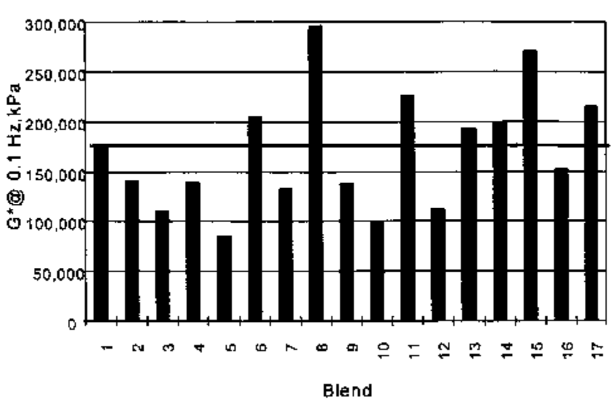


Figure 11. Complex shear modulus (G) at 0.1 Hz from frequency sweep test (26°C).*

As indicated in Table 38, complementary paired blends with the same gradation (coarse, intermediate, and fine) and ratio of natural/crushed sand but asphalt contents different by 1.0 percent show differences in complex shear modulus from 45,464 to 692,962 kPa. In seven of the eight pairs, the low

TABLE 38 Comparison of complementary paired blends: Complex shear modulus at 10 Hz

Complementary Paired Blends (x,y)[1]	G* (kPa) Blend x	Blend y	Difference
(2,10)	847,796	746,226	101,570
(11,3)	1,280,180	816,905	463,275
(4,12)	907,350	861,886	45,464
(13,5)	1,316,647	747,098	569,549
(6,14)	1,120,624	1,296,443	175,819
(15,7)	1,569,446	876,484	692,962
(8,16)	1,607,628	1,018,974	588,654
(17,9)	1,303,125	933,193	369,932

[1] Blend with low level of variable A listed first.

TABLE 39 Comparison of complementary paired blends: Shear loss modulus at 10 Hz

Complementary Paired Blends (x,y)[1]	G″ (kPa) Blend x	Blend y	Difference
(2,10)	454,459	449,143	5,316
(11,3)	626,638	480,590	146,048
(4,12)	502,838	506,223	3,385
(13,5)	714,379	470,102	244,277
(6,14)	554,996	618,575	63,579
(15,7)	697,442	473,121	224,321
(8,16)	767,588	562,826	204,762
(17,9)	663,907	504,376	159,531

[1] Blend with low level of variable A listed first.

level of asphalt content produces values of G* higher than the high level of asphalt content. Increasing asphalt content appears to decrease the complex shear modulus. This result matches expectations. For one pair (6,14) the high level of asphalt content has a higher complex shear modulus than the low level. It should be noted that the 6,14 pair also exhibited this anomalous behavior in the RSST-CH and SS-CH tests. For this complementary pair, the permanent shear strain decreased slightly as the asphalt content increased.

Data in Table 39 indicate a similar response as Table 38. Complementary paired blends show differences in shear loss modulus from 3,385 to 244,277 kPa. In six of the eight pairs, the low level of asphalt content produces values of G″ higher than the high level of asphalt content. Increasing asphalt content appears to decrease the shear loss modulus. This result matches expectations. Two pairs (4,12 and 6,14) exhibit behavior where the high level of asphalt content has a higher shear loss modulus than the low level. Testing error may have resulted in the differences in the 4,12 pair.

CVs for complex shear modulus (G*) at 10 Hz and 26°C averaged 11 percent for all 17 mixtures. The median CV for all mixtures was 9 percent. The single mixture CV varied from 3 to 42 percent. The CVs were essentially the same for the 0.1-Hz data. The CVs for shear loss modulus (G″) were virtually identical to those for the maximum shear strain. CVs for G″ at 10 Hz and 26°C averaged 9 percent for all 17 mixtures. The median CV for all mixtures was 9 percent. The single mixture CV varied from 0 to 35 percent.

Although it was intended, a statistical analysis could not be performed on results of the FS-CH test at 41°C. Table 40 indicates the results of the FS-CH tests (G* at 10 Hz) at 26°C and 41°C. Despite the lack of statistical analysis, the effect of test temperature on a given mixture can be noted. This is illustrated in Figure 14.

TABLE 40 Frequency sweep test results at 26°C and 41°C

Blend	G^*_{10Hz} (kPa) 26°C	41°C
1	1,069,907	192,077
2	847,796	267,917
3	816,905	n/a
4	907,350	331,138
5	747,098	132,924
6	1,120,624	270,195
7	876,484	191,480
8	1,607,628	518,486
9	933,193	217,999
10	746,226	84,453
11	1,280,180	323,055
12	861,886	n/a
13	1,316,647	501,699
14	1,296,443	272,328
15	1,569,446	390,027
16	1,018,974	304,279
17	1,303,125	n/a

SUMMARY

Variables and levels were selected to represent normal variables and allowable production tolerances in the production of an asphalt mixture. The following variables were selected:

- Variable A: Asphalt content;
- Variable B: Fine gradation (0.3-mm sieves and smaller);
- Variable C: Coarse gradation (4.75-mm sieves and larger);
- Variable D: Intermediate gradation (2.36-, 1.18-, and 0.6-mm sieves); and
- Variable E: Ratio of natural and crushed sand.

High and low values for these variables were established based on normal production tolerances. These tolerances are as follows:

- ±6 percent on all sieves 2.36 mm and larger;
- ±4 percent on 1.18- and 0.6-mm sieves;
- ±3 percent on 0.3-mm sieve;
- ±2 percent on 0.15- and 0.075-mm sieves;
- ±0.5 percent on asphalt content; and
- ±10 percent on natural sand.

Volumetric and densification properties were analyzed including: percent G_{mm} at N_{design} (or percent of air voids), percent G_{mm} at $N_{initial}$, percent G_{mm} at $N_{maximum}$, and densification slope (m_{SGC}). Mechanical properties were analyzed including permanent shear strain (γ_{5000}) from the RSST-CH, rate of accumulation of permanent shear strain (m_{RSST}) from the RSST-CH, maximum shear strain (γ_{max}) from the SS-CH, final shear strain (γ_{final}) from the SS-CH, complex shear modulus (G*) from FS-CH, and shear loss modulus (G″) from the FS-CH.

Blends 2 to16 are variations, within acceptable tolerances, of the control mixture (Blend 1). It is important to note that the blends used in testing are artificially created to meet the requirements of the experiment to study the effects of the variables on material properties. Many of these blends would not occur naturally during production.

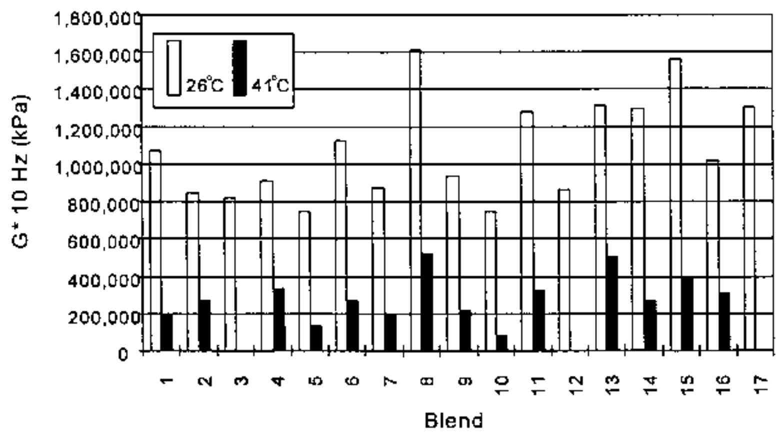


Figure 14. Effect of test temperature on frequency sweep test.

CONCLUSIONS

The conclusions of this study pertain to the specific combination of materials used in the experiment. It is very likely that different aggregates and gradations will have different sensitivities to changes in material components. For instance, a 9.5-mm gravel mixture may have a different sensitivity to changes in intermediate gradation than the study mixture.

Volumetric and Densification Properties

1. The 17 blends resulted in compacted specimens with air voids from 0.0 to 9.4 percent at N_{design}. The control mixture (Blend 1) had 4.2 percent air voids. The VMA varied from 10.2 to 18.3 percent at N_{design}. The control mixture had 13.7 percent VMA.
2. Complementary pairs (all variables with same levels except for asphalt content) indicated air void differences from 0.8 to 2.7 percent. In all cases, the blend with the higher asphalt content resulted in the higher percent G_{mm} at N_{design} and lower air voids. The differences between complementary pairs are consistent with expectations from the Superpave mix design equations. Superpave equations relate 1 percent change in asphalt content to 2.5 percent change in air voids.
3. Initial analysis of percent G_{mm} at N_{design} indicated that the main effects of asphalt content, fine gradation, and coarse gradation, as well as the interaction of asphalt content and fine gradation, have significant effects on the percent G_{mm} at N_{design} (percent of air voids).
4. The main effects of intermediate gradation and ratio of natural and crushed sand appeared to have an insignificant effect on the percent G_{mm} at N_{design} (percent of air voids). However, comparison of identical blends (ignoring the intermediate gradation and ratio of natural and crushed sand as variables) indicated a difference in air voids of 3 to 6 percent. These differences indicate that either the intermediate gradation and ratio of natural and crushed sand have an effect on the percent G_{mm} at N_{design} (percent of air voids), although not as significant as other variables, or the third-order interactions aliased with these variables have an effect.
5. Based on the analysis, it appears to be an incorrect assumption that all third-order and higher interactions can be neglected. It is likely that all interactions are potentially important. Testing the remaining two quarters (16 blends) of the factorial could prove this hypothesis.
6. The analysis of percent G_{mm} at $N_{initial}$ indicated the following significant effects:
   - The interaction of asphalt content and fine gradation *aliased* with the fourth-order interaction of asphalt content, coarse gradation, intermediate gradation, and ratio of natural and crushed sand (AB+ACDE).
   - Coarse gradation *aliased* with the third-order interaction of fine gradation, intermediate gradation, ratio of natural and crushed sand (C+BDE).
   - Asphalt content *aliased* with the fifth-order interaction of all five variables (A+ABCDE).
   - The interaction of asphalt content and coarse gradation *aliased* with the fourth-order interaction of asphalt content, fine gradation, intermediate gradation, and ratio of natural and crushed sand (AC+ABDE).
   - Fine gradation *aliased* with the third-order interaction of coarse gradation, intermediate gradation, and ratio of natural and crushed sand (B+CDE).
7. The analysis of percent G_{mm} at $N_{maximum}$ indicated the following significant effects:
   - The interaction of asphalt content and fine gradation *aliased* with the fourth-order interaction of asphalt content, coarse gradation, intermediate gradation, and ratio of natural and crushed sand (AB+ACDE).

- Fine gradation *aliased* with the third-order interaction of coarse gradation, intermediate gradation, ratio of natural and crushed sand (B+CDE).
- Asphalt content *aliased* with the fifth-order interaction of all five variables (A+ABCDE).
- Coarse gradation *aliased* with the third-order interaction of fine gradation, intermediate gradation, and ratio of natural and crushed sand (C+BDE).

8. The analysis of densification slope (m_{SGC}) indicated the following significant effects:
   - The interaction of asphalt content and coarse gradation *aliased* with the fourth-order interaction of asphalt content, fine gradation, intermediate gradation, and ratio of natural and crushed sand (AC+ABDE).
   - Fine gradation *aliased* with the third-order interaction of coarse gradation, intermediate gradation, ratio of natural and crushed sand (B+CDE).
   - The interaction of asphalt content and fine gradation *aliased* with the fourth-order interaction of asphalt content, coarse gradation, intermediate gradation, and ratio of natural and crushed sand (AB+ACDE).
   - Intermediate gradation *aliased* with the third-order interaction of fine gradation, coarse gradation, and ratio of natural and crushed sand (D+BCE).
9. The interaction of asphalt content and fine gradation appears to have the most significant effect on all volumetric and densification properties. Blends with high levels of asphalt content and fine gradation have higher densification (percent G_{mm} at $N_{initial}$, N_{design}, and $N_{maximum}$) and lower air voids than blends with low levels of asphalt content and fine gradation.
10. Asphalt content has a significant effect on all volumetric and densification properties except for densification slope. This is consistent with the Superpave mix design equations, since compaction curves are translated as asphalt content is changed rather than rotated.

Mechanical Properties

Repeated Shear Constant Height (RSST-CH)

11. The 17 blends resulted in specimens with permanent shear strain (γ_{5000}) values from 3.32 to 10.90 percent at 7 percent air voids. The control mixture (Blend 1) had a γ_{5000} of 4.28 percent. Seven blends had permanent shear strains less than the control and nine blends had permanent shear strains greater than the control.
12. The 17 blends resulted in specimens with rates of accumulation of permanent shear strain (m_{RSST}) from 0.2177 to 0.4178. Blend 1 had an m_{RSST} of 0.2589. Seven blends had m_{RSST} values less than the control and nine blends had m_{RSST} values greater than the control.
13. Complementary pairs (all variables with same levels except for asphalt content) indicated differences in γ_{5000} from 0.11 to 4.74 percent and differences in m_{RSST} from 0.0045 to 0.0975. In six of eight cases, the blend with the higher asphalt content resulted in the higher γ_{5000} and m_{RSST} values. In the other two cases the differences were minor. Testing error may have resulted in the differences.
14. The analysis of permanent shear strain (γ_{5000}) indicated the following significant effects:
   - The interaction of asphalt content and coarse gradation *aliased* with the fourth-order interaction of asphalt content, fine gradation, intermediate gradation, and ratio of natural and crushed sand (AC+ABDE).
   - Asphalt content *aliased* with the fifth-order interaction of all five variables (A+ABCDE).
   - The interaction of asphalt content and fine gradation *aliased* with the fourth-order interaction of asphalt content, coarse gradation, intermediate gradation, and ratio of natural and crushed sand (AB+ACDE).
   - The interaction of fine gradation and coarse gradation *aliased* with the interaction of intermediate gradation and ratio of natural and crushed sand (BC+DE).
   - Coarse gradation *aliased* with the third-order interaction of fine gradation, intermediate gradation, and ratio of natural and crushed sand (C+BDE).
15. The analysis of the rate of accumulation of shear strain (m_{RSST}) indicated the following significant effects:
   - The interaction of asphalt content and coarse gradation *aliased* with the fourth-order interaction of asphalt content, fine gradation, intermediate gradation, and ratio of natural and crushed sand (AC+ABDE).
   - Coarse gradation *aliased* with the third-order interaction of fine gradation, intermediate gradation, and ratio of natural and crushed sand (C+BDE).
   - The interaction of asphalt content and fine gradation *aliased* with the fourth-order interaction of asphalt content, coarse gradation, intermediate gradation, and ratio of natural and crushed sand (AB+ACDE).
   - The interaction of fine gradation and coarse gradation *aliased* with the interaction of intermediate gradation and ratio of natural and crushed sand (BC+DE).
   - Asphalt content *aliased* with the fifth-order interaction of all five variables (A+ABCDE).
16. The interaction of asphalt content and coarse gradation appears to have the most significant effect on the results of the RSST-CH.
17. The main effects of intermediate gradation and ratio of natural and crushed sand appeared to have an insignificant effect on the permanent shear strain (γ_{5000}) and rate of accumulation of shear strain (m_{RSST}). However, comparison of identical blends (ignoring the interme-

diate gradation and ratio of natural and crushed sand as variables) indicated a difference in permanent shear strain of 0.38 to 7.36 percent. These differences indicate that either the intermediate gradation and ratio of natural and crushed sand have an effect on the results of the RSST-CH, although not as significant as other variables, or the third-order interactions aliased with these variables have an effect. However, some of the paired blends (such as the 7,14 pair) did not indicate any differences in permanent shear strain or rate of accumulation of shear strain.

18. A hypothesis was made that results of the RSST-CH would relate to the densification slope, m_{SGC}. This hypothesis was proven incorrect as there was little relationship between the permanent shear strain or rate of accumulation of shear strain and densification slope.

Simple Shear Constant Height (SS-CH)

19. The 17 blends resulted in specimens with maximum shear strain (γ_{max}) values from 1,272 to 6,060 µstrains. The control mixture (Blend 1) had a γ_{max} of 2,712 µstrains. Seven blends had maximum shear strains less than the control and nine blends had maximum shear strains greater than the control.
20. The 17 blends resulted in specimens with final shear strain (γ_{final}) values from 918 to 4,958 µstrains. The control mixture (Blend 1) had a γ_{final} of 2,082 µstrains. Seven blends had final shear strains less than the control and nine blends had final shear strains greater than the control.
21. Complementary pairs (all variables with same levels except for asphalt content) indicated differences in γ_{max} from 5 to 3,697 µstrains and differences in γ_{final} from 111 to 3,145 µstrains. In six of eight cases, the blend with the higher asphalt content resulted in the higher shear strain values.
22. The analysis of maximum and final shear strain indicated the following significant effects:
    – Asphalt content *aliased* with the fifth-order interaction of all five variables (A+ABCDE).
    – Coarse gradation *aliased* with the third-order interaction of fine gradation, intermediate gradation, and ratio of natural and crushed sand (C+BDE).
23. Although a statistical analysis was not performed on SS-CH results at 41°C, a strong temperature effect was noted. Maximum shear strains at 41°C increased by 1.2 to 3.5 times the maximum shear strains at 26°C.

Frequency Sweep Constant Height (FS-CH)

24. The 17 blends resulted in specimens with complex shear modulus (G^*_{10Hz}) values at 10 Hz and 26°C from 746,226 to 1,607,628 kPa. The control mixture (Blend 1) had a G^*_{10Hz} of 1,069,907 kPa. Nine blends had complex shear modulii less than the control and seven blends had complex shear modulii greater than the control.
25. The 17 blends resulted in specimens with shear loss modulus (G''_{10Hz}) values from 449,143 to 767,588 kPa. The control mixture (Blend 1) had a G''_{10Hz} of 570,088 kPa. Ten blends had shear loss modulii less than the control and six blends had shear loss modulii greater than the control.
26. Complementary pairs (all variables with same levels except for asphalt content) indicated differences in G^*_{10Hz} from 45,464 to 692,962 kPa. In seven of eight cases, the blend with the higher asphalt content resulted in the lower complex shear modulus (G^*_{10Hz}).
27. The analysis of complex shear modulus and shear loss modulus at 10 and 0.1 Hz indicated the following significant effects:
    – Asphalt content *aliased* with the fifth-order interaction of all five variables (A+ABCDE).
    – Coarse gradation *aliased* with the third-order interaction of fine gradation, intermediate gradation, and ratio of natural and crushed sand (C+BDE).
28. Although a statistical analysis was not performed on FS-CH results at 41°C, a strong temperature effect was noted. Complex shear modulii at 41°C were 0.11 to 0.38 times the complex shear modulii at 26°C.

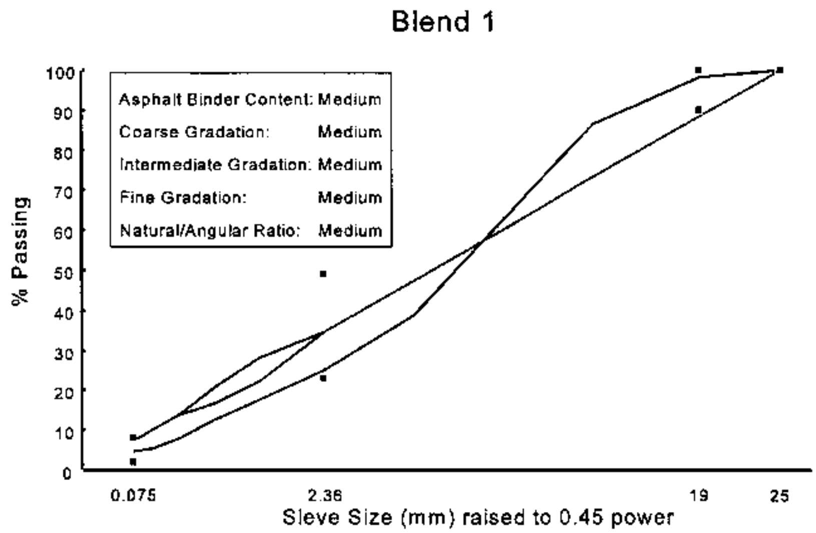
General

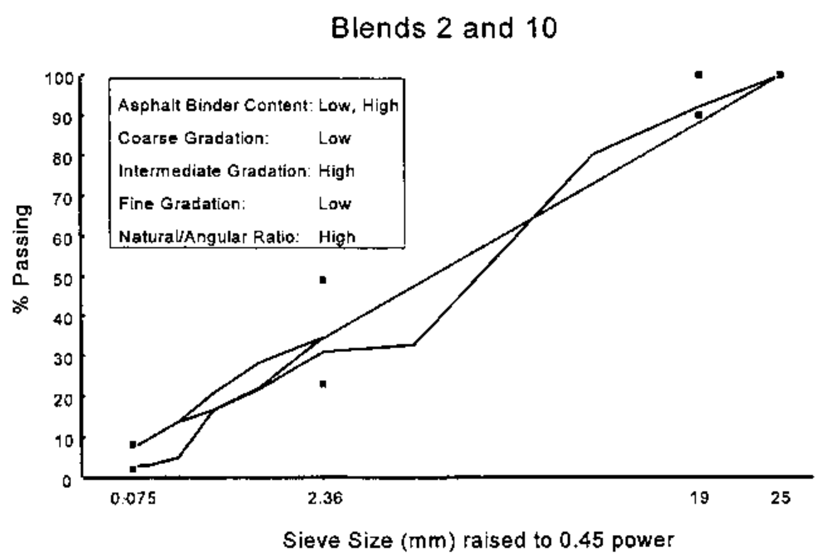
29. The 16 blends that represented variations of Blend 1 indicated changes in mechanical properties as follows:
    • RSST-CH: 0.75 to 2.5 times the permanent shear strain;
    • SS-CH: 0.5 to 2.25 times the maximum shear strain; and
    • FS-CH: 0.7 to 1.5 times the complex shear modulus at 10 Hz.
30. Volumetric and densification properties appear to perform adequately in estimating mixture mechanical properties but may not be absolutely reliable. In six of eight cases where the mixture had lower air voids (from volumetric analysis) than the control, the mixture also had higher permanent shear strain. In five of eight cases where the mixture had lower air voids than the control, the mixture also had higher maximum shear strains and lower complex shear modulii. Two exceptions are Blend 3 and Blend 13. Blend 3 had higher air voids (5.4 percent) than the control, but higher permanent shear strain (6.65 percent), higher maximum shear strain (4,726 µstrains), and lower complex shear modulus (816,905 kPa) than the control. Blend 13 had lower air voids (1.9 percent) than the control but lower permanent shear strain (4.22 percent), lower maximum shear

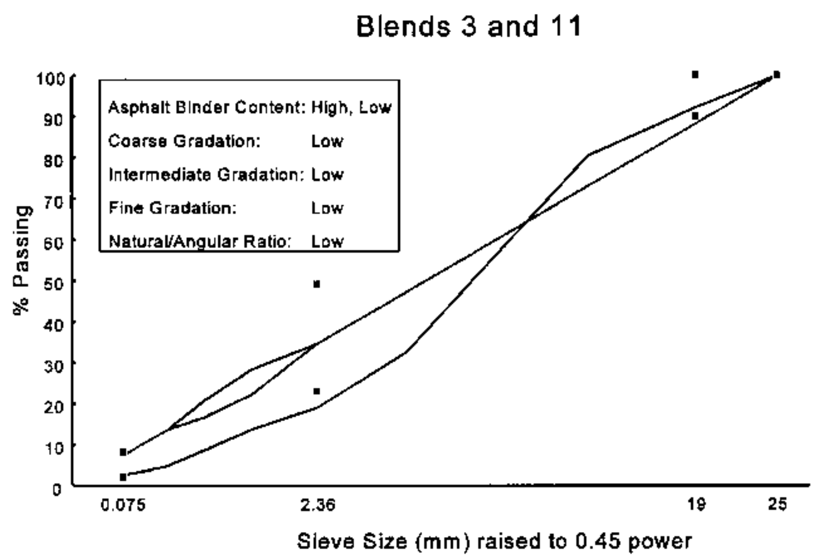
strain (2,363 µstrains), and higher complex shear modulus (1,316,647 kPa) than the control.

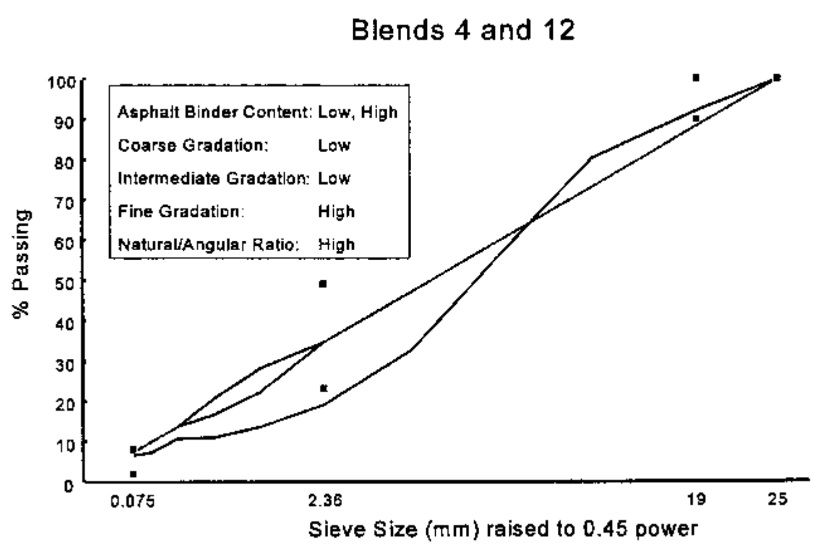
31. In general, asphalt content appears to have the most significant effect on volumetric and mechanical properties. The ratio of natural and crushed sand did not appear to significantly effect mechanical properties. For the combination of aggregates in the research, the percent of natural sand in the mixture did not have as significant an effect on mechanical properties as expected.

FIELD SENSITIVITY BLEND GRADATIONS

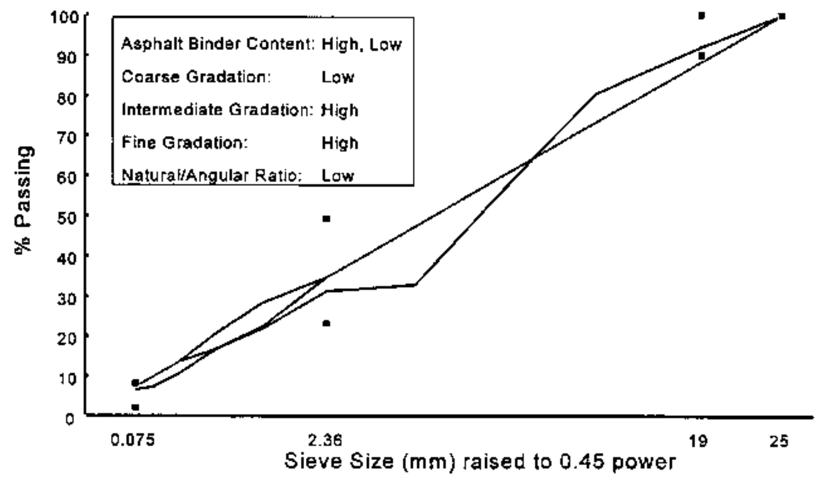




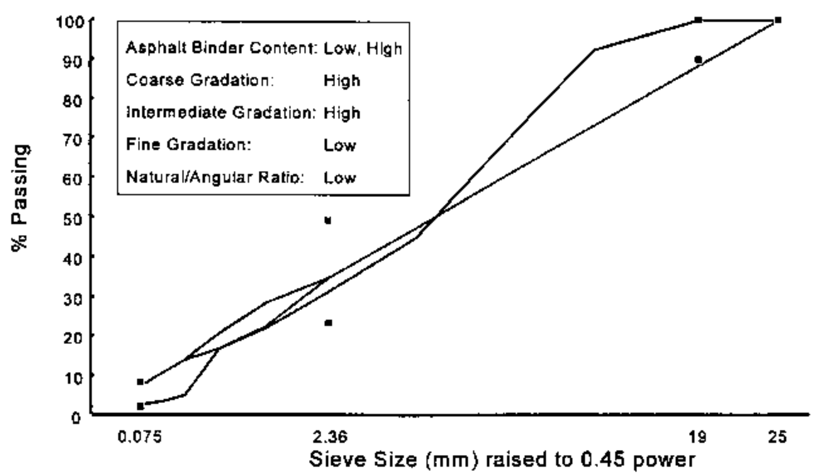

Blends 3 and 11
Asphalt Binder Content: High, Low
Coarse Gradation: Low
Intermediate Gradation: Low
Fine Gradation: Low
Natural/Angular Ratio: Low
% Passing
0
10
20
30
40
50
60
70
80
90
100
0.075
2.36
19
25
Sieve Size (mm) raised to 0.45 power


Blends 4 and 12
Asphalt Binder Content: Low, High
Coarse Gradation: Low
Intermediate Gradation: Low
Fine Gradation: High
Natural/Angular Ratio: High
% Passing
0
10
20
30
40
50
60
70
80
90
100
0.075
2.36
19
25
Sieve Size (mm) raised to 0.45 power

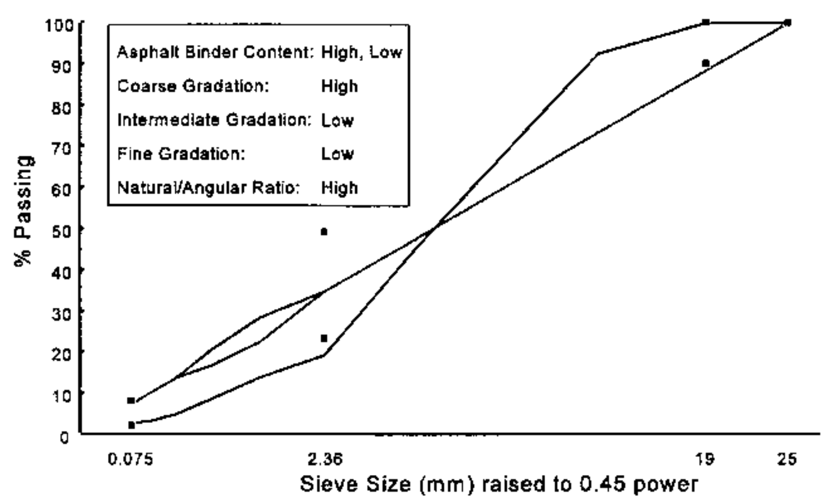
Blends 5 and 13

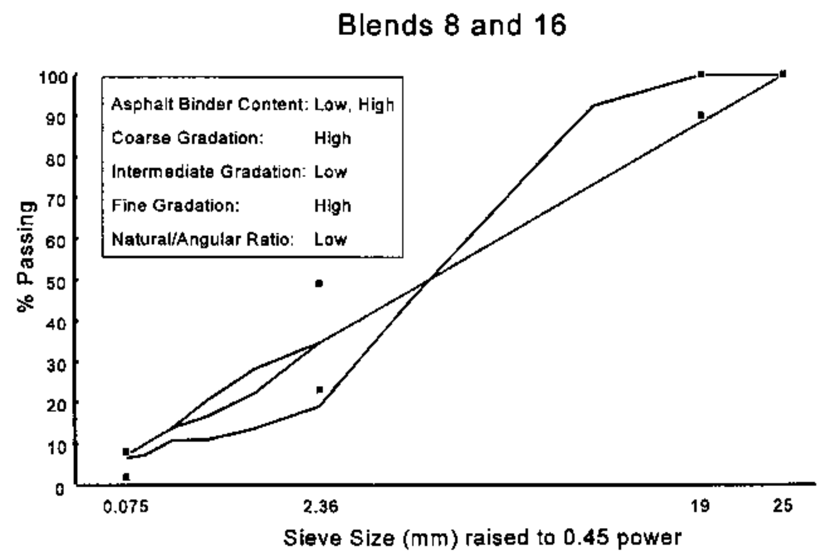


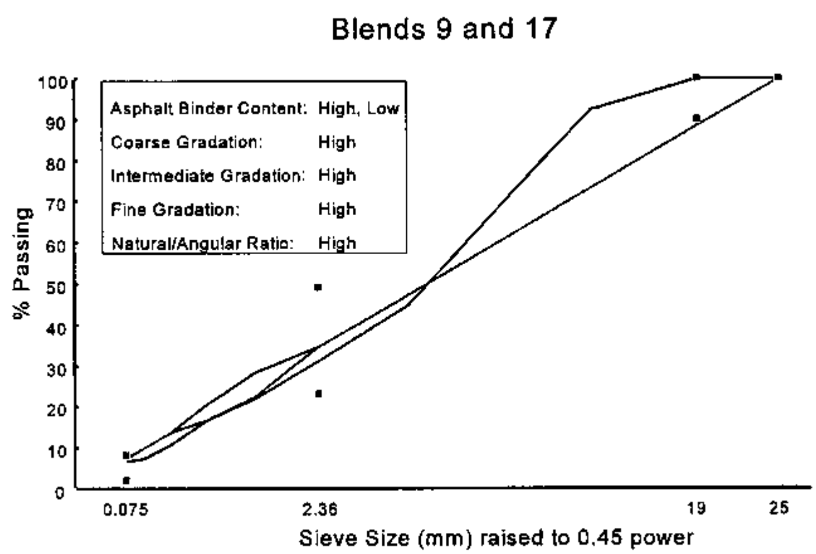
Blends 6 and 14



Blends 7 and 15




Blends 8 and 16
Asphalt Binder Content: Low, High
Coarse Gradation: High
Intermediate Gradation: Low
Fine Gradation: High
Natural/Angular Ratio: Low
% Passing
100
90
80
70
60
50
40
30
20
10
0
0.075
2.36
19
25
Sieve Size (mm) raised to 0.45 power


Blends 9 and 17
Asphalt Binder Content: High, Low
Coarse Gradation: High
Intermediate Gradation: High
Fine Gradation: High
Natural/Angular Ratio: High
% Passing
100
90
80
70
60
50
40
30
20
10
0
0.075
2.36
19
25
Sieve Size (mm) raised to 0.45 power

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

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

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

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
TRB	Transportation Research Board
U.S.	United States