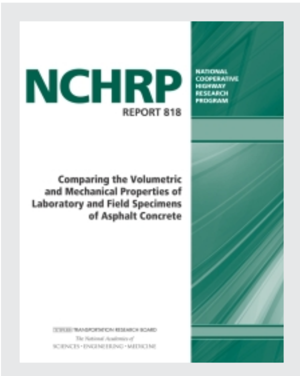

Comparing the Volumetric and Mechanical Properties of Laboratory and Field Specimens of Asphalt Concrete

DETAILS

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AUTHORS

Mohammad, Louay N.; Elseifi, Mostafa A.; Cooper, Samuel B., III; Hughes, C. S.; Button, Joe W.; and Ervin L. Dukatz, Jr.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 818

Comparing the Volumetric and Mechanical Properties of Laboratory and Field Specimens of Asphalt Concrete

Louay N. Mohammad
Mostafa A. Elseifi
Samuel B. Cooper, III
Louisiana Transportation Research Center
Louisiana State University
Baton Rouge, LA

C. S. Hughes
Charlottesville, VA

Joe W. Button
College Station, TX

Ervin L. Dukatz, Jr.
MTE Services, Inc.
Onalaska, WI

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Christopher Hedges, *Manager, National Cooperative Highway Research Program*
Edward T. Harrigan, *Senior Program Officer*
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Haifang Wen, *Washington State University, Pullman, WA*
James M. Winford, Jr., *Prairie Contractors, Inc., Opelousas, LA*
Zhanping You, *Michigan Technological University, Houghton, MI*
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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents a proposed practice for evaluating the cause and magnitude of variability of specimen types tested in quality control and/or assurance programs for asphalt paving projects. Thus, the report will be of immediate interest to engineers in state highway agencies and the construction industry with responsibility for testing asphalt mixtures and conducting quality control and/or assurance programs.

Many transportation agencies conduct quality assurance (QA) programs on asphalt paving projects. QA requires the contractor and the owner agency to share testing responsibilities. Typically, the contractor conducts the majority of the testing for quality control and acceptance purposes, and the agency conducts fewer tests to verify the contractor's test results. Testing may measure both volumetric properties, such as air voids (V_a), voids in mineral aggregate (VMA), and asphalt content, and mechanical properties such as loaded-wheel test (LWT) rut depth, indirect tensile test (IDT) strength, and dynamic modulus (E*).

The results of QA testing conducted by the agency and the contractor are often compared statistically to verify the contractor's test results. Such comparisons help the agency judge whether its QA test results are from the same population as the contractor's test results. However, because the tests are performed by different operators using different equipment and with potentially different methods, variability of the test results is inevitable.

A further source of variability arises when results from laboratory-mixed and compacted (LL) specimens are compared to those from plant-mixed, laboratory-compacted (PL) specimens, or plant-mixed, field-compacted (PF) specimens, or both, on a single project. A major barrier to conducting a sound QA program is quantifying the variability that arises when it is necessary to compare the properties of asphalt mixture specimens that may be (1) produced in a laboratory or at the plant, (2) compacted in different physical locations, and (3) compacted in the laboratory or in-place on the pavement.

The objectives of this research were to (1) determine causes of variability and tolerances for volumetric and mechanical properties of dense-graded asphalt mixtures measured within and among the three specimen types; and (2) propose a practice for state DOTs to incorporate these results in specifications and criteria for (a) quality assurance, (b) mix design verification or validation, and (c) structural design and forensic studies. The research was conducted by the Louisiana Transportation Research Center, Louisiana State University, Baton Rouge, Louisiana, and supported by MTE Services, Inc., Onalaska, Wisconsin.

The research was conducted in two phases. In Phase I, datasets of laboratory and field test data were collected and pooled in a meta-analysis in an attempt to determine (1) levels of variability in asphalt mixtures and (2) the factors causing variability among and between the three specimen types. Despite the inclusion of 25 extensive datasets representing roughly

8,000 individual mixtures in the meta-analysis, the results of the analysis were inconclusive. Phase II was then undertaken—a program testing LL, PL, and PF specimens from paving projects across the United States to quantify the effects of process-based factors on the variability of volumetric and mechanical properties of the specimen types.

The key outcome of the research is a proposed practice in Chapter 6 for evaluating the cause and magnitude of variability within and among the three specimen types. In addition, tolerances of volumetric and conversion factors between the three specimen types of mechanical properties evaluated are proposed based on the average difference between specimen comparisons for the mixtures evaluated in Phase II. Agencies may use these proposed values to evaluate and adjust their current tolerances, as discussed in Chapters 6 and 7.

This report fully documents the research. Four appendixes are available to download from the NCHRP Project 09-48 web page at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2503:

- Appendix A Literature Review
- Appendix B Phase I Preliminary Research Meta-Analysis
- Appendix C Individual Mixture Analysis
- Appendix D Job Mix Formulae

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Comparing the Volumetric and Mechanical Properties of Laboratory and Field Specimens of Asphalt Concrete

Mix properties that deviate appreciably from design during the production and construction of asphalt mixtures often lead to premature pavement distress or even failure. The objective of this project was to quantify sources and causes of variability in the measurements of volumetric and mechanical properties of dense-graded asphalt mixtures for three types of specimens that may be encountered during design, production, and construction. In addition, the effects of variation among specimen types on pavement performance prediction were evaluated. This was accomplished by evaluating common volumetric and mechanical properties of the three specimen types (design, production, and construction) from a nationwide compilation of 11 mixtures from various states throughout the United States. Variations in key production process factors—specifically the return of baghouse fines, delay in specimen fabrication, aggregate absorption, aggregate hardness, and stockpile moisture content—were evaluated in this study. For each mixture, the following volumetric and mechanical properties were evaluated for the three specimen types:

- **Volumetric properties:** air voids, voids in the mineral aggregate, voids filled with asphalt, aggregate bulk specific gravity, mixture maximum specific gravity, asphalt binder content, and gradation.
- **Mechanical properties:** loaded-wheel test (LWT) rut depth, axial dynamic modulus, and indirect tensile test (IDT) dynamic modulus.

Based on the experimental, statistical, and analytical analyses conducted in this study, the following conclusions may be drawn:

- The effects of the process-based factors (i.e., return of baghouse fines, delay in specimen fabrication, aggregate absorption, aggregate hardness, and stockpile moisture content) on the volumetric and mechanical properties were not as pronounced as originally hypothesized. Results of a contractor survey showed that contractors are actively making adjustments based on their experience with the processes in their region.
- With respect to the effects of process-based factors on mechanical properties, it was concluded that these factors did not have a significant effect on the differences of mechanical properties among the three specimen types. The lack of the observed effects of process-based factors may result from the variations in the mechanical properties being strongly controlled by compaction effort. Many of the individual mixture comparisons showed that plant-mixed, field-compacted (PF) specimens were significantly softer than laboratory-mixed, laboratory-compacted (LL) and plant-mixed, laboratory-compacted (PL) specimens, even though the air voids were the same for both sets of specimens. This finding was

Table S-1. Conversion factors.

Comparison	Conversion Factor
Design (LL) / Production (PL)	1.0
Design (LL) / Construction (PF)	0.75
Production (PL) / Construction (PF)	0.75

attributed to differences in compaction effort and confinement conditions between the two compaction processes (laboratory and field).

- Slight differences in gradation, while within state tolerances, may lead to significant differences in important volumetric properties (e.g., air voids and voids filled with asphalt).
- Tolerance recommendations were developed based on the average difference among specimen comparisons for the 11 national mixtures evaluated. Based on these findings, specifying agencies should evaluate and adjust their current tolerance values. These tolerance values encompass mixtures from around the country. Therefore, more regional values may be appropriate.
- Conversion factors among the three specimen types were developed for the loaded-wheel test (LWT). Conversion factors can be used to assess whether or not an as-built mixture will be expected to meet performance indicators developed with the laboratory design. The conversion factors (see Table S-1) indicate that laboratory-compacted specimens typically resulted in 33% less rut depth than field-compacted specimens. Therefore, if the LWT rut depth of a PF specimen is required to be 6 mm at 20,000 passes, the laboratory-compacted mixture should have a rut depth of 4.5 mm at 20,000 passes. This relationship will be important as agencies transition toward performance-based specifications.
- The modulus determined from IDT was generally 80% of the modulus determined from axial testing. The difference between axial and IDT moduli determined at high temperature was much more variable, which was likely due to the increased influence of the loading mode at high temperature; some mixtures exhibited both higher and lower values of modulus when comparing IDT dynamic modulus with axial dynamic modulus.

CHAPTER 1

Introduction

Maintenance and growth of U.S. infrastructure is vital to the economic and social prosperity of the country. For this reason, significant resources must be allocated to ensure that adequate paving mixtures are designed, produced, and constructed. In 2005, of the approximately 4 million miles of roads in the United States, 2.6 million were paved with either Portland cement or asphalt cement concrete. Approximately 94% of the paved roads were surfaced with asphalt concrete mixtures. This scale of infrastructure has enabled the American public and business to travel 3 trillion vehicle miles annually (Brown et al. 2009).

1.1 Asphalt Mixture Design

Asphalt mixture design is most commonly defined as the process by which an aggregate gradation and optimum asphalt binder content are determined to meet prescribed criteria associated with pavement performance (Brown et al. 2009). From the 1940s to the 1990s, most asphalt concrete mixtures were designed using the Marshall or Hveem methods. During the 1990s, states began implementing the Superpave mixture design method as a result of the Strategic Highway Research Program (SHRP). The purpose of this program was to develop mixture design methods that could be used to predict pavement performance. In the Superpave procedure, volumetric properties in association with expected traffic levels are used to determine the optimum asphalt binder content. As of 2012, most state DOTs have implemented the Superpave mixture design. Regardless of the mix design method selected, the primary reason for conducting mixture design procedures is to determine a suitable combination of aggregates and asphalt binder for optimum pavement performance. The resulting "recipe" is termed the job mix formula (JMF). During production, the design JMF should be verified and revised through the plant to accommodate production and field conditions (Brown et al. 2009).

1.2 Asphalt Mixture Production

The basic purpose of an asphalt mix plant is to proportion, heat, and combine the components of the mixture design as per the design. The aggregate structure in the JMF is typically a blend of three or four different aggregates, while the asphalt binder is normally a performance grade (PG) asphalt binder with or without additives (e.g., antistrips or polymers). Large-scale production of the mixture in the plant is difficult to duplicate during laboratory design protocols (Brown et al. 2009). For this reason, quality control (QC) and quality acceptance or quality verification (QV) testing is conducted to ensure that the mixture produced is appropriate for what is designed. In this project, the combination of QC and quality acceptance activities will be defined by the AASHTO definition of quality assurance (QA). QA testing is used as a basis of pay for the contractor.

1.3 QA Testing

Adequate QA practices, which include testing conducted by the contractor and acceptance testing conducted by the state, are the keys to obtaining a satisfactory product and ensuring that a constructed hot mix asphalt (HMA) pavement is what the designer specified (AASHTO R 10). Years of experience indicate that deviation from either material or construction specifications often leads to premature pavement distress or even failure (Hughes 2005).

1.4 Problem Statement

There is a need to identify and quantify causes, sources, and levels of variability in volumetric and mechanical properties of mixtures from the design, production, and construction of the mixture. This requires evaluation of three possible scenarios for production of asphalt mixture specimens: (1) laboratory-mixed, laboratory-compacted specimens (LL), produced during the design process; (2) plant-mixed, laboratory-compacted specimens (PL), involving volumetric acceptance testing of plant-produced mix; and (3) plant-mixed, field-compacted specimens (PF), used during density acceptance testing of in situ pavement and forensic evaluation of as-built pavement. Although research studies have evaluated some aspects of this problem, a comprehensive national study is needed to provide a complete evaluation of all volumetric and mechanical properties of interest including, but not limited to, the recently introduced dynamic complex modulus. Additionally, with the increased emphasis on mechanical-empirical pavement design, an evaluation of variability among specimen types and its effect on pavement performance prediction is needed.

1.5 Objectives and Scope

The objectives of this project, as stated in the request for proposals, were to (1) determine causes of variability and the precision and bias for volumetric and mechanical properties of dense-graded asphalt mixtures measured within and between laboratory-mixed and -compacted [design (LL)] specimens, plant-mixed and laboratory-compacted [production (PL)] specimens, and plant-mixed and field-compacted [construction (PF)] specimens; and (2) prepare a recommended practice in AASHTO standard format for state DOTs to incorporate these results in their specifications and criteria. These objectives were accomplished by evaluating and comparing common volumetric and mechanical properties of the three specimen types through (1) a meta-analysis of existing data and (2) a laboratory experiment using 11 mixtures from various states across the United States. Variation in key production process factors—specifically the return of baghouse fines, delay in specimen fabrication, aggregate absorption, aggregate hardness, and stockpile moisture content—was evaluated in the laboratory experiment. For each mixture, the following volumetric and mechanical properties were measured for the three specimen types:

- **Volumetric properties:** air voids, voids in mineral aggregate, voids filled with asphalt, bulk specific gravity of the aggregate blend, mixture maximum specific gravity, asphalt binder content, and gradation.
- **Mechanical properties:** loaded-wheel tracking (LWT) rut depth, axial dynamic modulus (E*), and indirect tension dynamic modulus (IDT E*).

1.6 Research Method

To achieve the aforementioned objectives, the project was conducted in two phases (I and II) as follows:

Phase I
- Task 1: Conduct literature review
- Task 2: Survey, collect, and perform a meta-analysis on data from past research studies that relate to the following issues:
  - Levels of variability in asphalt mixtures
  - Factors causing variability between specimen types

Phase II
- Task 3: Develop the laboratory experimental plan
- Task 4: Execute the approved laboratory experiment
- Task 5: Conduct data analysis
  - Individual mix analysis to quantify magnitude of variation within each mix
  - Combined mix analysis to evaluate causes of variation
- Task 6: Develop specification recommendations based on results of the analysis
  - Evaluate effects on predicted performance using the *Mechanistic Empirical Pavement Design Guide* (MEPDG)
- Task 7: Prepare final report

Figure 1-1 summarizes the research method applied in Phases I and II of this study. In Phase I, the researchers collected and analyzed data from previously completed research projects that could be used to determine a solution to the problem statement. At the conclusion of Phase I, the research team and NCHRP agreed that the data collected were not sufficient to adequately answer the problem statement. Therefore, an experimental factorial was developed and conducted, completed as Phase II of the project. As shown in Figure 1-1, identifying and acquiring asphalt mixtures meeting the research criteria was an iterative process because some mixtures identified in the experimental factorial were not practical for field production. Once a mixture was identified, samples were collected during production and sent to the Louisiana Transportation Research Center (LTRC) where specimens were prepared and the laboratory evaluation of the mixture was conducted. Along with the production samples, contractor QC data were collected for analysis. The process was repeated until all the mixtures were collected to complete the experimental program. After all the mixtures were collected and analyzed, the individual data sets were combined into a meta-data set and analyzed to answer the project objectives.

1.7 Report Outline

This report has eight chapters, including this introductory chapter (Chapter 1). Chapter 2 describes the preliminary research and analysis conducted in Phase I to support the development of the experimental program. Chapter 3 presents the development of the experimental program, and Chapter 4 describes the methods used. Chapter 5 summarizes the individual mixture analyses and results. Chapter 6 presents the combined data analyses of the 11 asphalt mixtures. Chapter 7 presents the proposed tolerances and conversion factors developed from the statistical analyses of the individual and combined results. Finally, Chapter 8 summarizes findings and conclusions of the research.

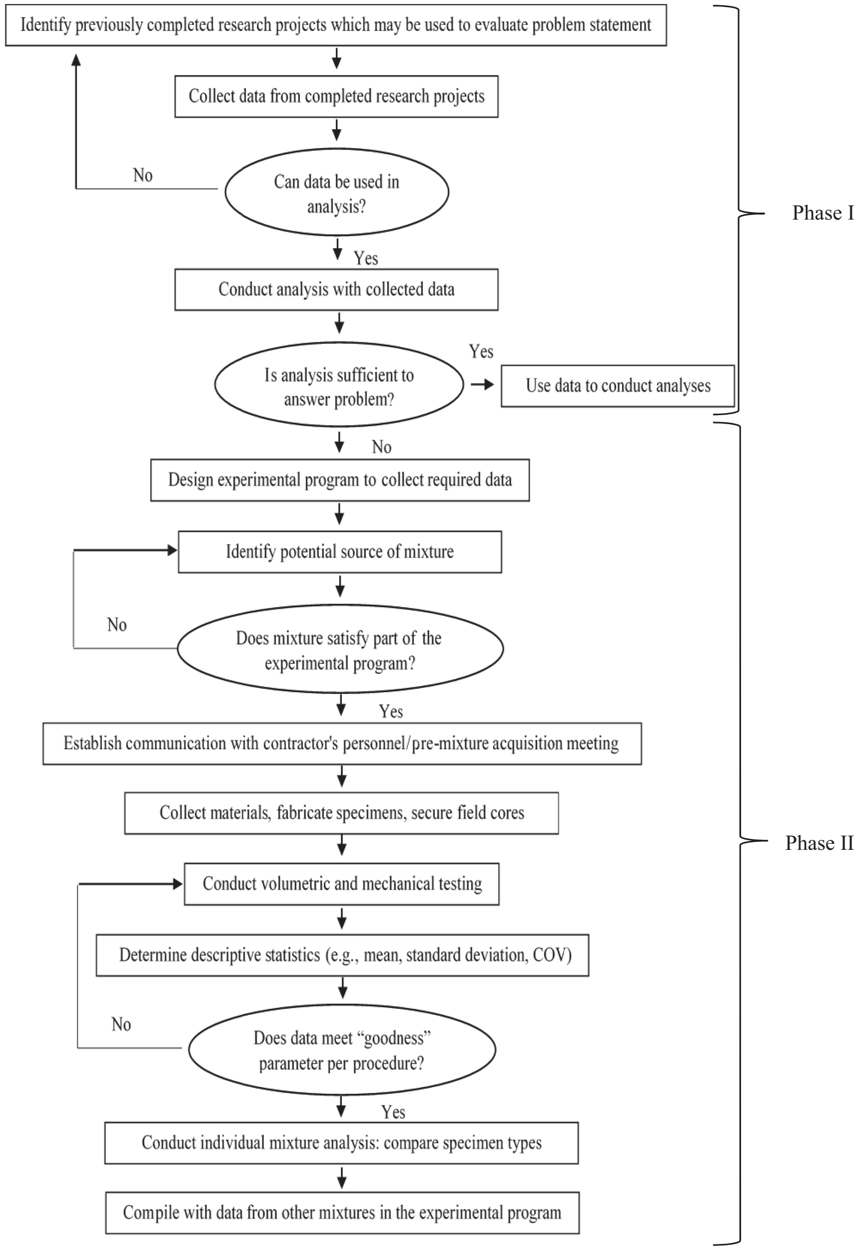


Figure 1-1. Research method flowchart.

CHAPTER 2

Phases I and IA

2.1 Phase I: Levels of Variability in Volumetric and Mechanical Properties of Asphalt Mixtures

As part of the literature review for this study, data were collected from projects around the country which could be used to meet the objectives of this study. This research effort is referred to as Phase I throughout this document.

2.1.1 Overview of Data Sets Analyzed

Figure 2-1 presents a map identifying the states that contributed data to this initial project phase. In addition to the state DOTs presented in Figure 2-1, the researchers obtained volumetric measurements collected in the Netherlands and from the FHWA mobile laboratory. Tables 2-1 and 2-2 present the data sets analyzed and the properties available in each data set. As shown in these tables, most of the data sets included PL and PF samples; only two included LL samples. Statistical analysis of the individual data sets and meta-analysis of the combined data sets were conducted to quantify levels of variability for the three specimen types considered in this project (i.e., LL, PL, and PF). The following sections provide details and information about the analysis conducted on each data set as well as the results of the meta-analysis.

2.1.2 Summary of the Statistical Analysis

Tables 2-3 and 2-4 present the levels of variability for each of the volumetric, gradation, and mechanical properties evaluated in Phase I. The data set from the Netherlands was not considered in this summary, because testing and construction practices in Europe are different from those in the United States. The data received from Texas and Oregon were not sufficient for the analysis (e.g., mixtures only contained one specimen type). In general, contractor and state measurements were similar and were shown to be statistically equivalent for most of the data sets. In addition, levels of variability presented in Table 2-3a and 2-3b were comparable for the state and the contractor measurements. Table 2-5 presents the average levels of variability for the volumetric and gradation properties evaluated in Phase I.

2.2 Phase IA: Factors Causing Variability Between Specimen Types

At the conclusion of Phase I, Phase IA was initiated to determine the magnitude and factors causing pair-wise differences among the three specimen types [design (LL), production (PL), and construction (PF)]. With the guidance of NCHRP, the following projects were reviewed as possible additional sources of data:

1. WesTrack (WesTrack Database and *NCHRP Web-Only Document 111*);
2. NCAT test track;
3. NCHRP Project 09-47A, "Performance and Properties of Warm Mix Asphalt Technologies";
4. California Heavy Vehicle Simulator data;
5. FHWA: Eastern, Central, and Western Federal Lands Highway Divisions;
6. Louisiana and Florida Accelerated Loading Facility (ALF) data;
7. Long-Term Pavement Performance (LTPP) data;
8. NCHRP Project 09-9(01), "Verification of Gyration Levels in the N_{design} Table";
9. Arizona Department of Transportation (AZDOT) from NCHRP Project 09-22, "Beta Testing and Validation of HMA PRS," and several AZDOT projects;
10. SHRP project reports and database; and
11. State planning and research reports.

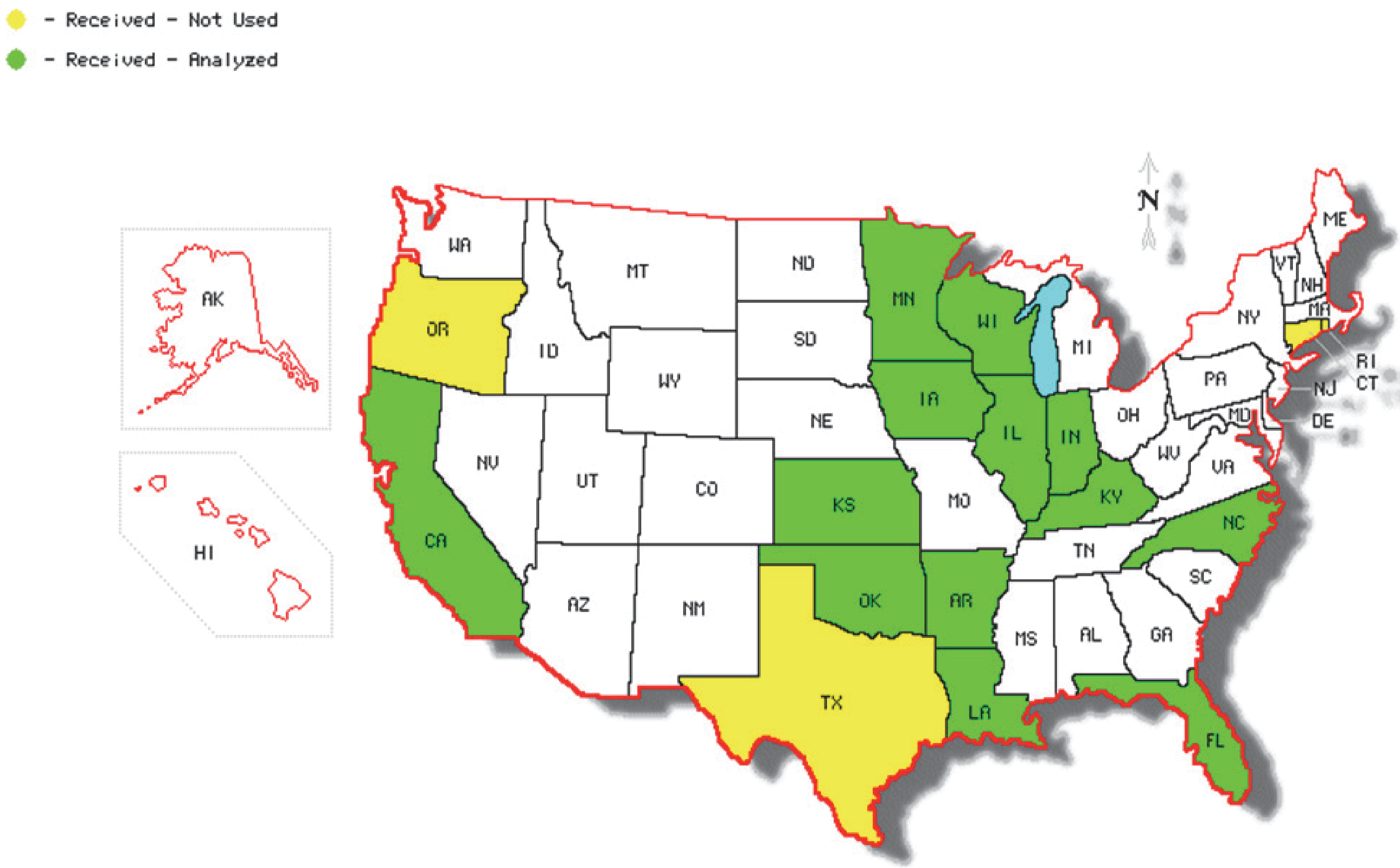


Figure 2-1. State DOTs that provided data to the project.

Aggregate gradation density was used as a quantitative method to identify mixes sensitive to minor changes in gradation and asphalt binder content and that may show greater variability between LL and PL specimens (D'Angelo and Ferragut 1991). Other mix types were identified in the literature as sensitive, including tender mixes, gap-graded mixes, and mixes that cross the maximum density line (MDL) multiple times. Tender mixes often exhibit a "hump" near the No. 30 sieve on the 0.45 power curve. However, none of the mixes in the Phase IA data sets was identified as tender, gap-graded, or as crossing the MDL multiple times.

Aggregate gradation density was quantified through the sum of absolute differences (SAD) from the MDL (Anderson and Bahia 1997). The SAD was normalized (NSAD) to the number of sieves reported in the data set, because not all projects reported the same number of sieves in the gradation analysis. As described by Equation 1, a mix with a high NSAD (i.e., above 8.25) indicates that its gradation deviates significantly from the MDL:

$$NSAD = \frac{\sum_{i}^{n} |\%P_i - P_{MDL}|}{n} \quad (1)$$

where

NSAD = normalized sum of absolute differences,
n = number of sieves considered in the gradation analysis,
P_i = % passing sieve i, and
P_{MDL} = % passing for the maximum density line at sieve i.

Table 2-6 summarizes the data collected during Phase IA. Although the researchers successfully collected most of the aforementioned data sets, data from SHRP, FHWA Eastern and Central Federal Lands Highway Divisions, and the California Heavy Vehicle Simulators (HVS) were not available. In addition to the data sets suggested, the researchers successfully collected data from the University of Nevada at Reno. Table 2-7 illustrates the factors identified to explain how construction processes may influence the magnitudes of the differences within and among the three specimen types (LL, PL, and PF). This project focused on process-based factors. Therefore, the influences of design-based factors [e.g., nominal maximum aggregate size (NMAS)] are not considered in this report. However, aggregate absorption and sensitive mixes were identified during the Phase I review and have been included in the analysis.

Table 2-1. Overview of the volumetric data sets.

Properties / State	Aggregate Gradation	Mixture											Performed by		
		Air Voids		Asphalt Binder Content		G_{mb}		Density		VMA	VFA	G_{mm}			
		Specimen Type	Test Method	Specimen Type	Test Method	Specimen Type	Test Method	Specimen Type	Test Method	Specimen Type	Specimen Type	Specimen Type	Contractor	State	Third-Party
CA	PL	-	-	PL	-	-	-	PF	-	-	-	-	Y	Y	-
FHWA	PL	PL	-	PL	IO NC	PL	-	-	-	PL	PL	PL	-	-	Y
FL	PL	PL	SSD	-	-	-	-	PF	SSD	PL	PL	-	Y	Y	Y
IL	-	PL	SSD	PL	IO	-	-	PF	NC	-	-	-	Y	Y	Y
IN	-	LL, PL	SSD	PL	IO	-	-	PF	SSD	PL	-	-	Y	Y	-
IA	-	PL	-	-	-	PF	SSD			-	-	PL	-	Y	-
KS	-	PL	-	-	-	-	-	PF	-	-	-	-	Y	Y	-
KY	PL	PL	SSD	PL, PF	IO, SE, NC, BC PT	PL, PF	SSD	PF	NC	PL	PL	-	Y	Y	-
LA(1)	-	PL, PF	SSD, VS PQI	-	-	-	-	-	-	-	-	-	-	Y	-
LA(2)	-	PL	SSD	-	-	-	-	PF	SSD	-	-		-	Y	-
NC	PL	PL	-	PL	-	PL	-	PF	SSD	PL	PL	PL	Y	Y	-
OK	PL	PL	SSD	PL	-	PL	SSD	-	-	PL	-	-	-	Y	-
WI	-	PL	-	PL	-	PL	-	PF	-	PL	-	PL	-	Y	-
OOMS	PL	PL, PF	-	PL	-	PL, PF	-	-	-	-	-	PL, PF	Y	-	-

G_{mb}: Mixture bulk specific gravity; G_{mm}: Mixture maximum specific gravity; SSD: Saturated Surface Dry; VS: Vacuum Sealing; PQI: Pavement Quality Indicator; IO: Ignition Oven; SE: Solvent Extraction; NC: Nuclear method; BC: Back Calculation method; PT: Printed Ticket method; Y: 'Yes.'; -: Not available.

Table 2-2. Summary of data sets analyzed in task 2 (mechanical).

	IDT Tensile Strength			Dynamic Modulus			Flow Number		
Test Methods / Source	PL	PF	LL	PL	PF	LL	PL	PF	LL
University of Arkansas						X			
Louisiana	X	X							
MnROAD				X			X		
FHWA				X		X	X		X

Table 2-3. Summary of levels of variability (st. dev.) for volumetric and gradation properties.

(a) Volumetric Properties

Properties	Performed By	Specimen Type	Variability		
			Min.	Max.	Average
AV, %	Contractor	PL	0.40	0.84	0.60
	State	PL	0.36	0.99	0.61
	Third-Party	PL	0.68	0.91	0.81
AC, %	Contractor	PL	0.17	0.22	0.19
	State	PL	0.17	0.24	0.20
	Third-Party	PL	0.18	0.21	0.20
VMA, %	Contractor	PL	0.37	0.58	0.49
	State	PL	0.38	0.65	0.53
	Third-Party	PL	0.51	0.64	0.58
VFA, %	Contractor	PL	3.40	4.08	3.73
	State	PL	4.01	4.93	4.34
	Third-Party	PL	4.20	5.16	4.68
G_{mb}	Contractor	PL	0.013	0.017	0.015
	State	PL	0.008	0.018	0.014
	Third-Party	PL	0.016	0.016	0.016
	State	PF	0.025	0.025	0.025
G_{mm}	Contractor	PL	0.012	0.012	0.010
	State	PL	0.008	0.012	0.009
	Third-Party	PL	0.011	0.011	0.011
Field Density, %	Contractor	PF	0.74	1.44	1.13
	State	PF	0.79	1.49	1.23
	Third-Party	PF	0.90	0.90	0.90

(b) Gradation Properties

Percent Passing Sieve Size	Contractor			State			Third Party		
	Range, %		Avg., %	Range, %		Avg., %	Range, %		Avg., %
	Min	Max		Min	Max		Min	Max	
25.0 mm	1.70	2.66	2.12	1.74	1.79	1.77	0.68	0.68	0.68
19.0 mm	0.82	2.59	1.93	0.91	2.26	1.64	1.28	1.28	1.28
12.5 mm	0.91	3.54	2.14	1.08	2.54	1.79	0.89	2.15	1.52
9.5 mm	1.61	3.75	2.60	1.82	2.54	2.25	1.65	2.29	1.97
No. 4	1.87	3.48	2.71	2.19	3.08	2.66	2.37	2.56	2.47
No. 8	1.75	2.38	2.13	2.12	2.73	2.30	1.76	2.07	1.92
No. 16	1.56	2.05	1.81	1.70	1.76	1.73	NA	NA	NA
No. 30	1.37	1.73	1.54	1.43	1.89	1.62	NA	NA	NA
No. 50	1.12	1.28	1.18	1.07	1.27	1.17	NA	NA	NA
No. 100	0.64	0.99	0.78	0.76	0.83	0.80	NA	NA	NA
No. 200	0.34	0.84	0.60	0.39	0.66	0.52	0.40	0.40	0.40

Table 2-4. Summary of levels of variability (COV) for mechanical properties.

Properties	COV Range, %		Average COV, %
	Min	Max	
Dynamic modulus	10.0	23.8	13.9
Phase angle	3.9	15.4	7.1
Flow number	37.3	52.1	45.2
Indirect tensile strength	11.9	15.4	13.7

2.2.1 Data Analysis

This section presents results of the individual analyses conducted for Arizona DOT (AZDOT) and University of Nevada, Reno, data sets as typical data sets as well as a summary of the entire data analysis. Additional details for the other data sets were presented in the interim report for Phase IA (Mohammad et al. 2009), available at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2503.

Table 2-5. Average levels of variability (st. dev.) for volumetric and gradation properties.

(a) Volumetric Properties

Property	Specimen Type	Range of St. Dev.	Avg.
Asphalt Binder Content, %	PL	0.17 – 0.29	0.20
Air Voids, %	PL	0.33 – 0.99	0.62
VMA, %	PL	0.38 – 0.64	0.54
VFA, %	PL	3.40 – 4.92	4.03
G_{mb}	PL	0.008 – 0.018	0.015
G_{mb}	PF	0.008 – 0.033	0.019
G_{mm}	PL	0.005 – 0.012	0.011
Field Density, %	PF	0.74 – 1.49	1.11

(b) Gradation Properties

Percent Passing Sieve Size, %	Specimen Type	Range of St. Dev.	Average
25.0 mm	PL	1.55 – 2.66	1.86
19.0 mm	PL	0.93 – 2.59	1.77
12.5 mm	PL	0.99 – 3.54	2.17
9.5 mm	PL	1.50 – 3.75	2.35
No. 4	PL	1.87 – 3.48	2.62
No. 8	PL	1.62 – 2.62	2.20
No. 16	PL	1.70 – 2.05	1.81
No. 30	PL	1.43 – 1.84	1.60
No. 50	PL	1.07 – 1.22	1.16
No. 100	PL	0.80 – 0.99	0.87
No. 200	PL	0.32 – 0.84	0.55

Arizona DOT Data Analysis

Data were collected from a research project conducted by the AZDOT. The primary objective of this research project was to formulate performance-based pay factor criteria using the concept of service life and remaining service life (Patni 2007). An increase or decrease in service life is a rational way to interpret the performance of in situ asphalt concrete mixture (field mix design) with respect to the laboratory mix design or the JMF. Table 2-8 describes the projects in the AZDOT data set.

Table 2-9 summarizes the volumetric properties provided in the AZDOT data set. Each project had one mixture and several lots. Bulk material was sampled from each lot, out of which four samples were compacted in the laboratory. The asphalt binder content and gradation of the sampled bulk material were measured using the ignition furnace. Data analysis was conducted to determine the magnitude of the differences (Δ) between design values (LL) and as-produced mixtures (PL) as indicative of production variability and to identify possible effects of selected factors on the variability of mixture volumetric properties. The only process-based factor considered in the AZDOT data set was aggregate gradation density (i.e., NSAD).

Table 2-10 summarizes the differences (Δ) between PL and LL volumetric properties for the AZDOT data set. These values represent the averages of ten mixtures. The gradation analysis was reduced to the four sieves shown in the table because the differences reported for all other sieves were negligible. The sieves analyzed are the sieves used for payment in Arizona. The absolute average differences shown Table 2-10 were calculated by taking the average of the absolute differences for all mixtures in the experiment. The positive and negative averages were calculated by taking the average of the sections in the experiment in which the difference was either positive or negative.

Figures 2-2 and 2-3 show the differences between PL and LL volumetric properties grouped by NSAD. It appears from the results shown in Figure 2-3 that the differences between PL and LL samples increased as the mix gradation departed from the maximum density line (i.e., greater NSAD). However, additional data are needed to verify this observation.

University of Nevada (Reno) Data Analysis

Data were collected from two projects conducted at the University of Nevada, Reno (UNR) (see Table 2-11). The objective of the first project, referred to as Experiment 1, was to compare the properties of a polymer-modified mixture

Table 2-6. Summary and description of collected data sets.

Data ID	Source	Meta Designation	Specimen Type	Status	Comments
1	NCAT	NT	PL, LL	Collected	2006 and 2009 Experiments
2	NCHRP Project 9-9	9.9	PL, PF	Collected	Data from 1999 to 2002
3	SPR – AZDOT	AZ	PL, LL, PF	Collected	Volumetric Properties
4	FDOT HVS	FL	PL, LL, PF	Collected	Experiments 5 and 6
		FL	PL and LL		
5	Louisiana ALF	LA	PL, LL, PF	Collected	Experiments 1, 2, 3, and 4
6	WesTrack	WS	PL, LL, PF	Collected	Original and Rehabilitation
7	LTPP	LT	PL, LL, PF	Collected	SPS 1 and SPS 9[1]
8	WF Lands	WF	PF, PL, LL	Collected	Three projects
9	LA G_{mm} Study	LA	PF, PL, LL	Collected	Five projects
10	LA 98-1B Study	LA	PL, LL	Collected	Three projects
11	Un. Nevada	----	PL, LL	Collected	No process-based factors[2]
12	NCHRP 9-22	----	PL, LL	Collected	No process-based factors[2]
13	California HVS	----	N/A	Not Collected	Requests were turned down

[1]: SPS 1 had limited data and SPS 9 did not contain multiple specimen types.
[2]: Collected data did not identify process-based factors.

Table 2-7. Factors considered as sources of variability within and among the three specimen types.

	ID	Factors	Details
Recommended Factors	1	Compaction methods	Difference between field and laboratory compaction methods
	2	Silo storage	Extended storage time at the plant may harden asphalt in the mix
	3	Baghouse fines	May affect mix gradation and other volumetric properties
	4	Reheating	May affect binder properties and thus compacted specimens
	5	Aggregate absorption	May differ between plant and lab and thus affect variability
	6	Plant type and settings	May affect mixture properties and thus variability
	7	Sampling location	Sampling location (e.g., plant, behind paver) may affect variability
Additional Factors	8	Gradation density	Sensitive mixes are more susceptible to mix proportions than non-sensitive mixtures
	9	Material transfer device	Use of MTD may reduce material and thermal segregation
	10	Aggregate degradation	Mixture production may increase the fines fraction for soft aggregates
	11	Aggregate moisture	Moisture in the stockpile may affect mix properties

Table 2-8. Descriptions of the AZDOT data set.

Project Name	No. of Lots	Binder Type	Sampled From	NMAS, mm
Blake Ranch	11	PG 64-22	Binder Course	19
Cienega Creek	16	PG 64-16	Binder Course	19
Clifford Wash	7	PG 64-16	Binder Course	19
Detrital Wash NB	24	PG 76-16	Binder Course	25
Detrital Wash SB	5	PG 70-10	Binder Course	19
Kaiser Springs	30	PG 70-16	Binder Course	19
Penzance Curves	13	PG 64-22	Binder Course	19
Sells Wash	11	PG 70-10	Binder Course	12.5
Temple Bar Road	14	PG 70-10	Binder Course	19
Two Guns	20	PG 64-22	Binder Course	19
Signal Road	24	PG 76-16	Binder Course	25

Table 2-9. Volumetric properties in the AZDOT data set.

No. of Mixtures	Specimen Type	Property	Replicates
10	Lab-mixed–Lab-compacted	Asphalt Binder Content, Air Voids, Aggregate gradation	1
	Plant-mixed–Plant-compacted	Asphalt Binder Content, Air Voids, Aggregate gradation	20-120
	Plant-mixed–Plant-compacted and Plant-mixed–Field-compacted	Air Voids	N/A

Table 2-10. AZDOT data set summary statistics.

Category	Comparison	Properties	Average Differences			Range	
			AAD	-Avg	+Avg	Min	Max
Volumetric	PL-LL	AC,%	0.19	-0.18	0.21	-0.51	0.65
	PL-PF	AV,%	0.64	-0.68	0.53	-0.98	0.70
Gradation	PL-LL	9.5 mm,%	2.49	-1.56	2.73	-2.43	5.33
		2.36 mm,%	1.23	-1.24	1.22	-2.67	3.86
		0.6 mm,%	1.88	-1.89	1.89	-5.00	4.57
		0.075 mm,%	0.48	-0.61	0.40	-0.92	0.98

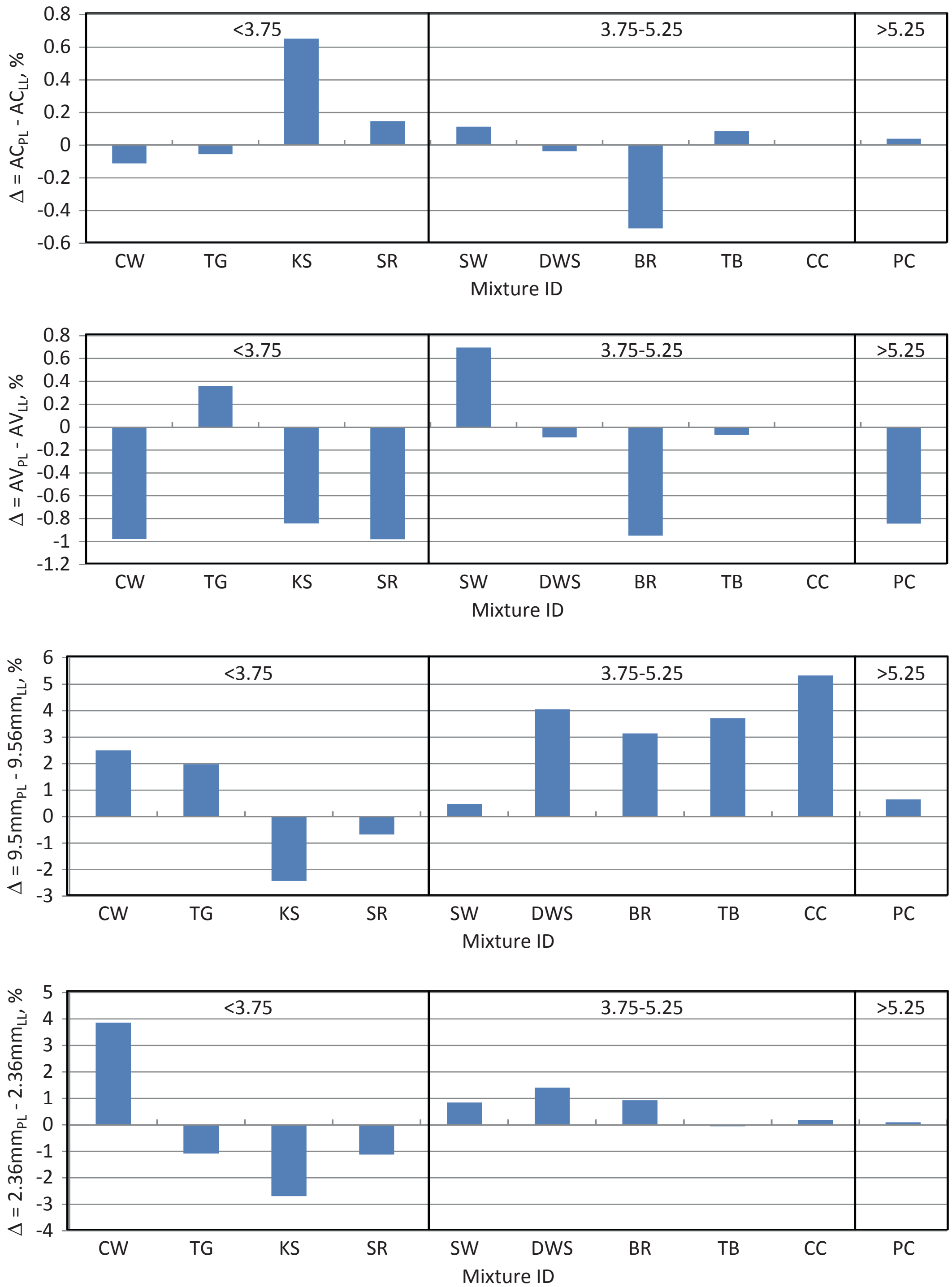
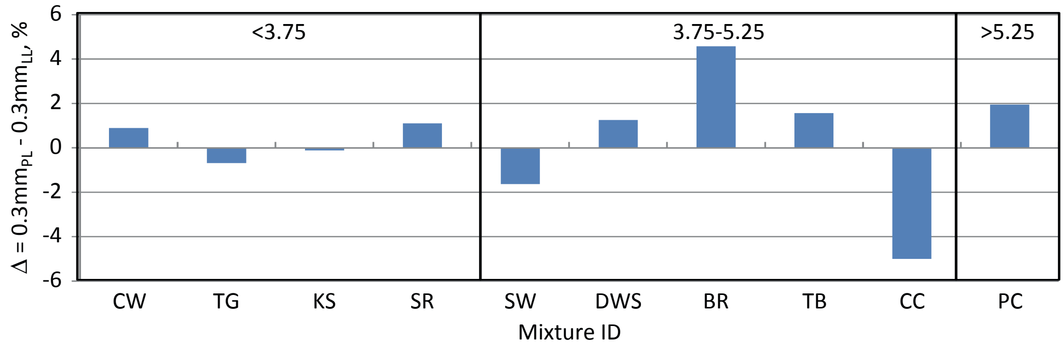


Figure 2-2. PL-LL asphalt binder content and gradation properties (grouped by NSAD).



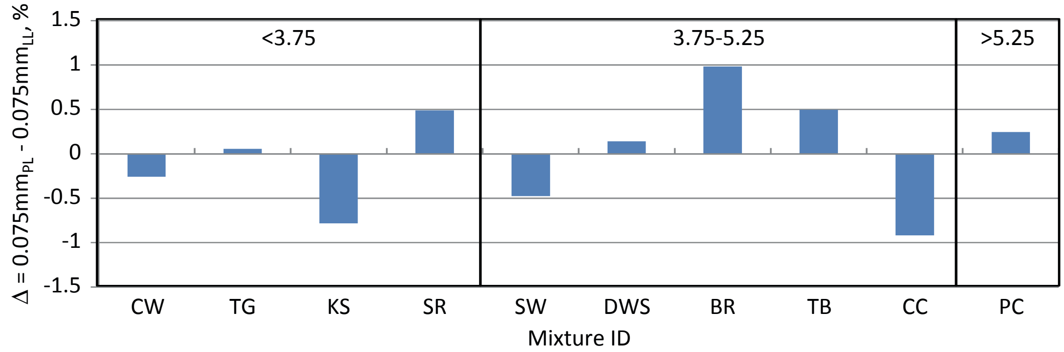
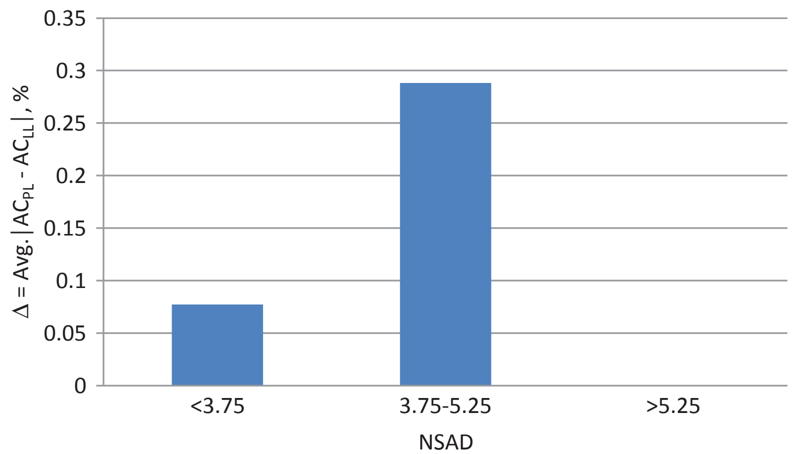


Figure 2-2. (Continued).



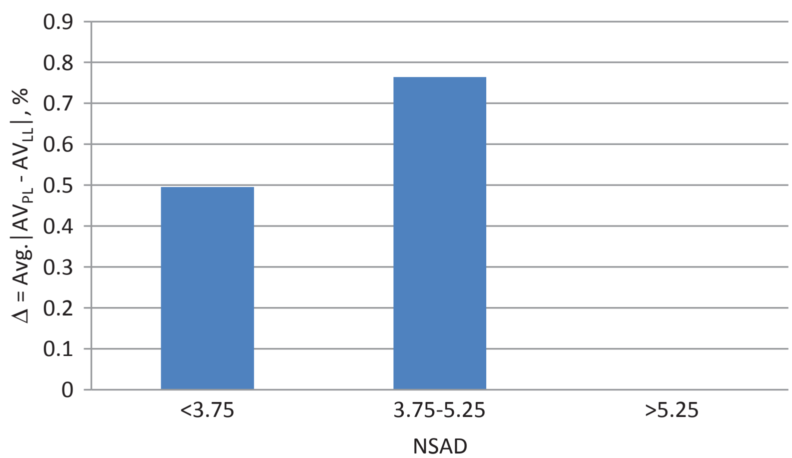


Figure 2-3. Absolute average differences (PL-LL) for asphalt binder content and gradation properties (grouped by NSAD).

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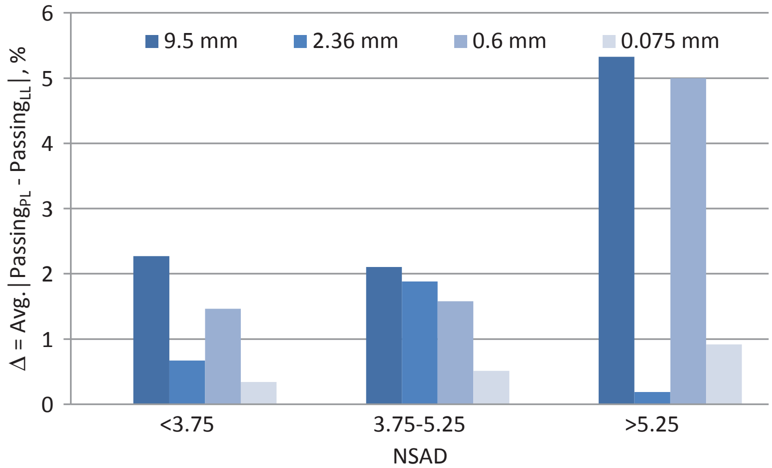


Figure 2-3. (Continued).

(AC-20P) to the properties of a mixture prepared using a high-viscosity base binder (AC-30). This 1994 study included an extensive laboratory factorial evaluating three Hveem-designed mixtures with varying asphalt binder type and gradation (Farooq and Sebaaly 1994). Three LL mixtures were tested. However, only two of the PL mixtures were evaluated. Hence, only two comparisons were available for evaluation. The laboratory data collected included the Lottman tensile strength ratio, IDT strength, resilient modulus (M_r), permanent deformation, and thermal cracking tests (see Table 2-11). In addition, some volumetric properties were available: mixture bulk specific gravity (G_{mb}), mixture maximum specific gravity (G_{mm}), and air voids (AV).

The second project, referred to as Experiment 2, compared mixtures designed using Superpave with mixtures designed using Hveem design methods (Sebaaly et al. 2005). Superpave mixture gradation satisfied the control points but did not consider the limits of the restricted zone. The experimental factorial consisted of testing both LL and PL specimens for the six mixtures. The mechanical tests evaluated included tensile strength ratio [TSR], Freeze Thaw (FrT), Asphalt Pavement Analyzer (APA), Repeated Load Test (RLT), Simple Shear Test (SST), and dynamic modulus (E*) (as shown in Table 2-11).

Data analysis was conducted to determine the magnitude of the differences between design values (LL) and production mixtures (PL). However, the process-based factors in the experiment were not varied, which did not allow the assessment of the causes of the differences and variability among the three specimen types.

To serve as a reference to the calculated values, differences are expressed in terms of the percentage differences from LL measurements. Tables 2-12 and 2-13 summarize the differences (Δ) for the UNR data sets. The absolute average difference (AAD) values shown in these tables are the average of all the absolute differences for all mixtures in the experiment. The positive and negative averages were calculated by taking the average of the sections in the experiment in which the difference was either positive or negative. The range shown is between the largest negative difference and the largest positive difference observed in all sections. Differences between PL

Table 2-11. Overview of UNR data set.

Year	Designation	No. of Mixtures	Specimen Type	Mechanical Test	Replicates
1994	Experiment 1	2	Lab-mixed–Lab-compacted	ITS, Mr, TSR, E_c[2]	3
			Plant-mixed–Plant-compacted	ITS, Mr, TSR	3
2005	Experiment 2	3	Lab-mixed–Lab-compacted	TSR, FrT, APA, RLT, SST, E*	2-3[1]
			Plant-mixed–Plant-compacted	TSR, FrT, APA, RLT, SST, E*	2-3[1]

[1]APA consisted of two replicates; [2]Creep Modulus

Table 2-12. UNR delta summary statistics (Experiment 1).

Category	Comparison	Properties	Average Differences			Range	
			AAD	-Avg	+Avg	Min	Max
Mechanical	(PL-LL)/LL	Mr@0°C, % LL	13.3	N/A	13.3	12.0	14.6
	(PL-LL)/LL	Mr@34°C, % LL	39.3	N/A	39.3	23.4	55.2
	(PL-LL)/LL	Mr@77°C, % LL	10.5	-4.4	16.6	-4.4	16.6
	(PL-LL)/LL	Mr@104°C, % LL	16.0	N/A	16.0	9.3	22.6
	(PL-LL)/LL	TSR, % LL	12.6	N/A	12.6	4.7	20.5
Volumetric	PL-LL	G_{mb}	.047	-0.047	N/A	-0.088	-0.007
	PL-LL	G_{mm}	.063	N/A	0.063	0.008	.118

and LL complex modulus values did not appear to be influenced by the test temperatures. In addition, the TSR values of PL samples were greater than those of LL samples for both experiments. This may be attributed to asphalt binder oxidation during production.

2.2.2 Summary of the Data Analysis

Tables 2-14 and 2-15 present the levels of variability for each of the volumetric and mechanical properties evaluated. The confidence intervals for the means shown in these tables were calculated based on Equation 2 (Law 2007):

$$\text{Confidence Limits} = \text{ADD} \pm t_{n-1,1-\alpha/2} * \text{stdev} \qquad (2)$$

where

AAD = absolute average difference,

$t_{n-1,\,1-\alpha/2}$ = is the upper $1-\alpha/2$ critical point for a t distribution with $n-1$ degrees of freedom (α is the level of significance set at 5%), and

stdev = standard deviation of the AAD for the analyzed data sets.

Confidence intervals are not presented for the properties in which only one data set was available. Other differences, indicated by N/A, were not available in the collected data sets. As shown in these tables, differences among the three specimen types varied widely as evidenced by the high standard deviation and the confidence intervals computed for some of the properties. These wide variations are due to many factors,

Table 2-13. UNR delta summary statistics (Experiment 2).

Category	Comparison	Properties	Averages			Range	
			AAD	-Avg	+Avg	Min	Max
Mechanical	(PL-LL)/LL	TSR, % LL	9.5	----	9.5	4.1	14.6
	(PL-LL)/LL	Rut Depth (APA), % LL	19.4	-29.7	14.2	-47.3	32.9
	(PL-LL)/LL	Accumulated Strain (RLT), % LL	22.4	-44.1	42.6	-72.2	42.6
	(PL-LL)/LL	Accumulated Strain (RLT), % LL	2.1	-2.1	----	-3.5	----
	(PL-LL)/LL	Accumulated Strain (SST), % LL	40.0	----	40.0	24.9	56.2
	(PL-LL)/LL	Dynamic Modulus @ 14°F, 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, 0.lHz, % LL	49.3	-26.3	65.7	-49.6	87.7
	(PL-LL)/LL	Dynamic Modulus @ 40°F, 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, 0.lHz, % LL	63.8	-19.6	88.1	-35.3	245.6
	(PL-LL)/LL	Dynamic Modulus @ 70°F, 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, 0.lHz, % LL	77.7	-10.2	91.1	-17.7	232.4
	(PL-LL)/LL	Dynamic Modulus @100°F, 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, 0.lHz, % LL	65.8	-10.6	97.7	-25.1	179.2
	(PL-LL)/LL	Dynamic Modulus @130°F, 25Hz, 10Hz, 5Hz, 1Hz, 0.5Hz, 0.lHz, % LL	46.3	-11.9	54.9	-17.5	168.0

Table 2-14. Summary of differences among the three specimen types for volumetric and gradation properties.

(a) Volumetric Properties

Property	Comparison	Average Differences		Confidence Intervals	
		AAD	St. Dev.	Low Limit	High Limit
Asphalt Binder Content, %	PF-PL	0.250	----	----	----
	PF-LL	0.237	0.021	0.170	0.303
	PL-LL	0.277	0.131	-0.020	0.573
Air Voids, %	PF-PL	N/A	N/A	N/A	N/A
	PF-LL	0.510	0.286	-0.400	1.420
	PL-LL	0.806	0.295	0.137	1.474
VMA, %	PF-PL	N/A	N/A	N/A	N/A
	PF-LL	N/A	N/A	N/A	N/A
	PL-LL	1.230	0.537	-1.082	3.542
G_{mm}	PF-PL	0.038	----	----	----
	PF-LL	0.030	----	----	----
	PL-LL	0.032	0.022	-0.030	0.094
G_{mb}	PF-PL	0.059	0.052	-0.166	0.284
	PF-LL	0.054	----	----	----
	PL-LL	0.250	----	----	----

(b) Gradation Properties

Percent Passing Sieve Size, %	Comparison	Average Differences		Confidence Intervals	
		AAD	St. Dev.	Low Limit	High Limit
25 mm	PL-LL	1.56	2.133	-5.227	8.347
19 mm	PF-LL	0.09	----	----	----
	PL-LL	0.779	0.935	-1.431	2.989
12.5 mm	PF-LL	1.19	----	----	----
	PL-LL	1.367	0.645	-0.092	2.826
9.5 mm	PF-LL	1.14	----	----	----
	PL-LL	2.246	1.257	-0.554	5.046
4.75 mm	PF-LL	1.15	----	----	----
	PL-LL	2.079	1.202	-0.639	4.797
2.36 mm	PF-LL	0.71	----	----	----
	PL-LL	1.829	1.216	-0.881	4.539
2.0 mm	PL-LL	3	----	----	----

Table 2-14. (Continued).

Percent Passing Sieve Size, %	Comparison	Average Differences		Confidence Intervals	
		AAD	St. Dev.	Low Limit	High Limit
1.18 mm	PF-LL	0.78	----	----	----
	PL-LL	1.538	1.078	-0.948	4.023
0.6 mm	PF-LL	0.77	----	----	----
	PL-LL	1.721	1.25	-1.064	4.506
0.425 mm	PL-LL	2.25	----	----	----
0.3 mm	PF-LL	0.73	----	----	----
	PL-LL	1.653	1.516	-1.777	5.083
0.18 mm	PL-LL	2.75	----	----	----
0.15 mm	PF-LL	0.79	----	----	----
	PL-LL	0.855	0.541	-0.392	2.102
0.075 mm	PF-LL	0.97	----	----	----
	PL-LL	0.617	0.388	-0.247	1.481

Table 2-15. Summary of differences among the three specimen types for the mechanical properties.

Category	Property	Comparison	Average Differences		Confidence Intervals	
			AAD	St. Dev.	Low Limit	High Limit
Moisture Susceptibility	Tensile Strength Ratio, (TSR), % LL	(PF-PL)/LL	10.55	2.47	-0.10	21.20
		(PF-LL)/LL	19.00	2.12	9.87	28.13
		(PL-LL)/LL	16.73	7.54	-4.21	37.66
Low-Temperature Cracking	Temperature @ fracture (T), % LL	(PF-PL)/LL	15.25	3.61	-0.27	30.77
		(PF-LL)/LL	14.60	12.73	-40.17	69.37
		(PL-LL)/LL	20.35	4.31	1.79	38.91
	Stress @ fracture (s), % LL	(PF-PL)/LL	33.20	0.99	28.94	37.46
		(PF-LL)/LL	17.85	9.40	-22.62	58.32
		(PL-LL)/LL	31.90	1.98	23.38	40.42
Beam Fatigue	No. Cycles @ failure (Nf), % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	42.50	N/A	----	----
		(PL-LL)/LL	N/A	N/A	N/A	N/A
	Phase Angle (PA), % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	15.30	N/A	----	----
		(PL-LL)/LL	N/A	N/A	N/A	N/A
	Stiffness (St), % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	19.50	N/A	----	----
		(PL-LL)/LL	N/A	N/A	N/A	N/A
APA	Rut Depth (APA), % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	19.40	N/A	----	----
RLT	% Strain @ 12,000 Cycles, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	22.40	N/A	----	----
	Cycles to 3% Strain, %LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	2.10	N/A	----	----

(continued on next page)

Table 2-15. (Continued).

Category	Property	Comparison	Average Differences		Confidence Intervals	
			AAD	St. Dev.	Low Limit	High Limit
SST	Strain @ 5,000 Cycles, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	40.00	N/A	----	----
Axial Dynamic Modulus	Dynamic Modulus @ 14°F, 25Hz, 10Hz, 5Hz, 1HZ, 0.5Hz, 0.1Hz, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	49.30	N/A	----	----
Axial Dynamic Modulus	Dynamic Modulus @ 40°F, 25Hz, 10Hz, 5Hz, 1HZ, 0.5Hz, 0.1Hz, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	63.80	N/A	----	----
Axial Dynamic Modulus	Dynamic Modulus @ 70°F, 25Hz, 10Hz, 5Hz, 1HZ, 0.5Hz, 0.1Hz, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	77.70	N/A	----	----
	Dynamic Modulus @ 100°F, 25Hz, 10Hz, 5Hz, 1HZ, 0.5Hz, 0.1Hz, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	65.80	N/A	----	----
	Dynamic Modulus @ 130°F, 25Hz, 10Hz, 5Hz, 1HZ, 0.5Hz, 0.1Hz, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	46.30	N/A	----	----
Resilient Modulus (Mr)	Mr @ 0°C, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	13.30	N/A	----	----
	Mr @ 34°C, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	39.30	N/A	----	----
	Mr @ 77°C, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	10.50	N/A	----	----
	Mr @ 104°C, % LL	(PF-PL)/LL	N/A	N/A	N/A	N/A
		(PF-LL)/LL	N/A	N/A	N/A	N/A
		(PL-LL)/LL	16.00	N/A	----	----

including differences in construction practices among agencies, differences in mix characteristics and designs among projects, and differences in variability between the different projects. Confidence intervals could not be developed for most of the mechanical properties because only two data sets were used.

2.3 Meta-Analysis

The statistical analyses presented in the previous sections were conducted on a per-data-set basis, and a summary was compiled to provide an overall quantification of the levels of differences between the three specimen types. However, many of the process-based factors were not documented in the data collected and were not known. As a result of these limitations, the effects of the identified factors on the calculated variability could not be directly assessed because only one condition was used in most of the collected data sets. To address this limitation, the individual data were combined in a meta-analysis that made use of data obtained from different sources to identify the influences of process-based factors on volumetric properties among the three specimen types (i.e., LL, PL, and PF).

In the meta-analysis, calculated differences (PL–LL, PF–LL, and PF–PL) among the three specimen types were combined in "meta-data" sets, assumed to originate from the same population. Statistical t-tests were then conducted to test the null hypothesis that the means of the differences between two of the three specimens are equal when a change is made to only one of the process-based factors. Some of the data grouped into the "meta-data" set did not originate from the same source, and the influences of unforeseen factors, such as mix design (i.e., NMAS), material properties, and construction practices in different states, may affect the validity of the comparison. In addition, conclusions from the t-test may be affected by the large difference in the mixtures of the meta-data set. Therefore, results of this analysis should only serve as a general indicator of future research needs.

A total of 230 mixtures were included in the meta-analysis. The volumetric properties considered were asphalt binder content, AV, VMA, G_{mm}, G_{mb}, and gradation. Mechanical properties were not evaluated because process-based factors were unknown or not varied in the combined data sets. Evaluated factors included use of baghouse fines, reheating, aggregate absorption, plant type, sampling location, and use of a material transfer vehicle. Statistical analysis was performed using the statistical analysis software (SAS). The SAS T-test procedure was used to compare the means of the differences between two of the three specimens when a change was made to only one of the aforementioned process-based factors. An F-test was used to check the equality of variances, and the appropriate p-value is reported. The p-values are summarized in Table 2-16 for the PL–LL differences. Blank cells indicate that either no observation was available for the factor or that the factor did not have two levels. The N values presented in Table 2-16 provide the sample sizes for the compared populations. The shaded cells are the statistical comparisons that were found significant, indicating that the evaluated factor may have an influence on the difference between the two specimen types. As shown in Table 2-16, most of the comparisons did not show statistical influences of the evaluated factors. Due to lack of available data, the tables developed for the PF–LL and PF–PL differences were mostly empty and are reported in Appendix B (available on the project webpage).

In addition to the results of the statistical analysis presented in the previous section, attempts were made to identify trends in the data by visual comparison using charts. The charts corresponding to statistically significant trends identified in Table 2-16 are shown in this section. Other comparative charts are presented in Appendix A. Figure 2-4 shows the delta chart for asphalt binder content sorted by sampling location. The number of field-sampled mixtures was much larger than the number of mixtures sampled at the plant. This may have affected the finding of the t-test. The mean difference for the field samples was –0.06% compared to the mean of +0.04% for the plant samples. This may be due to further aggregate absorption of asphalt binder during transportation.

Figure 2-5 shows the delta chart for aggregate gradation percent passing 9.5 mm grouped by reheating. Only 6 mixtures experienced reheating compared to 87 without reheating. Conclusions from the t-test may be affected by the large difference in the number of mixtures for each grouping. The mean for the non-reheated group was 2.0% as compared to

Table 2-16. Meta-analysis PL-LL statistical results summary.

PL-LL	Baghouse			Reheating			Aggregate Absorption			Plant Type			Sampling Location			MTV		
	P_{value}	N_{YES}	N_{NO}	P_{value}	N_{YES}	N_{NO}	P_{value}	N_{LOW}	N_{HIGH}	P_{value}	N_{DRUM}	N_{BATCH}	P_{value}	N_{PLANT}	N_{FIELD}	P_{value}	N_{YES}	N_{NO}
AC	0.23	25	6	0.09	7	133	0.72	24	3	0.97	103	9	0.01	17	52	0.65	75	17
AV	0.40	53	6	0.23	9	86	0.33	22	3	-	-	-	0.07	19	40	0.47	101	19
G_{mm}	-	-	-	0.76	5	5	-	-	-	0.80	31	9	-	-	-	-	-	-
G_{mb}	-	-	-	-	-	-	-	-	-	0.04	10	8	-	-	-	-	-	-
VMA	0.43	9	6	0.76	4	72	<0.01	12	3	-	-	-	0.43	9	6	0.39	67	9
25	-	-	-	0.88	3	68	-	-	-	-	-	-	-	-	-	0.83	67	4
19	0.30	49	6	0.98	6	86	0.55	19	2	-	-	-	0.84	15	40	0.10	105	11
12.5	0.91	50	6	0.30	6	87	0.87	19	3	-	-	-	0.59	16	40	0.34	101	16
9.5	0.12	50	6	0.01*	6	87	0.08	19	3	-	-	-	0.62	16	40	0.12	101	16
4.75	0.32	50	6	<0.01	6	87	0.51	19	3	-	-	-	0.49	16	40	<0.01	101	16
2.36	0.39	47	6	0.30	5	85	0.54	17	2	-	-	-	0.78	13	40	0.79	101	13
1.18	-	-	-	0.01	3	82	-	-	-	-	-	-	0.59	14	32	0.97	101	8
0.6	0.98	48	6	0.09	6	85	0.89	18	2	-	-	-	0.32	14	40	0.45	101	14
0.3	0.86	48	6	0.10	6	85	0.81	18	2	-	-	-	0.75	14	40	0.83	101	14
0.15	-	-	-	-	-	-	-	-	-	-	-	-	<0.01	6	34	0.26	95	6
0.075	0.43	49	6	0.01	5	87	0.81	18	3	-	-	-	0.93	15	40	0.05	101	15

*: $P_{value} < 0.05$ indicates statistical significance

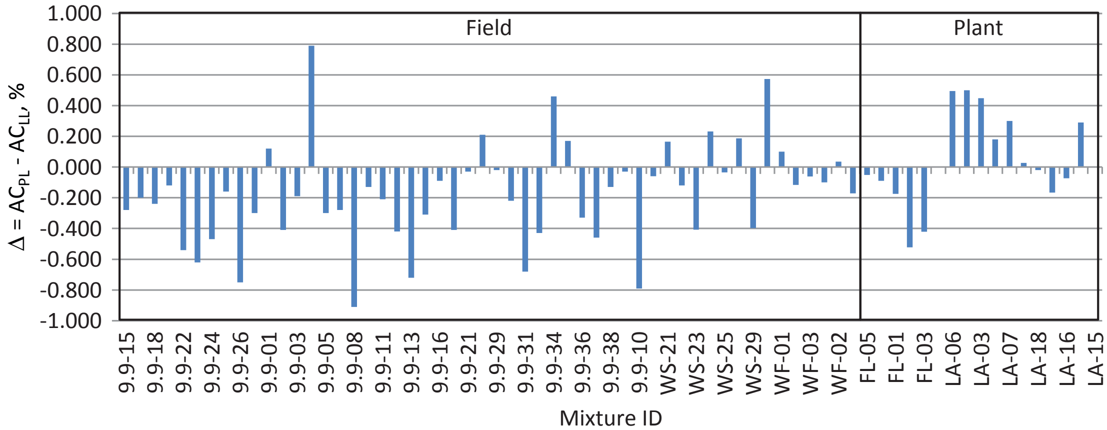


Figure 2-4. Meta-analysis: PL-LL asphalt binder content (grouped by sampling location).

−1.9% for the reheated group. Figure 2-6 shows the delta chart for aggregate gradation percent passing 4.75 mm grouped by reheating. Similarly, for this sieve, only 6 mixtures experienced reheating compared to 87 without reheating. Conclusions from the t-test may be influenced by the large disparity in the number of mixtures for each grouping. The mean for the non-reheated group was 2.2% as compared to a mean of −1.6% for the reheated group.

Figure 2-7 shows the delta chart for the aggregate gradation percent passing 4.75 mm grouped by material transfer vehicle (MTV) use. Similarly, results of the t-test may be affected by the large difference in the number of mixtures for each grouping. Furthermore, the sampling location was not known for about 50% of the data points in the MTV group, which could influence the conclusions, because plant-sampled materials will not be affected by the use of MTV. About 60% of the data in the "No MTV" group came from Louisiana and the Florida accelerated pavement test projects, which had low volumes of production. Figure 2-8 shows the delta chart for percent aggregate passing 1.18 mm grouped by reheating. For this comparison, only 3 mixtures experienced reheating compared to 82 without reheating. Conclusions from the t-test may be influenced by the large inequality in the number of mixtures for each grouping. The mean difference for the reheated group was −1.7% compared to a mean of 1.0% for the non-reheated group with most of the differences in the ± 4% range. The highest data point in the non-reheated group comes from a mixture which was adjusted during production. If the post-adjustment peak is considered, this difference reduces substantially.

Figure 2-9 shows the delta chart for percent aggregate passing 0.15 mm grouped by sampling location. For this comparison, only 6 mixtures were sampled at the plant compared to 34 sampled in the field. The mean difference for the field group was 0.2% as compared to 1.0% for the plant group. Most of the differences were within a range of ± 2%. The peak in the plant-sampled mixture came prior to an adjustment in the production of the mixture. If the post-adjustment samples are considered only, the delta is reduced considerably.

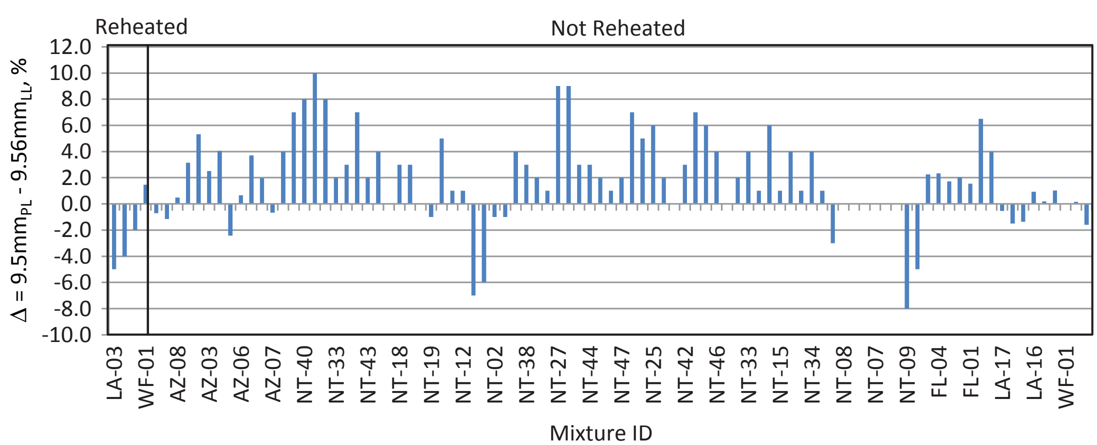


Figure 2-5. Meta-analysis: PL-LL aggregate gradation percent passing 9.5 mm (grouped by reheating).

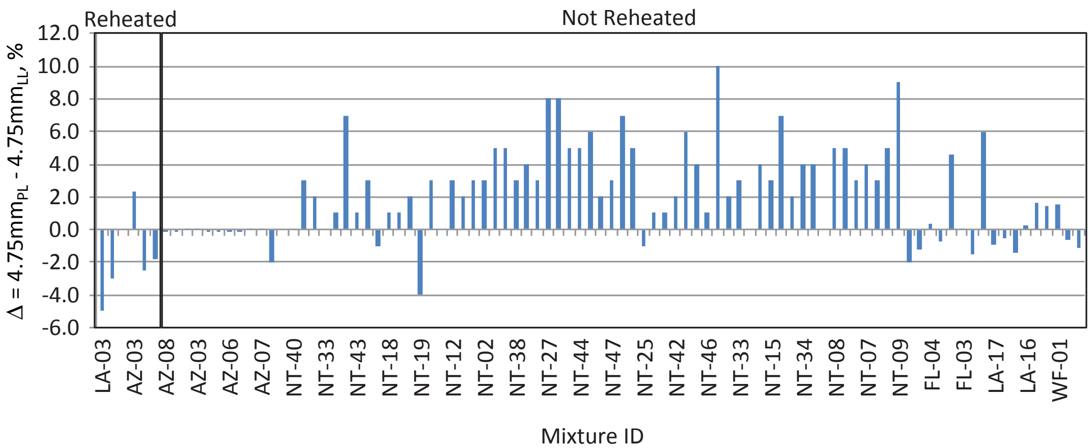


Figure 2-6. Meta-analysis: PL-LL aggregate gradation percent passing 4.75 mm (grouped by reheating).

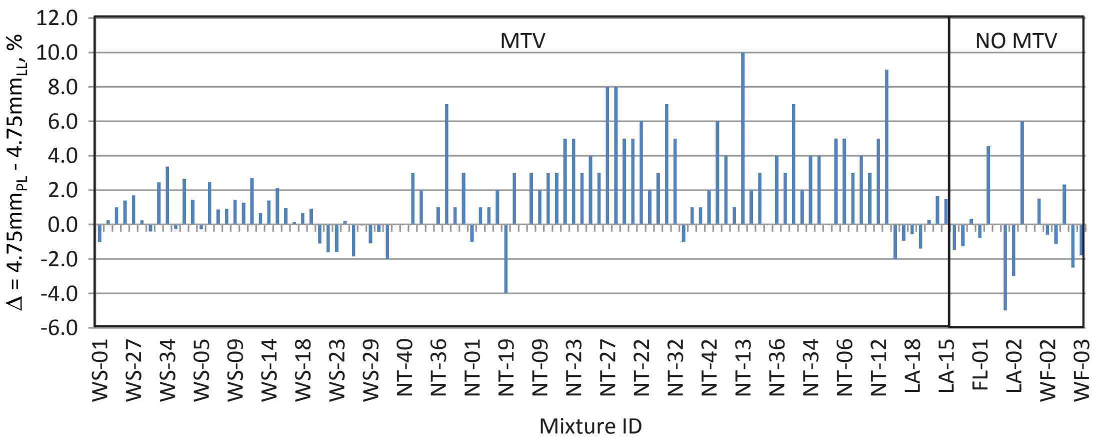


Figure 2-7. Meta-analysis: PL-LL aggregate gradation percent passing 4.75 mm (grouped by MTV).

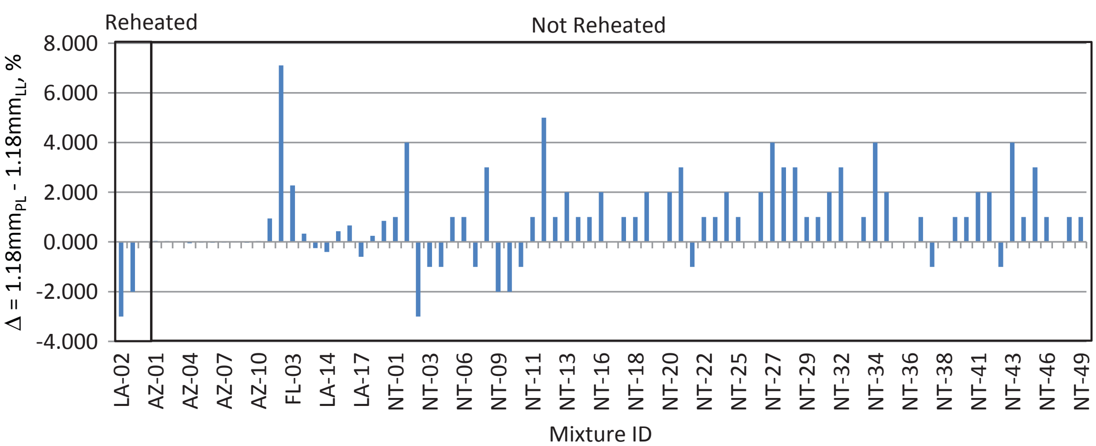


Figure 2-8. Meta-analysis: PL-LL aggregate gradation percent passing 1.18 mm (grouped by reheating).

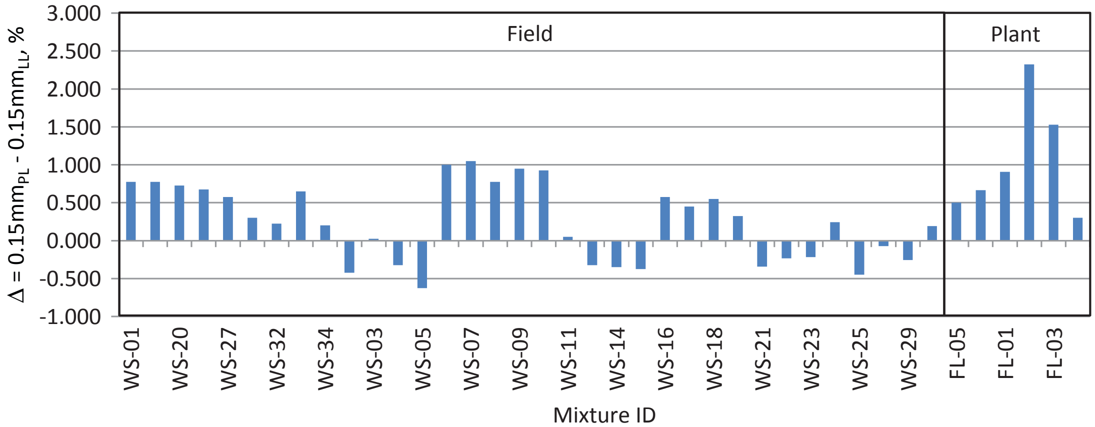


Figure 2-9. Meta-analysis: PL-LL aggregate gradation percent passing 0.15 mm (grouped by sampling location).

Conclusions from the t-test may be affected by the large difference in the number of mixtures for each grouping.

Figure 2-10 shows the delta chart for percent aggregate passing 0.075 mm grouped by reheating. Conclusions from the t-test may be affected by the large inequality in the number of mixtures for each grouping. Figure 2-11 shows the delta chart for mixture bulk specific gravity grouped by plant type. For this comparison, sample sizes are similar, albeit small, between the two groups. However, the data in the analysis is all from a single dataset (LTPP). One may hypothesize from this comparison that the difference between PL and LL for G_{mb} is greater for drum plant than for batch plant. However, the p-value from the t-test is nearly insignificant (0.04) at 95% confidence.

Figure 2-12 shows the delta chart for voids in the mineral aggregate (VMA) grouped by aggregate absorption. For this comparison, only 3 mixtures used highly absorptive aggregate as compared to 12 mixtures using non-absorptive aggregate. Conclusions from the t-test may be influenced by the large inequality in the number of mixtures for each grouping. Most the data points were in the ±1% range.

2.4 Conclusions and Findings of Phase IA

The objective of Phase IA was to determine the cause and magnitude of the differences and variances in measured volumetric and mechanical properties among three specimen types (i.e., laboratory-mixed–laboratory-compacted [LL], plant-mixed–laboratory-compacted [PL], and plant-mixed–field-compacted [PF]). In Phase IA of this project, specific highway and research agencies were contacted to collect existing volumetric and mechanical data in order to achieve the objectives of the project. Individual data analysis was conducted to quantify levels of differences among the three specimen types for volumetric and mechanical properties. The analysis found that the influence of NSAD on the different volumet-

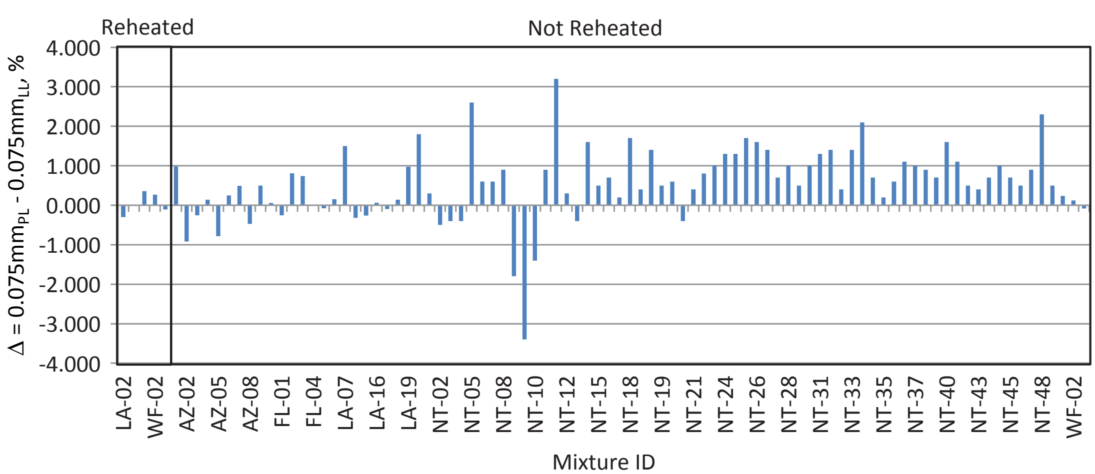


Figure 2-10. Meta-analysis: PL-LL aggregate gradation percent passing 0.075 mm (grouped by reheating).

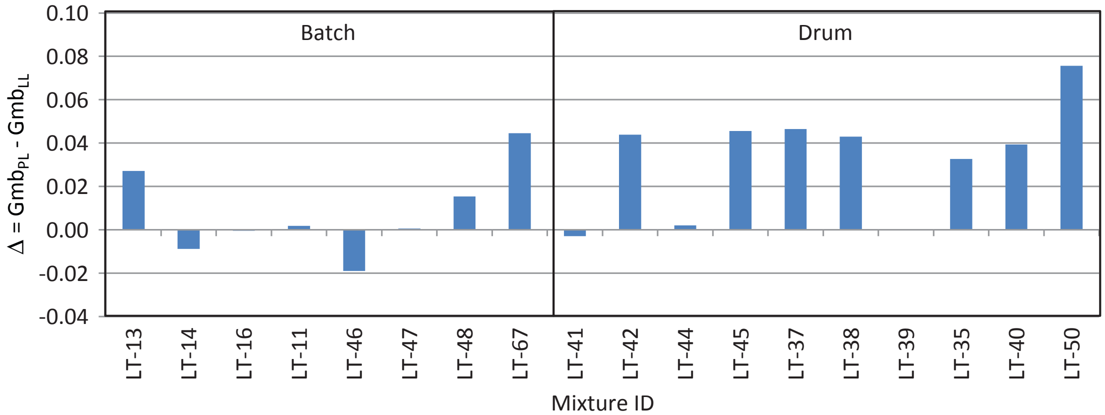


Figure 2-11. Meta-analysis: PL-LL mixture bulk specific gravity (grouped by plant type).

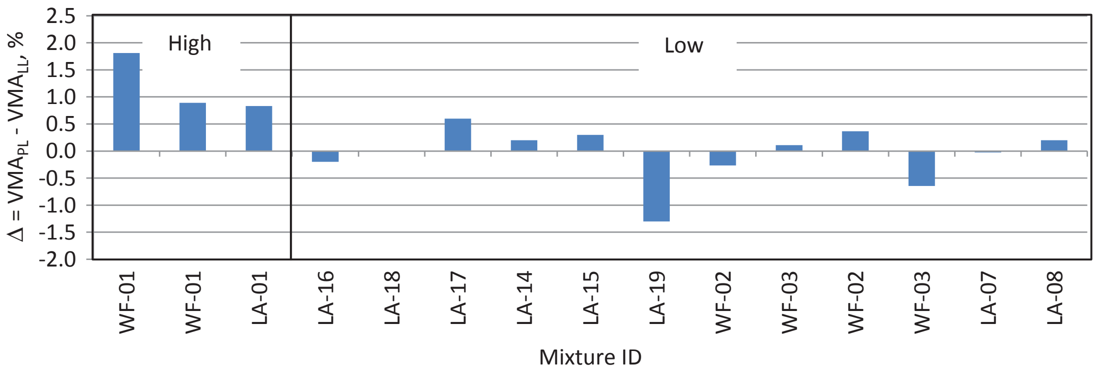


Figure 2-12. Meta-analysis: PL-LL voids in the mineral aggregate (grouped by aggregate absorption).

ric properties was mixed and was mostly inconclusive. Major limitations were encountered, because the collected data sets did not methodically vary most of the process-based factors identified as potential causes of variability. In addition, many of the process-based factors were not documented in the data collected and were not known. Because of these limitations, the effects of the identified factors on the calculated variability could not be directly assessed because only one condition was used in most of the collected data sets.

To address this limitation, the collected data were combined in a meta-analysis that made use of data obtained from different sources to identify causes and levels of variability for volumetric and mechanical properties among the three specimen types (i.e., LL, PL, and PF). However, these data were not homogeneous and the influences of unforeseen factors, such as mixture design, were not considered. It is difficult to determine whether or not the statistically significant differences determined by the meta-analysis were caused by sample size inequalities or if they were true representations of the effects of the process-based factors. Therefore, results of this analysis only served as a general indicator of the need for continued research, which is addressed in Phase II of this study.

CHAPTER 3

Experimental Program

This chapter describes the experimental program used to generate and analyze the data required to meet the project objectives.

3.1 Determine Process-Based Factors

Research conducted in Phases I and IA of this project indicated that the effects of some process-based factors on the variability of properties from the three specimen types should be quantified. Several discussions with NCHRP were held to identify the most relevant construction-based factors to consider. The factors of interest are listed in Table 3-1.

3.2 Mixture Evaluation

This section summarizes the volumetric and mechanical test methods conducted in this project. Chapter 4 describes the test procedures used in detail. Table 3-2 presents the volumetric properties evaluated and their respective test procedures. Table 3-3 presents the mechanical test procedures used in this study.

3.3 Test Factorial Design

In the experimental plan, each process-based factor was varied between two contrasting levels (low and high) based on a 2^k factorial design, where k is the number of factors. Based on the proposed factorial design, the total number of test combinations for each volumetric and mechanical property of interest was 2^5 factor combinations multiplied by three specimen types for a total of 96 combinations. Each test combination was conducted in triplicate to determine within-specimen variability. In total, 96 test combinations × 8 volumetric properties × 3 replications = 2,304 properties (576 samples) were required for the full factorial design in order to assess the variability in volumetric properties, and 96 test combinations × 3 mechanical properties × 3 replications = 768 test samples were needed for the assessment of the variability in the selected mechanical properties. The number of mechanical samples assumes that the axial dynamic modulus was only to be conducted for LL and PL samples, given sample size limitations.

Given the large numbers of required test samples, a fractional factorial design was used to reduce the number of tests required to assess the influence of the factors shown in Table 3-1. A quarter fractional design reduced the number of test samples ($2^{5-2} = 8 \times 3$ specimen types = 24 test combinations) to $24 \times 8 \times 3 = 576$ for the volumetric properties and $24 \times 3 \times 3 = 216$ for the mechanical properties. These numbers were manageable for the proposed volumetric and mechanical properties. Results of the fractional factorial analysis allow the quantification of causes of variability within and among the three specimen types. However, a main effects model must be used, which eliminates 2-factor and higher order interactions from the model. All conclusions presume the validity of the main effects model.

To illustrate, Table 3-4 presents a sample of the factor combinations that were to be conducted to assess levels and causes of variability within and among the three specimen types for asphalt binder content (AC). Table 3-4 was repeated for each specimen type and the differences (Δ) between the three specimen types (PF–PL, PL–LL, and PF–LL) were calculated. The statistical analysis software (SAS) PROC FACTEX feature was used to develop the fractional factorial design. Definitions of factors 1 through 5 are given in Table 3-1. A negative sign indicates that the factor is at the low level and a positive sign indicates that the factor is at the high level. For each factor combination presented in Table 3-4, the researchers quantified the responses (i.e., Δ between the AC averages [for the three replications] measured for the three specimen types, and the levels of variability measured for LL, PL, and PF specimens).

The main effect of a given factor (1 to 5) is a measure of the change in response (i.e., variability) due to a change in an individual factor. The main effect for each factor is determined based on Equation 3:

Table 3-1. Description of process-based factors.

Factor	Evaluation Method
1. Baghouse Fines	Evaluate the effects of using baghouse fines on volumetric and mechanical mix properties. Evaluate mixtures both with and without using baghouse fines. In addition, sample baghouse fines and characterize to determine if the type of baghouse fines has an effect.
2. Reheating	Reheating is determined by allowing the mixture to cool to room temperature, then heating to compaction temperature and compacting. Prepare specimens after mixture is allowed to cool for a period of 3 days.
3. Aggregate Absorption	Measure absorption of the aggregates in the mixture using water absorption. Mixtures are classified as having either high or low absorption.
4. Aggregate Degradation	Toughness of the aggregates in the mixture is used to determine the amount of aggregate degradation in the mixture. Classify mixtures as either soft or hard, based on the toughness of the aggregates used in the mixture. Aggregate degradation shall be measured using the Micro Duvall.
5. Aggregate Stockpile Moisture	Monitor aggregate stockpile moisture. Produce HMA mixtures after a significant rain event and during dry conditions.

Table 3-2. Volumetric testing method.

Volumetric Property	Test Method
Air Voids	AASHTO T 166 AASHTO T 209 AASHTO T 269
Mixture Maximum Specific Gravity, G_{mm}	AASHTO T 209
Asphalt Binder Content	AASHTO T 164
Aggregate Gradation	AASHTO T 30
Aggregate Bulk Specific Gravity, G_{sb}	AASHTO T 84 AASHTO T 85

Table 3-3. Mechanical testing method.

Mechanical Property	Test Method
Loaded-Wheel Test	AASHTO T 324
Axial Dynamic Modulus	AASHTO T 342
Indirect Dynamic Modulus	Kim et al. (2004)

$$e_i = \frac{\sum_{i=1}^{n} d_i R_i}{8} \tag{3}$$

where

e_i = main effect for factor i = 1, 2, 3, 4, and 5;
n = number of design runs (n = 8);
R_i = response; and
d_i = ± sign from Table 3-4 (i.e., −1 and 1).

For example, to calculate the main effect for asphalt absorption by aggregates, e_3, on the differences between PL and LL, Equation 4 is used:

$$e_3 = ((-)(\Delta1 + (-)(\Delta2 + (-)(\Delta3 + (-)\Delta4 + \cdots (+)(\Delta7(+)(\Delta8))/8 \tag{4}$$

where

Δ = differences between PL and LL averages for each factor combination presented in Table 3-4.

Table 3-4. SAS fractional factorial design output.

Factor Combination Number	Factor ID					Response ID
	Baghouse Return	Mixture Reheating	Aggregate Absorption	Aggregate Degradation	Aggregate Moisture	
1[a]	-	-	-	-	-	R_1
2	+	-	-	-	-	R_2
3	-	+	-	-	-	R_3
4	+	+	-	-	-	R_4
5	…	…	…	…	…	…
6	…	…	…	…	…	…
7	-	+	+	+	+	R_7
8	+	+	+	+	+	R_8

[a]For example, AC is measured for a mix produced with no baghouse fines and for a mixture prepared with low absorption and soft aggregates. Prior to production, the moisture in the aggregates' stockpile is low. Testing was conducted at the plant with no reheating.

Table 3-5. Fractional factorial design.

Mixture ID	Baghouse Fines	Reheating	Aggregate Absorption	Aggregate Degradation	Aggregate Moisture Content
Mix 1	No	No	Low	Soft	High
Mix 2*	No	No	High	Hard	Low
Mix 3	No	Yes	Low	Hard	Low
Mix 4*	No	Yes	High	Soft	High
Mix 5	Yes	No	Low	Hard	High
Mix 6	Yes	No	High	Soft	Low
Mix 7	Yes	Yes	Low	Soft	Low
Mix 8	Yes	Yes	High	Hard	High

• Not produced

For example, AC is measured for a mix produced with no baghouse fines and for a mix prepared with low absorption and soft aggregates. Before production, the moisture in the aggregate stockpile is low. Testing was conducted at the plant with no reheating.

The fractional factorial design is clarified in Table 3-5 to show the factor combinations required to complete the main effects model. The researchers managed to collect mixtures that satisfied six of the eight conditions shown in Table 3-5, but Mixtures 2 and 4 were difficult to locate or impractical for contractors to produce and were excluded. Therefore, the research was completed by the collection of 13 mixtures commonly produced in different climatic regions of the United States. However, because of complications in production, only 11 mixtures were included in the analysis.

3.4 Mixture Descriptions

Mixture descriptions are provided in Table 3-6. All JMFs are presented in Appendix D which is available on the project web page. Drum plants were used in the production of each mixture.

Table 3-6. Mixture descriptions.

Mix ID	Source	Design Asphalt Binder Content	PG Asphalt Binder Used	% RAP	Binder Replacement Ratio	Comments
1WI	Mathy Construction of Onalaska, WI from a project on U.S. Highway 61	5.7%	64-28	20%	17%	Medium traffic (2,000,000 ESAL)
3MN	Minnesota DOT from a project on Highway 8 in Chisago County near Lindstrom, MN	5.0%	64-28	25%	26%	The 'no reheat' specimens were not provided for this mixture, which was acceptable because it satisfies the factorial presented in Table 3-5.
5WI	Stark Asphalt of Milwaukee, WI, from a project on a segment of State Highway 60	5.3%	64-28	15%	13%	The nominal maximum aggregate size of the mixture was 12.5 mm.
5LA90	Prairie Construction of Opelousas, LA, from a project on U.S. Highway 90	4.1%	64-22	20%	29%	
5LA61	Barriere Construction of Metairie, LA, from construction on U.S. Highway 61	4.7%	76-22m	14%	21%	Elastomeric-polymer-modified
5VA	Virginia DOT from a mixture produced by Superior Paving Corp	5.2%	64-22	30%	29%	
5SD	South Dakota DOT from a mixture produced by Spencer Quarry	5.3%	58-34	20%	28%	Hydrated lime was used as an anti-strip and was introduced using a pug mill at the plant, prior to drying the aggregate.

Table 3-6. (Continued).

Mix ID	Source	Design Asphalt Binder Content	PG Asphalt Binder Used	% RAP	Binder Replacement Ratio	Comments
6FL	Community Asphalt from the rehabilitation of a state highway in Lee County, FL	6.0%	76-22	15%	17%	
7IA	Mathy Construction of Onalaska, WI, from construction on U.S. Highway 169 in Humboldt County, IA	6.2%	58-28	12%	9.6%	
8LA	Diamond B Construction of Amite, LA, from a project on State Highway 441 in Tangipahoa Parish, LA	5.0%	82-22 CRM	0%	0%	The design asphalt binder content was 5.0% using a polymer-modified PG 70-22M asphalt binder. The paving mixtures PL and PF were produced using PG 82-22 asphalt binder modified with crumb rubber. To remain consistent with the plant-produced mixture, the asphalt binder used for LL specimen fabrication was PG 82-22. The mixture contained 0% RAP. The plant was having trouble getting density at the JMF asphalt binder content. Therefore, the target asphalt binder content was increased to 5.4% to obtain laboratory and field air void values meeting specifications. The need for the higher asphalt binder content may be attributed to the use of crumb rubber in plant production, which increased the binder stiffness over that of the original PG 70-22M asphalt binder.

CHAPTER 4

Method

4.1 Description of Specimen Preparation

Three possible scenarios for production of asphalt mixture specimens were considered in this project: (1) laboratory-mixed–laboratory-compacted specimens (LL) produced during the design process; (2) plant-mixed–laboratory-compacted specimens (PL) produced for volumetric acceptance and QC testing of plant-produced mix; and (3) plant-mixed–field-compacted specimens (PF), used in testing in situ pavement. The following sections detail the procedures followed to prepare the three specimen types.

4.1.1 Laboratory-Mixed–Laboratory-Compacted (LL) Specimens

Figure 4-1 depicts the sample collection and fabrication process for LL specimens. The composition of LL specimens is detailed in the JMF (Appendix D) resulting from the laboratory design process (AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures"). The following steps were used to make the LL specimens:

1. Aggregates from each stockpile were sampled in accordance with ASTM D75, "Standard Practice for Sampling Aggregates." [Figure 4-1(a) and (b)];
2. Aggregates were oven dried at 110°C to constant mass;
3. Dry aggregates were separated into individual sieve sizes, [Figure 4-1(c) and (d)] (AASHTO T 27, "Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates");
4. Aggregates were blended in accordance with the JMF, [Figure 4-1 (e)] (AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures");
5. The aggregate blend was heated to production temperature, (AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures");
6. Liquid asphalt binder was mixed with the heated aggregate blend in accordance with the JMF, [Figure 4-1 (f) and (g)] (AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures");
7. The resulting mixture was put in an oven at the production temperature (which varied with asphalt binder performance grade) for short-term aging and volumetric stabilization in accordance with AASHTO R 30, "Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)";
8. Samples were prepared for compaction and testing size requirements in accordance with AASHTO R 47, "Standard Practice for Reducing Samples of Hot Mix Asphalt (HMA) to Testing Size"; and
9. The loose mixture was compacted into specimens using the Superpave gyratory compactor (SGC) to meet testing protocols. [Figure 4-1 (h), (i), and (j)] (AASHTO T 312, "Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor").

4.1.2 Plant-Mixed–Laboratory-Compacted (PL) Specimens

Figure 4-2 depicts the sample collection and fabrication process for PL specimens. The PL samples were composed of asphalt mixture collected from the truck in accordance with ASTM D979, "Standard Practice for Sampling Bituminous Paving Mixtures." The mix constituents of each PL specimen are detailed in the mix JMF (Appendix D). The following steps were used to make the PL specimens:

1. Samples were fabricated by collecting loose mixture from the truck according to state protocol and ASTM D979, "Standard Practice for Sampling Bituminous Paving Mixtures," [Figure 4-2 (c) and (d)];
2. Loose mixture was split into required weight size in accordance with AASHTO R 47, "Standard Practice for Reducing Samples of Hot Mix Asphalt (HMA) to Testing Size," [Figure 4-2 (e)];

Figure 4-1. Laboratory-mixed–laboratory-compacted (LL) specimen fabrication.

Figure 4-2. Plant-mixed–laboratory-compacted (PL) specimen fabrication.

3. The mixture was put in the oven and brought to compaction temperature (typically in less than 45 minutes) (Figure 4-2 (f)); and
4. The mixture was compacted using the SGC in accordance with AASHTO T 312, "Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor." (Figure 4-2 (g) and (h)). In some cases, reheating of the specimens was required to evaluate the effect of time delay in specimen fabrication. Additional 5-gallon buckets of loose mixture were sampled from the truck and stored at room temperature for 3 days. Mixture from the buckets was then reheated to compaction temperature (typically for 1 hour) and specimens were prepared. This reheating was done to model the asphalt absorption into the aggregate that typically occurs when samples are taken from a project, stored, and reheated before conducting QA testing. This is different from holding the sample at an elevated temperature to artificially age the mixture. Other than the short-term aging used to prepare the samples for specimen fabrication, possible effects of long-term aging were not evaluated in this study.

4.1.3 Plant-Mixed–Field-Compacted (PF) Specimens

Figure 4-3 depicts the construction and sample collection process for PF specimens. The PF samples consisted of cores collected after placement and compaction of the asphalt mixture. The cores were trimmed to ensure that only the mixture of interest was obtained (i.e., without the underlying layers). Each core was then trimmed to the required specimen size for testing.

4.2 Volumetric Tests

This section describes how the volumetric properties identified in the test factorial were determined.

4.2.1 Aggregate Gradation

The aggregate gradation was determined in accordance with AASHTO T 27, "Sieve Analysis of Fine and Coarse Aggregates." The aggregate gradation represents the particle size distribution of the aggregates in the mixtures.

4.2.2 Aggregate Bulk Specific Gravity (G_{sb}) and Absorption

The blended aggregate specific gravity and water absorption were determined in accordance with AASHTO T 84, "Specific Gravity and Absorption of Fine Aggregate" and AASHTO T 85, "Specific Gravity and Absorption of Coarse Aggregate." The bulk specific gravity represents the ratio of the mass in air of a unit volume of a material (including both permeable and impermeable voids) at a standard temperature to the mass in air of an equal volume of water at the same temperature. Equation 5 presents the mathematical computation for determining aggregate bulk specific gravity (G_{sb}).

Figure 4-3. Plant-mixed–field-compacted (PF) specimen fabrication.

$$G_{sb} = \frac{\text{Aggregate Oven Dry Weight}}{\left(\begin{array}{c}\text{Aggregate SSD weight} - \\ \text{Aggregate Submerged Weight}\end{array}\right) * \gamma_{water}} \quad (5)$$

When the total aggregate consists of separate fractions of coarse aggregate, fine aggregate, and mineral filler, all having different specific gravities, the bulk specific gravity for the aggregate blend is calculated. Equation 6 is used to calculate the specific gravity of an aggregate blend:

$$G_{blend} = \frac{P_1 + P_2 + \cdots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \cdots + \frac{P_n}{G_n}} \quad (6)$$

where

G_{blend} = average specific gravity;
$P_1, P_2, \ldots P_n$ = weight percentages of fraction 1, 2, . . . , n; and
$G_1, G_2, \ldots G_n$ = specific gravity values for fraction 1, 2, . . . , n.

Additionally, the blend absorption is computed using Equation 7:

$$Absorption_{blend} = P_1 A_1 + P_2 A_2 + \cdots + P_n A_n \quad (7)$$

where,

$Absorption_{blend}$ = average absorption;
$P_1, P_2, \ldots P_n$ = weight percentages of fractions 1, 2, . . . , n; and
$A_1, A_2, \ldots A_n$ = absorption percentages for fractions 1, 2, . . . , n.

4.2.3 Mixture Bulk Specific Gravity (G_{mb})

The mixture bulk specific gravity was determined in accordance with AASHTO T 166, "Bulk Specific Gravity of Compacted Asphalt Mixtures using Saturated Surface-Dry Specimens (SSD)." This parameter was used to determine weight per unit volume of the compacted mixture. It was very important to measure G_{mb} as accurately as possible, given that it is used to convert weight measurements to volumes. Any small errors in G_{mb} will be reflected in significant volume errors, which may be undetected. In addition, G_{mb} was required for volumetric evaluation and determination of mixture density in accordance with AASHTO T 269, "Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures." Equation 8 presents the mathematical computation for determining mixture bulk specific gravity (G_{mb}):

$$G_{mb} = \frac{\text{Specimen Oven Dry Weight}}{\left(\begin{array}{c}\text{Specimen SSD weight} - \\ \text{Specimen Submerged Weight}\end{array}\right) * \gamma_{water}} \quad (8)$$

4.2.4 Mixture Maximum Specific Gravity (G_{mm})

This parameter was measured experimentally using the test procedure described in AASHTO T 209, "Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures." The theoretical maximum specific gravity, or theoretical maximum density, is the density of an asphalt concrete mix without air voids, or the highest possible density of the mix. The theoretical maximum specific gravity was used for calculating volumetric parameters. Equation 9 is used for determining mixture maximum specific gravity (G_{mm}):

$$G_{mm} = \frac{\text{Dry Weight}}{\left(\begin{array}{c}\text{Dry Weight} + \text{Pycnometer Calibration} - \\ \text{Specimen, Pycnometer, and Water}\end{array}\right) * \gamma_{water}} \quad (9)$$

4.2.5 Asphalt Binder Content (AC)

The asphalt binder content of the mixtures was determined in accordance with AASHTO T 164, Method B, "Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)." Method B describes the procedure for quantitative extraction by use of a reflux apparatus. Solvent extraction was selected due to its higher repeatability and accuracy when compared to other extraction methods. Solvent extraction uses a chemical solvent (trichloroethylene [TCE]) to separate asphalt binder from the aggregate. The weight of the asphalt removed is determined and the asphalt binder content is computed.

4.3 Mechanical Tests

This section describes how the mechanical properties identified in the test factorial were determined.

4.3.1 Loaded-Wheel Test (LWT)

This test was conducted according to AASHTO T 324, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)." This device was manufactured by PMW, Inc., of Salina, KS. The test applies a repetitive load on gyratory specimens compacted to 7 ± 1.0% air voids that have a diameter of 150 mm and a thickness of 40 mm. This test is considered a torture test that produces damage by rolling a 703-N stainless steel wheel across the surface of a compacted gyratory sample, submerged in 50°C water for 20,000 passes at 52 passes a minute. Four states (Arkansas, Ohio, Texas, and Utah) have implemented rutting performance criteria based on the Hamburg type wheel tracking test. Current research has shown that, for Louisiana, LWT-measured rut depths of 10 mm and 6 mm can be used as performance targets for low and high traffic, respectively (Kim et al. 2015). Other states, such as Texas, allow up to 12.5 mm of rut depth after a minimum number of passes based on the performance grade of the binder. The rut depths at 1,000; 5,000; and 20,000 cycles were measured and used in the analysis. The stripping inflection point (SIP) was also determined from this test and used in the analysis where applicable. A standard 50°C testing temperature was used for all mixtures studied in order to combine the mixture test results for meta-analysis. LTPPBind software was used to verify that the high temperature for the mixture was greater than 50°C.

4.3.2 Axial Dynamic Modulus (E*)

This test was conducted in accordance with AASHTO T 342, "Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures," by applying a uniaxial sinusoidal (i.e., haversine) compressive stress to an unconfined HMA cylindrical test specimen. The haversine compressive stress was applied on each sample to achieve a target vertical strain level of 100 microns in an unconfined test mode.

The dynamic modulus is mathematically defined as the maximum (i.e., peak) dynamic stress (σ_0) divided by the peak recoverable axial strain (ε_0):

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{10}$$

Following the AASHTO T 342 testing protocol, samples were tested at temperatures of −10, 4.4, 20, 37.8, and 54.4°C and at loading frequencies of 0.1, 0.5, 1.0, 5, 10, and 25 Hz at each temperature for the development of master curves for use in pavement response and performance analysis.

4.3.3 IDT Dynamic Modulus (IDT E*)

IDT dynamic modulus of the mixtures was measured according to the draft test procedure proposed by Kim et al. (2004), "Dynamic Modulus Testing of Asphalt Concrete in Indirect Tension Mode." This test was conducted by applying a sinusoidal compressive stress to the diametric axis of an unconfined cylindrical HMA test specimen. Dynamic modulus tests were conducted at temperatures of −10, 10, and 35°C and at loading frequencies 0.1, 0.5, 1.0, 5, and 10 Hz at each temperature for the development of master curves. The compressive stress was applied on each sample to achieve target strain levels (40–60 horizontal microstrain and <100 vertical microstrain) in the linear viscoelastic region. Equation 11 presents the mathematical relationship between load and deformation in the indirect tension-loading mode:

$$|E^*| = \frac{2P_0}{\pi a d}\,\frac{\beta_1\gamma_2 - \beta_2\gamma_1}{\gamma_2 V_0 - \beta_2 U_0} \tag{11}$$

where

P_0 = Peak-to-peak load, N;
a = loading strip width, m;
d = thickness of specimen, m;
V_0 = peak-to-peak vertical deformation, m;
U_0 = peak-to-peak horizontal deformation, m; and
γ_1, γ_2, β_1, and β_2 = geometric constants.

The geometric constants are functions of gauge length, specimen diameter, and loading strip width. A loading strip of 19.0 mm width is required when testing 150-mm-diameter specimens (AASHTO T 322/ASTM D4123). Table 4-1 presents the coefficients derived and used in this research. Samples were first compacted, using a Superpave gyratory compactor, to a 75-mm height by 150-mm diameter and then cut to the test specimen dimensions of a 38-mm height by 150-mm diameter. Laboratory specimens were compacted to the same air void levels measured in PF cores immediately following construction (~7 to 8%). Triplicates were tested for each specimen type.

4.4 Statistical Analyses

Statistical Analysis Software (SAS) version 9.2 was used to determine the statistical significance of the comparison between specimen types. An analysis of variance (ANOVA) with a significance level of $\alpha = 0.05$ was used to determine the statistical significance. Within ANOVA, individual pair-wise property comparisons (i.e., PL vs. LL, PL vs. PF, and LL vs. PF) were conducted using Duncan's Multiple Comparison Test (MCT) (Freund and Wilson 1997). Triplicate specimens were

Table 4-1. IDT dynamic modulus geometric constants.

Gauge Length, mm	Loading Strip Width, mm	Specimen Diameter, mm	β_1	β_2	γ_1	γ_2
38.1	19.0	150	-0.0147	-0.0047	0.0043	0.0136
50.8	19.0	150	-0.0199	-0.0062	0.0054	0.0173
76.2	19.0	150	-0.0317	-0.0091	0.0069	0.0229

evaluated for each specimen type. Additionally, an analysis of covariance (ANCOVA) was conducted with the guidance of a statistician. The ANCOVA allows the individual process-based factors from the mixtures to be used in determining the main effects.

4.4.1 Statistical Basics

Four main sources of variability contribute to the measured overall variation defined in Freund and Wilson (1997). The first type is "inherent variation" (i.e., random variation due to the material itself that cannot be removed). The second type is "sampling and testing variation," which includes variability due to sampling technique, test procedure, operator, equipment, and calibration. The third type of variation is "within-batch variation," or the variability observed between samples taken from the same batch. The fourth type of variation is "batch-to-batch variation," or the variability observed between batches (i.e., from one batch to another). The most widely used measure of variability in the asphalt pavement practice is the standard deviation (St Dev or s), defined as follows (Freund and Wilson 1997):

$$s=\sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \tag{12}$$

where

x = the individual values of the measured (or response) variable;
$\bar{x}$ = the sample mean (or sample average); and
n = the sample size.

The sample standard deviation (with n–1 degrees of freedom) measures the square root of the sum of the squared deviations of the individual observations (or measurements) from the sample average. The variability in mechanical properties of an asphalt mixture is often expressed in terms of the coefficient of variation (COV). The COV is a normalized measure of dispersion of a probability distribution. It is defined as follows:

$$\mathrm{COV}(\%)=100*\frac{s}{\bar{x}} \tag{13}$$

where

s = the sample standard deviation and
$\bar{x}$ = the sample mean.

The COV is dimensionless and measures variability relative to the sample mean without considering the units used to define the sample mean and standard deviation. However, when the mean is close to zero, the COV becomes very sensitive to small changes in the mean. The COV is used to measure the variability of test results when the standard deviation (testing error) increases in proportion to the magnitude of the result.

4.4.2 Analysis of Variance

Statistical ANOVA is used to determine whether the means of response variables measured on two or more populations are statistically equivalent. The null hypothesis is that the population means (of the response variables) are statistically equivalent; the alternate hypothesis is that the population means are not statistically equivalent. Assuming that the response variables are normally distributed and that the variances are statistically equivalent for all populations, the test statistic MSTR/MSE follows the non-central F distribution (see Equations 14 and 15 for the definitions of MSTR and MSE). When the null hypothesis is true, the non-centrality parameter is zero, causing the test statistic to follow the central F distribution. Therefore, large values of the test statistic (which result in small p-values) support the alternate hypothesis, while small values (which result in large p-values) support the null hypothesis. SAS version 9.2 was used to determine the statistical significance of the comparison of specimen types.

$$\mathrm{MSTR}=\sum n_i\left(\bar{x}_i-\bar{\bar{x}}\right)^2 \div \mathrm{df}_1 \tag{14}$$

$$\mathrm{MSE}=\sum(n_i-1)s_i^2 \div \mathrm{df}_2 \tag{15}$$

where

MSTR = Mean square treatment;
MSE = Mean standard error;
$\bar{x}_i$ = the sample average for group (or population) i;
$\bar{\bar{x}}$ = the overall average of all observations taken; and
df = degrees of freedom.

If the null hypothesis is rejected, then the conclusion is that all population means are not statistically equivalent. If the means are concluded to be not statistically equivalent, the next step is to determine which of the population means are equivalent and which are different, at least on a pair-wise basis. Several multiple comparison tests are available for evaluating individual pairs evaluated under the ANOVA procedure. The Duncan multiple-range test was used in this study at a level of significance of 0.05.

4.4.3 Precision Limits

ASTM C802, "Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test

Methods for Construction Materials," defines single-operator precision (also known as repeatability) as "an estimate of the difference that may be expected between duplicate measurements made on the same material in the same laboratory by the same operator using the same apparatus within a time span of a few days." On the other hand, multi-laboratory precision (also known as reproducibility) is "an estimate of the difference that may be expected between measurements made on the same material in two different laboratories." (ASTM C802, pg. 3).

VMA and voids filled with asphalt are calculated properties whose precision depends on the measurement precision of the aggregate bulk specific gravity and aggregate effective specific gravity. Similarly, air voids (AV) is a calculated property whose precision depends on the measured bulk specific gravity of the compacted mixture (G_{mb}) and the maximum theoretical specific gravity of the mixture (G_{mm}). ASTM D4460, "Standard Practice for Calculating Precision Limits Where Values Are Calculated from Other Test Methods," presents methods to estimate precision limits for properties that are calculated. If a property involves the addition or subtraction of test results from two other standards, the standard deviation on which precision limits should be set is calculated from Equation 16:

$$\sigma_{x\pm y} = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{16}$$

where

$\sigma_{x\pm y}$ = standard deviation for determining precision limits of a test result for a new standard based on either an addition or subtraction of test results from two other standards;

σ_x = standard deviation from precision statement of one of the standards on which new standard is based; and

σ_y = standard deviation from precision statement of other standard on which new standard is based.

If a property involves the multiplication of test results from two other standards, the standard deviation on which precision limits should be set is calculated from Equation 17:

$$\sigma_{xy} = \sqrt{\bar{y}^2\sigma_x^2 + \bar{x}^2\sigma_y^2} \tag{17}$$

where

σ_{xy} = standard deviation for determining precision limits of a test result for a new standard based on the products of two other test results from two other standards;

$\bar{y}$ = mean of average value of Y variable; and

$\bar{x}$ = mean of average of X variable.

If a property involves the division of test results from two other standards such as air voids, the standard deviation on which precision limits should be set is calculated from Equation 18:

$$\sigma_{x/y} = \sqrt{\frac{\bar{y}^2\sigma_x^2 + \bar{x}^2\sigma_y^2}{\bar{y}^4}} \tag{18}$$

where

$\sigma_{x/y}$ = standard deviation for determining precision limits of a test result for a new standard based on the quotient of two other test results from two other standards; and all other terms as previously defined.

4.4.4 Descriptive Statistics and Data Quality

The mean, standard deviation, and coefficient of variation were determined for each data set (i.e., mixture) generated from the experimental plan. Three replicates within each specimen type for each property were measured and, given that split samples were obtained, replicates were assumed to be from the same population. ASTM C670, "Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials," defines the acceptable difference between two test results (d2s) as the difference between two individual test results that would be equaled or exceeded in only one case in 20 under normal and correct operation of the method. This d2s value is computed by multiplying the appropriate standard deviation by $2\sqrt{2}$ (equal to 2.8). In cases where more than two test results are available, the standard deviation is multiplied by a multiplier corresponding to the number of test results, given in Table 1 of ASTM C670 (reproduced herein as Table 4-2. An example data quality evaluation for mixture maximum specific gravity data is shown in Table 4-3.

The standard deviation reported from the experiment for three replicates is not directly comparable to the standard

Table 4-2. ASTM C670 maximum acceptable range.

No. of Test Results	Multiplier of (1s) or (1s%) for Maximum Acceptable Range^
2	2.8
3	3.3
4	3.6
5	3.9
6	4.0
7	4.2
8	4.3
9	4.4
10	4.5

^ Values were obtained from Table A7 of "Order Statistics and Their Use in Testing and Estimation," Vol 1, by Leon Harter, Aerospace Research Laboratories, United States Air Force

Table 4-3. Example of data quality criterion applied to mixture maximum specific gravity data.

Test Results					Computed AASHTO T 209 limit		
G_{mm} data			n	Max - Min	St dev (from T 209)	Multiplier (from ASTM C670)	Acceptable range
2.508	2.514	2.524	3	0.016	0.0051	3.3	0.017*

*Acceptable Range = 0.0051 x 3.3 = 0.017

deviation reported by the corresponding AASHTO standard test method. The standard deviation reported by the AASHTO method is calculated for the entire population from a large number of replicates (e.g., $n_{Gmm} = 626$, $n_{AC} = 308$, $n_{AV} = 654$). Thus, it should not be expected that the standard deviation of the data set with n=3 would match that of the population. However, the standard deviations calculated for the three replicates were often lower than the ones reported by AASHTO, which indicates good control of the experiment.

4.4.5 Individual Mixture Analyses

SAS version 9.2 was used to determine the statistical significance of the comparison of specimen types. A t-test with a significance level of $\alpha = 0.05$ was used for comparing the means when only two groupings (i.e., PL vs. LL only) were available. However, most of the comparisons had more than two groupings (i.e., PL vs. LL vs. PF). For these comparisons, an ANOVA with a significance level of $\alpha = 0.05$ was used to determine the statistical significance. Within ANOVA, individual pair-wise comparisons (i.e., PL vs. LL, PL vs. PF, and LL vs. PF) were conducted using Duncan's MCT.

4.5 Delta Analyses

The term delta, Δ, is used to identify the difference between the mean values of two specimen types (LL, PL, and PF) of any given parameter (e.g., AV, G_{mm}, Rut Depth, Modulus). For example, Equation 19 represents the mathematical relationship for calculation of the delta of rut depth between LL and PL specimens within a mixture:

$$\Delta_{Rut\ Depth,PL\text{-}LL} = Mean_{Rut\ Depth,PL} - Mean_{Rut\ Depth,LL} \qquad (19)$$

Once the Δ values for each mixture were determined, additional analyses were conducted to determine which factors had the greatest effect on the differences between specimen types.

Meta-analysis was conducted to evaluate the effects of process-based based factors on the magnitude of the differences among specimen types. Specifically, the ANCOVA was conducted with the guidance of a statistician. The ANCOVA allows the individual process-based factors from the mixtures to be used in determining the main effects. This differs from the original analysis developed in the experimental factorial, which could not be used due to inability to collect the entire factorial. The original factorial required categorical evaluation of the process-based factors (i.e., high and low). In the ANCOVA, the numerical values associated with each process-based factor were incorporated into the analysis (e.g., absorption = 1.7%). The analysis was conducted for the differences of properties measured among LL, PL, and PF specimens of the evaluated mixtures. For the meta-analysis, all plant-produced-laboratory-compacted specimens were designated as PL. The meta-data considered whether or not the sample was reheated. Table 4-4 presents an example of the format of the data input for the asphalt binder content. As shown in the table, each mixture evaluated was treated as a replicate in each property comparison (i.e., LL-PF, LL-PL, and PL-PF). This means that each comparison has 11 observations with 10 degrees of freedom available for the evaluation. Each specimen comparison was performed individually to determine which factors had a statistically significant effect on the considered property (i.e., volumetric and mechanical). The level of significance used in the analysis was $\alpha = 0.05$.

Table 4-5 presents an example of the ANCOVA for the difference in asphalt binder content among specimen types. A p-value less than 0.05 indicates a statistically significant relationship. As shown in the table, the use of baghouse fines return had a statistically significant effect on the difference between laboratory-prepared specimens as compared to plant-produced specimens. This is as expected, especially if baghouse fines are not used during laboratory mixture design. The effect of aggregate absorption was marginal for the LL comparisons. There were no statistically significant process-based factors for the PL-PF comparisons. This seems reasonable for AC content because both PL and PF specimens are processed through the plant.

4.6 Pavement Performance Prediction

AASHTOWare Pavement ME Design software was used to evaluate the effects of the measured mechanical properties (i.e., E*) for the three specimen types (LL, PL, PF) on the

Table 4-4. ANCOVA data set example.

Comparison Data				Process-Based Factors				
Specimen Comparison	Mixture ID	Replicate	Δ, AC - %	Baghouse	Reheat	Aggregate Absorption - %	Aggregate Hardness - %	Stockpile Moisture Content - %
Lab-mixed–Lab compacted—Plant-mixed–Plant compacted	Mix1	1	-0.25	No	No	1.7	38	4.8
	Mix2	2	0.00	Yes	Yes	1.6	50	3.3
	Mix3	3	0.00	Yes	Yes	2.1	14	5.0
	Mix4	4	-0.30	No	Yes	0.8	17	3.5
	Mix5	5	0.06	Yes	No	1.2	22	5.0
	Mix6	6	0.29	Yes	No	0.7	22	5.4
	Mix7	7	0.04	Yes	No	1.3	18	5.4
	Mix8	8	0.20	Yes	No	0.5	15	4.5
	Mix9	9	0.30	Yes	Yes	0.5	15	4.0
	Mix10	10	-0.20	Yes	No	2.8	37	2.8
Lab-mixed–Lab compacted—Plant-mixed–Plant compacted	Mix1	1	-0.11	No	No	1.7	38	4.8
	Mix2	2	0.30	Yes	Yes	1.6	50	3.3
	Mix3	3	0.10	Yes	Yes	2.1	14	5.0
	Mix4	4	-0.70	No	Yes	0.8	17	3.5
	Mix5	5	0.11	Yes	No	1.2	22	5.0
	Mix6	6	0.07	Yes	No	0.7	22	5.4
	Mix7	7	-0.03	Yes	No	1.3	18	5.4
	Mix8	8	0.20	Yes	No	0.5	15	4.5
	Mix9	9	0.40	Yes	Yes	0.5	15	4.0
	Mix10	10	-0.10	Yes	No	2.8	37	2.8
Plant-mixed–Plant compacted—Plant-mixed–Field-compacted	Mix1	1	-0.14	No	No	1.7	38	4.8
	Mix2	2	-0.30	Yes	Yes	1.6	50	3.3
	Mix3	3	-0.10	Yes	Yes	2.1	14	5.0
	Mix4	4	0.40	No	Yes	0.8	17	3.5
	Mix5	5	-0.05	Yes	No	1.2	22	5.0
	Mix6	6	0.22	Yes	No	0.7	22	5.4
	Mix7	7	0.07	Yes	No	1.3	18	5.4
	Mix8	8	0.00	Yes	No	0.5	15	4.5
	Mix9	9	0.10	Yes	Yes	0.5	15	4.0
	Mix10	10	-0.10	Yes	No	2.8	37	2.8

predicted performance for four pavement structures. Three structures representing typical pavements used in Louisiana were used for three traffic levels (low, medium, and high). The fourth pavement structure, adopted from a research study conducted in North Carolina and published by Underwood et al. (2011), represented an actual pavement in service in North Carolina. Figure 4-4 depicts the pavement structures evaluated in this study. The layer of interest is the HMA layer. The mechanistic-empirical analysis was conducted by altering the material properties of the HMA layer, based on the results of the experimental program; Level 1 analysis was used. All other layer properties were kept constant.

4.6.1 Design Inputs

A pavement structure was designed as a new flexible pavement with a service life of 20 years; given that results were compared relatively, default calibration factors were used in the analysis. The national default value available in Pavement ME Design for the initial international roughness index (IRI)

Table 4-5. Results of the ANCOVA.

Comparison	Process-Based Factor	F Value	p-value
Design (LL) - Construction (PF)	Baghouse	15.77	0.0165
	Reheat	0.07	0.8111
	Absorption	7.46	0.0524
	Hardness	0.42	0.5538
	Moisture	2.81	0.1689
Design (LL) - Production (PL)	Baghouse	60.41	0.0015
	Reheat	4.52	0.1006
	Absorption	8.96	0.0402
	Hardness	1.62	0.2719
	Moisture	0.06	0.8148
Production (PL) - Construction (PF)	Baghouse	3.23	0.1466
	Reheat	2.66	0.1784
	Absorption	0.57	0.4940
	Hardness	0.54	0.5028
	Moisture	0.70	0.4499

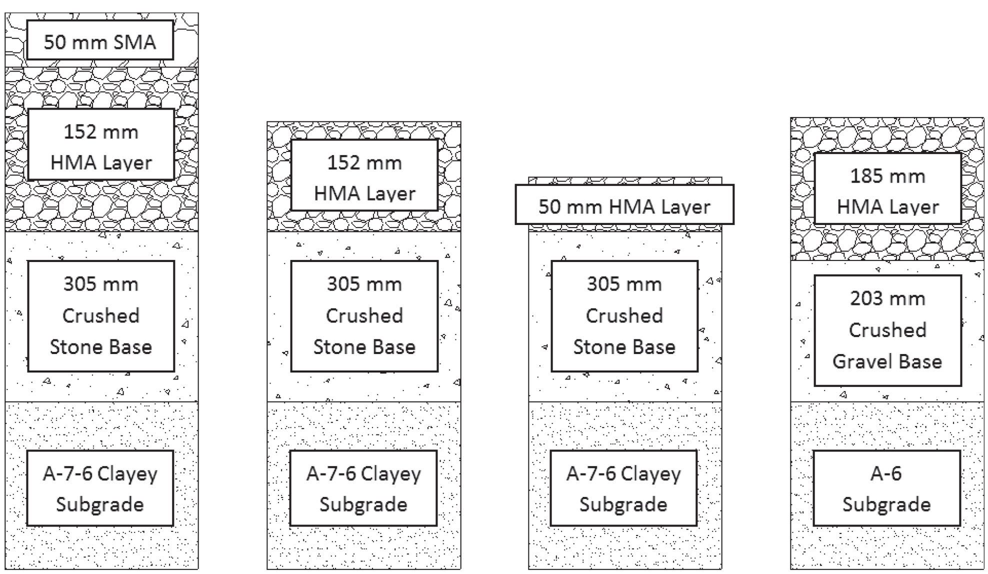
was used in the analysis. However, values consistent with the Louisiana Pavement Management System (PMS) failure limits were used for terminal IRI and total permanent deformation. Louisiana PMS uses index values to describe pavement distress limits. In order to use these limits in Pavement ME Design, the index values were converted to the appropriate units. Louisiana Department of Transportation and Development (LADOTD) provided conversion equations for IRI and rutting as well as trigger values for rehabilitation. The values used in this study are given in Table 4-6. The national default reliability level of 90% for interstate and primary routes was used in the analysis. In addition, analyses were conducted at a reliability level of 50%, which more closely models typical pavement distresses.

4.6.2 Traffic

Average annual daily traffic (AADT) values for multiple traffic classifications, as well as truck factors and distribution for vehicle classes 1 to 13, were provided by LADOTD. Given that Pavement ME Design only supports truck classes 4 to 13, vehicle classes 1 to 3 were not considered, and the LADOTD vehicle class distributions were adjusted to consider only classes 4 to 13. Monthly distribution data were obtained from previous research (Ishak et al. 2009). The national default values from LTPP data for hourly distribution and growth factor were used. Table 4-6 shows the average daily truck traffic (ADTT) values associated with the traffic levels evaluated in this study.

4.6.3 Climate

Climatic data were obtained from Pavement ME Design climate database for the city of Baton Rouge, LA (NCHRP Project 1-37A). One hundred and sixteen months of data were available for the selected location. The average water table depth was assumed to be 2.1 m. The water table depth determined via Equation 20 estimates the water table based



a) High Traffic b) Medium Traffic c) Low Traffic d) Underwood-Low (Underwood et al., 2011)

Figure 4-4. Typical pavement designs considered in the performance analysis.

Table 4-6. Louisiana PMS failure triggers.

Distress	Traffic Level (ADTT)		
	High (14,554)	Medium (1,992)	Low (816)
IRI (mm/km)	1973 (125 in/mile)	3175 (200 in/mile)	3969 (250 in/mile)
Rut Depth (mm)	9.6 (3/8 in)	14.2 (9/16 in)	14.2 (9/16 in)

on surface elevations in the Gulf Coast regions in the United States (Williams and Williamson 1989). The elevation was determined from Pavement ME Design climate database:

$$\text{Water Table Altitude} = \text{Land-surface altitude} * .8978 \qquad (20)$$

4.6.4 Asphalt Mixture Layer Properties

Dynamic modulus values were determined from laboratory testing (Level 1 inputs). IDT dynamic modulus testing was conducted using triplicate samples. Air void contents of the samples were controlled between 7% and 8%. The COV of the test results was less than 20% for all test temperatures and frequencies. For performance evaluation using moduli determined in the indirect testing mode, 54°C moduli values were extrapolated from the constructed master curves developed from laboratory testing due to the temperature constraints for dynamic modulus determined in the indirect mode of loading. This extrapolation approach is based on the work by Bonaquist and Christensen (2005). A reduced temperature range could be used to create master curves similar to that of full experimental testing (Guercio et al. 2005).

4.6.5 Base and Subgrade Properties

Resilient modulus (M_R) values for crushed limestone and clayey subgrade were collected from previous projects (Mohammad et al. 2008) and were used in the analysis of the various pavement structures. These values were kept constant for all four pavement structures.

4.7 Development of Specification Recommendations

A recommended practice that addressed the cause and magnitude of variability within and among the three specimen types (i.e., LL, PL, and PF) was developed from the data collected in the experimental program. Volumetric data were evaluated and tolerance values were proposed. Additionally, mechanical data were evaluated and conversion factors for estimating the values of the three specimen types were proposed.

CHAPTER 5

Results and Discussion

5.1 Individual Mixture Analyses

The following sections present analyses of the data measured on the individual mixtures described in Chapter 4. Details of the analyses for the mixtures are presented in Appendix C. In the tables in the following subsections, crossed and shaded cells indicate significant difference; blank cells indicate that there is no statistical difference. The following abbreviations are used throughout the tables: LL: lab-mixed–lab-compacted, PL: plant-mixed–lab-compacted, PLR: plant-mixed–lab-compacted (reheated); PF: plant-mixed–field-compacted.

5.1.1 Summary of Mixture 1WI Analysis

Tables 5-1 and 5-2 summarize the statistical comparisons conducted for Mixture 1WI. Statistically significant comparisons are indicated with a crossed and highlighted cell. Results presented in the tables indicate that differences appear to be interrelated among the volumetric properties, which may be expected, because these properties depend on one another. On the other hand, differences in mechanical properties appear to be mainly influenced by the compaction effort and procedure, because the main differences were found between laboratory-compacted and field-compacted specimens.

5.1.2 Summary of Mixture 3MN Analysis

Tables 5-3 and 5-4 summarize the statistical comparisons conducted for Mixture 3MN. Statistically significant comparisons are indicated with a crossed and highlighted cell. Results presented in the tables indicate that differences occur throughout the volumetric and mechanical evaluation. The recycled asphalt pavement (RAP) provided for design (LL) specimens may have been different from the RAP used during production (PL and PF). This would explain the differences observed between LL and PL specimens. Differences in mechanical properties appear to be mainly influenced by the compaction effort and process, because the main differences were found between laboratory-compacted and field-compacted specimens.

5.1.3 Summary of Mixture 5WI Analysis

Tables 5-5 and 5-6 summarize the statistical comparisons conducted for Mixture 5WI. Results presented in Table 5-5 indicate that the LL specimens were different from the plant-produced specimens for most volumetric properties. The main reason for these differences is possibly the low air voids of the LL specimens and a slight increase in fine contents. On the other hand, differences in mechanical properties appear to be mainly influenced by the compaction effort for laboratory-compacted and field-compacted specimens. In addition, differences between LL and PL specimens may be attributed to asphalt oxidation during the production process, differences in air voids content (AV for LL = 7.9% vs. PL = 7.1% vs. PLR = 7.3%), or both.

5.1.4 Summary of Mixture 5LA90 Analysis

Tables 5-7 and 5-8 summarize the statistical comparisons conducted for Mixture 5LA90. Results presented in Table 5-7 indicate that the LL specimens were different from the plant-produced specimens in most volumetric properties. The main reason for these differences is possibly the low air voids of the LL specimens and a slight increase in fines and asphalt binder contents. On the other hand, differences in mechanical properties appear to be mainly influenced by the compaction effort for comparisons of PL and PF specimens. In addition, differences between PL and PLR specimens may be attributed to asphalt aging during time delay in specimen fabrication, a large difference in asphalt content (AC for PL = 4.3% vs. PLR = 4.0%), or both. Given previous findings that reheating had no effect, the difference appears more likely due to AC.

(*text continues on page 46*)

Table 5-1. Summary of the statistical comparisons (volumetrics)—Mixture 1WI.

(a)

Property	Comparison					
	LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Air Voids	X		NA	NA	NA	
VMA		X	NA	NA	NA	X
VFA	X	X	NA	NA	NA	
G_{mm}	X	X				
AC						
G_{sb}						

(b)

Property	Sieve	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Aggregate Percent Passing Sieve	12.5 mm	X	X	X			
	4.75 mm						
	0.600 mm						
	0.075 mm						

Table 5-2. Summary of the statistical comparisons (mechanical)—Mixture 1WI.

(a)

Property	Passes	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
LWT Rut Depth	1,000			X	X	X	
	5,000			X	X	X	
	10,000						
	20,000						

Table 5-2. (Continued).

(b)

Property	Temperature, Frequency	Comparison		
		LL-PL	LL-PLR	PL-PLR
Axial Dynamic Modulus	-10°C, 25Hz			
	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz			
	-10°C, 0.5Hz			
	-10°C, 0.1Hz			
	4°C, 25Hz			
	4°C, 10Hz			
	4°C, 5Hz			
	4°C, 1Hz			
	4°C, 0.5Hz			
	4°C, 0.1Hz			
	25°C, 25Hz			
	25°C, 10Hz			
	25°C, 5Hz			
	25°C, 1Hz			
	25°C, 0.5Hz			
	25°C, 0.1Hz			
	38°C, 25Hz			
	38°C, 10Hz			
	38°C, 5Hz			
	38°C, 1Hz			
	38°C, 0.5Hz			
	38°C, 0.1Hz			
	54°C, 25Hz			
	54°C, 10Hz			
	54°C, 5Hz			
	54°C, 1Hz			
	54°C, 0.5Hz			
	54°C, 0.1Hz			

(c)

Property	Temperature, Frequency	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
IDT Dynamic Modulus	-10°C, 10Hz						
	-10°C, 5Hz						
	-10°C, 1Hz						
	-10°C, 0.5Hz						
	-10°C, 0.1Hz						
	10°C, 10Hz			X	X	X	
	10°C, 5Hz			X	X	X	
	10°C, 1Hz			X	X		
	10°C, 0.5Hz				X	X	
	10°C, 0.1Hz			X	X	X	
	35°C, 10Hz			X			
	35°C, 5Hz			X			
	35°C, 1Hz			X	X	X	
	35°C, 0.5Hz	X	X	X	X	X	
	35°C, 0.1Hz			X	X	X	

Table 5-3. Summary of the statistical comparisons (volumetrics)—Mixture 3MN.

(a)

Property	Comparison		
	LL-PLR	LL-PF	PLR-PF
AV	X	NA	
VMA			
VFA	X		
G_{mm}			
AC	X		
G_{sb}			

(b)

Property	Sieve	Comparison		
		LL-PLR	LL-PF	PLR-PF
Percent Passing	12.5mm	X	X	
	4.75mm	X		X
	0.600mm	X	X	
	0.075mm		X	

Table 5-4. Summary of the statistical comparisons (mechanical)—Mixture 3MN.

(a)

Property	Passes	Comparison		
		LL-PLR	LL-PF	PLR-PF
LWT Rut Depth	1,000			
	5,000			
	10,000		X	
	20,000		X	X

(b)

Property	Temperature, Frequency	Comparison
		LL-PLR
Axial Dynamic Modulus	-10°C, 25Hz	
	-10°C, 10Hz	
	-10°C, 5Hz	
	-10°C, 1Hz	
	-10°C, 0.5Hz	
	-10°C, 0.1Hz	
	4°C, 25Hz	
	4°C, 10Hz	
	4°C, 5Hz	
	4°C, 1Hz	
	4°C, 0.5Hz	
	4°C, 0.1Hz	
	25°C, 25Hz	
	25°C, 10Hz	
	25°C, 5Hz	
	25°C, 1Hz	
	25°C, 0.5Hz	
	25°C, 0.1Hz	
	38°C, 25Hz	
	38°C, 10Hz	
	38°C, 5Hz	
	38°C, 1Hz	
	38°C, 0.5Hz	
	38°C, 0.1Hz	
	54°C, 25Hz	
	54°C, 10Hz	X
	54°C, 5Hz	X
	54°C, 1Hz	
	54°C, 0.5Hz	
	54°C, 0.1Hz	

(c)

Property	Temperature, Frequency	Comparison		
		LL-PLR	LL-PF	PLR-PF
IDT Dynamic Modulus	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz			
	-10°C, 0.5Hz			
	-10°C, 0.1Hz			X
	-10°C, 0.01Hz	X		X
	10°C, 10Hz		X	X
	10°C, 5Hz		X	
	10°C, 1Hz		X	
	10°C, 0.5Hz			
	10°C, 0.1Hz		X	X
	10°C, 0.01Hz	X	X	X
	30°C, 10Hz	X	X	X
	30°C, 5Hz	X	X	X
	30°C, 1Hz	X	X	X
	30°C, 0.5Hz	X	X	X
	30°C, 0.1Hz	X	X	X
	30°C, 0.01Hz		X	X

Table 5-5. Summary of the statistical comparisons (volumetrics)—Mixture 5WI.

(a)

Property	Comparison					
	LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
AV	X	X	NA			
VMA	X	X				
VFA	X	X				
G_{mm}	X			X	X	
AC						
G_{sb}						

(b)

Property	Sieve	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Aggregate Percent Passing Sieve	12.5mm						
	4.75mm	X			X	X	
	0.600mm			X	X	X	
	0.075mm	X		X	X	X	

Table 5-6. Summary of the statistical comparisons (mechanical)—Mixture 5WI.

(a)

Property	Passes	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
LWT Rut Depth	1,000	X	X		X	X	
	5,000		X		X	X	
	10,000		X		X	X	
	20,000	X	X		X	X	

(b)

Property	Temperature, Frequency	Comparison		
		LL-PL	LL-PLR	PL-PLR
Axial Dynamic Modulus	-10°C, 25Hz	X	X	
	-10°C, 10Hz	X	X	
	-10°C, 5Hz	X	X	
	-10°C, 1Hz	X	X	
	-10°C, 0.5Hz	X	X	
	-10°C, 0.1Hz	X	X	
	4°C, 25Hz	X	X	
	4°C, 10Hz	X	X	
	4°C, 5Hz	X	X	
	4°C, 1Hz	X	X	
	4°C, 0.5Hz	X	X	
	4°C, 0.1Hz	X	X	
	25°C, 25Hz	X	X	
	25°C, 10Hz	X	X	
	25°C, 5Hz	X	X	
	25°C, 1Hz	X	X	
	25°C, 0.5Hz	X	X	
	25°C, 0.1Hz	X	X	
	38°C, 25Hz	X	X	
	38°C, 10Hz	X	X	
	38°C, 5Hz	X	X	
	38°C, 1Hz	X	X	
	38°C, 0.5Hz	X	X	
	38°C, 0.1Hz	X	X	
	54°C, 25Hz	X	X	
	54°C, 10Hz	X	X	
	54°C, 5Hz	X	X	
	54°C, 1Hz	X	X	
	54°C, 0.5Hz	X	X	
	54°C, 0.1Hz			

(continued on next page)

Table 5-6. (Continued).

(c)

Property	Temperature, Frequency	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
IDT Dynamic Modulus	-10°C, 10Hz		X	X	X	X	
	-10°C, 5Hz		X	X	X	X	
	-10°C, 1Hz		X	X	X	X	
	-10°C, 0.5Hz		X	X	X	X	
	-10°C, 0.1Hz			X	X	X	
	10°C, 10Hz			X	X	X	
	10°C, 5Hz			X	X	X	
	10°C, 1Hz			X	X	X	X
	10°C, 0.5Hz			X		X	
	10°C, 0.1Hz			X	X	X	
	35°C, 10Hz			X		X	
	35°C, 5Hz			X			
	35°C, 1Hz			X	X	X	
	35°C, 0.5Hz	X	X	X	X	X	
	35°C, 0.1Hz			X	X	X	

Table 5-7. Summary of the statistical comparisons (volumetrics)—Mixture 5LA90.

(a)

Property	Comparison					
	LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
AV	X	X	NA			
VMA						
VFA	X	X				
G_{mm}	X	X	X	X		
AC						
G_{sb}						

(b)

Property	Sieve	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Aggregate Percent Passing Sieve	12.5 mm						
	4.75 mm						
	0.600 mm						
	0.075 mm		X	X			

Table 5-8. Summary of the statistical comparisons (mechanical)— Mixture 5LA90.

(a)

Property	Passes	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
LWT Rut Depth	1,000	X	X				
	5,000	X	X		X	X	
	10,000	X	X				
	20,000	N/A	N/A	N/A			

(b)

Property	Temperature, Frequency	Comparison		
		LL-PL	LL-PLR	PL-PLR
Axial Dynamic Modulus	-10°C, 25Hz			
	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz			
	-10°C, 0.5Hz			
	-10°C, 0.1Hz			X
	4°C, 25Hz			X
	4°C, 10Hz			X
	4°C, 5Hz			X
	4°C, 1Hz			X
	4°C, 0.5Hz			X
	4°C, 0.1Hz			X
	25°C, 25Hz			X
	25°C, 10Hz			X
	25°C, 5Hz			X
	25°C, 1Hz			X
	25°C, 0.5Hz			X
	25°C, 0.1Hz			X
	38°C, 25Hz			X
	38°C, 10Hz			X
	38°C, 5Hz			X
	38°C, 1Hz			X
	38°C, 0.5Hz			X
	38°C, 0.1Hz			X
	54°C, 25Hz			X
	54°C, 10Hz			X
	54°C, 5Hz			X
	54°C, 1Hz			X
	54°C, 0.5Hz			X
	54°C, 0.1Hz			X

(c)

Property	Temperature, Frequency	Comparison		
		PL-PF	PLR-PF	PL-PLR
IDT Dynamic Modulus	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz			
	-10°C, 0.5Hz			
	-10°C, 0.1Hz		X	
	10°C, 10Hz	X	X	
	10°C, 5Hz	X	X	
	10°C, 1Hz		X	X
	10°C, 0.5Hz	X	X	X
	10°C, 0.1Hz		X	X
	35°C, 10Hz		X	X
	35°C, 5Hz		X	X
	35°C, 1Hz		X	X
	35°C, 0.5Hz		X	X
	35°C, 0.1Hz		X	X

5.1.5 Summary of Mixture 5LA61 Analysis

Tables 5-9 and 5-10 summarize the statistical comparisons conducted for Mixture 5LA61. Results presented in Table 5-9 indicate that the LL and PL specimens were statistically different from the reheated plant-produced specimens (PLR) for most volumetric properties. The main reason for these differences is possibly the low air voids of the PLR specimens (average AV for PLR = 3.1%). Differences in mechanical properties were also noted among LL, PL, PLR, and PF specimens.

5.1.6 Summary of Mixture 5VA Analysis

The following observations are made with respect to the analysis of the test results of Mixture 5VA as summarized in Tables 5-11 and 5-12. The use of hard and low absorption aggregates did not lead to differences in mix gradation or the volumetric properties of the produced mix as compared to the JMF. Rutting performance of the mix in the LWT was excellent for all three specimen types. No stripping was observed for this mixture. Consistent with the mechanical testing of previous mixtures, laboratory-compacted specimens exhibited lower average rut depth than field-compacted specimens. Significant differences were observed between LL and PL specimens in axial E* testing. However, there appears to be little practical difference between the specimen types. Indirect tension E* reveals differences among the specimen types. These differences were particularly noted for PL comparisons, which is consistent with other mixtures tested.

5.1.7 Summary of Mixture 5SD Analysis

Results of the analysis of Mixture 5SD, summarized in Tables 5-13 and 5-14, showed that slight differences in gradation, while within state tolerances, might lead to significant differences in important volumetric properties, such as AV and VFA. The use of hydrated lime as an anti-stripping agent appeared to have a pronounced effect on the rutting performance of the mix. Differences in compaction procedure and efforts resulted in poor rutting performance for field-compacted specimens.

5.1.8 Summary of Mixture 6FL Analysis

Test results of Mixture 6FL showed differences throughout the volumetric and mechanical parameters evaluated. Statistical comparisons are summarized in Tables 5-15 and 5-16. With respect to volumetric differences, the deviations were within the acceptable tolerance for most state agencies and the mixtures are, therefore, practically similar. The differences in mechanical values, particularly, dynamic modulus, can be attributed to construction practice followed by the contractor. The mixture was produced during the day and allowed to remain in the silo until production began the same night. This time delay of about 4 to 6 hours may have resulted in additional binder aging, absorption, or both, neither of which was accounted for during laboratory mixing and specimen fabrication.

5.1.9 Summary of Mixture 7IA Analysis

Tables 5-17 and 5-18 summarize the statistical comparisons conducted for Mixture 7IA. Statistically significant comparisons are indicated by a crossed and shaded cell. Table 5-17 indicates that differences appear to be interrelated between the volumetric properties, which may be expected, because these properties depend on each other. Soft aggregates used in this mix did not appear to affect aggregate gradation. On the other

(*text continues on page 52*)

Table 5-9. Summary of the statistical comparisons (volumetrics)—Mixture 5LA61.

(a)

Property	Comparison					
	LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Air Voids		X				X
VMA		X		NA		X
VFA		X				X
G_{mm}	X	X	X			
Asphalt Binder Content						
G_{sb}	X					

(b)

Property	Sieve	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Aggregate Percent Passing Sieve	12.5 mm						
	4.75 mm						
	0.600 mm	X	X	X			
	0.075 mm	X		X			X

Table 5-10. Summary of the statistical comparisons (mechanical)— Mixture 5LA61.

(a)

Property	Passes	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
LWT Rut Depth	1,000						
	5,000						
	10,000						
	20,000	X					

(b)

Property	Temperature, Frequency	Comparison		
		LL-PL	LL-PLR	PL-PLR
Axial Dynamic Modulus	-10°C, 25Hz			
	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz			
	-10°C, 0.5Hz			
	-10°C, 0.1Hz			
	4°C, 25Hz			
	4°C, 10Hz			
	4°C, 5Hz			
	4°C, 1Hz			
	4°C, 0.5Hz			
	4°C, 0.1Hz			
	25°C, 25Hz			
	25°C, 10Hz			
	25°C, 5Hz			
	25°C, 1Hz			
	25°C, 0.5Hz			
	25°C, 0.1Hz			
	38°C, 25Hz			
	38°C, 10Hz			
	38°C, 5Hz			
	38°C, 1Hz			
	38°C, 0.5Hz			
	38°C, 0.1Hz			
	54°C, 25Hz			
	54°C, 10Hz			
	54°C, 5Hz			
	54°C, 1Hz			
	54°C, 0.5Hz			
	54°C, 0.1Hz			

(c)

Property	Temperature, Frequency	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
IDT Dynamic Modulus	-10°C, 10Hz						
	-10°C, 5Hz						
	-10°C, 1Hz						
	-10°C, 0.5Hz						
	-10°C, 0.1Hz						
	10°C, 10Hz						
	10°C, 5Hz						
	10°C, 1Hz						
	10°C, 0.5Hz						
	10°C, 0.1Hz						X
	30°C, 10Hz			X		X	
	30°C, 5Hz					X	X
	30°C, 1Hz						
	30°C, 0.5Hz			X		X	X
	30°C, 0.1Hz	X		X		X	X

Table 5-11. Summary of the statistical comparisons (volumetrics)—Mixture 5VA.

(a)

Property	Comparison		
	LL-PL	LL-PF	PL-PF
Air Voids		NA	
VMA			
VFA			
G_{mm}			
Asphalt Binder Content			
G_{sb}	X		

(b)

Property	Sieve	Comparison		
		LL-PL	LL-PF	PL-PF
Aggregate Percent Passing Sieve	12.5 mm	X	X	
	4.75 mm	X		
	0.600 mm			
	0.075 mm		X	X

Table 5-12. Summary of the statistical comparisons (mechanical)—Mixture 5VA.

(a)

Property	Passes	Comparison		
		LL-PL	LL-PF	PL-PF
LWT Rut Depth	1,000			X
	5,000			
	10,000			
	20,000			

(b)

Property	Temperature, Frequency	Comparison LL-PL
Axial Dynamic Modulus	-10°C, 25Hz	
	-10°C, 10Hz	
	-10°C, 5Hz	
	-10°C, 1Hz	
	-10°C, 0.5Hz	
	-10°C, 0.1Hz	
	4°C, 25Hz	
	4°C, 10Hz	
	4°C, 5Hz	
	4°C, 1Hz	X
	4°C, 0.5Hz	X
	4°C, 0.1Hz	X
	25°C, 25Hz	
	25°C, 10Hz	
	25°C, 5Hz	X
	25°C, 1Hz	X
	25°C, 0.5Hz	X
	25°C, 0.1Hz	X
	38°C, 25Hz	X
	38°C, 10Hz	X
	38°C, 5Hz	X
	38°C, 1Hz	X
	38°C, 0.5Hz	X
	38°C, 0.1Hz	X
	54°C, 25Hz	X
	54°C, 10Hz	X
	54°C, 5Hz	X
	54°C, 1Hz	X
	54°C, 0.5Hz	X
	54°C, 0.1Hz	X

(c)

Property	Temperature, Frequency	Comparison		
		LL-PF	LL-PL	PL-PF
IDT Dynamic Modulus	-10°C, 10Hz		X	X
	-10°C, 5Hz		X	X
	-10°C, 1Hz		X	X
	-10°C, 0.5Hz		X	X
	-10°C, 0.1Hz		X	X
	10°C, 10Hz	X	X	X
	10°C, 5Hz	X	X	X
	10°C, 1Hz	X	X	X
	10°C, 0.5Hz	X	X	X
	10°C, 0.1Hz	X	X	X
	35°C, 10Hz	X	X	X
	35°C, 5Hz		X	X
	35°C, 1Hz		X	X
	35°C, 0.5Hz		X	X
	35°C, 0.1Hz		X	X

Table 5-13. Summary of the statistical comparisons (volumetrics)—Mixture 5SD.

(a)

Property	Comparison		
	LL-PLR	LL-PF	PLR-PF
Air Voids	X	NA	
VMA	X		
VFA	X		
G_{mm}	X	X	
Asphalt Binder Content			
G_{sb}			

(b)

Property	Sieve	Comparison		
		LL-PLR	LL-PF	PLR-PF
Aggregate Percent Passing Sieve	12.5 mm			
	4.75 mm	X	X	
	0.600 mm	X	X	
	0.075 mm			

Table 5-14. Summary of the statistical comparisons (mechanical)—Mixture 5SD.

(a)

Property	Passes	Comparison LL-PLR	Comparison LL-PF	Comparison PLR-PF
LWT Rut Depth	1,000	X	X	X
	5,000	X	X	X
	10,000	X	X	X
	20,000	X	X	X

(b)

Property	Temperature, Frequency	Comparison LL-PLR
Axial Dynamic Modulus	-10°C, 25Hz	
	-10°C, 10Hz	
	-10°C, 5Hz	
	-10°C, 1Hz	
	-10°C, 0.5Hz	
	-10°C, 0.1Hz	
	4°C, 25Hz	
	4°C, 10Hz	
	4°C, 5Hz	
	4°C, 1Hz	X
	4°C, 0.5Hz	X
	4°C, 0.1Hz	X
	25°C, 25Hz	X
	25°C, 10Hz	X
	25°C, 5Hz	X
	25°C, 1Hz	X
	25°C, 0.5Hz	X
	25°C, 0.1Hz	
	38°C, 25Hz	
	38°C, 10Hz	
	38°C, 5Hz	
	38°C, 1Hz	
	38°C, 0.5Hz	
	38°C, 0.1Hz	
	54°C, 25Hz	
	54°C, 10Hz	
	54°C, 5Hz	
	54°C, 1Hz	
	54°C, 0.5Hz	
	54°C, 0.1Hz	

(c)

Property	Temperature, Frequency	Comparison LL-PLR	Comparison LL-PF	Comparison PLR-PF
IDT Dynamic Modulus	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz			
	-10°C, 0.5Hz			
	-10°C, 0.1Hz			
	-10°C, 0.01Hz			
	10°C, 10Hz			
	10°C, 5Hz			
	10°C, 1Hz			
	10°C, 0.5Hz			
	10°C, 0.1Hz			
	10°C, 0.01Hz	X		
	30°C, 10Hz			
	30°C, 5Hz			
	30°C, 1Hz			
	30°C, 0.5Hz			
	30°C, 0.1Hz			
	30°C, 0.01Hz			

Table 5-15. Summary of the statistical comparisons (volumetrics)—Mixture 6FL.

(a)

Property	Comparison LL-PL	Comparison LL-PF	Comparison PL-PF
Air Voids	X	NA	
VMA	X		
VFA	X		
G_{mm}	X	X	
Asphalt Binder Content		X	
G_{sb}	X		

(b)

Property	Sieve	Comparison LL-PL	Comparison LL-PF	Comparison PL-PF
Aggregate Percent Passing Sieve	12.5 mm			
	4.75 mm			
	0.600 mm	X	X	X
	0.075 mm		X	X

Table 5-16. Summary of the statistical comparisons (mechanical)—Mixture 6FL.

(a)

Property	Passes	Comparison		
		LL-PL	LL-PF	PL-PF
LWT Rut Depth	1,000			
	5,000			
	10,000			
	20,000			

(b)

Property	Temperature, Frequency	Comparison LL-PL
Axial Dynamic Modulus	-10°C, 25Hz	X
	-10°C, 10Hz	X
	-10°C, 5Hz	X
	-10°C, 1Hz	X
	-10°C, 0.5Hz	X
	-10°C, 0.1Hz	X
	4°C, 25Hz	X
	4°C, 10Hz	X
	4°C, 5Hz	X
	4°C, 1Hz	X
	4°C, 0.5Hz	X
	4°C, 0.1Hz	X
	25°C, 25Hz	X
	25°C, 10Hz	X
	25°C, 5Hz	X
	25°C, 1Hz	X
	25°C, 0.5Hz	X
	25°C, 0.1Hz	X
	38°C, 25Hz	X
	38°C, 10Hz	X
	38°C, 5Hz	X
	38°C, 1Hz	X
	38°C, 0.5Hz	X
	38°C, 0.1Hz	X
	54°C, 25Hz	X
	54°C, 10Hz	X
	54°C, 5Hz	X
	54°C, 1Hz	X
	54°C, 0.5Hz	X
	54°C, 0.1Hz	X

(c)

Property	Temperature, Frequency	Comparison		
		LL-PL	LL-PF	PL-PF
IDT Dynamic Modulus	-10°C, 10Hz			X
	-10°C, 5Hz		X	X
	-10°C, 1Hz		X	X
	-10°C, 0.5Hz		X	X
	-10°C, 0.1Hz		X	X
	-10°C, 0.01Hz		X	X
	10°C, 10Hz	X		X
	10°C, 5Hz	X		X
	10°C, 1Hz	X		X
	10°C, 0.5Hz	X		X
	10°C, 0.1Hz	X		X
	10°C, 0.01Hz	X		X
	30°C, 10Hz	X	X	X
	30°C, 5Hz	X	X	X
	30°C, 1Hz	X	X	X
	30°C, 0.5Hz	X	X	X
	30°C, 0.1Hz	X	X	X
	30°C, 0.1Hz	X	X	X

Table 5-17. Summary of the statistical comparisons (volumetrics)—Mixture 7IA.

(a)

Property	Comparison					
	LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Air Voids		X		NA		X
VMA		X				X
VFA	X	X				X
G_{mm}	X	X	X	X		X
Asphalt Binder Content	X	X		X	X	
G_{sb}		X	X	X	X	X

(b)

Property	Sieve	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
Percent Passing	12.5 mm		X				
	4.75 mm		X			X	X
	0.600 mm	X	X	X			
	0.075 mm						

Table 5-18. Summary of the statistical comparisons (mechanical)—Mixture 7IA.

(a)

Property	Passes	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
LWT Rut Depth	1,000						
	SIP			X	X	X	

(b)

Property	Temperature, Frequency	Comparison		
		LL-PL	LL-PLR	PL-PLR
Axial Dynamic Modulus	-10°C, 25Hz			
	-10°C, 10Hz	X		
	-10°C, 5Hz	X		
	-10°C, 1Hz	X		
	-10°C, 0.5Hz	X		
	-10°C, 0.1Hz	X	X	
	4°C, 25Hz			
	4°C, 10Hz	X		
	4°C, 5Hz	X	X	
	4°C, 1Hz	X	X	
	4°C, 0.5Hz	X	X	
	4°C, 0.1Hz	X	X	
	25°C, 25Hz	X	X	
	25°C, 10Hz	X	X	
	25°C, 5Hz	X	X	
	25°C, 1Hz	X	X	
	25°C, 0.5Hz	X	X	
	25°C, 0.1Hz	X	X	
	37°C, 25Hz	X	X	
	37°C, 10Hz	X	X	
	37°C, 5Hz	X	X	
	37°C, 1Hz	X	X	
	37°C, 0.5Hz	X	X	
	37°C, 0.1Hz	X	X	
	54°C, 25Hz	X	X	
	54°C, 10Hz	X	X	
	54°C, 5Hz	X	X	
	54°C, 1Hz			
	54°C, 0.5Hz			
	54°C, 0.1Hz			

(continued on next page)

Table 5-18. (Continued).

(c)

Property	Temperature, Frequency	Comparison					
		LL-PL	LL-PLR	LL-PF	PL-PF	PLR-PF	PL-PLR
IDT Dynamic Modulus	-10°C, 10Hz			X	X	X	
	-10°C, 5Hz			X	X	X	
	-10°C, 1Hz			X	X	X	
	-10°C, 0.5Hz			X	X	X	
	-10°C, 0.1Hz			X	X	X	
	-10°C, 0.01Hz			X	X	X	
	10°C, 10Hz			X	X	X	
	10°C, 5Hz			X	X	X	
	10°C, 1Hz			X	X	X	
	10°C, 0.5Hz			X	X	X	
	10°C, 0.1Hz			X	X	X	
	10°C, 0.01Hz			X	X	X	
	30°C, 10Hz			X	X	X	
	30°C, 5Hz			X	X	X	
	30°C, 1Hz			X	X	X	
	30°C, 0.5Hz			X	X	X	
	30°C, 0.1Hz			X	X	X	
	30°C, 0.01Hz						

hand, all specimen types performed poorly in the LWT test by reaching the tertiary flow region before 5,000 passes. At 1,000 passes, no differences were observed among the specimen types. In the dynamic modulus test, the main differences were observed between LL specimens when compared to PL and PLR specimens.

5.1.10 Summary of Mixture 8LA Analysis

Tables 5-19 and 5-20 summarize the statistical comparisons conducted for Mixture 8LA. Test results showed that the use of hard and high absorption aggregates (blend absorption is 2.0%) did not substantially affect the mix gradation or the volumetric properties of the produced mix as compared to the JMF. Further, while this mixture was produced with high absorption aggregates, reheating did not influence the VMA or VFA of the produced mix. Rutting performance of the mix in the LWT was excellent for all three specimen types. This behavior is commonly observed for crumb-rubber modified asphalt binder. Consistent with the mechanical testing of previous mixtures, laboratory-compacted specimens had lower average rut depth than field-compacted specimens. No substantial differences were noted between LL and PLR specimens in LWT and axial E* testing.

5.2 Combined Statistical Analysis

5.2.1 Effect of Specimen Type on Differences Among Specimen Types

Figure 5-1 presents the combined summary of the volumetric differences observed. The direction of the statistical difference represents whether the relationship was positive or negative. For instance, a negative difference for the LL-PL comparison indicates that the value was significantly greater for the PL specimen when compared to the LL specimen.

Table 5-19. Summary of the statistical comparisons (volumetrics)—Mixture 8LA.

(a)

Property	Comparison		
	LL-PLR	LL-PF	PLR-PF
Air Voids			
VMA		NA	NA
VFA	X		
G_{mm}			
Asphalt Binder Content			
G_{sb}	X	X	

(b)

Property	Sieve	Comparison		
		LL-PLR	LL-PF	PLR-PF
Aggregate Percent Passing Sieve	12.5 mm			
	4.75 mm			
	0.600 mm	X		
	0.075 mm	X	X	

Table 5-20. Summary of the statistical comparisons (mechanical)—Mixture 8LA.

(a)

Property	Passes	Comparison		
		LL-PLR	LL-PF	PLR-PF
LWT Rut Depth	1,000			
	5,000		X	
	10,000		X	X
	20,000		X	X

(b)

Property	Temperature, Frequency	Comparison
		LL-PLR
Axial Dynamic Modulus	-10°C, 25Hz	
	-10°C, 10Hz	X
	-10°C, 5Hz	X
	-10°C, 1Hz	
	-10°C, 0.5Hz	
	-10°C, 0.1Hz	
	4°C, 25Hz	X
	4°C, 10Hz	X
	4°C, 5Hz	X
	4°C, 1Hz	X
	4°C, 0.5Hz	
	4°C, 0.1Hz	
	25°C, 25Hz	
	25°C, 10Hz	
	25°C, 5Hz	
	25°C, 1Hz	
	25°C, 0.5Hz	
	25°C, 0.1Hz	
	38°C, 25Hz	
	38°C, 10Hz	
	38°C, 5Hz	
	38°C, 1Hz	
	38°C, 0.5Hz	
	38°C, 0.1Hz	
	54°C, 25Hz	
	54°C, 10Hz	
	54°C, 5Hz	
	54°C, 1Hz	
	54°C, 0.5Hz	
	54°C, 0.1Hz	

(c)

Property	Temperature, Frequency	Comparison		
		LL-PLR	LL-PF	PLR-PF
IDT Dynamic Modulus	-10°C, 10Hz			
	-10°C, 5Hz			
	-10°C, 1Hz		X	X
	-10°C, 0.5Hz		X	X
	-10°C, 0.1Hz		X	X
	-10°C, 0.01Hz		X	X
	10°C, 10Hz	X	X	
	10°C, 5Hz	X	X	
	10°C, 1Hz	X	X	
	10°C, 0.5Hz		X	
	10°C, 0.1Hz		X	
	10°C, 0.01Hz			
	30°C, 10Hz	X		X
	30°C, 5Hz	X		X
	30°C, 1Hz	X		X
	30°C, 0.5Hz			X
	30°C, 0.1Hz		X	X
	30°C, 0.01Hz		X	X

AV, VMA, and VFA were only computed for laboratory-compacted specimens (i.e., LL and PL). Therefore, there are no comparisons involving field-compacted specimens (PF) because the target air voids was different. Figure 5-1 shows the statistical differences that exist for each comparison. However, some of the properties are interrelated. The differences in air voids are mainly attributed to differences within the G_{mm} measurements. Asphalt binder content resulted in the least amount of statistical difference among the three specimen types. This was expected, because asphalt binder content is typically well controlled during production. Many of the statistical differences observed were within the tolerance of the test procedure and are, therefore, considered practically equivalent.

Table 5-21 summarizes the frequency of statistical and practical differences observed within the combined data set. For example, LL versus PL comparison of air voids was statistically different for 60% of the cases. However, the difference was practically significant for only 20% of the mixtures tested. Practical significance was defined as a measured test difference greater than the d2s precision range reported in the relevant AASHTO test procedure, when available.

5.2.2 Effect of Process-Based Factors on Magnitude of Differences Among Specimen Types

An analysis of covariance (ANCOVA) was conducted for each of the volumetric and mechanical properties evaluated in the study. Table 5-22 presents the results of the ANCOVA conducted on the volumetric properties. The highlighted cells indicate a statistically significant effect of a process-based factor on a specific volumetric property. As shown in this table, the effects of process-based factors on the differences between production (PL) and construction (PF) specimens were minimal. This is reasonable, given the similarity between these two specimen types (e.g., baghouse is used in both PL and PF specimens). The effect of time delay of specimen fabrication

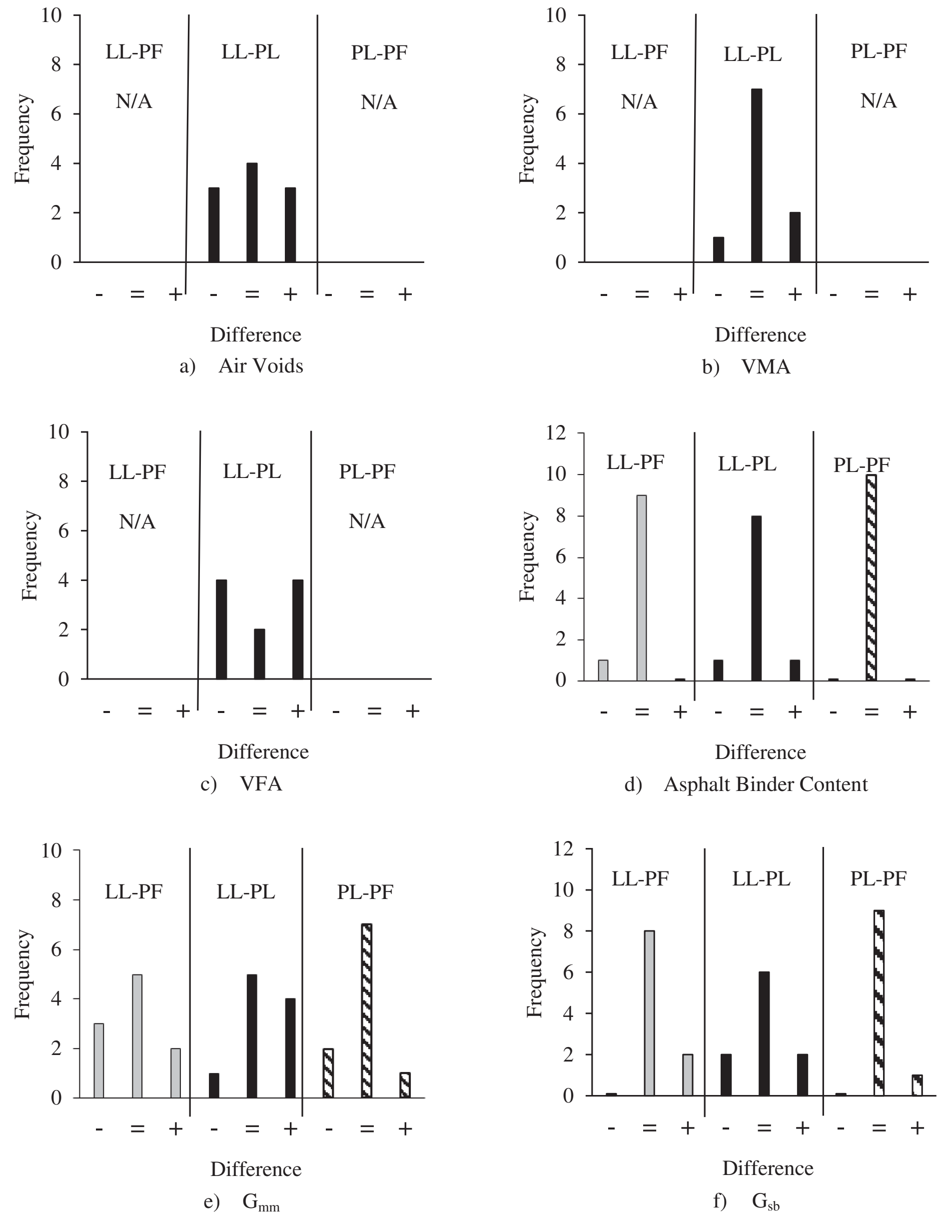


Figure 5-1. Summary of the statistical comparisons (volumetric)—combined.

Table 5-21. Summary of the statistical comparisons (volumetric)—combined.

Comparison	% Statistically Different / % Practically Different					
	Air Voids	VMA	VFA	G_{mm}	AC	G_{sb}
LL vs. PF	----	----	----	50% / 20%	10% / 0%	20% / 20%
LL vs. PL	60% / 20%	30% / 10%	80% / 50%	50% / 10%	20% / 20%	40% / 10%
PL vs. PF	----	----	----	30% / 20%	10% / 10%	10% / 10%

Table 5-22. Summary of the ANCOVA—volumetric properties.

Comparison	Parameter	Baghouse	Time Delay	Aggregate Absorption	Aggregate Hardness	Stockpile Moisture
Design (LL) - Production (PL)	Air Voids					X
	VMA					
	VFA					
	AC	X		X		
	G_{mm}					
	G_{sb}					
	Gradation	X			X	
Design (LL) - Construction (PF)	AC	X				
	G_{mm}					
	G_{sb}					
	Gradation	X			X	X
Production (PL) - Construction (PF)	AC					
	G_{mm}					
	G_{sb}					
	Gradation					

was not significant in any comparison. Significant factors in the analysis are summarized below:

- The return of baghouse fines showed a statistically significant effect on AC as well as gradation.
- Aggregate absorption showed a statistically significant effect on AC between design and production specimens.
- Aggregate hardness had a statistically significant effect on gradation between laboratory-mixed and plant-produced specimens.
- Stockpile moisture had a significant effect on the measured air voids between design and production specimens.

Table 5-23 presents the results of the ANCOVA for the mechanical properties. Only one effect of process-based factors on the differences among specimen types for the mechanical properties was noted. Aggregate hardness was statistically significant for IDT dynamic modulus between design (LL) and construction (PF) specimens. Results of the meta-analysis for the mechanical properties also showed that there is no statistically significant effect due to time delay in specimen fabrication. The lack of observed effects of process-based factors may result from the variations in the mechanical properties being strongly controlled by compaction effort. Many of the individual mixture comparisons showed that field-compacted specimens (PF) were significantly different from laboratory-compacted specimens (LL and PL). This finding was attributed to differences in compaction effort and confinement conditions between the two compaction processes (laboratory and field). In addition, differences in aggregate orientation due

Table 5-23. Summary of the ANCOVA—mechanical properties.

Comparison	Parameter	Baghouse	Time Delay	Aggregate Absorption	Aggregate Hardness	Stockpile Moisture
Design (LL) - Production (PL)	LWT					
	Axial Dynamic Modulus					
	IDT Dynamic Modulus					
Design (LL) - Construction (PF)	LWT					
	IDT Dynamic Modulus				X	
Production (PL) - Construction (PF)	LWT					
	IDT Dynamic Modulus					

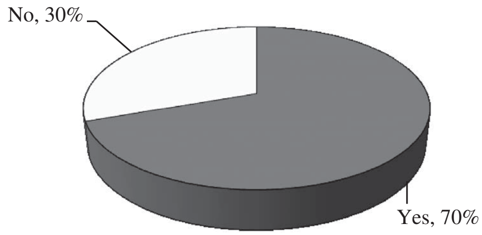


Figure 5-2. Question 5 re Baghouse fines used during mixture design.

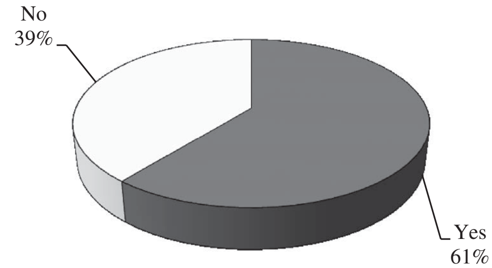


Figure 5-4. Question 7 re VMA collapse prior to fine-tuning.

to compaction efforts may affect the mechanical properties deviations among specimen types.

Results from a nationwide survey of contractors and agencies conducted in this research suggest that competent contractors understand how to control the process-based factors affecting their mixture during production. For example, several contractors incorporate baghouse dust into their mixture design process when the baghouse dust is to be returned during production. Further, contractors that use soft or absorptive aggregate account for aggregate breakdown during the mixture design process by increasing the quantity of fine aggregate. Figures 5-2 through 5-5 present the results of the nationwide contractor survey on the effects of process-based factor during production and design. The figures indicate that contractors sufficiently understand how their materials will change through the production process. For instance, VMA collapse is often reduced by fine-tuning the production process. VMA collapse is the loss of VMA during plant production of asphalt mixtures.

5.2.3 Effects of Specimen Type on Measured Dynamic Modulus

Figure 5-6 presents two typical master curves constructed from the indirect dynamic modulus data for the three specimen types. As shown in this figure, the dynamic modulus of field-compacted specimens (PF) was generally lower than that of laboratory-compacted specimens. This difference is commonly attributed to differences in compaction effort and aggregate orientation between lab and field compaction. Figure 5-6 also shows that the dynamic modulus of the plant-produced mixture (PL) was generally stiffer than or similar to that of the laboratory-mixed specimens (LL). This may be attributed to the hardening of the binder at the plant as compared to the laboratory, since the indirect tensile strength test is very sensitive to the binder stiffness.

Figure 5-7 compares the laboratory-measured dynamic modulus among the three specimen types evaluated and presents the percentage difference among the average modulus values normalized with respect to the plant production specimens (PL). Normalization allows comparisons to be made among the ten mixtures tested by removing the influence of varying characteristics (e.g., binder grade, binder content, and gradation). Typically, the construction specimens yielded a lower modulus value (indicated by a positive bar) than the laboratory-compacted specimens. As shown in Figure 5-7, the largest differences were observed for the comparisons involving field-compacted (i.e., PF) specimens. This may be attributed to differences in particle orientation and compaction effort between field- and laboratory-compacted specimens. Figures 5-6 and 5-7 show that the percentage difference increased with testing temperature. Further, the specimens fabricated with plant-produced mixture (PL) were generally stiffer than those of laboratory-produced mixture (LL).

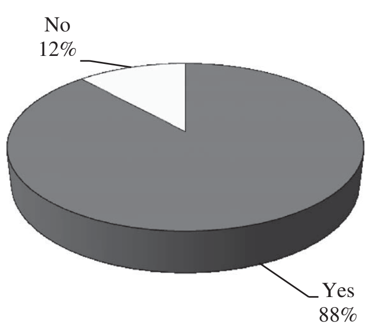


Figure 5-3. Question 6 re Account for plant breakdown during mixture design.

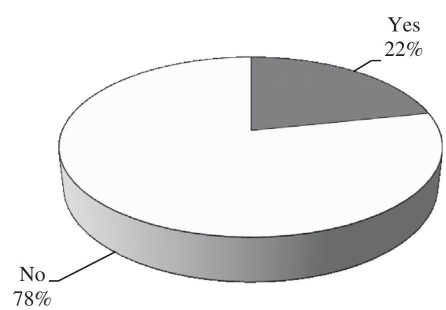


Figure 5-5. Question 8 re VMA collapse after fine-tuning.

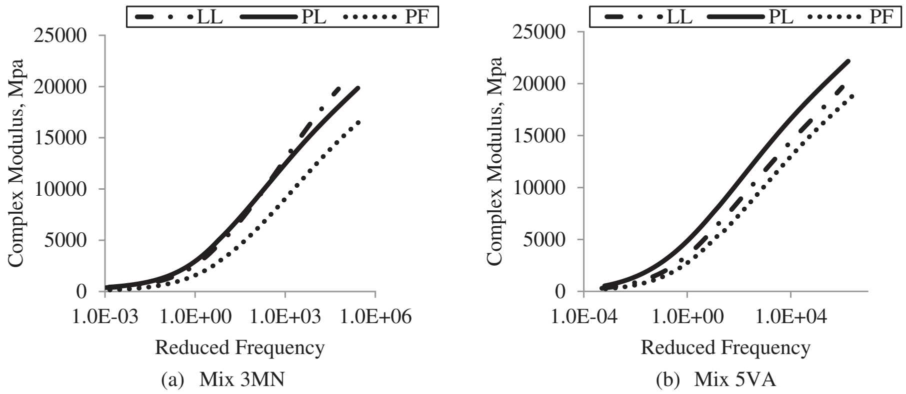


Figure 5-6. IDT E*—Master curve comparison.

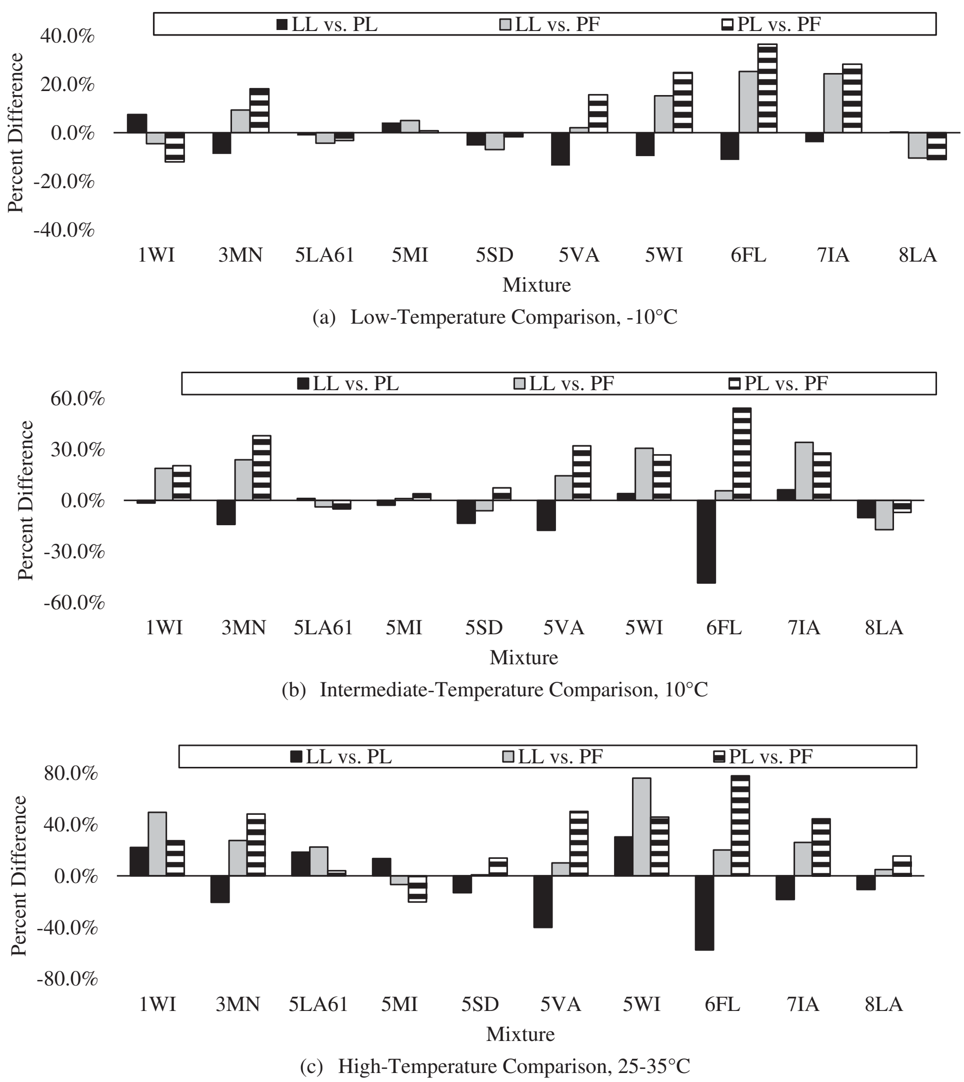


Figure 5-7. IDT E* delta comparison—delta modulus/PL modulus.

Table 5-24. Descriptive statistics—|delta modulus|/PL modulus.

Temperature, °C	Comparison	Mean, %	Minimum, %	Maximum, %
-10	LL vs. PL	7	1	14
	LL vs. PF	11	2	25
	PL vs. PF	15	1	37
10	LL vs. PL	12	3	49
	LL vs. PF	16	2	34
	PL vs. PF	22	4	54
25-35	LL vs. PL	25	11	58
	LL vs. PF	26	1	76
	PL vs. PF	35	4	78

Table 5-24 presents the absolute value (averages, minimums, and maximums) of the percent differences for the comparisons. The table shows that, as the testing temperature increases, the mean percent difference also increases and that the comparisons of the core specimens, PF, with the LL samples resulted in the largest differences for each temperature region. The maximum difference of 78% observed was for PL vs. PF at 25 to 35°C.

ANOVA with a significance level of α = 0.05 was used to determine statistical significance. Within the ANOVA, individual pair-wise comparisons (i.e., PL vs. LL, PL vs. PF, and LL vs. PF) were conducted using Duncan's MCT. Figure 5-8

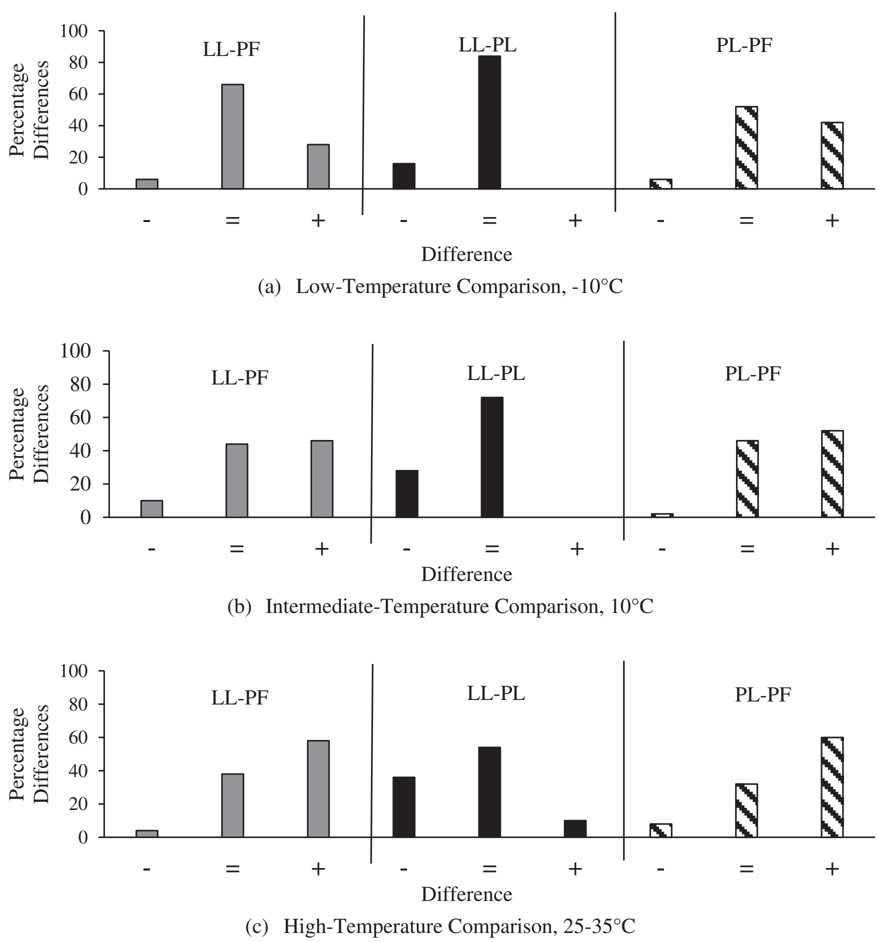


Figure 5-8. Histogram of IDT E statistical differences.*

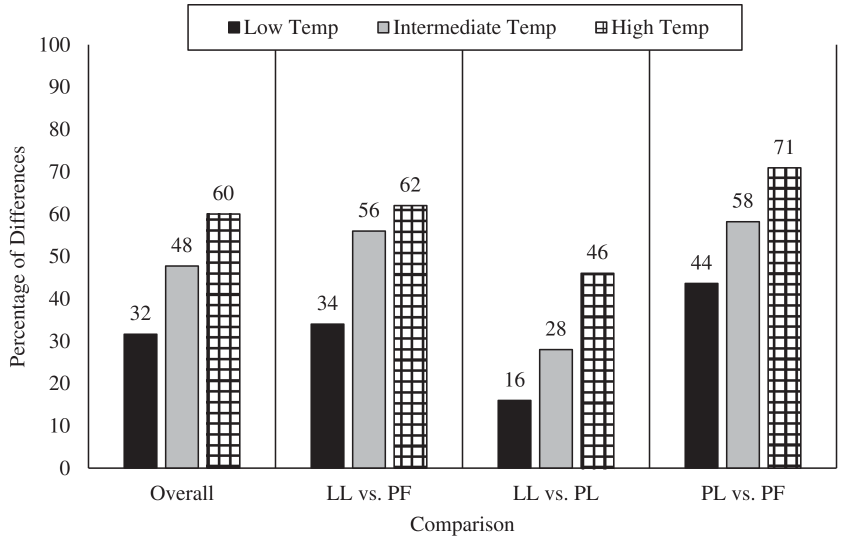


Figure 5-9. IDT E* statistical summary.

presents the results of the ANOVA. The histogram represents the percentages of statistical differences observed. The bars indicate the direction of the statistical differences. For the −10°C comparisons in Figure 5-8, the design LL modulus was significantly greater than the PF core modulus in 28% of the comparisons. The statistical comparisons among the three specimen types showed statistical differences among all specimen types, especially at intermediate and high temperatures. The least difference was observed at low temperature. Further, the PF samples (field cores) yielded significantly lower values than the LL (laboratory-compacted) specimens.

Figure 5-9 presents the percentage of statistically significant differences observed for each comparison. The figure shows that the LL versus PL comparison resulted in the fewest percentages of statistically significant differences. In contrast, comparisons that included PF specimens resulted in statistically significant differences for over 50% of the cases. The percentage of statistically significant differences increased with the increase in testing temperature.

CHAPTER 6

Proposed Guidelines for Recommended Practice

6.1 Specification Recommendations

This section presents the development of a draft proposed AASHTO recommended practice that addresses the cause and magnitude of variability within and among the three specimen types (i.e., LL, PL, and PF). Data collected in Task 4 were used to develop the specification recommendations.

6.1.1 Single-Operator Tolerance Among Specimen Types

The individual data sets were combined to calculate the expected deviation among specimen types. The delta values from the 10 mixtures were assumed to originate from the same population. Table 6-1 presents the average, minimum, and maximum differences observed from the mixtures evaluated. The confidence limit represents the 95% confidence band for the parameters measured. The confidence limit was determined by multiplying the standard deviation of the differences by the t-value associated with alpha = 0.05 ($t_{\alpha=0.05}$ = 1.96). Equation 21 represents the equation used to develop the 95% confidence intervals for each of the design vs. production parameters shown in Table 6-1.

$$\text{Tolerance, } x_{i,LL\text{-}PL} = \text{Standard Deviation, } x_{i\,\text{Delta},\,LL\text{-}PL} \times t_{(\alpha=0.05,\,\infty)} \quad (21)$$

Where x_i = production parameters, viz., AV, VMA, VFA, AC, G_{mm}, G_{sb}, %Passing 0.075 mm

Figures 6-1 through 6-4 compare the tolerances developed from the mixtures in this study and current state agencies' tolerance values. The figures show that many states allow deviations between the submitted JMF and values reported during production that are higher than the tolerances developed in this study. These findings indicate that, the within-laboratory testing (single-operator and same equipment) variation is less than the between-laboratory testing tolerance. Based on these findings, it may be reasonable for states to review their current tolerance values and to determine if a reduction in tolerance from design to production is warranted where the design laboratory is also the QC laboratory. Many of states determine asphalt binder content by means of ignition oven. Therefore, the tolerance developed by solvent extraction would need to be further evaluated for comparison to the ignition method. Typically, solvent extraction results in a lower standard deviation when compared to ignition. Consequently, the tolerance for ignition would be slightly higher.

6.1.2 Maximum Acceptable Difference

In addition to single-operator tolerance values, the combined data were used to evaluate a range of acceptable differences (d2s) for each parameter. The range was determined in accordance with ASTM C670, "Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials." As stated in ASTM C670, the maximum acceptable range is a function of the standard deviation of the test parameter and the number of specimens tested. Table 6-2 presents the table in ASTM C670 that is used to determine the multiplier to compute the acceptable range. Equation 22 presents how the values from ASTM C670 were used to generate acceptable ranges for the properties evaluated. Agencies may use these findings to evaluate current specifications. These values may be higher than specified agency maximum allowable differences because the data in this study were generated from multiple regions of the country. State agency tolerance values should be developed using local data.

$$\text{Maximum Acceptable Range, } x_{i,LL\text{-}PL} = \text{Standard Deviation, } x_{i\text{Delta},\,LL\text{-}PL^*} \times 3.3 \quad (22)$$

*LL–PF, or PL–PF

Where x_i = production parameters, viz., AV, VMA, VFA, AC, G_{mm}, G_{sb}, % Passing 0.075 mm

Table 6-1. Single-operator tolerance.

Comparison	Property	Avg.	Min	Max	Confidence Limit (Tolerance)
Design (LL) - Production (PL)	Air Voids,%	0.6	0.0	1.3	0.8
	VMA,%	0.4	0.0	2.1	1.2
	VFA,%	4.0	0.3	9.9	5.4
	Asphalt Binder Content,%	0.2	0.0	0.4	0.2
	G_{mm}	0.014	0.002	0.039	0.020
	G_{sb}	0.011	0.002	0.025	0.014
	Passing 0.075 mm, %	0.4	0.0	0.9	0.5
Design (LL) - Construction (PF)	Asphalt Binder Content,%	0.2	0.0	0.3	0.2
	G_{mm}	0.011	0.000	0.020	0.013
	G_{sb}	0.010	0.001	0.033	0.019
	Passing 0.075 mm, %	0.7	0.1	1.3	0.7
Production (PL) - Construction (PF)	Asphalt Binder Content,%	0.1	0.0	0.4	0.2
	G_{mm}	0.009	0.001	0.027	0.018
	G_{sb}	0.008	0.000	0.031	0.017
	Passing 0.075 mm, %	0.5	0.1	0.8	0.5

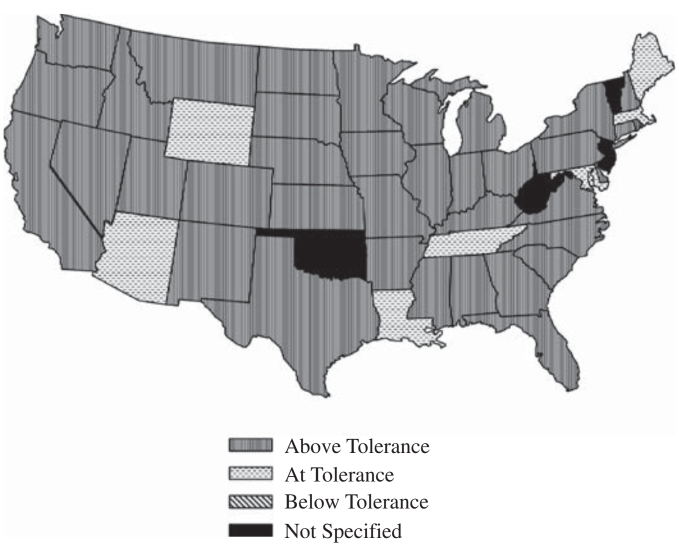


Figure 6-1. Tolerance comparison—asphalt binder content.

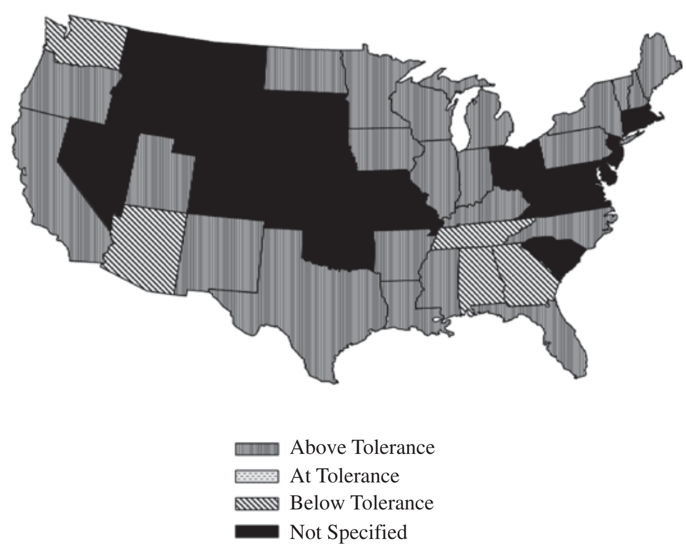


Figure 6-2. Tolerance comparison—air voids, N design.

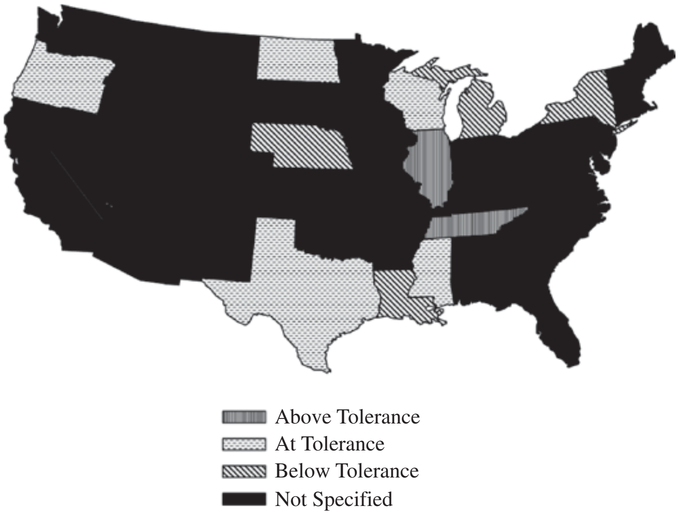


Figure 6-3. Tolerance comparison—G_{mm}, design vs. production.

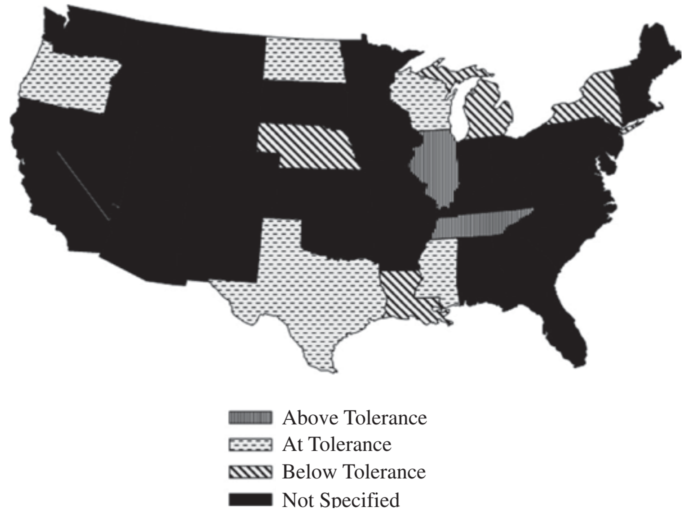


Figure 6-4. Tolerance comparison—VMA, design vs. production.

Figures 6-5 through 6-8 compare the tolerances developed from the mixtures in this study with current state tolerance values. The figures show that many states allow deviations between the submitted JMF and values reported during production, which are within the maximum allowable deviations observed in this study.

6.1.3 Development of Conversion Factors for Mechanical Comparison

As agencies move toward developing performance-related specifications (PRS), it will be beneficial to develop a relationship between mechanical tests among the different specimen types (design, production, and construction). To start this process, the average values of the mechanical property for each specimen type were divided by the average of the same property of another specimen type, as described by Equation 23 for the LWT rut depths for the 1WI mixture. The resulting conversion factor may be used to convert the data developed from a design specimen (LL) to produce results closer to those expected for the production (PL) or construction (PF) values.

$$\text{Average Rut Depth}_{\text{LL, 1WI}}/\text{Rut Depth}_{\text{PL, 1WI}} = \text{Rut Depth Conversion Factor}_{\text{LL/PL,1WI}} \quad (23)$$

Table 6-2. Maximum acceptable range.

Comparison	Property	Maximum Acceptable Range
Design (LL) - Production (PL)	Air Voids,%	± 1.3
	VMA,%	± 2.0
	VFA,%	± 9.1
Design (LL) - Production (PL)	Asphalt Binder Content,%	± 0.30
Design (LL) - Construction (PF)		± 0.30
Production (PL) - Construction (PF)		± 0.30
Design (LL) - Production (PL)	G_{mm}	± 0.034
Design (LL) - Construction (PF)		± 0.022
Production (PL) - Construction (PF)		± 0.030
Design (LL) - Production (PL)	G_{sb}	± 0.024
Design (LL) - Construction (PF)		± 0.032
Production (PL) - Construction (PF)		± 0.029
Design (LL) - Production (PL)	Passing 0.075 mm, %	± 0.80
Design (LL) - Construction (PF)		± 1.2
Production (PL) - Construction (PF)		± 0.80

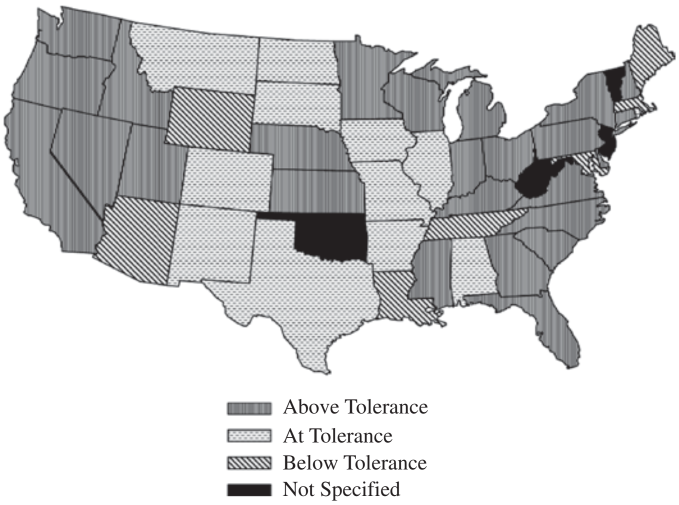


Figure 6-5. Maximum range comparison—asphalt binder content.

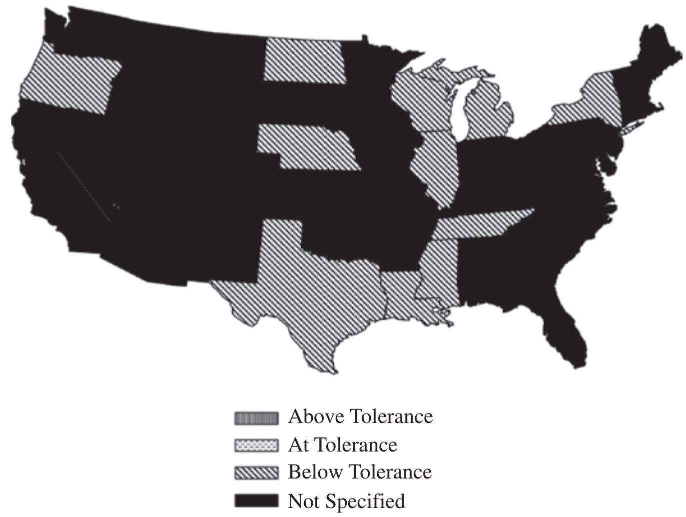


Figure 6-7. Maximum range comparison—G_{mm}, LL vs. PL.

Conversion factors were developed for each of the 10 mixtures evaluated in this project. Table 6-3 presents the conversion factors developed from the LWT test data. The table shows that the average conversion factor between the design (LL) and production (PL) results is 1.0. Thus, on average, the rut depths observed from design specimens (mixed and compacted in the laboratory, LL) were similar to those of the production samples (those produced in the asphalt plant and compacted in the laboratory, PL). Conversely, the table shows an average conversion factor of 0.75 for design (LL) vs. construction (PF) and production (PL) vs. construction (PF). This indicates that, on average, the field-compacted (PF) specimens had a 33% higher rut depth than laboratory-compacted (LL and PL) samples. This relationship is observed throughout the mechanical evaluation among the specimen types and is attributed to differences in compaction effort between laboratory-compacted and field-compacted specimens.

Table 6-4 presents the conversion factor analysis for axial dynamic modulus. Given specimen size constraints, only laboratory-compacted specimens (LL, PL) were available for evaluation in this case. The analysis shows that, on average, the conversion factor between design and production specimens is close to one at low and intermediate temperatures. As the temperature increases, the differences in dynamic modulus become more pronounced. The conversion factor in the high-temperature region indicates that the LL specimens have a lower modulus value than that of PL specimens. This may be attributed to binder oxidation during production.

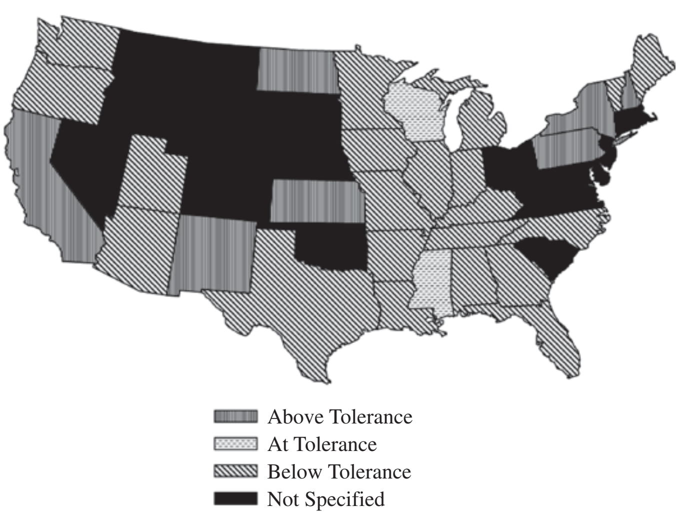


Figure 6-6. Maximum range comparison—air voids, N design.

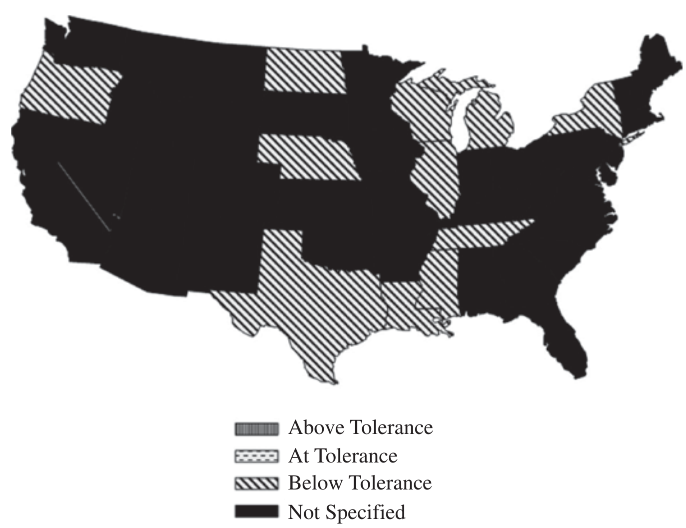


Figure 6-8. Maximum range comparison—VMA.

Table 6-3. LWT conversion factor.

Comparison	No. of Passes	Average Conversion	Conversion Range	
			Min	Max
Design (LL)/ Production (PL)	1000	1.0	0.5	1.6
	5000	1.0	0.6	1.6
	10000	1.0	0.6	1.9
	15000	0.8	0.6	1.1
	20000	0.8	0.5	1.2
	Average	1.0		
Design (LL)/ Construction (PF)	1000	0.8	0.4	1.2
	5000	0.8	0.3	1.2
	10000	0.7	0.3	1.1
	15000	0.7	0.3	1.1
	20000	0.7	0.2	1.1
	Average	0.75		
Production (PL)/ Construction (PF)	1000	0.8	0.3	1.0
	5000	0.7	0.3	1.1
	10000	0.7	0.3	1.1
	15000	0.7	0.2	1.2
	20000	0.9	0.2	1.4
	Average	0.75		

Table 6-5 presents the results of the conversion factor analysis for IDT dynamic modulus. As shown in this table, no conversion in the modulus data among the specimen types is required in the low-temperature region, nor is a conversion factor required at any temperature between laboratory-compacted specimens. However, a conversion factor is required between the modulus values of field- and laboratory-compacted specimens at intermediate and high temperatures.

Table 6-4. Axial dynamic modulus conversion factor.

Comparison	Temperature, °C	Average Conversion	Conversion Range	
			Min	Max
Design (LL)/ Production (PL)	-10.0	1.0	0.7	1.1
	4.4	1.0	0.7	1.1
	25.0	0.9	0.6	1.1
	37.8	0.8	0.5	1.1
	54.4	0.8	0.5	1.2

Figure 6-9 compares master curves developed from design and construction specimens tested using IDT dynamic modulus. The figure shows that the curves are similar at low temperature and then diverge in the intermediate- and high-temperature regions.

Figure 6-10 presents the results of the converted master curve. The conversion factors presented in Table 6-5 were applied to the intermediate- and high-temperature modulus values prior to the development of the master curve. As shown in the figure, the resulting converted construction master curve closely matches the design master curve. This conversion may be useful predicting distresses with programs such as Pavement ME Design.

6.2 Effect of Variability on Performance

Effect of construction variability on predicted performance was quantified. Results of dynamic modulus testing from LL, PL, and PF specimens were used as the material input into mechanistic-empirical (ME) design models to evaluate the effect of specimen type on the predicted performance of pavement structures for varying traffic conditions (i.e., low, medium, and high). Pavement ME Design was used as a tool

Table 6-5. IDT dynamic modulus conversion factor.

Temperature, °C	Comparison	Average Conversion	Conversion Range	
			Min	MAx
-10	Design (LL)/Production (PL)	1.0	0.8	1.1
	Design (LL)/Construction (PF)	1.0	0.9	1.3
	Production (PL)/ Construction (PF)	1.1	0.9	1.4
10	Design (LL)/Production (PL)	0.9	0.8	1.1
	Design (LL)/Construction (PF)	1.2	0.8	1.5
	Production (PL)/ Construction (PF)	1.3	0.9	1.7
25-35	Design (LL)/Production (PL)	1.0	0.6	1.4
	Design (LL)/Construction (PF)	1.4	0.9	2.1
	Production (PL)/ Construction (PF)	1.5	0.8	2.2

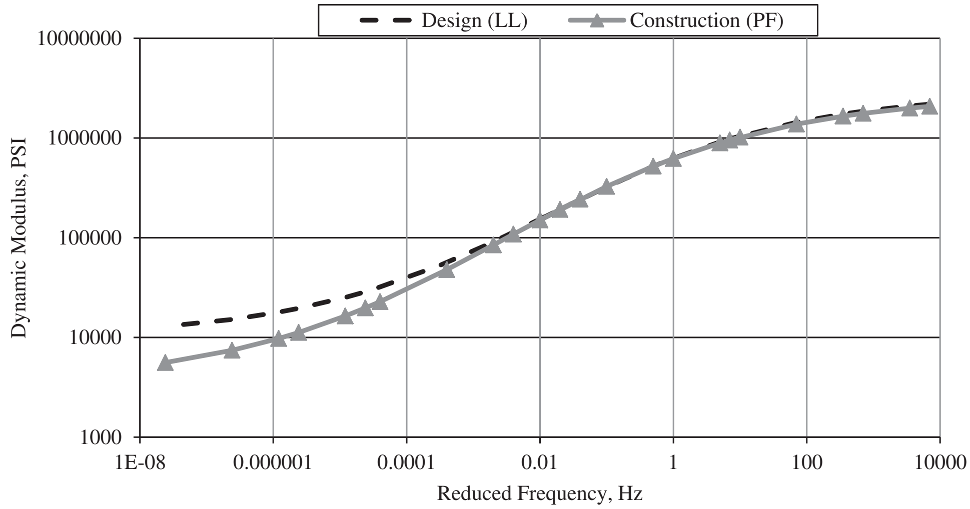


Figure 6-9. Master curve comparison.

to predict pavement performance. Previous research shows variability in the dynamic complex modulus of 10% or less resulted in a change in the predicted level of performance of 10% or less. However, variability in the dynamic modulus of 20% changed the design life of the pavement structures by up to 42%, and the design HMA thickness was affected by as much as 19% (Mohammad et al. 2012).

Figure 6-11 presents the results of the effects of specimen type on the Pavement ME Design predictions of common pavement distresses. The figure shows that performance prediction was affected by specimen type. In general, the largest difference observed was for production versus construction specimens. Design versus production comparisons resulted in the least difference. These findings further illustrate how laboratory compaction results in a particle orientation different from that of field compaction. Rutting in the asphalt layer was the most influenced distress. This was expected given the differences observed in the modulus of the specimens at high temperature. Total rutting was less affected than AC rutting due to the common influences of base and subgrade rutting. Alligator cracking showed a difference as high as 60% between production and construction specimens. The predicted IRI was the performance parameter least influenced by the change in specimen type.

Table 6-6 summarizes the percentage difference of distress predictions among specimen types. The range of percentages was developed by determining the percentage difference among the specimen types for each mixture and evaluating the minimum and maximum difference for each distress. As shown in Table 6-6, the use of design (LL) or production (PL) moduli would result in significant differences in pavement performance prediction as compared to construction (PF)

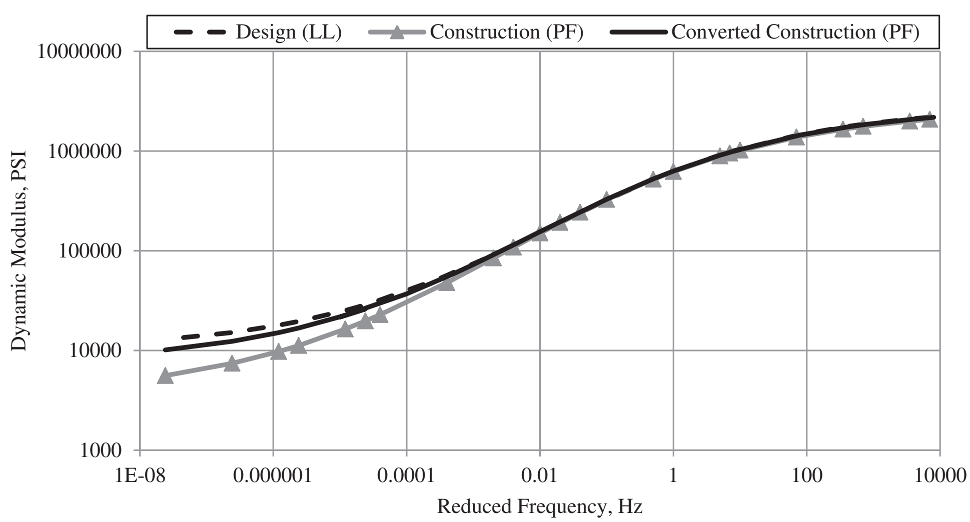


Figure 6-10. Converted master curve comparison.

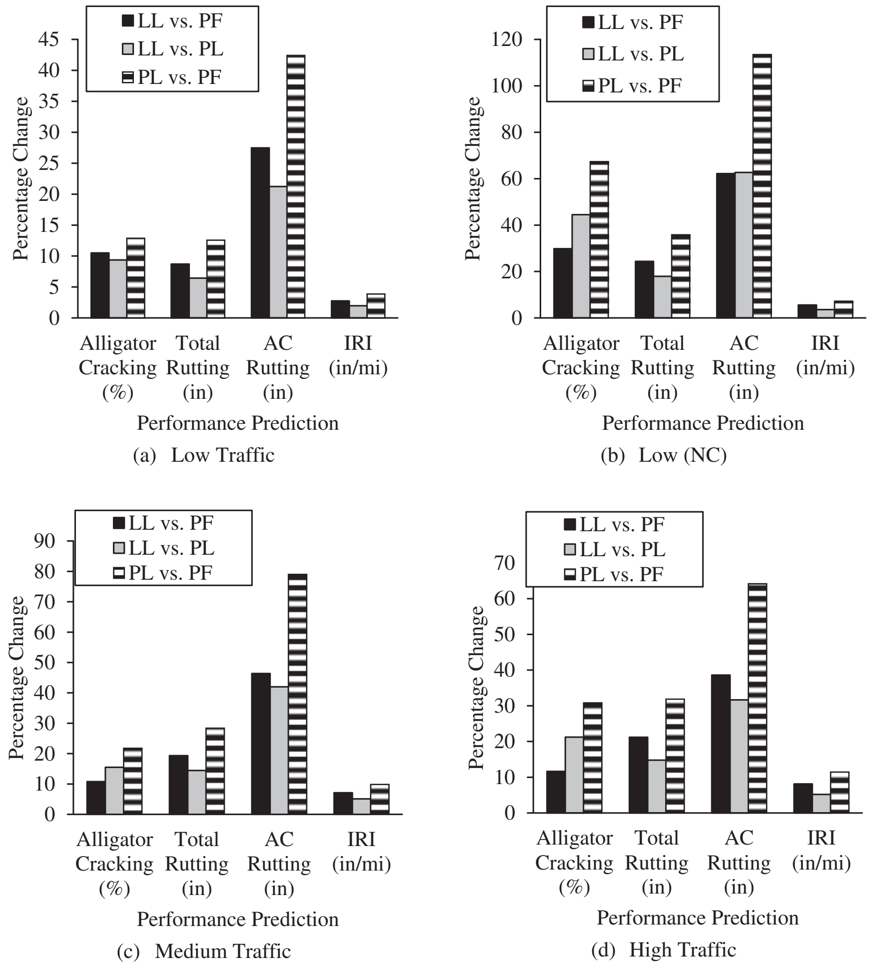


Figure 6-11. Average performance impact.

moduli. The "true" in-service prediction should be based on plant-produced field-compacted specimens (i.e., core) because they represent the final product after production and compaction. However, regular extraction of cores from the installed pavement may be challenging.

Results of this analysis indicate that pavement performance predictions obtained from dynamic moduli measured for different specimen types would not be equivalent without the use of proper conversion factors to account for differences in production and compaction between specimen types. Further evaluation of these factors is needed before using the developed conversion factors in the design process. The current Pavement ME Design prediction models were largely calibrated with the properties of plant-produced specimens from

Table 6-6. Effect of specimen types on pavement prediction.

Distress	Comparison	Range of Percent Difference
Alligator Cracking	LL vs. PL	9 - 44
	LL vs. PF	11 - 30
	PL vs. PF	13- 67
Asphalt Layer Rutting	LL vs. PL	21 - 63
	LL vs. PF	27 - 62
	PL vs. PF	42 - 114
IRI	LL vs. PL	2 - 5
	LL vs. PF	3 - 8
	PL vs. PF	4 - 11

LTPP General Pavement Study (GPS) sections, which would account for these differences.

The following findings reflect the results of the performance prediction analysis:

- Specimens prepared in the field and in the laboratory exhibited large and significant differences in performance prediction, especially between laboratory-compacted and field-compacted specimens. This finding is attributed to the differences in the compaction efforts and procedures between the field and the laboratory. Current Pavement ME Design prediction models were largely calibrated with the properties of plant-produced specimens from LTPP GPS sections, which would account for these differences.
- Results of the Pavement ME Design analysis showed that the performance predictions are affected by specimen type. Rutting in the asphalt layer was the most influenced distress. Further, alligator cracking showed a difference as high as 60% between production and construction specimens.

CHAPTER 7

Implementation Recommendations

7.1 Effect of Process-Based Factors

The following section discusses the process-based factors affecting the differences among specimen types evaluated in this research study. This experiment was designed to evaluate the effects of five specific processes (i.e., baghouse fines, reheating, aggregate absorption, aggregate degradation, and aggregate stockpile moisture). Although the results of the study showed that the effects of these processes were not significant for most parameters evaluated, Table 7-1 summarizes factors that had a significant effect on those parameters. Federal, state, and local transportation officials may be able to use these findings to determine whether these processes may affect mixtures in their respective regions.

- With respect to air voids, the producer should ensure that stockpile moisture content is accounted for. This practice minimizes the magnitude of the difference between production and design specimens.
- Regarding asphalt binder content, if the owner agency requires the return of baghouse fines during production, mixture designs should consider the return of baghouse fines during specimen preparation.
- Regarding gradation, the return of baghouse fines, aggregate hardness, and stockpile moisture all had a significant effect on the laboratory-produced and plant-produced mixtures. Therefore, design specimens should account for baghouse dust and aggregate breakdown.

Process-based factors did not have a significant effect on the VMA, VFA, G_{mm}, and G_{sb} of the mixtures evaluated in this study. Process-based factors did not have a significant effect on comparisons between production (PL) specimens and construction (PF) specimens. This is logical because these mixtures were produced through the asphalt plant and, therefore, experienced the same processes (i.e., stockpile moisture, baghouse return, and breakdown from plant mixing). Process-based factors did not have a significant effect on differences in mechanical properties among the three specimen types.

7.2 Volumetric Properties Tolerance Recommendation

Table 7-2 presents the tolerance values developed in this study. The proposed tolerances reflect the average difference among specimen comparisons for the ten mixtures. Based on these findings, specifying agencies may be able to evaluate and adjust their current tolerance values. Section 6.1.1 illustrates how these tolerances may be used to evaluate current specification tolerances. These tolerance values encompass mixtures from around the country. Therefore, development of regional or local values may be appropriate.

7.3 Conversion of Mechanical Properties Among Specimen Types

The following section details how agencies can implement the average conversion factors discussed in Section 6.1.3.

7.3.1 Loaded-Wheel Test Conversion

Table 7-3 presents proposed LWT conversion factors, which can be used to assess whether an as-built mixture will be expected to meet performance indicators developed with the laboratory design. The conversion factors indicate that the laboratory-compacted specimens typically resulted in 33% less rut depth than field-compacted specimens. Therefore, if the LWT rut depth of a PF specimen is required to be 6 mm at 20,000 passes, the laboratory-compacted mixture should have a rut depth of 4.5 mm at 20,000 passes. This relationship will be important as agencies transition toward performance-based specifications.

Table 7-1. Effects of process-based factors on volumetric properties.

Property	Comparison	Significant Process
AV	Design (LL) - Production (PL)	Stockpile Moisture
VMA		None
VFA		None
AC	Design (LL) - Production (PL)	Baghouse fine return and aggregate absorption
	Design (LL) - Construction (PF)	Baghouse fine return
	Production (PL) - Construction (PF)	None
G_{mm}	Design (LL) - Production (PL)	None
	Design (LL) - Construction (PF)	None
	Production (PL) - Construction (PF)	None
G_{sb}	Design (LL) - Production (PL)	None
	Design (LL) - Construction (PF)	None
	Production (PL) - Construction (PF)	None
Gradation	Design (LL) - Production (PL)	Baghouse fine return and aggregate hardness
	Design (LL) - Construction (PF)	Baghouse fine return, aggregate hardness, and stockpile moisture
	Production (PL) - Construction (PF)	None

7.3.2 Axial Dynamic Modulus Conversion

Table 7-4 presents the average conversion factors for axial dynamic modulus comparisons among design and production specimens. Typically, moduli of the laboratory-mixed specimens were 80% of those of the plant-mixed specimens at higher testing temperatures. Rutting models in pavement distress prediction programs (e.g., Pavement ME Design) use the dynamic modulus of the asphalt mixture to predict the rutting in the pavement. The results of the model may vary based on the specimen type used to determine the dynamic modulus. The predictive models are often calibrated with field data using modulus values determined during design or production. For this reason, agencies may find converting the modulus data to suit their calibration needs beneficial.

Figure 7-1 presents how an agency can use the conversion factors presented in this report.

Table 7-2. Volumetric tolerance recommendations.

Property	Comparison	Tolerance Recommendation
AV, %	Design (LL) - Production (PL)	± 0.8
VMA, %		+ 1.2
VFA, %		± 5.4
AC, %	Design (LL) - Production (PL)	± 0.2
	Design (LL) - Construction (PF)	
	Production (PL) - Construction (PF)	
G_{mm}	Design (LL) - Production (PL)	± 0.020
	Design (LL) - Construction (PF)	± 0.013
	Production (PL) - Construction (PF)	± 0.018
G_{sb}	Design (LL) - Production (PL)	± 0.014
	Design (LL) - Construction (PF)	± 0.019
	Production (PL) - Construction (PF)	± 0.017
Aggregate Passing 0.075 mm, %	Design (LL) - Production (PL)	± 0.5
	Design (LL) - Construction (PF)	± 0.7
	Production (PL) - Construction (PF)	± 0.5

Table 7-3. LWT conversion recommendations.

Comparison	Conversion Factor
Design (LL) / Production (PL)	1.0
Design (LL) / Construction (PF)	0.75
Production (PL) / Construction (PF)	0.75

Table 7-4. Axial dynamic modulus conversion recommendations.

Comparison	Temperature, °C	Conversion Factor
Design (LL)/ Production (PL)	-10.0	1.0
	4.4	1.0
	25.0	0.9
	37.8	0.8
	54.4	0.8

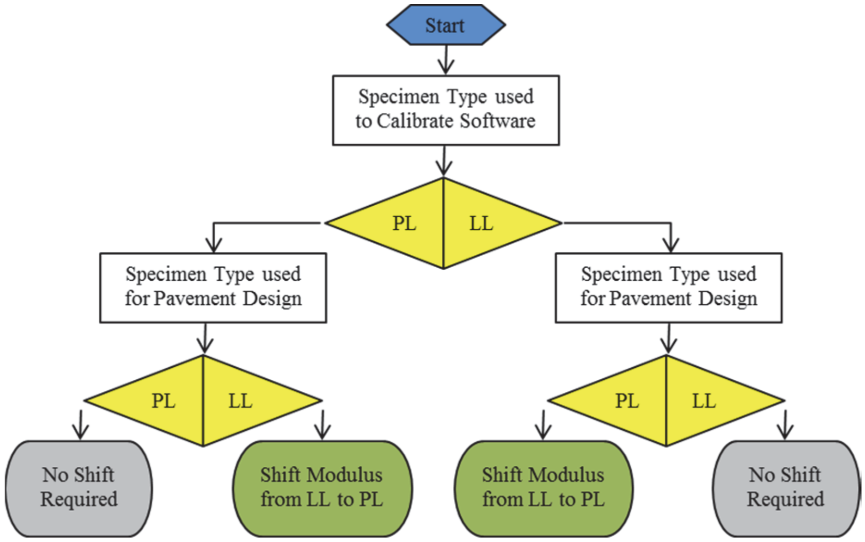


Figure 7-1. Dynamic modulus conversion decision tree.

7.3.3 IDT Dynamic Modulus Conversion

Table 7-5 presents the average conversion factors for IDT dynamic modulus determined for the three specimen types evaluated in this study. The conversion factor for design and production specimens is 1.0. Therefore, no conversion was required between design and production specimens. However, the conversions between laboratory-compacted and field-compacted specimens were more pronounced. This was especially noted for intermediate- and high-temperature conversions. A designer can use these conversion factors to estimate the dynamic modulus of the field core from mixture collected during production or mixture produced in the laboratory.

Table 7-5. IDT dynamic modulus conversion recommendations.

Temperature, °C	Comparison	Conversion
-10	Design (LL)/Production (PL)	1.0
	Design (LL)/Construction (PF)	1.0
	Production (PL)/Construction (PF)	1.1
10	Design (LL)/Production (PL)	0.9
	Design (LL)/Construction (PF)	1.2
	Production (PL)/Construction (PF)	1.3
25-35	Design (LL)/Production (PL)	1.0
	Design (LL)/Construction (PF)	1.4
	Production (PL)/Construction (PF)	1.5

7.3.4 Correlation Between Axial and IDT Dynamic Modulus

Table 7-6 compares proposed conversion factors obtained for axial and IDT dynamic modulus. The conversion factors were determined based on the average percent difference of the mixtures evaluated. An outlier analysis was performed before the correlation factors were determined. This resulted in discarding the percent difference data from Mix 10, because it was not within a 95% confidence band with respect to the population. The data show that the conversion factor for intermediate- and low-temperature values should be nearly 0.80. This means that the modulus determined from IDT was generally 80% of the modulus determined from axial testing. The difference between axial and IDT determined at high temperature was much more variable, probably because of the increased influence of the loading mode at high temperature; some mixtures exhibited both higher and lower values of modulus when comparing IDT dynamic modulus with axial dynamic modulus.

Table 7-6. IDT vs. axial dynamic modulus correlation.

IDT vs. Axial	Correlation Factor
Low-Temperature Comparison, -10°C	0.81
Intermediate-Temperature Comparison, 10°C	0.75
High-Temperature Comparison, 25 - 35°C	0.90

CHAPTER 8

Summary and Conclusions

This research was intended to quantify the magnitude and cause of the differences of commonly measured parameters of asphalt mixtures among specimen types. This was accomplished by evaluating the volumetric and mechanical properties of three specimen types [design (LL), production (PL), and construction (PF)] from 10 mixtures from various states throughout the country. Variations in the production process were identified and varied throughout the mixtures. Specifically, variations in the return of baghouse fines, delay in specimen fabrication, aggregate absorption, aggregate hardness, and stockpile moisture content were evaluated for their effects on volumetric properties (AV, VMA, VFA, bulk specific gravity of the aggregate blend, mixture maximum specific gravity, AC, and gradation) and mechanical properties (LWT rut depth, axial dynamic modulus, and IDT dynamic modulus) of the three specimen types.

Measured differences in volumetric and mechanical properties were used to develop proposed tolerance values and conversion factors among properties for the three specimen types. In addition, the effects of specimen types on predicted pavement performance were evaluated. Conclusions of this study are discussed in the following sections.

8.1 Effect of Process-Based Factors

The research results showed that the effects of the process-based factors were not as pronounced as originally hypothesized and are only significant between laboratory-mixed specimens (design) and plant-produced specimens (production and construction). The latter finding was expected, because both the production and construction specimens were prepared from plant-produced mixtures, which were subjected to the same process conditions (i.e., plant mixing, baghouse return, and stockpile moisture). Finally, a contractor survey showed that contractors are actively making adjustments based on their experience with the processes in their region.

Findings indicated that there were no significant effects of process-based factors on the differences among specimen types for VMA, VFA, G_{mm}, and G_{sb} of the mixtures evaluated in this study. Additionally, the process-based factors did not have a significant effect on the differences of mechanical properties among the three specimen types. The lack of the observed effects of process-based factors may result from the variations in the mechanical properties being strongly controlled by compaction effort. Many of the individual mixture comparisons showed that field-compacted specimens (PF) were significantly different from laboratory-compacted specimens (LL and PL). This finding was attributed to differences in compaction effort and confinement conditions between the two compaction processes (laboratory and field).

Process-based factors were found to influence the differences among the three specimen types in the following instances:

- Stockpile moisture had a significant effect on the difference in air voids between design and production specimens. This may be attributed to aggregates not having sufficient time to dry during production or to improper quantification of stockpile moisture content.
- Return of the baghouse fine dust had a significant effect on observed differences in asphalt binder content among design, production, and construction specimens. This finding may warrant the use of baghouse fines during the design of mixtures in regions where return of baghouse fines is required. Additionally, aggregate absorption had a significant influence on the difference in asphalt content measured between design and production specimens.
- Return of the baghouse fine dust was a significant influence in the measured difference between the aggregate passing the #200 sieve among the design, production, and construction specimens. This finding may warrant the use of baghouse fines during the design of mixtures in regions where return of baghouse fines is required. In addition, aggregate hardness had a significant effect on the differences in the aggregate passing the #200 sieve among the design, production, and construction specimens.

8.2 Proposed Tolerances

Proposed tolerances were developed based on the average difference between specimen comparisons for the 10 mixtures evaluated. Specifying agencies may use these proposed values to evaluate and adjust their current tolerances, as discussed in Chapters 6 and 7. Because these proposed values are based on mixtures from around the United States, agencies may want to use similar procedures to develop regional values.

8.3 Mechanical Conversion Among Specimen Types

Conversion factors were developed to enable estimation of the volumetric and mechanical properties of a particular specimen type without having to collect additional specimens. In particular, a conversion factor will allow the designer to estimate the mechanical value of the as-built material (i.e., field core) during the laboratory design of the mixture. This may be particularly useful with the implementation of performance-related specifications. Conversions for LWT, axial dynamic modulus, and IDT dynamic modulus are provided.

8.4 Effect of Specimen Type on Pavement Performance Prediction

Results indicate that pavement performance predictions obtained from dynamic moduli measured for different specimen types would not be equal without the use of proper correlation factors to account for differences in production and compaction among specimen types.

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Abbreviations and Acronyms

AAD	Absolute average difference
AADT	Average annual daily traffic
AC	Asphalt binder content
ADTT	Average daily truck traffic
ALF	Accelerated loading facility
ANCOVA	An analysis of covariance
ANOVA	An analysis of variance
APA	Asphalt pavement analyzer
AV	Air voids
BC	Back calculation method
COV	Coefficient of variation
E*	Dynamic modulus
FrT	Freeze thaw
Gmb	Mixture bulk specific gravity
Gmm	Mixture maximum specific gravity
GPS	General Pavement Study
Gsb	Aggregate bulk specific gravity
HMA	Hot mix asphalt
HVS	Heavy vehicle simulators
IDT	Indirect tensile test
IO	Ignition oven
IRI	International roughness index
ITS	Indirect tensile strength
JMF	Job mix formula
LL	Laboratory-mixed, laboratory-compacted
LTPP	Long-Term Pavement Performance
LTRC	Louisiana Transportation Research Center
LWT	Loaded-wheel test
MCT	Multiple Comparison Test
MDL	Maximum density line
ME	Mechanistic-empirical
Mr	Resilient Modulus
MSE	Mean standard error
MSTR	Mean square treatment
MTV	Material transfer vehicle
NC	Nuclear method
NMAS	Nominal maximum aggregate size

NSAD	Normalized sum of absolute differences
PF	Plant-mixed and field-compacted
PG	Performance grade
PL	Plant-mixed and laboratory-compacted
PLR	Plant-mixed—laboratory-compacted with reheating
PMS	Pavement Management System
PMW	Precision Machine & Welding (Company)
PQI	Pavement Quality Indicator
PRS	Performance-related specifications
PT	Printed ticket method
QA	Quality assurance
QC	Quality control
QV	Quality verification
RAP	Recycled asphalt pavement
RLT	Repeated load test
SAD	Sum of absolute differences
SAS	Statistical analysis software
SE	Solvent extraction
SGC	Superpave gyratory compactor
SIP	Stripping inflection point
SSD	Saturated surface dry
SST	Simple shear test
St Dev	Standard deviation
TSR	Tensile strength ratio
UNR	University of Nevada, Reno
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregate
VS	Vacuum Sealing

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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