Louisiana Transportation Research Center

Final Report 410

Performance Evaluation of Louisiana Superpave Mixtures

by

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TECHNICAL REPORT STANDARD PAGE

1. Report No. FHWA/LA.06/410

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Performance Evaluation of Louisiana Superpave Mixtures

5. Report Date
December 2008

6. Performing Organization Code

7. Author(s)
Louay N. Mohammad, Ph.D.
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8. Performing Organization Report No.
410

9. Performing Organization Name and Address
Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

10. Work Unit No.
736-99-0537

11. Contract or Grant No.
98-1B

12. Sponsoring Agency Name and Address
Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

13. Type of Report and Period Covered
Final Report; March 1998-December 2002

14. Sponsoring Agency Code

15. Supplementary Notes
Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

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The test results showed that high volume mixtures appeared to have higher IT strengths, lower IT and axial creep slopes, and higher shear stiffnesses when compared to those of low volume mixtures. This indicates that high volume mixtures generally possessed better rut resistance than the low volume mixtures considered. The compaction efforts (the N-design levels), dust/AC ratio, film thickness, and the percent of aggregate passing the 0.075 mm sieve were observed to have certain relations with the rut susceptibility of Superpave mixtures. The Power-law gradation analysis indicated that all four Power-law gradation parameters (aCA, nCA, aFA, and nFA) were sensitive to the mixture mechanistic properties evaluated. This implies that the proposed Power-law gradation analysis could be used as the bridge between aggregate gradation design and mixture performance evaluation. Finally, the early field performance of those Superpave mixtures was studied and compared to their laboratory performance test results.

17. Key Words
Superpave mix design, asphalt, mixtures, performance, rutting susceptibility, SST, MTS, APA, gradation

18. Distribution Statement
Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
166

22. Price
N/A

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LTRC Project No. 98-1B
SP 736-99-0537
LTRC Report No. 410

conducted for

Louisiana Transportation Research Center

December 2008

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ACKNOWLEDGEMENTS

This research project was funded by the Louisiana Transportation Research Center (LTRC) and the Louisiana Department of Transportation and Development (LADOTD) under LTRC project no. 98-1B. The authors would like to thank Oscar Porras Ortiz, Keith Beard, and all others who provided valuable help in this study.

IMPLEMENTATION STATEMENT

This study was conducted to assist LADOTD in developing performance data for Superpave mixtures. The results of this study demonstrated that the rutting susceptibility of Superpave mixtures can be reasonably predicted from laboratory fundamental engineering tests, especially the Superpave Shear Tester (SST) tests and the APA rutting simulative test. This study provides a general guideline for asphalt pavement engineers and researchers on how to evaluate the performance of Superpave mixtures and which fundamental mixture properties can be determined from laboratory tests. Specifically, the following recommendations are made for direct implementation in Superpave mix design:

- For QA/QC in plant production of Superpave mixtures, the indirect tensile strength test at 25^{o} C is recommended. The indirect tensile strength value for a Superpave mixture with seven percent air voids shall be at least 150 psi (1.03 MPa).

- For durability/strength proof checking in laboratory Superpave mix design, the Asphalt Pavement Analyzer (APA) test, at 60^{o}C, is recommended. The average rut depths of three beams or six cylindrical SGC samples shall be less than 6.1, 4.2, and 3.5 mm, respectively for Level-I ($N_{design} = 75$), Level-II ($N_{design} = 100$), and Level-III ($N_{design} = 125$) Superpave mixtures.

- For permanent deformation properties of Superpave mixtures, the indirect tensile creep, frequency sweep at constant height, and repetitive shear at constant height tests are also recommended.

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INTRODUCTION

Background

Asphalt concrete mixtures have been used on pavements for more than a century. Asphalt mixtures combine bituminous binder and aggregate to produce a pavement structure that is flexible over a wide range of climatic conditions. Since the discovery of the petroleum asphalt refining process and the growth of the interstate system, asphalt mixtures have seen widespread use in pavement applications in the United States (i.e., asphalt binder usage increased from less than 3 million tons in 1920 to more than 30 million tons in 2000 [1]). Currently, more than 93 percent of all the road surfaces in the U.S. are paved with asphalt mixtures.

The design of asphalt mixtures evolved with its increased use. In the early 1900s, engineers designed asphalt mixtures based totally on their personal experiences. Three major asphalt mixture design methods were developed in the United States in the first half of the twentieth century: the Hubbard-Field method, the Marshall mix design method, and the Hveem mix design method [1]. The Hubbard-Field method was originally developed in the 1920s for sheet asphalt mixtures with 100 percent passing the 4.75 mm sieve and later modified to cover the design of coarser asphalt mixtures. The Hubbard-Field Stability test is a laboratory test that measures the strength of the asphalt mixture with a punching-type shear load. The Hveem mix design method was developed by the California Department of Highways materials and design engineer in the 1930s. The Hveem stabilometer measures an asphalt mixture's ability to resist lateral movement under a vertical load. The Hveem mix design is still used in California and other western states. The Marshall mix design was originally developed by a Mississippi State Highway Department engineer and refined in the 1940s by the Corps of Engineers for designing asphalt mixtures for airfield pavements. The primary features of the Marshall mix design are a density/voids analysis and the stability test. The optimum asphalt content is determined by the ability of a mix to satisfy stability, flow, and volumetric properties. According to a survey done in 1984, approximately 75 percent of the state highway departments used some variation of the Marshall method, while the remaining 25 percent used some variation of the Hveem method [2].

The Marshall and Hveem mix design methods have played important roles in the traditional asphalt mix design; however, both of them are based on empirical relationships and do not produce fundamental engineering properties of the compacted asphalt mixture that are related to pavement design and performance. Establishing uniform specifications for different areas is also difficult. Despite the best efforts put into those existing mix design methods, severe rutting and cracking are common in asphalt pavements, due to abruptly increased traffic loads in terms of increased vehicle-miles, higher tire pressure, and varying environmental conditions (from very cold to hot regions). Against this background of declining performance and durability in pavements (including both asphalt and Portland concrete), the Strategic Highway Research Program (SHRP) was approved by Congress in 1987 to improve the performance and durability of United States roads and make those roads safer for both motorists and highway workers [1].

Superpave Mix Design – Research and Implementation

SHRP was established by Congress in 1987 as a five year, $150 million research program to improve the performance and durability of highways in the United States. One third of the $150 million research fund of SHRP was spent on asphalt cement and concrete research to develop a system that would relate the material characteristics of hot mix asphalt to pavement performance. The final product was a new system called Superpave, short for Superior Performing Asphalt Pavements. Superpave represents an improved system for specifying asphalt binders and mineral aggregates, developing asphalt mixture design, and analyzing and establishing pavement performance prediction. It incorporates performance-based asphalt material characterization according to the design environmental conditions to improve performance by controlling rutting, low temperature cracking, and fatigue cracking. The Superpave mix design method can be divided into two stages: Superpave mix design (Level 1) and Superpave abbreviated and complete mix analysis (Levels 2 and 3). Superpave Level 1 mix design is an improved material selection and volumetric mix design process. Level 2 mix design procedures use the volumetric mix design as a starting point and include a battery of performance tests to arrive at a series of performance predictions. Level 3 mix design includes a more comprehensive array of tests and results to achieve a more reliable level of performance prediction [1]. Currently, only Level 1 (renamed as volumetric) mix design is a mature procedure.

In the first stage of Superpave mix design (Level 1), asphalt mixes are designed by a method similar to the traditional volumetric proportioning but with a different type of compaction device— the Superpave Gyratory Compactor (SGC). The mixtures are ultimately evaluated in terms of a desired level of performance. In the second stage of Superpave (Levels 2 and 3) abbreviated and complete mix analysis, different material tests are performed with the Superpave Shear Tester (SST) and the Indirect Tensile Tester (IDT). Fundamental engineering properties are obtained through these tests. The material parameters are applied to sophisticated Superpave performance prediction models. These models consider not only the materials characteristics but also the pavement structure and seasonal environmental changes. Performance testing utilizes new equipment and procedures to ensure that Superpave mixtures exhibit acceptable amounts of the distress types that were considered by

SHRP researchers: permanent deformation, fatigue cracking, and low temperature cracking [3]. However, this second stage of Superpave abbreviated and complete mix analysis has not been fully implemented and is currently under evaluation. The Federal Highway Administration (FHWA) made a significant decision related to this Superpave process element. Basically, more research is necessary to perfect this prediction process. Substantial corrections and enhancements are considered mandatory to make the performance prediction models and analysis software reliable and suitable for general use by the industry [4].

Highway agencies across the country are gaining experience as the Superpave system continues to progress from research to implementation. A multitude of new developments helps to continuously refine the system, providing guidance in construction practices and encouraging continued implementation. By 2002, the Performance Graded binder specifications had been fully implemented in 47 states and the District of Columbia. At least 30 states have adopted the consensus aggregate properties outlined in the Superpave system. At least 33 states have implemented Superpave mix design. And 13 states report implementation is on the way. Only four states (California, Idaho, Nevada, and Rhode Island) do not currently have firm implementation plans [5].

Implementation activities for the Superpave binder specification and mix design are likely to continue for the next several years. The Superpave mix analysis, however, has not been implemented and is currently under evaluation because further research is needed in the performance prediction models. While the Superpave software is available, some research has been done and is currently underway seeking to correlate test parameters and performance.

A major investigation that involved Superpave mixes was ALF/WesTrack Accelerated Performance Testing. WesTrack is the FHWA's test facility in Nevada for developing performance related specifications for hot-mix asphalt pavement construction. When coarse-graded Superpave sections placed at the track in June of 1997 had very rapid rutting failures, a forensic team composed of academicians, asphalt industry representatives, and state highway agency engineers was assembled to study the early failures and, if appropriate, make recommendations for revising the Superpave procedures [6]. Roadway samples were taken from 11 sections (out of the original 26 sections placed) to evaluate the properties of the in-place mixtures and compare these data to initial production test results. Another set of cores was examined on four rut testers (French, Hamburg, Asphalt Pavement Analyzer, and PurWheel) and the Superpave Shear Tester to determine if test results from these devices correlated well with actual track performance. All of the mixes were 19 mm nominal maximum aggregate size. Nine sections were coarse-graded Superpave mixes containing an unmodified performance grade PG 64-22 binder. The other two sections were Nevada DOT mixes that contained a very different aggregate gradation and an AC-20P SBS modified binder. The Nevada mixes were designed using Hveem mixture design criteria.

Among the forensic team's conclusions was that the principal cause of rutting at WesTrack was a relatively high design binder content, which resulted from high VMA values in conjunction with relatively low mastic stiffness. Of the 11 mixes evaluated, the mixture with the least rutting had a low binder content, high dust to binder ratio, and relatively low VMA. The Nevada DOT mixtures, which had low binder contents and low design VMA, performed better than the replacement coarse-graded mixtures. The forensic team also found that resistance of the coarse-graded Superpave mixes to rutting was significantly affected by in-place density. Therefore, they recommended, among other things, that for coarse-graded mixes (below the restricted zone), the dust to binder ratio should be set at 0.8 to 1.6, in contrast to the current setting at 0.6 to 1.2 in AASHTO provisional specification MP2-97. For coarse-graded Superpave mixtures, the VMA should be restricted to two percent above the minimum value. AASHTO MP2-97 currently sets minimum VMA requirements for mixes but does not set maximums.

Mogawer and Stuart performed a study by using the Federal Highway Administration's Accelerated Loading Facility (ALF) to validate the Superpave binder parameter for rutting and several mixture tests that have been developed to predict rutting susceptibility [7]. Five binders with Superpave Performance Grades of 58-34, 58-28, 64-22, 76-22, and 82-22 were used. All five binders were used with a gradation having a nominal maximum aggregate size of 19.0 mm. In addition to the ALF, the French Pavement Rutting Tester, Georgia Loaded-Wheel Tester, Hamburg Wheel-Tracking Device, and the cumulative permanent strains from a repeated load test were used in the investigation. Results from all tests ranked the five surface mixtures similarly based on the average data. Rankings based on statistics were different, and no laboratory mixture test was clearly the best test based on ALF. In this study, binders with higher rutting factors, as measured by G*/sin delta, generally provided mixtures with lower rutting susceptibilities for a given nominal maximum aggregate size. They also observed that the increase in nominal maximum aggregate size significantly decreased rutting susceptibility based on ALF. None of the laboratory mixture tests they utilized adequately predicted this effect.

An article by Kuennen reports that, after the first years of in-field experience with Superpave pavements, Superpave mixes in certain regions of the country are performing well, even though they include aggregate fines that fall within the restricted zone. However, there have been cases where compacting Superpave pavements lifts can be more complicated than conventional pavements [8].

In an investigation aimed to evaluate and compare three methods for classifying aggregate particle shape and texture —AASHTO TP33 (ASTM C1252), ASTM D3398 (Index of Particle Shape and Texture), and the flow rate method— Khosla et al. found that, within the range of mineral filler content and type used in their study (four natural river sands and a crushed granite), increasing the amount of mineral filler had a beneficial effect on the rutting performance. They recognized that, although the rutting performance is enhanced, it should be noted that the asphalt content is reduced at a higher mineral filler content, which may have a detrimental effect on other mixture properties such as fatigue, thermal cracking, and ravelling [9].

Lancaster and Shatnawi conducted a field and laboratory evaluation of the volumetric (Level I) Superpave mix design procedure. The evaluation consisted of constructing field test sections in January 1996 and conducting various laboratory performance tests. The performance testing included repetitive simple shear tests at a constant height, frequency sweep tests at a constant height, repetitive direct tension, and Laboratoire Central des Ponts et Chausses wheel tracking testing [10]. Lancaster and Shatnawi concluded that all mixes placed on their project would be anticipated to perform adequately. Field performance has supported the laboratory findings.

At present, Superpave mixture design is still based solely on volumetric design specifications. One of the major control parameters in the Superpave volumetric design is the percentage of voids in the mineral aggregate (VMA). Several researchers and highway agencies have reported that difficulties exist in meeting the minimum VMA requirements [11-13]. Recent studies [13, 14] showed that the VMA requirement based on nominal maximum aggregate size does not take into account the gradation of the mixture, ignores the film thickness of the asphalt binder, and is thus insufficient to correctly differentiate good performing mixtures from poor performing ones. Meanwhile, higher VMA mixtures cannot guarantee to provide better Superpave mixtures that are durable and more fatigue and rut resistant than the lower ones [15]. Further, Kandhal et al. [11] suggested a minimum average asphalt film thickness be used instead of minimum VMA to ensure mix durability.

The importance of aggregate characteristics has been emphasized in the Superpave mixture design procedure. Certain gradation limits, including the restricted zone, for different nominal maximum size aggregates have been put into Superpave gradation guidelines. The restricted zone was meant to be a guide for establishing the gradation of a mixture, but many states have found that the restricted zone has rejected many mixes that had been used successfully in the past [16]. Based on the recommendations from the NCHRP Project 9-14, "Investigation of the Restricted Zone in the Superpave Aggregate Gradation Specification," the restricted zone has been eliminated entirely from the Superpave mixture design system by the Superpave Expert Task Group (ETG).

Most states currently accept both coarse-graded (gradation below the restricted zone) and fine-graded (gradation above the restricted zone) Superpave mixtures [17-19]. A rutting susceptibility study [19] indicated that no significant differences in rut potential occurred between two coarse-graded and fine-graded asphalt mixtures. In his study, Anderson [10] showed that (1) at 13 percent VMA, the coarse mixture has higher shear stiffness, higher critical temperature, and lower estimated rut depth than the fine mixture. At 15 percent VMA, the coarse mixture still has a lower estimated rut depth than the fine mixture but has a substantially lower shear stiffness and critical temperature; (2) in repeated shear tests, the coarse mixture indicated no significant difference in rutting characteristics between 13 percent and 15 percent VMA. However, there is significant difference between the rutting characteristics of a fine mixture with 13 percent VMA and a fine mixture with 15 percent VMA; (3) in shear frequency sweep test, the stiffness and critical temperature of the coarse mixture decreased substantially as the VMA increased. The coarse mixture appeared much more sensitive to VMA than did the fine mixture. As reported by Nukunya et al. [20], VMA did not appear to be related to age-hardening rate (durability), fracture resistance, or rutting resistance for coarse-graded mixtures. Factors such as gradation void structure, and perhaps film thickness, appeared to have a stronger effect on these characteristics. Therefore, the need for definitive guidelines for the selection of suitable aggregate gradation, either coarse-graded or fine-graded, becomes apparent, especially when premature pavement failures such as early rutting occur shortly after construction [21].

Superpave is a totally new system, which requires new equipment and test procedures. Little experience has been accumulated in Louisiana. In an effort to implement the Superpave system in Louisiana, the Louisiana Department of Transportation and Development's (LADOTD) Asphalt Concrete Hot Mix Specification Committee established seven subcommittees to develop an implementation plan. The first phase of the implementation plan included nine field projects throughout the state, which were designed and constructed between August 1997 and December 1998 utilizing the Superpave specification. In the advent of the modified Superpave specification (modified gyration design table [Ndesign]), another twelve projects were chosen and constructed between 1999 and 2000 as the second phase of Superpave implementation in Louisiana. The goal of this project is to provide a clearer understanding of the fundamental engineering properties of those Superpave mixtures implemented through a suite of comprehensive material tests. This report documents those fundamental engineering properties in detail and analyzes the performance of Superpave mixtures based on volumetric and engineering properties. This data will aid in the overall knowledge of the critical performance components of HMA mixtures. The knowledge and experience obtained from this project will facilitate the future complete implementation of the Superpave mixture design method in the state of Louisiana.

OBJECTIVES

The primary objective of this research was to evaluate the fundamental engineering properties and mixture performance of Superpave HMA mixtures in Louisiana through laboratory mechanistic tests, aggregate gradation analysis, and field performance. A secondary objective of this investigation was to ascertain mix design variables on mixture performance. The following were the specific objectives of the proposed study:

- Conduct Superpave Shear Tester (SST) tests on the selected asphalt mixtures to evaluate rutting performance in terms of mixture resistance to shear flow (complex shear modulus/phase angle, permanent shear strain, etc.).

- Conduct Indirect Tension (IT) tests to characterize the fundamental engineering properties of the selected asphalt mixtures in terms of tensile strength, resilient modulus, and axial and indirect tensile creep compliance.

- Conduct simulative rut tests using the Asphalt Pavement Analyzer (APA), and compare the results to other fundamental engineering tests.

- Study aggregate gradation curves on the selected asphalt mixtures, and correlate the characteristics of gradation curves of the selected asphalt mixtures to their fundamental engineering properties.

- Correlate volumetric variables (e.g., air void, VMA, and VFA) of the selected asphalt mixtures to their fundamental engineering properties.

- Compare early field performance to laboratory engineering test results.

SCOPE

This project included 30 Superpave mixtures selected from 21 field implementation projects in Louisiana. Fourteen of these projects were designed for high volume traffic (greater than 30 million ESALs), 12 for intermediate volume traffic (3 to 30 million ESALs), and the rest for low volume traffic (less than 3 million ESALs). Seven fundamental engineering tests were performed on those mixtures in order to obtain their fundamental engineering properties; those tests included four MTS tests: axial creep, indirect tensile creep, indirect tensile strength and strain, and resilient modulus, and three Superpave Shear Tester (SST) tests: frequency sweep at constant height (FSCH), simple shear at constant height (SSCH), and repeated shear at constant height (RSCH). In addition, a rut simulative test, the Asphalt Pavement Analyzer (APA) wheel load test, was also employed to directly evaluate the rut susceptibility of those Superpave mixtures.

METHODOLOGY

Projects Identification

Figure 1 presents the locations of 21 Superpave implementation projects considered for this study; a total of 30 Superpave mixtures, from either wearing course or binder course, were selected. Table 1 presents the general information about these projects as well as the corresponding mixture designations. According to different design and implementation time histories, these projects can be further categorized into two groups: Phase I—eight projects constructed between 1997 and 1998, and Phase II—thirteen projects constructed between 1999 and 2001.

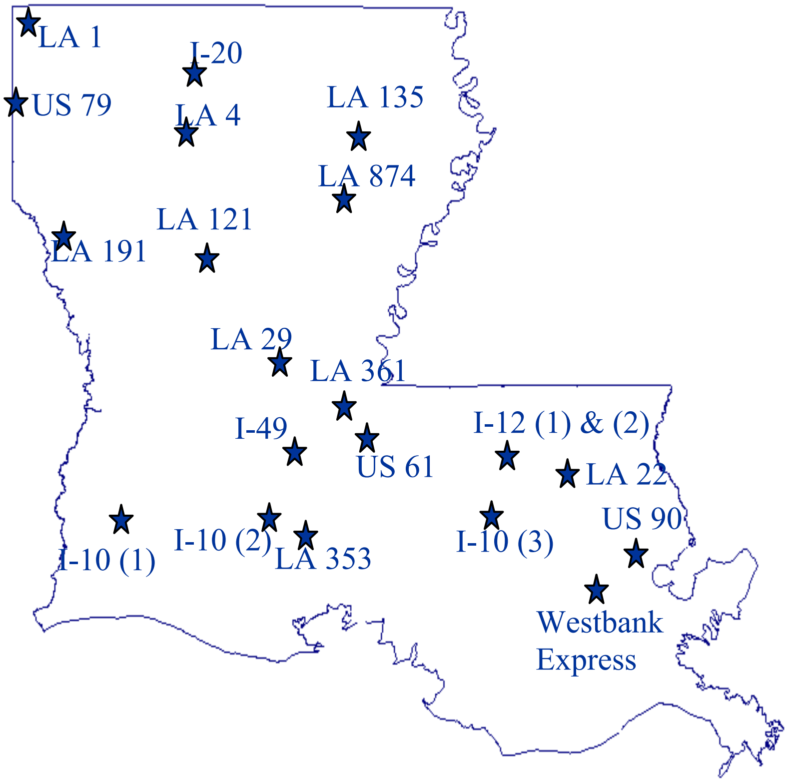


Figure 1
Project locations

Table 1
Project information and mixture designation

Projects		NMAS (mm)	Mix Type (course)	Binder Type	Gradation	Compaction Effort (Ndesign)	Mix Designation
Phase I	LA 22	19	Binder	AC-30	Coarse	96	1BI22
		19	Wearing	PAC-30	Coarse	96	1WI22
	LA 121	19	Binder	AC-30	Coarse	96	1BI121
		19	Wearing	PAC-30	Coarse	96	1WI121
	LA 353	19	Binder & Wearing	PAC-40	Fine	96	1BWI353
	US 61-1	19	Wearing	PAC-40	Coarse	109	1WII61
	US-61-2	25	Binder	PAC-40	Coarse	109	2BII61
	Westbank Express	19	Wearing	PAC-40	Coarse	126	1WIIIwe
		25	Binder	PAC-40	Coarse	126	2BIIIwe
	LA 4	25	Binder	AC-30	Coarse	96	2BI4
	US 90	25	Binder	PAC-40	Coarse	109	2BII90
	I 20	25	Binder	PAC-40	Fine	126	2BIII20
Phase II	LA 361	19	Wearing	PG70-22M	Fine	75	I-1
	LA 191	19	Wearing	PG70-22M	Fine	75	I-2
	LA 874	19	Wearing	PG70-22M	Coarse	75	I-3
	LA 135	19	Wearing	PG70-22M	Coarse	75	I-4
	LA 1	19	Wearing	PG76-22M	Coarse	100	II-1
	US 79	19	Wearing	PG76-22M	Coarse	100	II-2
	LA 29	19	Wearing	PG76-22M	Coarse	100	II-3
	I 10 (1) Calcasieu	19	Wearing	PG76-22M	Coarse	125	III-1
		25	Binder	PG76-22M	Coarse	125	III-25-1
	I-10 (2) Acadian	19	Wearing	PG76-22M	Coarse	125	III-2
		25	Binder	PG76-22M	Coarse	125	III-25-2
	I-12 (1) Livingston	19	Wearing	PG76-22M	Coarse	125	III-3
	I-10 (3) Ascension	19	Wearing	PG76-22M	Coarse	125	III-4
		25	Binder	PG76-22M	Coarse	125	III-25-3
		25	Binder	PG76-22M	Coarse	125	III-25-4
	I 49	19	Wearing	PG76-22M	Coarse	125	III-5
		19	Binder	PG76-22M	Coarse	125	III-6
	I 12 (2) Denham springs	19	Wearing	PG76-22M	Coarse	125	III-7

Phase I Projects

Phase I includes 12 Superpave mixtures. As shown in Table 1, the nominal maximum aggregate size (NMAS) of those mixtures was either 19 or 25 mm. Three types of asphalt binders, one conventional viscosity graded AC-30, and two polymer-modified asphalt binders meeting LADOTD specifications for PAC-30 and PAC-40 were used in those mixtures. The Superpave mix design was followed by the AASHTO PP-28 (1994) "Standard Practice for Designing Superpave HMA." It is important to note that Phase I Superpave mixtures in this study were designed according to the original Superpave gyratory compaction table in the Superpave mix design system. It included three design traffic levels: low, medium, and high volumes. The $N_{initial}$, $N_{design,}$ and N_{max} were 7, 96, and 152 gyrations; 8, 109, and 174 gyrations; and 9, 126, and 204 gyrations for the low, medium, and high volume mixtures, respectively.

Phase II Projects

Phase II consists of 18 Superpave mixtures selected from 12 field implementation projects. Similar to those in Phase I, two types of NMAS mixtures were selected in Phase II. The 19-mm mixture is designed for wearing course, and the 25-mm mixture for binder course. The Superpave mixture design still followed the AASHTO PP-28 but used the updated Superpave design gyration table [22]. It included three design traffic levels: low (less than 3 million ESALs), intermediate (3-30 million ESALs), and high volume (greater than 30 million ESALs). The $N_{initial}$, $N_{design,}$ and N_{max} for the three traffic level mixtures were 7, 75, and 115 gyrations; 8, 100, and 160 gyrations; and 9, 125, and 205 gyrations, respectively. Two elastometric polymer-modified asphalt binders meeting the Louisiana PG Specifications [13] of 70-22M and 76-22M were used. The PG 70-22M binder was used for low volume mixtures, whereas, PG 76-22M was specified for intermediate volume and high volume mixtures.

Asphalt Mixtures

Superpave mixtures evaluated in this study were plant produced mixtures. Contractors, upon the approval of the LADOTD, designed and supplied the plant mixed mixtures for use in this study. As stated earlier, all Superpave mixtures were designed according to the AASHTO PP-28 specification.

Job Mix Formula

Tables 2 and 3 present the job mix formulas (JMFs) for the 12 Phase I and 18 Phase II Superpave mixtures, respectively. As shown in Tables 2 and 3, most of those mixtures used one of four aggregate types: granite, novaculite, limestone, or sandstone. Those mixtures were further categorized into three levels according to the design gyration number of each mixture. The new Level I mixtures included the four low volume (N_{design} = 75) mixtures from the Phase-II project. The new Level II mixtures combined the three intermediate volume (N_{design} = 100) mixtures from Phase II and eight Phase I mixtures with a design gyration number of either 96 or 109. The rest of the mixtures (N_{design} = 125 or 126) were put into a group called the Level III. Figures 2-6 provide the corresponding gradation curves for each group of mixtures. It is noted that all mixtures met the Superpave aggregate consensus properties and gradation limits. The low volume mixtures had a higher percentage of natural sand than the high volume ones. The majority of mixtures in this study were coarse-graded (gradation curve passes below the restricted zone). This type of gradation was widely chosen in Louisiana because it is relatively easy to meet the VMA requirements in a Superpave mix design. Only four mixtures in this study were fine-graded (gradation curve passes above the restricted zone): mixes I-1, I-2, $1BWI_{353,}$ and $2BIII_{20}$, shown in Figures 2-6.

Table 2
Job mix formula of Phase-I Superpave mixtures

Mix Designation		I20-B	US90-B	US61-B	WE-B	LA4-B	US61-W	LA22-B	LA121-W	WE-W	LA121-B	LA22-W	LA353
Job Mix Formula	Asphalt	3.3%PAC40	4.1%PAC40	3.5%PAC40	3.1%PAC40	4.0%AC30	4.2%PAC40	4.2%AC30	4.7%PAC30	4.6%PAC40	3.7% AC30	4.6%PAC30	4.7%PAC40
	Aggregate	30%1.5”BR	41%#5LS	38%#5LS	50%#5LS	46%1/2”+	30%#11LS	55%#78LS	45%#78LS	48%#67SS	37%#78LS	50%#78LS	32%NV
		20%5/8”BR	19%#68LS	32%#8LS	19%#RAP	20%1/2”-	29%#67LS	15%RAP	24%#67LS	34%#11LS	22%#67LS	30%#11LS	28%GR
		19%RAP	11%#57LS	14%RAP	17%#78LS	19%RAP	19%#8SS	12%#67LS	22%#11LS	18%#78LS	19%RAP	15%#67LS	10%CS
		7%FS	14%RAP	9%#11LS	14%#11LS	15% screen	12%#78LS	8%#11LS	9%Sand		17%#11LS	5%CS	5%FS
		24% screens	15%#11LS	7%CS			10%CS	10%Sand			5%CS		
Gradation	Sieve Size (mm)	% Passing											
	37.5	100	100	100	100	100	100	100	100	100	100	100	100
	25	98	96	97	96	98	100	100	100	100	100	100	100
	19	84	84	86	84	81	98	98	98	93	98	98	97
	12.5	72	61	73	60	68	84	87	83	76	84	86	86
	9.5	61	47	66	46	54	71	66	62	61	64	66	72
	4.75	42	28	40	29	36	43	31	32	35	35	36	51
	2.36	35	19	22	21	22	29	23	23	22	25	25	40
	1.18	26	15	16	15	18	20	19	18	15		17	32
	0.6	21	12	13	12	12	16	16	14	10	15	13	25
	0.3	16	8	10	9	8	10	9	8	8	9	8	16
	0.075	4.6	4.4	5	4.7	4.4	5	3.8	3.8	5	4.3	4.6	5.1

Table 2 (cont.)
Job mix formula of Phase-I Superpave mixtures

Mix Designation		I20-B	US90-B	US61-B	WE-B	LA4-B	US61-W	LA22-B	LA121-W	WE-W	LA121-B	LA22-W	LA353
Job Mix Formula	Asphalt	3.3%PAC40	4.1%PAC40	3.5%PAC40	3.1%PAC40	4.0%AC30	4.2%PAC40	4.2%AC30	4.7%PAC30	4.6%PAC40	3.7% AC30	4.6%PAC30	4.7%PAC40
	Aggregate	30%1.5"BR	41%#5LS	38%#5LS	50%#5LS	46%1/2"+	30%#11LS	55%#78LS	45%#78LS	48%#67SS	37%#78LS	50%#78LS	32%NV
		20%5/8"BR	19%#68LS	32%#8LS	19%#RAP	20%1/2"-	29%#67LS	15%RAP	24%#67LS	34%#11LS	22%#67LS	30%#11LS	28%GR
		19%RAP	11%#57LS	14%RAP	17%#78LS	19%RAP	19%#8SS	12%#67LS	22%#11LS	18%#78LS	19%RAP	15%#67LS	10%CS
		7%FS	14%RAP	9%#11LS	14%#11LS	15% screen	12%#78LS	8%#11LS	9%Sand		17%#11LS	5%CS	5%FS
		24% screens	15%#11LS	7%CS			10%CS	10%Sand			5%CS		
	Design air void, %	4.3	4.0	3.9	3.9	4.0	4.3	3.7	4.3	3.8	4.2	3.9	
	VMA,%	13.4	13.9	13.1	13.7	14.0	13.4	14.3	14.1	13.5	14.1	14.1	
	VFA,%	67.9	71.2	70.2	71.6	71.7	67.9	74.5	69.8	71.9	70.7	72.4	
	CAA,%	100		100	99		100	97	100	100	100	100	100
	FAA,%	48		45			46	48	44	49		48	42
	Flat & Elongated, %(5:1)	1		1	1		0	0	0	0	0	0	1
	Natural Sand,%	7		6.9			10	10	9	0	5	5	15
Gradation	Sieve Size (mm)	%Passing											
	37.5	100	100	100	100	100	100	100	100	100	100	100	100
	25	98	96	97	96	98	100	100	100	100	100	100	100
	19	84	84	86	84	81	98	98	98	93	98	98	97
	12.5	72	61	73	60	68	84	87	83	76	84	86	86
	9.5	61	47	66	46	54	71	66	62	61	64	66	72
	4.75	42	28	40	29	36	43	31	32	35	35	36	51
	2.36	35	19	22	21	22	29	23	23	22	25	25	40
	1.18	26	15	16	15	18	20	19	18	15		17	32
	0.6	21	12	13	12	12	16	16	14	10	15	13	25
	0.3	16	8	10	9	8	10	9	8	8	9	8	16
	0.075	4.6	4.4	5	4.7	4.4	5	3.8	3.8	5	4.3	4.6	5.1

Table 3
Job mix formula of Phase-II Superpave mixtures (level I & level II)

Mix Designation		I-1	I-2	I-3	I-4	II-1	II-2	II-3
Job Mix Formula	Asphalt	4.6%BM1*	4.7%BM1*	4.5%BM1*	5%BM1*	4.8%BM2*	5.1%BM2*	4.4%BM2*
	Aggregate	30%#67Gr	25%Rh	25%#67LS	16%LS	32% -1”Nova	26% -1”Nova	27%#67LS
		35%#78Gr	40%Rh	10%#8LS	34%LS	21% -3/4”Nova	14%-3/4”Nova	40%#78LS
		20%#11Gr	10%C/S	14%C/S	40%LS	37%Screening	14%12.5mm	25%#11LS
		11%C/S	5%F/S	51%#11LS	10%C/S	10%C/S	36%Screening	8%C/S
		4%F/S	20%Rh				10%C/S	
	Design air void, %	4.0	4.0	4.5	4.1	4.0	4.0	4.3
	VMA,%	13.8	13.5	14.6	13.9	13.9	15.0	13.9
	VFA,%	71.3	70.7	69.2	70.4	71.5	73.6	69.0
	CAA,%	100	100	100	100	100	100	100
	FAA,%	46	45	46	45	45	45	45
	Flat & Elongated, %(5:1)	0	1	1	1	0	1	0
	Natural Sand,%	15	15	14	10	10	10	8
Gradation	Sieve Size (mm)	% Passing						
	25	100	100	100	100	100	100	100
	19	97	98	99	97	97	96	98
	12.5	84	86	88	85	82	84	83
	9.5	72	73	82	68	69	73	63
	4.75	52	54	53	45	44	50	35
	2.36	44	42	32	31	31	35	25
	1.18	37	36	23	22	22	22	19
	0.6	29	29	14	17	16	17	15
	0.3	17	17	8	11	10	12	8
	0.075	4.8	4.8	3.8	4	4	5.2	3.8

*BM1 is PG70-22M, BM2 is PG 76-22M

Table 3 (Cont.)

Job mix formula of Phase-II Superpave mixtures (level III)

Mix Designation		III-1	III-2	III-3	III-4	III-5	III-6	III-7	III-25-1	III-25-2	III-25-3	III-25-4
Job Mix Formula	Asphalt	4.5%BM2	4.6%BM2	5%BM2	4.5%BM2	4.5%BM2	4.5%BM2	4.9%BM2	4.2%BM2	4.3%BM2	3.8%BM2	4.0%BM2
	Aggregate	42%#67SS	20%#67LS	24.3%W.C	25%LS	25%#67LS	30.4%#67LS	26%#67	52%LS	37%#5LS	44.1%#5 LS	36%#5LS
		35%#78LS	14%#78LS	12.2%#67SLS	25%LM	18%#78LS	24%#78LS	44%#78	28%#78LS	36%#78LS	15.2%#78LS	21%#78LS
		8%C/S	45%#78SS	18.6#11SLS	45%LS	47%#1-1 LS	20%RAP	15%SmCr	11%#11LS	12%RAP	21.2%#11LS	28%#11LS
		15%BS	16%LS	39.8%#67	5%CO	10%C/S	20%#1-1 LS	6%C/S	9%C/S	11%LS	4.2%CO	15%RAP
			5%C/S	5.1%CO			5.6%C/S	9%SS		4%C/S	15.3%RAP	
	Design air void, %	4.5	4.1	4.0	4.0	4.2	4.1	4.1	4.1	4.4	4.1	4.0
	VMA,%	13.7	13.7	14.9	13.5	14.1	13.9	14.2	12.9	13.3	12.8	13.0
	VFA,%	67.4	70.1	73.1	70.4	70.5	70.8	71.2	68.5	66.9	68.3	69.2
	CAA,%	100	100	100	100	100	97	97	100	100	100	100
	FAA,%	50	45	38	48	45	45	45	45	44	47	49
	Flat & Elongated, %(5:1)	0	0	1	1	0	0	0	0	0	1	2
	Natural Sand,%	23	5	5.1	5	10	5.6	6	9	4	4.2	0
Gradation	Sieve Size (mm)	% Passing										
	37.5	100	100	100	100	100	100	100	100	100	100	100
	25	100	100	100	100	100	100	100	93	96	97	97
	19	93	97	98	96	99	98	98	74	86	84	86
	12.5	77	86	80	82	86	85	84	48	66	61	66
	9.5	64	67	69	65	75	70	64	36	46	50	51
	4.75	32	29	47	45	47	40	31	21	25	36	37
	2.36	20	21	31	32	26	25	22	16	19	23	24
	1.18	15	15	20	23	19	18	17	14	14	15	16
	0.6	10	14	15	15	15	14	14	11	12	12	12
	0.3	5	10	9	9	9	8	10	7	8	8	9
	0.075	3	5.3	4.5	5.2	4.4	4.2	4	3.4	3.8	4.8	5.35

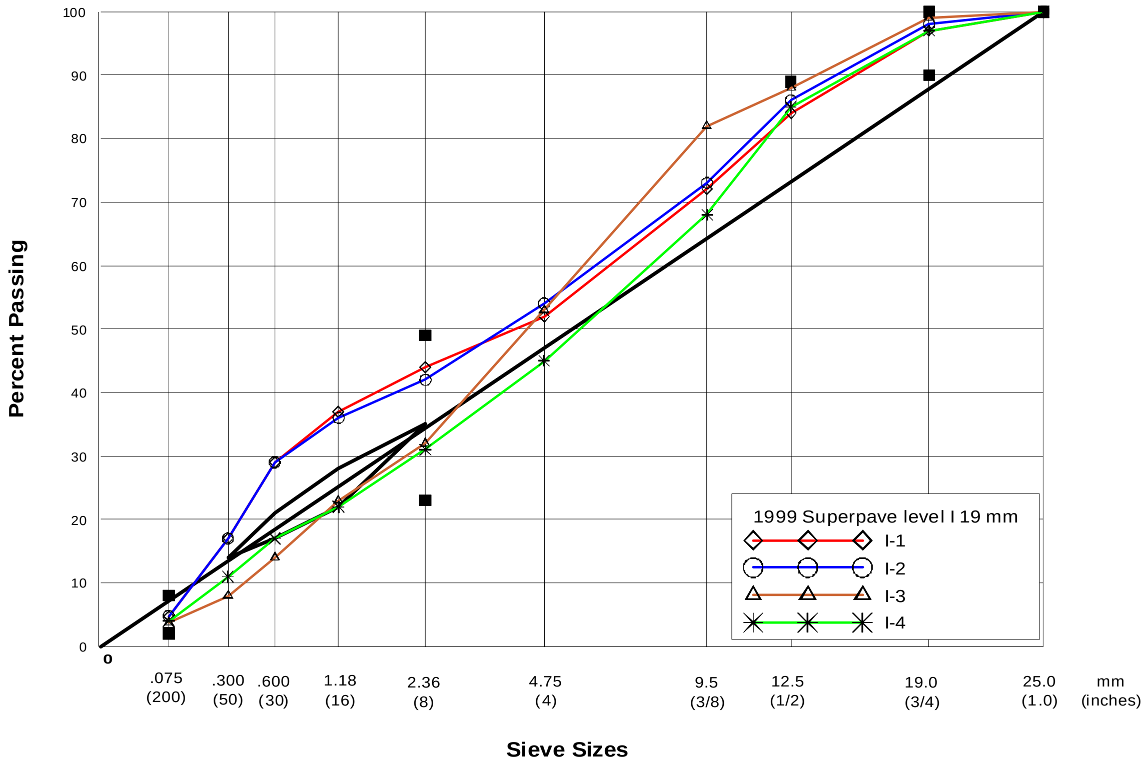


Figure 2
Aggregate gradations of Superpave Level I mixtures with 19 mm NMAS

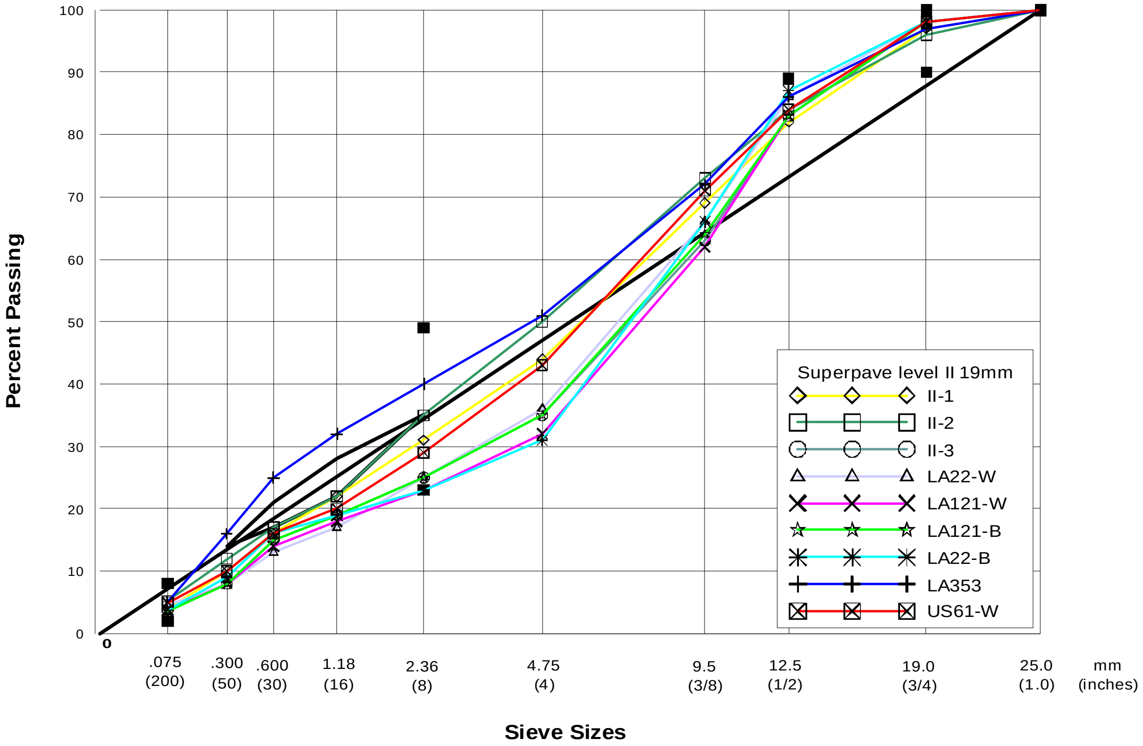


Figure 3
Aggregate gradations of Superpave Level II mixtures with 19 mm NMAS

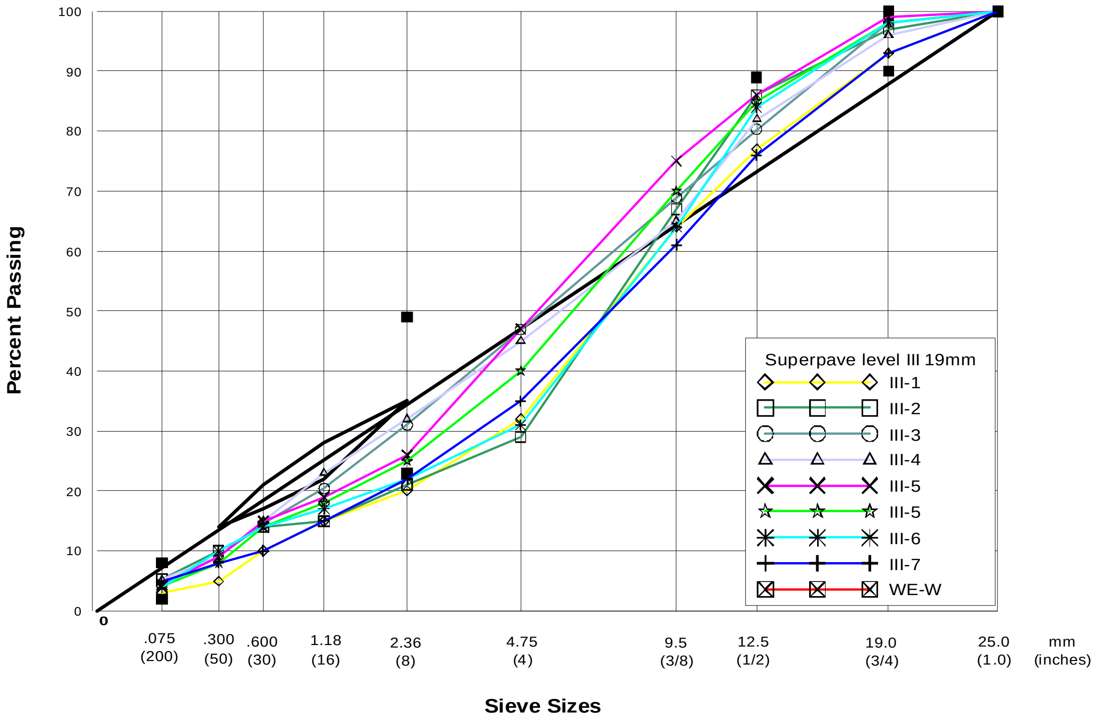


Figure 4

Aggregate gradations of Superpave Level III mixtures with 19 mm NMAS

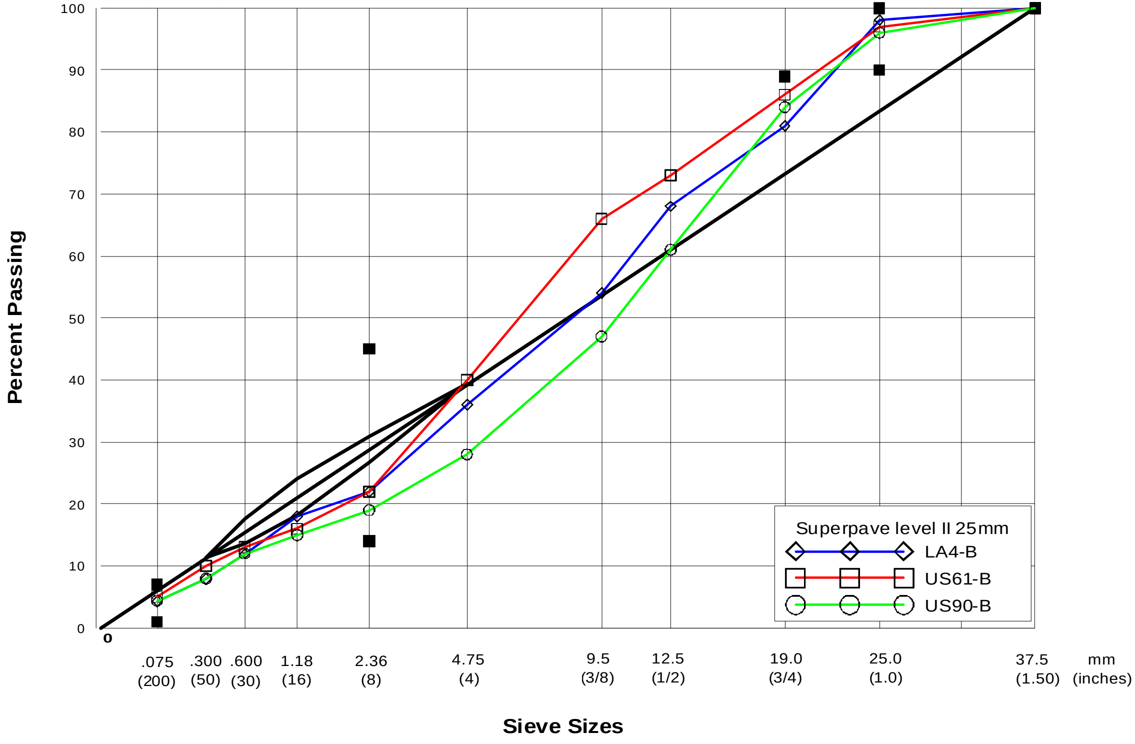


Figure 5

Aggregate gradations of Superpave Level II mixtures with 25 mm NMAS

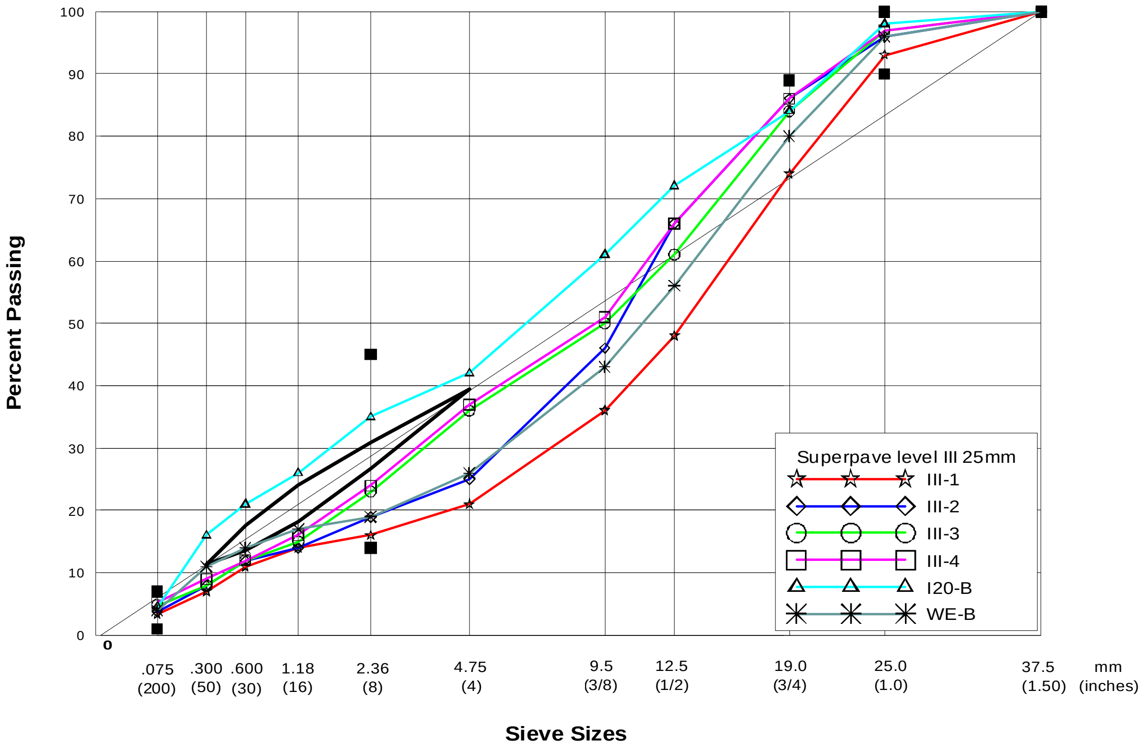


Figure 6

Aggregate gradations of Superpave Level III mixtures with 25 mm NMAS

Asphalt Binder Information

Three types of asphalt cement, a conventional viscosity graded AC-30 and two polymer-modified asphalt binders meeting LADOTD specifications for PAC-30 and PAC-40, were included in Phase I Superpave mix design. Table 4 presents the related asphalt binder specifications. These binders were also classified using the Superpave PG system, as shown in Table 5. It is noted that both AC-30 and PAC-30 binders met Superpave PG-64-22 specification, while PAC-40 met PG-70-22 specification.

Table 4
Asphalt binder specifications

SPECIFICATIONS				
Original Properties				
	AASHTO Test Method	AC-30	PAC-30	PAC-40
Viscosity, 60 °C (140 °F), Pa.s	T 202	300 ± 60		
Viscosity, 135 °C (275 °F), Pa.s	TP 48	0.35 min.	3.0 max.	3.0 max.
Penetration, 25 °C (77 °F), 100 g, 5 s	T 49	55 min.	50-75	50
Flash Point, Cleveland open cup, °C	T 48	232 min.	232 min.	232 min.
Solubility in trichloroethylene, %	T 44	99 min.	99 min.	99 min.
Separation of Polymer, 163 °C (325 °F), 48 hr Difference in softening point from top and bottom Sample °C			2 max.	2 max.
Force Ductility Ratio, (F2/F1, 4°C (39°F),5 cm/min, @ 30 cm elongation) F2 = F @ 30 cm, F1 = Peak Force				0.3 min.
Test on residue from thin-film oven test				
Viscosity, 60 °C (140 °F), Pa.s max.	T 202	1200 max.		
Ductility, 25 °C (77 °F), 50 mm/min, mm	T 51	1000 min.		
Penetration, 25 °C (77 °F), 100 g, 5 s	T 49		30 min.	25 min.
Mass Loss %	T 240	0.5 max.		
Spot Test (Standard Naphtha Solvent)	T 102	Neg.		
Elastic Recovery, 25 °C, 10 cm elongation, %			40 min.	60 min.

For Phase II Superpave projects, two elastometric polymer-modified asphalt binders, PG70-22M and PG76-22M, were used and conformed to the specifications of Superpave PG-70-22 and PG 76-22. The related specifications and test results can be found elsewhere [22]. Table 6 presents the binder type and the percentage of binder from recycled asphalt pavement (RAP) used on each mixture considered in this study. RAP was used on all binder course asphalt mixtures.

Table 5
Superpave binder specification test results (Phase-I)

	AC-30	PAC-30	PAC-40
Original Binder			
Rotational Viscosity at 135 °C, Pa-s	0.52	0.63	0.92
Dynamic Shear Rheometer, G*/sin δ, kPa			
76 °C			0.87
70 °C	0.78	0.8	1.02
64 °C	1.63	1.8	
RTFO			
Dynamic Shear Rheometer, G*/sin δ, kPa			
76 °C		0.97	1.58
70 °C	1.66	1.35	2.47
64 °C	3.54	1.26	
PAV			
Dynamic Shear Rheometer, G*/sin δ, kPa	3725	3300	3403
Bending Beam Creep Stiffness S, MPa	238	100	99
Bending Beam Creep Stiffness m, MPa	0.310	0.350	0.380
PG Grade	64-22	64-22	70-22

Table 6
Mixture binder type and RAP percentage

Mixture	Binder	AC % from RAP	Mixture	Binder	AC % from RAP
1BI$_{22}$	AC 30	0.9	I-4	PG70-22M	-
1WI$_{22}$	PAC 30	-	II-1	PG76-22M	-
1BI$_{121}$	AC 30	1.0	II-2	PG76-22M	-
1WI$_{121}$	PAC 30	-	II-3	PG76-22M	-
1BWI$_{353}$	PAC 40	-	III-1	PG76-22M	-
1WII$_{61}$	PAC 40	-	III-2	PG76-22M	-
1WIIwe	PAC 40	-	III-3	PG76-22M	0.6
2BI4	AC 30	1.0	III-4	PG76-22M	-
2BII90	PAC 40	0.7	III-5	PG76-22M	-
2BII$_{61}$	PAC 40	0.8	III-6	PG76-22M	1.0
2BIII$_{WE}$	PAC 40	1.0	III-7	PG76-22M	-
2BIII$_{20}$	PAC 40	1.0	III-25-1	PG76-22M	-
I-1	PG70-22M	-	III-25-2	PG76-22M	-
I-2	PG70-22M	-	III-25-3	PG76-22M	0.7
I-3	PG70-22M	-	III-25-4	PG76-22M	0.6

Mixture Volumetric Properties

Table 7 presents the specification requirements and the design volumetric properties of the mixtures in this study.

Table 7
Design volumetric data of Superpave mixtures

Mixture	N$_{design}$	VTM (%)	VMA (%)	VFA (%)	AC %	Dust/Pb$_{eff}$	Film Thickness (microns)
I-1	75	4.0	13.8	71.3	4.6	1.12	7.0
I-2		4.0	13.5	70.7	4.7	1.17	6.7
I-3		4.5	14.6	69.2	4.5	0.86	10.9
I-4		4.1	13.9	70.4	5.0	0.94	9.6
II-1	100	4.0	13.9	71.5	4.8	0.93	9.9
II-2		4.0	15.0	73.6	5.1	1.08	9.4
II-3		4.3	13.9	69.0	4.4	0.93	10.7
1WI$_{22}$	96	3.9	14.1	72.4	4.6	1.05	10.6
1WI$_{121}$		4.3	14.1	69.8	4.7	0.9	11.1
1BI$_{121}$		4.2	14.1	70.5	4.4	1.02	9.5
1BI$_{22}$		3.7	14.3	74.5	5.1	0.83	11.5
1BWI$_{353}$		4.1	13.5	69.9	4.7	1.24	6.8
2BI$_{4}$		4.0	14.0	71.7	5.0	0.99	11.1
1WII$_{61}$	109	4.3	13.4	67.9	4.2	1.28	8.2
2BII$_{61}$		3.9	13.1	70.2	4.3	1.28	8.7
2BII$_{90}$		4.0	13.9	71.2	4.8	1.05	10.9
III-1	125	4.5	13.7	67.4	4.5	0.77	13.5
III-2		4.1	13.7	70.1	4.6	1.29	9.2
III-3		4.0	14.9	73.1	5.0	0.94	11.1
III-4		4.0	13.5	70.4	4.5	1.27	8.7
III-5		4.2	14.1	70.5	4.5	1.02	10.0
III-6		4.1	13.9	70.8	4.5	1.00	10.6
III-7		4.1	14.2	71.2	4.9	0.88	11.2
III-25-1		4.1	12.9	68.5	4.2	0.92	11.5
III-25-2		4.4	13.3	66.9	4.3	0.99	10.7
III-25-3		4.1	12.8	68.3	3.8	1.30	9.0
III-25-4		4.0	13.0	69.2	4.0	1.41	8.6
1WIIIWE	126	3.8	13.5	71.9	4.6	1.19	10.1
2BIII20		4.3	13.4	67.9	4.3	1.18	7.0
2BIII$_{WE}$		3.9	13.5	71.1	4.1	1.15	9.9
Spec.		3-5	>13.0 for 19mm >12.0 for 25mm	65-78	N/A	0.6-1.6	N/A

In general, all mixtures met the Superpave volumetric requirements. The last column of Table 7 contains the values of film thickness. The thickness of the asphalt cement film around a particular aggregate is a function of the surface area of the aggregate mass and the percentage of asphalt cement in the mixture. The computation of the film thickness in this study is followed by the method provided in the literature [23].

Experimental Design

A suite of fundamental engineering property tests was designed and performed in this study. Test protocols and the corresponding engineering properties are listed in Table 8. They include indirect tensile strength (ITS), indirect tensile creep, axial creep, indirect tensile modulus, frequency sweep at constant height (FSCH), repeated shear at constant height (RSCH), simple shear at constant height (SSCH), and Asphalt Pavement Analyzer (APA) rut tests.

Table 8
Engineering property tests and protocols

No.	Tests	ENGINEERING PROPERTIES	Protocol
1	Axial Creep at 40 ^{0}C	Permanent deformation	Tex-231-F
2	Indirect Tensile (IT) Creep at 40 ^{0}C	Permanent deformation	Mohammad et al. 1993
3	I T Strength at 25 ^{0}C	Fracture Properties	AASHTO T245
4	I T Resilient Modulus at 5- 25- 40- ^{0}C	Resilient Modulus (Stiffness)	ASTM D4123
5	Repeated Shear at Constant Height at	Permanent strain (Rut Susceptibility)	AASHTO TP7
6	Simple Shear at Constant Height at	Rutting and fatigue cracking	AASHTO TP7
7	Frequency Sweep at Constant Height at	Rutting and fatigue cracking (viscoelastic)	AASHTO TP7
8	Asphalt Pavement Analyzer at 60ºC	Simulative rut depth	PTI

Specimen Preparation

Cylindrical specimens were fabricated for fundamental engineering property tests in this study. Sufficient materials were secured from the HMA plant production facility and compacted in the Superpave Gyratory Compactor (SGC) to a diameter of either 101.6 mm or 150 mm and heights of between 120 mm to 150 mm. Specimens for ITS, IT, and axial creep tests were cut to a height of 63.5 mm from the 101.6 mm diameter SGC samples. The FSCH, RSCH, and SSCH test specimens were obtained from a 150 mm SGC sample and cut to a height of 50 mm. The specimen air voids for the 101.6 mm diameter and 150 mm diameter were 4 ± 1 percent and 7.0 ± 1.0 percent, respectively. Triplicate samples were used for each test.

Test Description

Indirect Tensile Strength (ITS) Test. This test was conducted at 25° C according to AASHTO T245. A cylindrical specimen is loaded to failure at a deformation rate of 50.8 mm/min using an MTS machine. The IDT strength was used in the analysis.

Indirect Tensile Creep (IT Creep) Test. At testing temperatures of 40°C (104°F), a compressive load of 1112.5 N (250 lbf) was applied on the sample, using the stress controlled mode of the MTS test system. The load was applied for 60 minutes or until sample failure. The deformations acquired during this time were used to compute the creep modulus as follows:

$$S(T) = \frac{3.59P}{t \cdot \delta V(T)} \tag{1}$$

where,
$S(T)$ = creep modulus at time T, MPa;
P = applied vertical load, N;
t = sample thickness, mm; and
$\delta V(T)$ = vertical deformation at time T, mm.

The creep modulus versus time (termed as the creep slope) is plotted on a log-log scale and used in the analysis.

Indirect Tensile Resilient Modulus Test. The specimens will be tested at 5, 25, and 40°C (40, 77, and 104°F) according to a modified ASTM D4123. At these temperatures, 15, 10, and 5 percent of the ITS test failure load were used as the peak value of the cyclic load, respectively.

Axial Creep Test. This test mainly reflects the mixture aggregate skeleton's resistance to permanent deformation under a sustained load. The test was conducted in accordance with the Test Method Tex-231-F. The test temperature was 40º C. A static load of 0.787 kN (176.7 lbf) was applied for one hour along the longitudinal axis of the specimen. The axial deformation of the specimen was continuously measured and subsequently used to calculate creep properties, such as stiffness and permanent strain. These data were used to evaluate the permanent deformation characteristics of asphalt mixtures.

Frequency Sweep at Constant Height Test. The FSCH test is conducted according to AASHTO TP7 Procedure E. It is a strain controlled test that applies a shear stress to a cylindrical test specimen to produce a shear strain with a peak amplitude of 0.0005 mm/mm. Sinusoidal shear loading is applied at a sequence of 10 frequencies (10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz) to produce a sinusoidal shear strain. The properties obtained from this test were dynamic shear modulus and phase angle.

Repetitive Shear at Constant Height Test. This test was conducted according to AASHTO TP7 Procedure F. It is a controlled stress test that applies haversine shear stress pulses to a cylindrical specimen. The shear stress amplitude is applied with a maximum shear stress of 68 kPa for a loading time of 0.1 seconds and a rest period of 0.6 seconds. A varying axial load is applied automatically during each cycle to maintain the specimen at constant thickness or height. Repetitive loading is applied for a total of 5,000 repetitions or until 5 percent permanent shear strain is reached by the sample. The primary response variable from this test is the cumulative permanent shear strain at the end of testing.

Simple Shear at Constant Height Test. As described in test procedure G of the AASHTO TP7, the simple shear at constant height (SSCH) test is a controlled stress test that applies an increasing shear stress to a cylindrical test specimen until a specified shear stress level (35 kPa) is achieved. The specified shear stress is held constant for 10 seconds and then released (unloading) at a specific rate. The unloading period will last for 15 seconds to let the shear strain relax. During the test, a varying axial stress is applied automatically to maintain a constant height for the specimen. The primary response variable from this test is the maximum permanent shear strain at the end of testing.

Asphalt Pavement Analyzer Rut Test. Asphalt Pavement Analyzer (APA) is the new generation of the Georgia Loaded Wheel Tester. It simulates actual road conditions by rolling a concave-shaped metal wheel at a speed of approximately 60 cm/sec over a rubber hose pressurized at 0.7 MPa (100 psi) to 0.8 MPa (120 psi) to generate the effect of high tire pressure. The hose stays in contact with the sample's surface while the metal wheel rolls back and forth along the length of the hose for 8,000 cycles. The APA can test three beam samples (300 x 125 x 75 mm) or six cylindrical samples (150 mm x 75 mm) simultaneously.

DISCUSSION OF RESULTS

This discussion is divided into three parts. In Part I, the mechanistic test results for the Phase I Superpave mixtures were statistically analyzed based on different air void levels and the nominal maximum aggregate sizes (NMAS). In Part II, the aggregate gradations of the Phase II Superpave mixtures were first characterized using a Power-law regression analysis. Those obtained gradation parameters were then used to correlate with mixture mechanistic properties. The influences of volumetric properties (e.g. VMA, air voids, etc.) on fundamental engineering properties of Phase II Superpave mixtures were also addressed in this part of discussion. In Part III, Superpave mixtures from both Phase I and Phase II projects were analyzed in groups based on compaction effort (design gyratory compaction level), gradation type (fine or coarse graded), NMAS, binder type, and RAP usage. Correlation analyses were also performed in this section on engineering properties of Superpave mixtures obtained from different fundamental engineering tests. Finally, the laboratory fundamental engineering test results were compared with the early field performance of those mixtures considered.

The SAS software was used in the statistical analysis in the discussion. A multiple comparison procedure, Fisher's least significant difference (LSD), was selected with a 95 percent confidence interval. This multiple comparison procedure ranks the mean test result values and places them in groups designated A, B, C, A/B, and so forth. The letter A is used to rank the group with the most desired mixture properties (e.g., the highest stiffness or lowest permanent strain, etc.) followed by other letter grades in the appropriate order. A double-letter designation, such as A/B, indicates that the mean test result of that group is not significantly different from either A or B.

Part I – Phase I Superpave Mixtures

Indirect Tensile Resilient Modulus Test

Elastic properties of the asphalt mixes were examined by the indirect tensile resilient modulus (M_r) test. Table 9 presents the measured M_r results for the 12 Phase I Superpave mixtures at three temperatures. As expected, the M_r values for all 12 mixtures decreased as the testing temperatures increased. From Table 9 and Figure 7, two clusters of mixes can be identified at low and intermediate temperatures. The cluster of mixtures with higher M_r values at low and intermediate temperatures includes mixtures 2BIII$_{20}$, 2BII$_{61}$, 1WII$_{61}$, and 1BI$_{22}$. No significant difference was found between the average M_r values of these mixes at low and intermediate temperatures, as evidenced in Table 9 by the A group. This cluster includes mixtures from the three levels of compaction effort used on binder and wearing courses with 19 and 25 mm NMAS. Therefore, no statement about the influence of these three variables could be made. Instead, it should be noted that three of these mixes were in the lowest specimen air void group (4±1 percent). In general, mixtures with lower air voids exhibited higher M_r values. At a high temperature, only the 1BI$_{22}$ mixture remained in the statistical group 'A' with the highest resilient modulus value. This mixture also had the highest binder film thickness and the lowest dust to asphalt ratio values among the twelve Phase I mixtures (Table 9), which is indicative of the influence of mastic on resilience properties.

Table 9
Resilient modulus test results – statistical grouping for all Phase I mixes

Mix	**VTM %**	**Resilient Modulus (MPa)**					
		4°C		**25°C**		**40°C**	
		Mean	Group	Mean	Group	Mean	Group
1BI$_{22}$	4±1	4713	A	3109	A	2461	A
1WII$_{61}$		4693	A	3060	A	2075	B
2BIII$_{20}$		4680	A	3270	A	1842	C
1WI$_{121}$	6±1	3883	B	2660	B	1696	C/D
2BII$_{90}$		3265	C/D	2068	D	1295	E/F
2BII$_{61}$		4493	A	3109	A	1885	B/C
2BI$_{4}$		2943	D	2242	C/D	1232	F
2BIII$_{WE}$		3629	B/C	2531	B/C	1752	C
1WIII$_{WE}$	8±1	3288	C/D	2578	B/C	1487	D/E
1BI$_{121}$		3803	B/C	2691	B	1802	C
1WI$_{22}$		4068	B/C	2423	B/C/D	1429	E/F
1BWI$_{353}$		3873	B	2402	B/C/D	1343	E/F

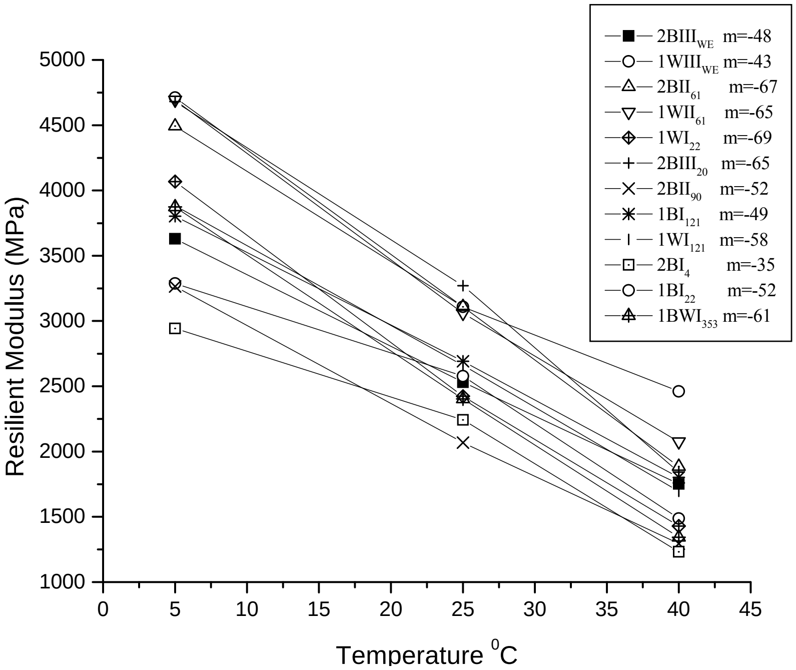


Figure 7
IT resilient modulus versus temperature (Phase-I)

In Table 10, the mean of the resilient modulus of all mixtures with 19 mm NMAS is compared to the mean of all mixtures with NMAS of 25 mm. Similarly, using the results of all mixtures, means for every level of compaction were computed and compared. Table 10 shows that neither the level of compaction nor the nominal maximum aggregate size influenced the results of this test. In other words, the resilient modulus of mixtures with different compaction levels was statistically similar at every temperature and NMAS.

Table 10
Resilient modulus test results – statistical grouping for classified Phase-I mixes

Variable		**Resilient Modulus (MPa)**					
		4°C		**25°C**		**40°C**	
		Mean	Group	Mean	Group	Mean	Group
NMAS	19 mm	3975	A	2696	A	1756	A
	25 mm	3802	A	2644	A	1604	A
Compaction Level	I	3798	A	2580	A	1662	A
	II	4150	A	2746	A	1752	A
	III	3865	A	2793	A	1694	A

Indirect Tensile Strength Test

The Indirect Tensile Strength (ITS) test was performed at 25º C (77º F) in this study. For this test, high indirect strength and strain values at failure are desirable properties for durable HMA mixtures. Table 11 presents the ITS test results for Phase I Superpave mixtures. As seen in Table 9, the mixtures with higher indirect tensile strength values were those with lower specimen air voids, specifically 2BIII$_{20}$, 1WII$_{61}$, and 1BI$_{22}$. Again, since this group of mixtures had different NMAS, level of compaction, and mix type, the influence of those variables could not be determined.

The means of the ITS test results classified by NMAS and levels of compaction were statistically grouped, as shown in Table 12. No influence on IT strength caused by either NMAS or level of compaction was observed. The statistical ranking is the same for all groups of mixtures. Concerning the IT Strain results, the mean value for 25mm Superpave mixtures was found statistically higher than that for 19 mm mixtures. Similarly, the mean strain value for Level III (N_{des}=126) mixtures was found statistically higher than that for Level I (N_{des}=97) mixtures. On the other hand, no statistical differences existed in the means of IT strains between Level II (N_{des}=109) mixtures and either Level I or Level III mixtures in the Phase I study.

Table 11
Indirect tensile strength test results - statistical grouping of all Phase-I mixes

Mix	VTM %	IT Strength (MPa)		IT Strain (%)	
		Mean	Group	Mean	Group
1WII$_{61}$	4 ± 1	2.002	B	0.51	D/E
1BI$_{22}$		1.911	B/C	0.27	G/H
2BIII$_{20}$		2.409	A	0.72	B
1WI$_{121}$	6 ± 1	1.691	C/D	0.63	B/C/D
2BII$_{90}$		1.183	E	0.70	B
2BII$_{61}$		1.546	D/E	0.40	E/F
2BI$_{4}$		1.020	F	0.64	B/C
2BIII$_{WE}$		1.587	D/E	0.88	A
1WIII$_{WE}$	8 ± 1	1.325	E	0.57	C/D
1BI$_{121}$		1.528	D/E	0.15	H
1WI$_{22}$		1.325	F	0.32	F/G
1BWI$_{353}$		1.554	D/E	0.86	A

Table 12
Indirect tensile strength results - statistical grouping of classified Phase-I mixes

Variable		IT Strength		IT Strain	
		Mean	Group	Mean	Group
NMAS	19 mm	1.62	A	0.47	B
	25 mm	1.55	A	0.67	A
Compaction Level	I	1.5	A	0.48	B
	II	1.6	A	0.54	A/B
	III	1.8	A	0.72	A

Axial Creep Test

This test was performed according to the Texas DOT axial creep test procedure [23]. Three test parameters can be derived from this test, namely, the creep stiffness, creep slope, and permanent strain at the end of the test. In general, a rut-resistant HMA mixture should have high creep stiffness, low creep slope, and low permanent strain values. Table 13 presents the average axial creep test results at 40º C (104º F) for Phase I Superpave mixtures grouped by different air voids. Figures 8 to 10 graphically represent the test results of creep stiffness, creep slope, and permanent strain, respectively. The Texas specification limits for all test parameters were also plotted on the corresponding figures.

Table 13
Axial creep test results - statistical grouping of all Phase-I mixtures

Mix	Air void (%)	Stiffness (MPa)		Slope (E-08 mm/mm/sec)		Permanent Strain (mm/mm)	
		Mean	Group	Mean	Group	Mean	Group
1BI$_{22}$	4 ± 1	66.3	B	7.6	A/B/C	5.3	B/C/D
1WII$_{61}$		82.2	A	4.3	A	2.77	B
1WI$_{121}$		49.1	C/D	10.1	C/D	5.7	C/D
2BIII$_{20}$	6 ± 1	86.7	A	4.5	A	2.55	B
2BII$_{61}$		78.6	A	7.5	A/B/C	4.5	B/C
2BII$_{90}$		52.4	C	6.2	A/B	4.1	B/C
2BI$_{4}$		38.4	E	22.9	F	9.93	E/F
1WIII$_{WE}$	8 ± 1	50.3	C/D	9.5	C/D	7.35	D/E
2BIII$_{WE}$		50.1	C/D	9.4	B/C/D	4.55	B/C
1BI$_{121}$		54.0	C	12.1	D	6.67	C/D
1WI$_{22}$		36.7	E	16.5	E	10.32	F
1BWI$_{353}$		41.8	D/E	7.4	A/B/C	6.32	C/D

In Figure 8, the axial creep test results are separated in groups according to the specimen air void percent. Results show that the group of mixtures with air voids in the range 8 ± 1 percent have stiffness values significantly lower than the values of the other two groups. Only two mixes, 2BI$_{4}$ and 1WI$_{22}$, did not meet the minimum TXDOT requirement for creep stiffness of 41.4 MPa (6000 psi), and both of these mixes were prepared at level I compactive effort. On the other hand, the mixes with the highest creep stiffness, 2BIII$_{20}$, 1WII$_{61}$, and 2BII$_{61}$, were compacted at levels II or III. That is, the compactive effort shows an effect on the results.

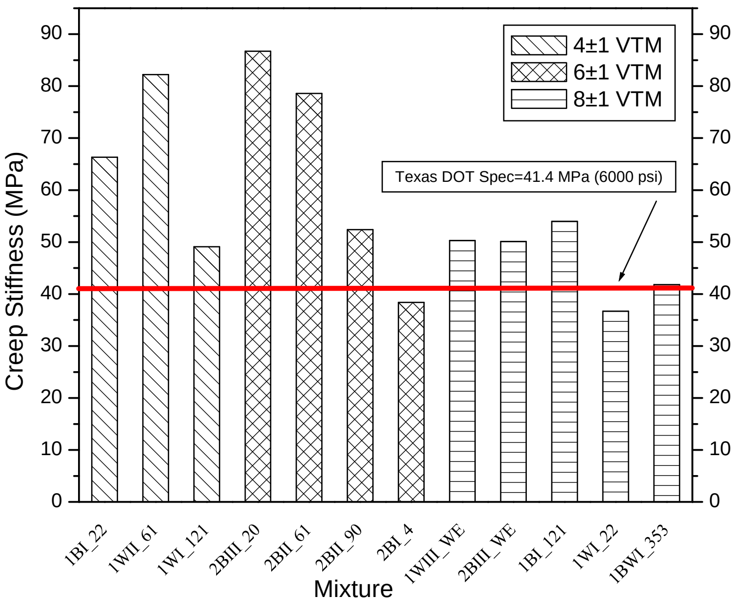


Figure 8
Creep stiffness from axial creep test at 40°C

The slope from the axial creep test, as seen in Figure 9, gives an indication of how susceptible a mixture is to creep strain under static loading. Therefore, a low slope is required if a mix is to resist rutting. The mixes with the highest slopes, an indication of higher rutting susceptibility, were 2BI$_{4}$, 1WI$_{22}$, and 1BI$_{121}$. All three of these mixes were compacted at level I, which corresponds to the axial creep stiffness results. Mixtures 2BI$_{4}$ and 1WI$_{22}$ also had the lowest creep stiffness, and this combination of high creep slope and low creep stiffness should show rapid rutting in the field. Similarly, the mixtures with the lowest slopes, 2BIII$_{20}$, 1WII$_{61}$, and 2BII$_{90}$, should exhibit better rutting resistance. Again, none of these three mixes with low slopes was compacted at level I. However, it is interesting to note that all 12 mixtures exceeded the Texas DOT requirement of a maximum of 3.5x10^{-8} on creep slope. This does not necessarily mean that all of these mixtures are bad. It may mean that criteria established under one set of local conditions are not always transferable to other locations because of differences in climate, materials, etc. However, the fact that all mixes exceeded the maximum creep slope does create concern about the potential field performance of all of these mixes.

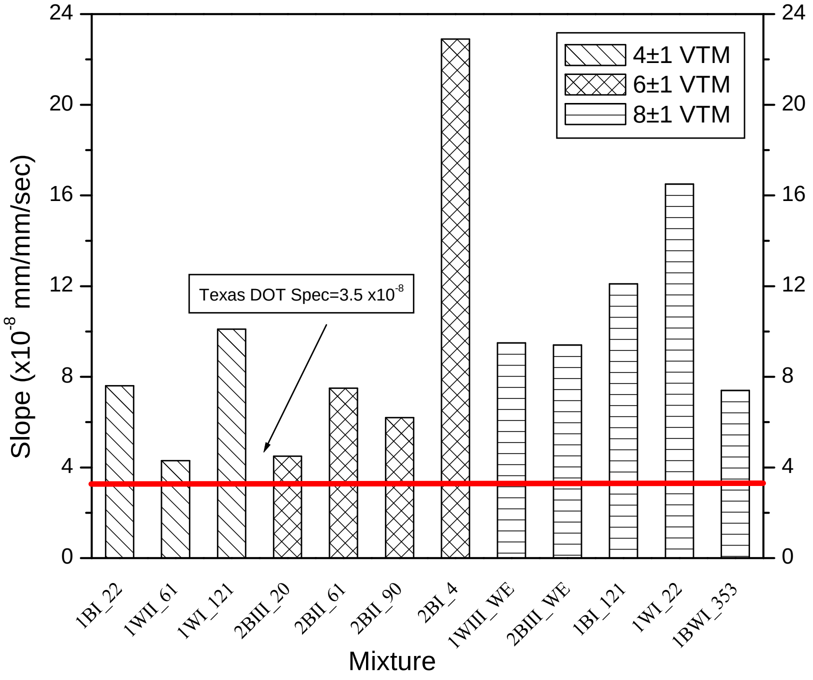


Figure 9
Slope from axial creep test at 40°C

The permanent strain from the axial creep test is shown in Figure 10. Mixes $2BI_4$ and $1WI_{22}$ show the greatest permanent axial creep strain of all of the 12 mixes. All of the mixtures compacted at level I had permanent strains that exceeded the Texas DOT maximum of $5.0X10^{-4}$ mm/mm. Of the mixes compacted at levels II and III, only $1WIII_{WE}$ exceeded the Texas DOT permanent strain maximum. Four percent air void mixes produced the lowest permanent strain overall, while eight percent air void mixes produced the highest.

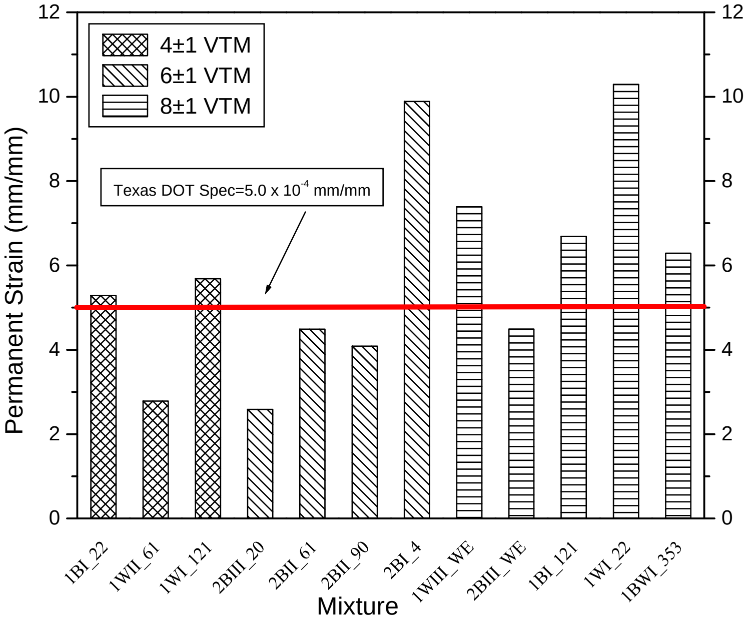


Figure 10
Permanent strain from axial creep test at 40°C

The statistical grouping of mixtures classified by NMAS and compaction level is presented in Table 14.

Table 14
Axial creep test results - statistical grouping of classified Phase-I mixes

Variable		**Stiffness**		**Slope**		**Perm. Strain**	
		Mean	Group	Mean	Group	Mean	Group
NMAS	19 mm	54.3	A	9.7	A	6.5	A
	25 mm	61.2	A	10.1	A	5.1	A
Compaction Level	I	47.7	B	12.8	B	7.5	B
	II	71.1	A	6.0	A	3.8	A
	III	62.3	A	7.8	A	4.8	A

While the NMAS variable does not show influence on this test (the means of the fundamental properties are statistically similar), the influence of the level of compaction effort is evident. In every case, the results of mixes with level I compaction were statistically different and inferior to those from mixes compacted at levels II or III. In other words, the stiffness was lower and the creep slope and permanent strain were higher for mixes at compaction level I than for mixes at compaction levels II or III. Additionally, no statistical difference was detected between the means of fundamental properties of mixes compacted at levels II or III.

Indirect Tensile Creep Test

Similar to the axial creep test, the indirect tensile creep (ITC) test performed at 40° C also provides an indication of the rutting susceptibility for the HMA mixtures. Low ITC slope values are desired properties for rut resistant HMA mixtures. Table 15 summarizes the ITC slope results for all Phase I mixtures considered. It shows that mixtures with the lowest creep slope were $2BIII_{20}$ (Group A/B) and $1WII_{61}$ (Group A), and those with the highest creep slope included $1BI_{22}$ (Group D/E), $2BII_{90}$ (Group E/F), and $2BI_4$ (Group F). These three mixtures all contained high film thickness and low Dust/asphalt ratio.

Table 15
Creep slope from the indirect tensile creep test-statistical grouping of all Phase-I mixes

Mix	Air Void %	Slope (KPa/sec)	
		Mean	Group
$1WII_{61}$	4 ± 1	1.86	A
$2BIII_{20}$		2.09	A/B
$1BI_{22}$		3.13	D/E
$1WI_{121}$	6 ± 1	3.04	D
$2BII_{61}$		2.97	D
$2BII_{90}$		3.50	E/F
$2BIII_{WE}$		2.81	C/D
$2BI_4$	8 ± 1	3.70	F
$1WIII_{WE}$		3.04	D
$1BI_{121}$		3.01	D
$1WI_{22}$		2.44	B/C
$1BWI_{353}$		2.99	D

Table 16 presents the statistical grouping of mixtures classified by NMAS and levels of compaction effort. As shown in Table 16, neither NMAS nor compaction effort had an influence on creep test results. The mean values of the slopes of all mixes were statistically similar in the analysis with respect to these two variables.

Table 16
Creep slope from the indirect tensile creep test-statistical grouping of classified Phase I mixes

Variable		Slope	
		Mean	Group
NMAS	19 mm	2.8	A
	25 mm	3.0	A
Compaction Level	I	3.1	A
	II	2.8	A
	III	2.6	A

Frequency Sweep Test at Constant Height

Viscoelastic properties of asphalt mixtures were examined by performing a frequency sweep test. The material property obtained from this test was a dynamic shear modulus, also called a complex shear modulus. Dynamic shear modulus (G*) is defined as the ratio of the peak shear stress amplitude to the peak shear strain amplitude; it is a measure of total stiffness of asphalt mixtures, and it is composed of elastic and viscous components of asphalt shear modulus. Thus far, the correlation between the dynamic shear modulus and pavement rutting has not been well established, although the fact that the strain generated in stiff asphalt mixtures under traffic loading is relatively small, minimizing pavement rutting is well known. The relationship between the complex shear modulus and the loading frequency, shown in Figure 11, indicates that, as the speed of loading on the specimen increases, the shear modulus increases.

The slope m of the relationship between complex shear modulus and loading frequency on logarithmic scales is used to indicate the susceptibility of the mixture to both rutting and fatigue cracking. HMAs with higher slopes are more susceptible to permanent deformation. The slopes recorded in Figure 11 indicate that, on average, the mixtures with level III compaction effort had the lowest slopes, and the level I mixtures had the highest slopes. The mean values of slope for each level of compaction effort were: 0.370, 0.380, and 0.388 for levels III, II, and I, respectively. The dynamic shear modulus results at 0.01 Hz, shown in Figure 12, indicate that the air void level had an effect on the shear modulus even for mixtures within a particular air void group. Within each air void group (e.g., 5 ± 1 or 7 ± 1 percent), the complex shear modulus decreased as the air voids increased. However, there was no consistent trend across all mixtures between complex shear modulus and air voids.

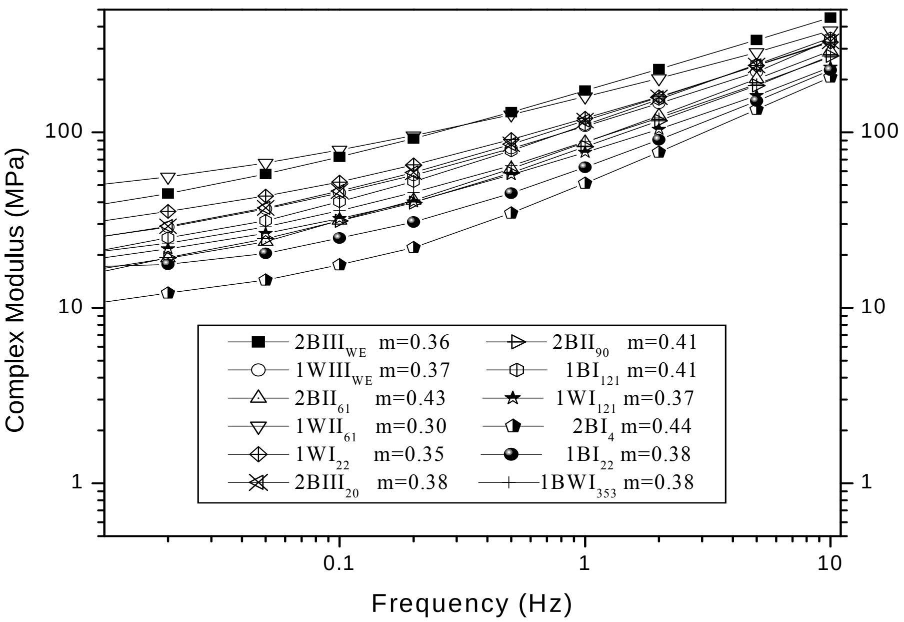


Figure 11
Slopes from the FSCH test at 48ºC

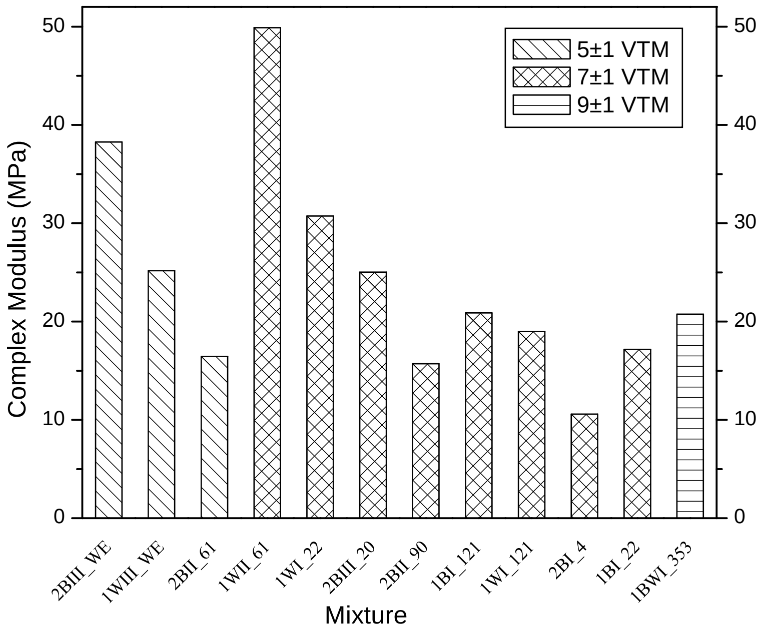


Figure 12
Complex Shear Modulus of FSCH test at 0.01 Hz and 48ºC

Repetitive Shear at Constant Height

Low permanent shear strain after 5,000 load repetitions is desirable for rut resistant mixtures. Figure 13 presents the relationship between permanent shear strain and load repetitions for all Phase I mixtures considered. It shows that a high percentage of the total permanent strain occurs during the first 500 repetitions. The mixtures with the best and worst responses to the shear loads are easily recognizable. Mixtures $1BI_{22}$ and $1WI_{121}$ showed the highest permanent shear strain. Both of these mixes were compacted at level I, have the lowest values of dust/asphalt ratio, and have the highest film thicknesses. On the other hand, the lowest permanent shear strain occurred for $2BIII_{WE}$ and $2BIII_{20}$. Both were compacted at level III, with the latter having a low film thickness.

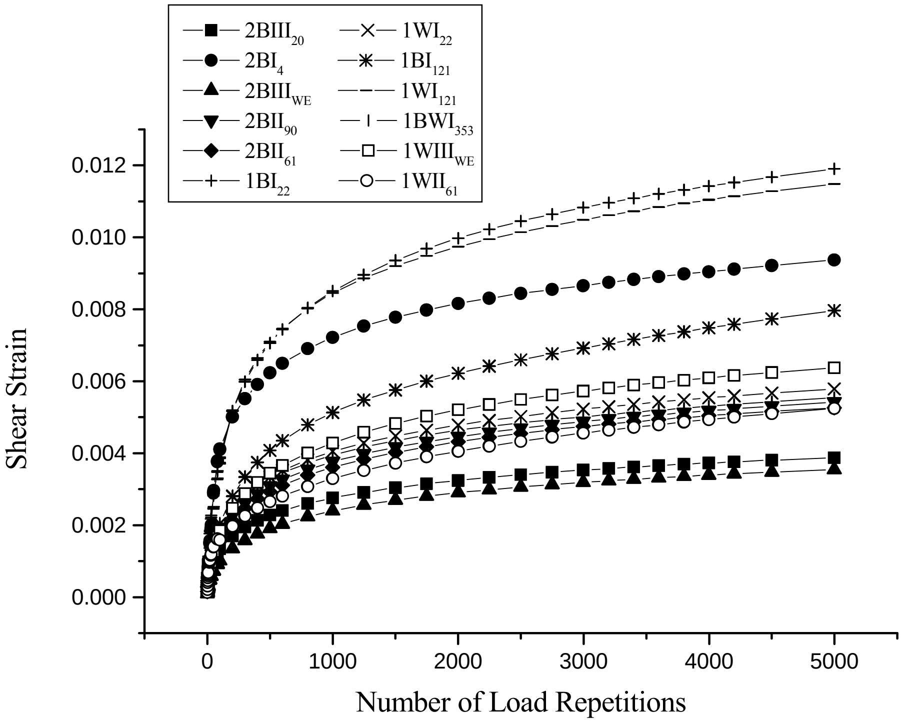


Figure 13
Permanent shear strain of repeated shear at constant height test at 48°C

Simple Shear at Constant Height

The simple shear at constant height (SSCH) test is a shear-loading creep test. Theoretically, a mixture that resists rutting should exhibit low permanent shear strain at the end of SSCH tests. Figure 14 presents the SSCH permanent shear strain results for all Phase I mixtures.

The mixtures with the highest shear strains were $1BI_{22}$ and $2BI_4$, which were compacted at level I and also contained low dust/asphalt ratios and high film thickness. The mixtures with the lowest shear strain values were $1WII_{61}$, $2BIII_{WE}$, and $1WI_{22}$. Mixtures with higher air voids tended to produce higher values of shear strain. The fact that the mixes with the highest shear strain in Figure 13 are not the same mixes that showed the highest shear strain in Figure 14 should be noted. Two possible reasons could have caused this difference: the two tests had not measured the same material responses; the two tests used different samples with different air voids.

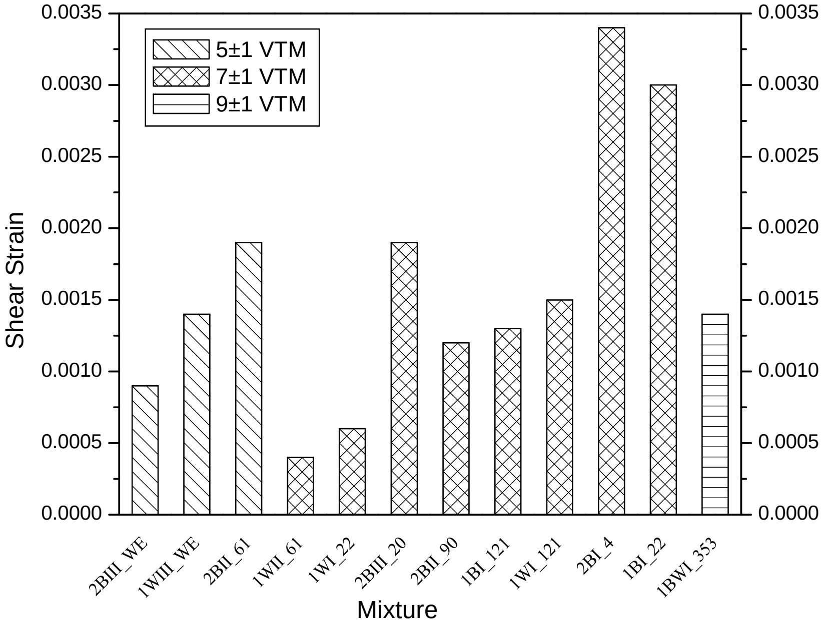


Figure 14
Permanent shear strain of simple shear at constant height test at 48°C

APA Rutting Test

Table 17 and Figure 15 present the APA test results of all Phase I mixtures expressed as the measured rut depth after 8,000 cycles. The specification value for a mix with acceptable performance should have a rut depth of 6 mm or less after 8,000 cycles. Most of the mixtures tested, with the exception of $2BI_4$ and $1BI_{121}$, met this criterion. The two mixtures that did not meet the specification contained high air voids and were designed at compaction level I.

On the other hand, the two mixtures with the lowest rut depth, $1BWI_{353}$ and $2BIII_{20,}$ have the lowest air voids and the lowest film thickness and are the only two mixes with gradations above the restricted zone. Four of the five mixes with the highest rut depths in Figure 12 match the four mixes in Figure 13 with the highest shear strain in the repeated shear at constant height test.

Table 17
APA rutting test results at 60°C- statistical grouping of all Phase I mixes.

Mix	Air Void %	Rutting (mm)	
		Mean	Group
$2BIII_{20}$	5 ± 1	2.70	B
$1BWI_{353}$		1.54	A
$1BI_{22}$	7 ± 1	4.80	C
$2BII_{61}$		4.20	B/C
$2BI_4$		7.80	D
$1WIII_{WE}$		3.80	B/C
$2BII_{90}$		4.10	B/C
$1WI_{121}$		4.60	C
$2BIII_{WE}$		4.20	B/C
$1WII_{61}$	9 ± 1	5.90	C/D
$1BI_{121}$		7.10	D
$1WI_{22}$		3.60	B/C

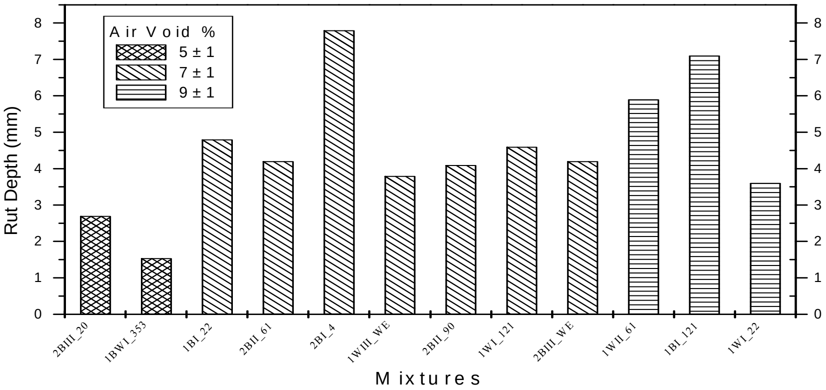


Figure 15
APA rut depths at 60ºC (Phase I)

Overall Ranking of Rut Susceptibility

Based on the engineering properties from these tests, an overall ranking of the HMAs was calculated to identify their susceptibility to permanent deformation. Table 18 shows the overall ranking results for the tests performed in the MTS apparatus, while the results of the overall ranking for tests conducted in the SST machine are presented in Table 19. Equal weight was given to each test in the calculation. The numbers assigned for the ranking are one through four: one was assigned to the mix with the most desirable results on each particular engineering property of the test, and four was assigned to the mix with the least desirable results. For instance, from the slope results in the Axial Creep Test (Table 16), the ranking one was given to the mix with the lowest slope, which is an indication of good performance on this property. Following the same logic, the number four was assigned to the mixture with the highest value on creep slope. A normalization procedure through interpolation was then adopted to rank the rest of the mixtures. After each engineering property was treated in a similar way, the ranks were averaged and then normalized from range one through four again. At the end of this process, mixes that resulted with smaller ranking numbers were, in general, considered less susceptible to rutting. Figures 16 and 17 present the normalized ranking of rut susceptibility. The results were grouped according to the specimens' air void content. Regarding the variables used in the code designation (NMAS, layer, and compaction effort), only the level of compaction effort shows some effect on the ranking of mixes. One should observe that, in most cases, the mixes with a level I compaction effort (i.e., for traffic ≤ 1 million ESAL's) had higher rankings; that is, they can be considered more susceptible to rutting than mixes compacted at levels II or III.

Table 18
Rank of rutting susceptibility from MTS test results

Air Void %	4 ± 1			6 ± 1					8 ± 1			
Mix	1WII$_{61}$	2BIII$_{20}$	1BI$_{22}$	2BII$_{61}$	2BIII$_{WE}$	1WI$_{121}$	2BII$_{90}$	2BI$_{4}$	1BWI$_{353}$	1BI$_{121}$	1WIII$_{WE}$	1WI$_{22}$
IT Creep	1.00	1.33	3.0	2.78	2.56	2.89	3.67	4.0	2.78	2.89	2.89	1.89
Axial Creep	1.11	1.0	1.96	1.59	2.30	2.51	2.01	4.0	2.59	2.64	2.67	3.73
Average	1.06	1.17	2.48	2.18	2.43	2.70	2.84	4.0	2.68	2.77	2.78	2.81
Normalized	1.0	1.11	2.45	2.15	2.40	2.67	2.81	4.0	2.66	2.74	2.76	2.79

Table 19
Rank of rutting susceptibility from SST test results

Air Void %	5 ± 1			7 ± 1							9 ± 1
Mix	2BIII$_{WE}$	1WIII$_{WE}$	2BII$_{61}$	1WII$_{61}$	1WI$_{22}$	2BIII$_{20}$	2BII$_{90}$	1BI$_{121}$	1WI$_{121}$	2BI$_{4}$	1BI$_{22}$	1BWI$_{353}$
FSCH	1.89	2.89	3.55	1.00	2.46	2.90	3.61	3.21	3.36	4.00	3.50	3.22
RSCH	1.82	2.90	2.21	1.28	1.64	1.00	1.78	3.70	4.00	2.19	3.63	2.48
SSCH	1.50	2.00	2.50	1.00	1.20	2.50	1.80	1.90	2.10	4.00	3.60	2.00
Average	1.74	2.595	2.75	1.094	1.77	2.13	2.40	2.94	3.15	3.40	3.58	2.57
Normalized	1.78	2.81	3.01	1.00	1.81	2.26	2.57	3.23	3.49	3.78	4.00	2.78

Rutting Susceptibility Ranking: 1 represents the lowest rutting susceptibility; 4 represents the highest. Therefore, the following scale was used to rank the mixtures:

1 = Excellent resistance to rutting
2 = Good resistance to rutting
3 = Fair resistance to rutting
4 = Marginal resistance to rutting

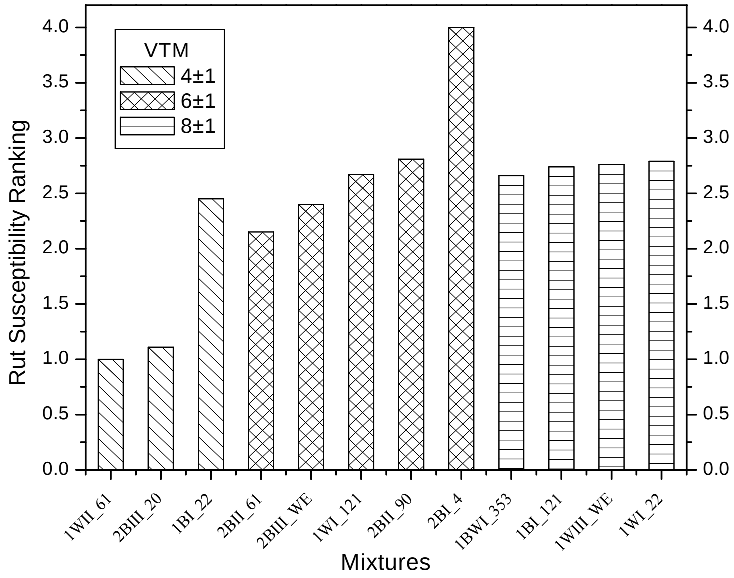


Figure 16
Rutting susceptibility ranking from MTS tests results

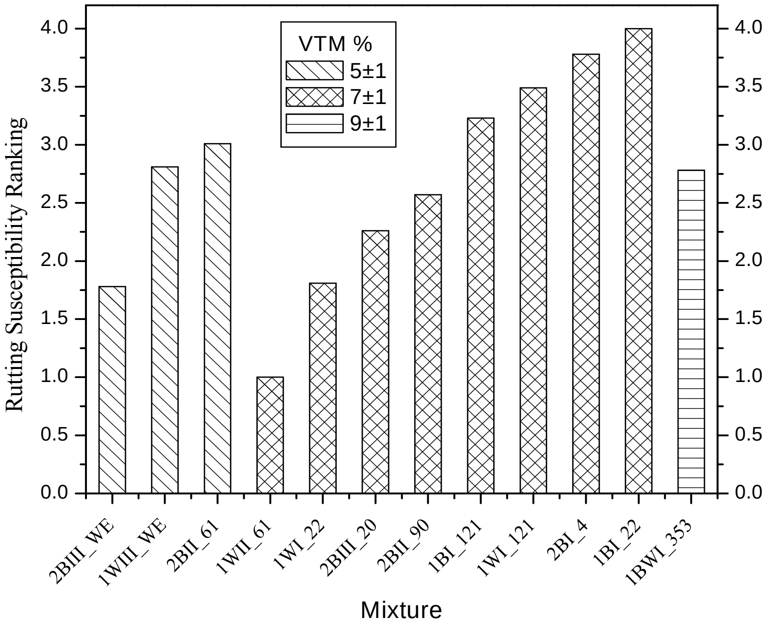


Figure 17
Rutting susceptibility ranking from SST tests results

Influence of Mix Variables on Test Results

A multiple regression analysis and a comparison of test results were performed in this section to determine the effect of mix design variables on the performance of the evaluated mixes. Explanation of each procedure follows.

Multiple Regression Analysis

A statistical analysis was conducted to determine the contribution of several mix variables to the test results. The statistical procedure used was a stepwise multiple regression analysis that correlated the mix variables to the fundamental engineering properties obtained from each test. The stepwise regression procedure is preferred when two or more of the independent variables are highly correlated with each other, which is the case here. At each step, the stepwise regression method adds an independent variable to the regression model only if the variable's inclusion significantly reduces the sum of squares for error below the value achieved before the variable was included.

The variables considered for the analysis were NMAS, percent of aggregate passing sieves 2.36 and 0.075 mm, film thickness, dust/asphalt ratio, voids in the mineral aggregate, level of compaction effort, and voids in total mix (within groups). In order to minimize the observed effect that air voids had on the test results, the program was run separately for each air void group.

Table 20 contains the results from the regression analysis for the tests conducted on the MTS machine. For example, on the axial creep test, the variable making the greatest contribution to stiffness was percent aggregate passing sieve 0.075 mm. In an analogous way, the variable contributing the most to creep slope was the film thickness. Table 21 presents the results of the stepwise multiple regression analysis for the tests performed on the SST apparatus. Table 22 shows the frequency of significant contributions of each variable on the results. The variables are approximately ordered from highest to lowest contribution. According to this analysis, the fact that the film thickness stands out as the most critical mix variable followed by VMA may be observed. The rest of the variables had moderate contributions.

It is important to mention that the contribution of VTM encountered on this analysis corresponds to air voids within each air void group. The analysis was done this way in order to avoid the strong effect that high air void content between different mixtures had on test results in the previous section. Recalling the cause of this situation and explaining how it was faced is also necessary.

During the Phase I specimen preparation, due to lack of quality control, the result was high dispersion in densities achieved between mixtures, which made it difficult to compare them. For instance, while the mixtures were designed to have approximately 4 percent air voids, the 4-inch testing samples contained air voids fluctuating from 3.9 percent up to 9.2 percent. The fluctuations on the specimen air voids caused variations on the rest of the volumetric properties because they are interrelated. A change in air void content, for instance, modifies the VMA and consequently the VFA values. It became obvious that a major cause of the high dispersion obtained in the test results was this large variation in the air void values of the specimens. The approach used to solve this situation was to classify the HMA mixtures according to the air void content encountered in the test specimens.

Table 20
Variables significant on MTS test results at the 0.05 Level- stepwise multiple regression analysis

% Air Void	MTS Test	Fundamental Property	1st Step			2nd Step			3rd Step		
			Variable	Prob>F	R^2	Variable	Prob>F	R^2	Variable	Prob>F	R^2
4 ± 1	Axial Creep	Stiffness	Pass 0.075	0.0018	0.996						
		Slope	Film T	0.0043	0.991						
		Per. Strain	Film T	0.01	0.98						
	IT Creep	Slope	Film T	0.0042	0.992						
6 ± 1	Axial Creep	Stiffness	Dust/AC	0.001	0.982	Pass 0.075	0.002	0.986			
		Slope	Pass 2.36	0.0012	0.98						
		Per. Strain	Pass 2.36	0.0002	0.994	Dust/AC	0.007	0.999	VTM	0.01	1.0
	IT Creep	Slope	VMA	0.0001	0.981						
8 ± 1	Axial Creep	Stiffness	NMAS	0.001	0.978	VMA	0.004	0.99	Film T	0.04	1.0
		Slope	Film T	0.003	0.962						
		Per. Strain	Film T	0.001	0.98						
	IT Creep	Slope	NMAS	0.0003	0.99						

Table 21
Variables significant on SST test results at the 0.05 level- stepwise multiple regression analysis

% Air Void	SST Test	Fundamental Property	1st Step			2nd Step		
			Variable	Prob>F	R^2	Variable	Prob>F	R^2
5 ± 1	Freq. Sweep C.H.	G* @ 0.01 Hz	Compaction Level	0.022	0.956			
	Freq. Sweep C.H.	Slope	VMA	0.0001	0.999			
	Rep. Shear C.H.	Perm. Shear Strain	VTM	0.0156	0.969			
	Simple Shear C.H.	Perm. Shear Strain	VTM	0.0214	0.958	VMA	0.0065	1.0
7 ± 1	Freq. Sweep C.H.	G* @ 0.01 Hz	Dust/AC	0.0003	0.904	NMAS	0.0023	0.987
	Freq. Sweep C.H.	Slope	VMA	0.0001	0.995			
	Rep. Shear C.H.	Perm. Shear Strain	Film Thick	0.0002	0.916			
	Simple Shear C.H.	Perm. Shear Strain	Film Thick	0.0041	0.771			

Table 22
Frequency of significant contributions of each mix variable at 0.05 level

Variables	Frequency of significance at 0.05 level		
	MTS	SST	Total
Film Thickness	6	2	8
VMA	2	3	5
Dust/AC	2	1	3
NMAS	2	1	3
VTM	1	2	3
Pass 2.36	2		2
Pass 0.075	2		2
Compaction Level		1	1

Classified Comparison of Mixtures

According to the test results, asphalt mixtures did not show similar responses. Significant differences in responses existed although all mixtures met Superpave mix design specifications. Contrasts were found in mixtures belonging to different air void groups (between groups) and in mixes within a specific air void range (within groups). The apparent reason for such variation in responses can be attributed, in the first case, to the high dispersion of the specimen air voids. While these mixtures were designed to have approximately 4 percent air voids, the test specimens contained air voids fluctuating from 3.9 percent up to 9.2 percent. To determine the reason for the variation in the second case (within an air void range) and to confirm the results from the multiple regression analysis, the following comparison of the mixtures was made. Tables 23 through 27 present a comparison of the mixtures classified in different groups of NMAS and compaction level. Five variables were included in the comparison to observe the influence of each on the test results. Again, the air void in the specimens was taken into consideration in this analysis. Therefore, only the mixes within an air void range could be compared with each other. Table 23 contains the coefficients of determination R^2 obtained from linear fits between the rut susceptibility ranking and the values of the mix variables included in Tables 24 to 27.

The variable consistently showing good correlation with the rut susceptibility ranking was binder film thickness. Higher values of binder film thickness corresponded to higher rutting susceptibility rankings. A possible explanation for this behavior is that most Superpave mixtures are coarser than traditional dense-graded pre-Superpave mixes. In other words, Superpave mixtures have lower surface areas to be coated with binder. However, the minimum VMA requirement is the same for both types of mixtures. This has resulted in binder film thicknesses in Superpave mixes that are significantly higher than those generally obtained in pre-Superpave mixtures, which can lower the stability of the mixtures.

Two other variables, percent of aggregate passing sieve 0.075 and dust/asphalt ratio, also showed some correlation with rutting susceptibility although, in this case, the relationships were inverse. Higher values of these interrelated mix variables corresponded to lower susceptibilities to rutting. Perhaps adding small amounts of fine dust to the binder may have the effect of making the asphalt cement/dust mixture behave as a more viscous binder, thus increasing the stability.

Table 23
Coefficients of determination, R^2, between rut ranking and mix variables values

Testing Apparatus	Mix Variable				
	VMA	Pass 2.36	Pass 0.075	Dust/AC	Film Thick
MTS 6 ± 1% AV	0.014	0.58	0.07	0.23	0.85
MTS 8 ± 1% AV	0.72	0.03	0.88	0.97	0.94
SST 7 ± 1% AV	0.004	0.94	0.81	0.92	0.69

Table 24
Comparison of rut ranking of HMAs with different NMAS (from MTS test results)

NMAS	**19 mm**							**25 mm**				
VTM %	4 ± 1		6	8 ± 1				4	6 ± 1			
Mix	1WII$_{61}$	1BI$_{22}$	1WI$_{121}$	1BWI$_{353}$	1BI$_{121}$	1WIII$_{WE}$	1WI$_{22}$	2BIII$_{20}$	2BII$_{61}$	2BIII$_{WE}$	2BII$_{90}$	2BI$_{4}$
Norm. Rank	1.0	2.45	2.67	2.66	2.74	2.76	2.79	1.11	2.15	2.40	2.81	4.0
VMA	13.2	15.0	15.1	17.7	16.9	16.6	18.0	13.9	15.6	16.4	16.7	16.6
%Pass 2.36	29	23	23	40	25	22	25	35	22	21	19	22
%Pass 0.075	5	3.8	3.8	5.1	4.3	5	4.6	4.6	5	4.7	4.4	4.4
Dust/AC$_f$	1.28	0.83	0.9	1.24	1.02	1.19	1.05	1.18	1.28	1.15	1.05	0.99
Ft(micron)	8.23	11.46	11.05	6.78	9.49	10.13	10.64	7.04	8.72	9.88	10.88	11.12

Table 25
Comparison of rut ranking of HMAs with different compaction Levels (from MTS test results)

Comp. Level	**Level I**						**Level II**			**Level III**		
VTM %	4 ± 1	6 ± 1		8 ± 1			4 ± 1	6 ± 1		4 ± 1	6 ± 1	8 ± 1
Mix	1BI$_{22}$	1WI$_{121}$	2BI$_{4}$	1BWI$_{353}$	1BI$_{121}$	1WI$_{22}$	1WII$_{61}$	2BII$_{61}$	2BII$_{90}$	2BIII$_{20}$	2BIII$_{WE}$	1WIII$_{WE}$
Norm. Rank	2.45	2.67	4.0	2.66	2.74	2.79	1.0	2.15	2.81	1.11	2.40	2.76
VMA	15.0	15.1	16.6	17.7	16.9	18.0	13.2	15.6	16.7	13.9	16.4	16.6
%Pass 2.36	23	23	22	40	25	25	29	22	19	35	21	22
%Pass 0.075	3.8	3.8	4.4	5.1	4.3	4.6	5	5	4.4	4.6	4.7	5
Dust/AC$_f$	0.83	0.9	0.99	1.24	1.02	1.05	1.28	1.28	1.05	1.18	1.15	1.19
Ft (micron)	11.46	11.05	11.12	6.78	9.49	10.64	8.23	8.72	10.88	7.04	9.88	10.13

Table 26
Comparison of rut ranking of HMAs with different NMAS (from SST test results)

NMAS	**19 mm**							**25 mm**				
% Air Void	5 ± 1	7 ± 1					9 ± 1	5 ± 1		7 ± 1		
Mix	1WIII$_{WE}$	1WII$_{61}$	1WI$_{22}$	1BI$_{121}$	1WI$_{121}$	1BI$_{22}$	1BWI$_{353}$	2BIII$_{WE}$	2BII$_{61}$	2BIII$_{20}$	2BII$_{90}$	2BI$_{4}$
Norm. Rank	2.81	1.00	1.81	3.23	3.49	4.00	2.78	1.78	3.01	2.26	2.57	3.78
VMA %	16.6	13.2	18.0	16.9	15.1	15.0	17.7	16.4	15.6	13.9	16.7	17.2
%Pass 2.36	22	29	25	25	23	23	40	21	22	35	19	22
%Pass 0.075	5	5	4.6	4.3	3.8	3.8	5.1	4.7	5	4.6	4.4	4.4
Dust/AC$_f$	1.19	1.28	1.05	1.02	0.9	0.83	1.24	1.15	1.28	1.18	1.05	0.99
Ft (micron)	10.13	8.23	10.64	9.49	11.05	11.46	6.78	9.88	8.72	7.04	10.88	11.12

Table 27
Comparison of rut ranking of HMAs with different compaction levels (from SST test results)

Comp. Level	**Level I**						**Level II**			**Level III**		
%Air Void	7 ± 1					9 ± 1	5 ± 1	7 ± 1		5 ± 1		7 ± 1
Mix	1WI$_{22}$	1BI$_{121}$	1WI$_{121}$	2BI$_{4}$	1BI$_{22}$	1BWI$_{353}$	2BII$_{61}$	1WII$_{61}$	2BII$_{90}$	2BIII$_{WE}$	1WIII$_{WE}$	2BIII$_{20}$
Norm. Rank	1.81	3.23	3.49	3.78	4.00	2.78	3.01	1.00	2.57	1.78	2.81	2.26
VMA	18.0	16.9	15.1	17.2	15.0	17.7	15.6	13.2	16.7	16.4	16.6	13.9
%Pass 2.36	25	25	23	22	23	40	22	29	19	21	22	35
%Pass 0.075	4.6	4.3	3.8	4.4	3.8	5.1	5	5	4.4	4.7	5	4.6
Dust/AC$_f$	1.05	1.02	0.9	0.99	0.83	1.24	1.28	1.28	1.05	1.15	1.19	1.18
Ft (micron)	10.64	9.49	11.05	11.12	11.46	6.78	8.72	8.23	10.88	9.88	10.13	7.04

Summary of the Findings of Phase I Study

The performance and fundamental engineering properties of the 12 Phase I Superpave mixtures in this project were analyzed. The influence of nine mix variables was considered. Those variables included: nominal maximum aggregate size (NMAS), mix type, level of compaction effort, dust/AC ratio, binder film thickness, voids in the total mix, voids in the mineral aggregate, percentage of aggregate passing the 0.075 mm sieve, and percentage of aggregate passing the 2.36 mm sieve. The following observations may be made based on the laboratory study of Phase I Superpave mixtures:

The design compaction level was observed to have certain influences on Superpave mixture rut susceptibility. Level I compactive effort (N_{design}=96) showed a higher rut susceptibility than levels II (N_{design}=109) and III (N_{design}=126). However, no significant difference could be found between mixtures compacted at levels II and III.

Asphalt mixtures in different air void groupings performed differently, but for mixtures within a certain air void group, the influence of the air void content was often minimal.

Concerning voids in the mineral aggregate VMA, no consistent trend was observed. Results from the stratified comparison produced very low coefficients of determination, whereas results from the multiple regression analysis identified this mix variable as one with a high contribution to test results.

The nominal maximum aggregate size showed no discernable influence on rut susceptibility, either from studying individual test results or from the multiple regression analysis.

The percentage of aggregate passing the 0.075 mm sieve exhibited an inverse relationship with the rut susceptibility ranking. Mixtures containing lower values of this variable appeared to be more susceptible to rutting. This means that increasing the amount of fine dust (up to a certain limit) by a small amount made the asphalt cement/dust mixture act as a more viscous binder, thus increasing the stability. The percentage of aggregate passing the 2.36 mm sieve, on the other hand, did not have an effect on the susceptibility to rutting.

Film thickness presented a strong, direct relationship with rut susceptibility. Mixtures with higher values of binder film thickness were more susceptible to permanent deformation. A possible explanation of this behavior is that, as those Superpave mixtures considered are usually coarser than pre-Superpave mixtures, they have lower aggregate surface areas to be coated with binder. Without a reduction in asphalt cement content, thicker binder films are caused and have a negative effect on the resistance to permanent deformation. The dust/AC ratio showed an inverse relation with rut susceptibility; that is, mixtures with lower dust/AC ratios appear to be more susceptible to rutting .

Part II – Phase II Superpave Mixtures

As described earlier, the Phase II projects included 18 Superpave mixtures, which were designed based on the updated Superpave mix design gyratory compaction table. Specifically, those mixtures can be categorized into three groups according to three traffic design levels or gyratory compaction numbers: low volume (N_{des} = 75), medium volume (N_{des} = 100), and high volume (N_{des} = 125).

Aggregate Gradation Analysis

In order to evaluate the influence of the aggregate gradation on mixture performance, a Power-law gradation analysis suggested by Ruth et al. [22] was used in this study. As shown in Figure 18, the Power-law gradation analysis characterizes the slopes and intercepts of the fine and coarse aggregate portions in an aggregate gradation curve. The Power-law equations used in this study are expressed as follows:

$$P_{CA} = a_{CA}(d)^{n_{CA}} \qquad \text{and} \qquad P_{FA} = a_{FA}(d)^{n_{FA}} \tag{2}$$

where,

P_{CA} or P_{FA} = percent by weight passing a given sieve have opening of width d;
a_{CA} = intercept constant for the coarse aggregate;
a_{FA} = intercept constant for the fine aggregate;
d = sieve opening width, mm;
n_{CA} = slope (exponent) for the coarse aggregate; and
n_{FA} = slope (exponent) for the fine aggregate.

Equation (2) indicates that a gradation analysis can be divided into two portions: the coarse aggregate (CA) and fine aggregate (FA) portions. In this study, a sieve size of 2.36 mm was selected as a divider for the CA and the FA portions in the regression analysis. In general, five sieves greater than or equal to 2.36mm were used for CA analysis, whereas four sieves smaller than the 2.36 mm were used for the FA regression (refers to the JMFs of the Phase II projects shown in Table 3).

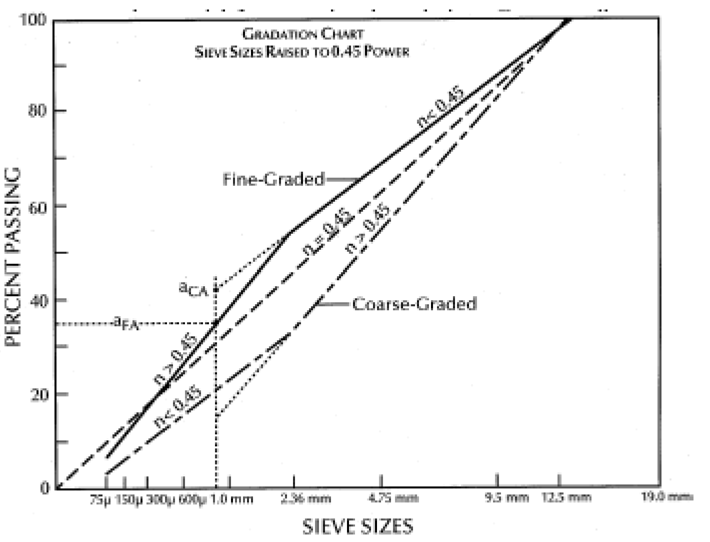


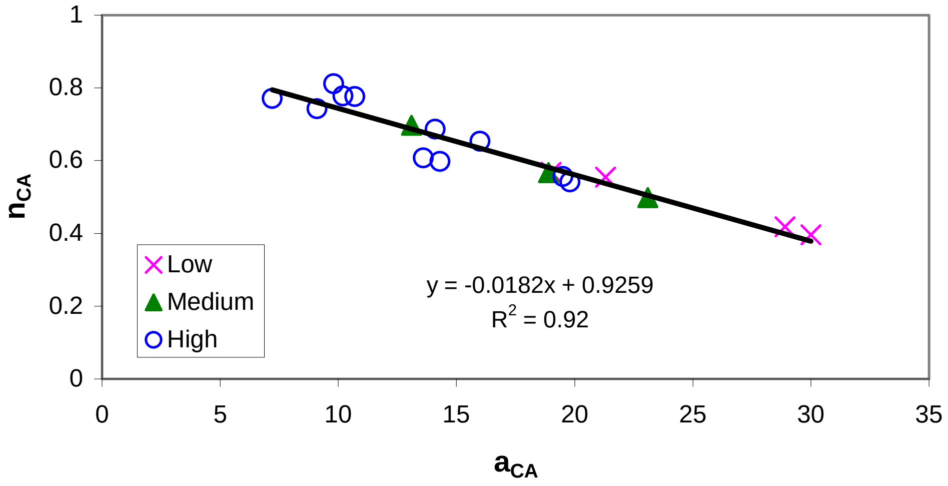
Figure 18
Conceptual differences between fine and coarse gradation [12]

Table 28 presents the results of the power law regression gradation analyses for the 18 mixtures considered in the Phase II projects. The coefficients of determination R^2 for the power-law regression equations were greater than 0.90 for all mixtures, as shown in Table 28. For the coarse-graded mixtures, the CA portion should have an $n_{CA} > 0.45$. The greater the n_{CA} is, the coarser the CA portion will be. For the FA portion, the n_{FA} value can be either greater or smaller than 0.45. The higher n_{FA} value indicates that the FA portion of an aggregate blend is finer.

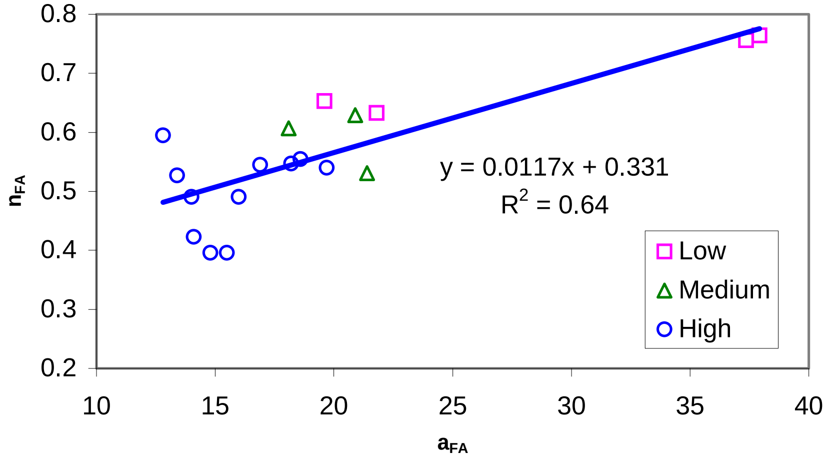
Figures 19 (a) and (b), respectively, present the relationships between the CA portion parameters (a_{CA} and n_{CA}) and the relationships between the FA portion parameters (a_{FA} and n_{FA}) for all mixtures in the Phase II study. In general, both portions appear to have a good linear correlation, although the linear relationship between a_{CA} and n_{CA} is stronger than that between a_{FA} and n_{FA}. As the n_{CA} increases, which means that the CA portion of a mixture blend becomes coarser (e.g., further below the maximum density line), the a_{CA} will decrease. Similarly, as the n_{FA} increases, the a_{FA} will increase, which will cause the FA portion of a mixture blend to become finer. Combining all four gradation parameters together will provide a complete aggregate gradation information for a certain mixture blend. Among the 18 mixtures in this study, the majority of the medium volume and high volume mixtures are coarser than low volume ones (e.g., higher n_{CA} and lower n_{FA}, Figure 19).

Table 28
Results of Power-law regression analyses for the Phase-II Superpave mixtures

Level	Mixture	Coarse Aggregate Portion, > 2.36 mm			Fine Aggregate Portion, < 2.36 mm		
		a_{CA}	n_{CA}	R^2	a_{FA}	n_{FA}	R^2
Low	I-1	30.0	0.396	0.99	37.920	0.764	0.99
	I-2	28.9	0.418	0.95	37.360	0.756	0.96
	I-3	21.3	0.555	0.97	19.6	0.653	0.99
	I-4	19.0	0.568	0.99	21.8	0.633	0.99
Medium	II-1	18.9	0.567	0.98	20.9	0.629	0.98
	II-2	23.1	0.498	0.99	21.4	0.531	0.96
	II-3	13.1	0.697	0.95	18.1	0.607	0.93
High	III-1	10.2	0.778	0.99	12.8	0.595	0.96
	III-2	9.8	0.812	0.96	15.5	0.396	0.97
	III-3	19.5	0.556	1.0	18.6	0.555	1.0
	III-4	19.8	0.541	0.99	19.7	0.54	0.98
	III-5	16.0	0.653	0.98	18.2	0.547	0.99
	III-6	14.1	0.687	0.99	16.9	0.545	0.95
	III-7	10.7	0.776	0.96	16.0	0.491	0.98
	III-25-1	7.2	0.771	0.99	13.4	0.527	0.97
	III-25-2	9.1	0.743	0.96	14.0	0.491	0.96
	III-25-3	13.6	0.607	0.99	14.1	0.423	0.99
	III-25-4	14.3	0.598	0.96	14.8	0.396	0.99



(a)



(b)

Figure 19
(a) and (b) Power-law predicted gradation parameters

Theoretically, both a_{CA} and a_{FA} represent the percent passing of aggregates on a 1 mm sieve. Figure 20 presents the relationships between a_{CA} (or a_{FA}) and the designed percent passing on 1.18 mm (or 0.6 mm) sieves for the Phase II mixtures in this study. As expected, both parameters had fairly good correlations with the percentages of aggregates passing on the sieves of 1.18 mm and 0.6 mm. Very high R^2-values were obtained for the parameter of a_{FA}. Such was expected because the a_{FA} values were obtained through the regression of the fine portion of a gradation curve, in which the percent passings on both 1.18 mm and 0.6 mm sieves were directly included in the analysis.

In addition, the fact that the n_{CA} and n_{FA} parameters represent the curvature properties of the coarse and fine portions of a gradation curve, respectively is noted. When the overall gradation curves change, they will change accordingly. Therefore, the four Power Law parameters (a_{CA}, a_{FA}, n_{CA}, and n_{FA}) presented in Table 28 can be used to describe a whole gradation curve without knowing the detail gradation information (i.e., sieve percent passing). Thus, those gradation parameters will be used in the following mixture performance analysis.

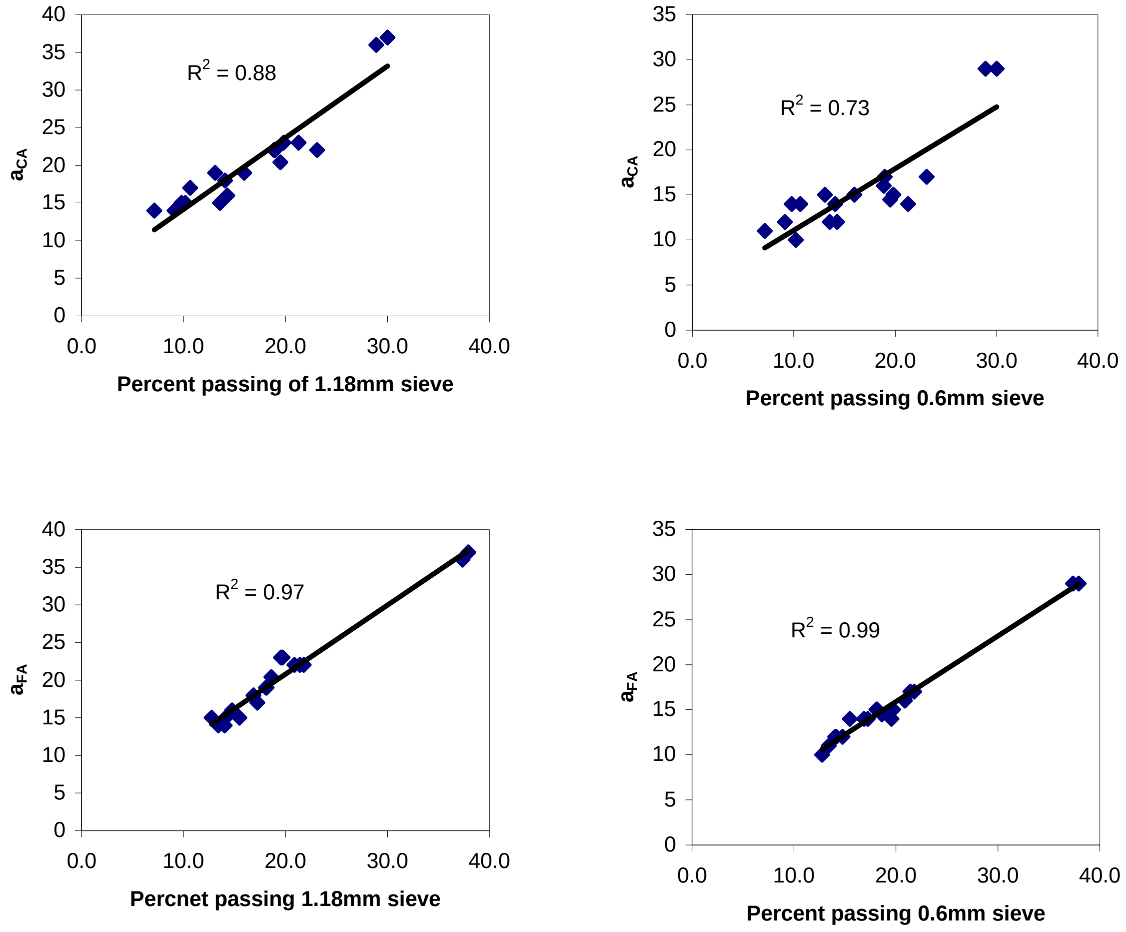


Figure 20
Relationships between gradation parameters and sieve percent passing

Indirect Tensile Strength (ITS) Test

Figure 21 presents the mean tensile strength test results for the 18 Superpave mixtures in the Phase II study. The overall average of the IT strength for the low volume, medium volume, and high volume mixtures was 1,855 kPa (269 psi), 2,085 kPa (302 psi), and 2,254 kPa (327 psi), respectively. Generally, both high volume and medium volume Superpave mixtures had relatively higher IT strength values than those of low volume mixtures. This can be explained by the stiffer binders (PG 76-22M) used in those higher volume mixtures. An exception is Mixture III-1, which had the lowest mean IT strength value among the 18 mixtures studied. The fact that Mixture III-1 possessed the lowest VFA (67.4 percent), highest design air void (4.5 percent), and highest film thickness (13.5 microns), as shown in Table 7, is interesting to note. In addition, this mixture had lower percent aggregate passing of 0.6 mm and 0.3 mm sieves than other mixtures considered.

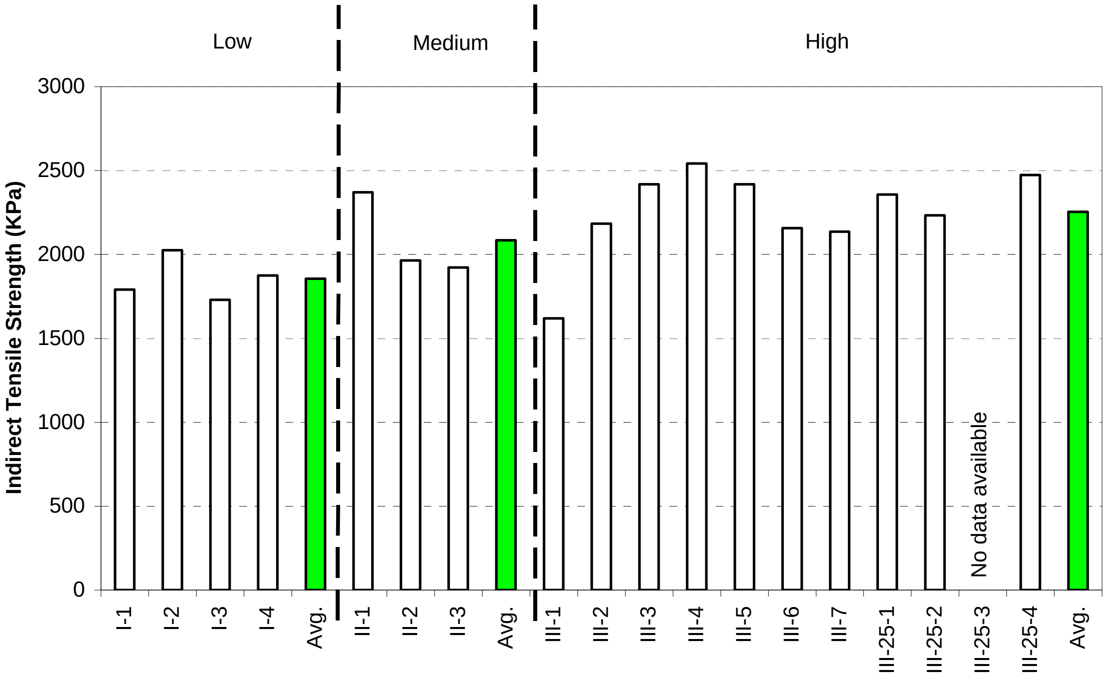


Figure 21
Results of the IT strength test

Regression analysis was performed between the IT strength results and the Power-law gradation parameters (a_{CA}, a_{FA}, n_{CA}, and n_{FA}) in order to evaluate the influence of aggregate gradation on the IT strength of HMA mixtures. The fact that only the 19 mm high volume mixtures were used in the regression analysis is noted. Other mixtures were not considered, due to the following considerations:

- Three different aggregate types (granite, rhyolite, and limestone) were used in the four low volume mixtures; two of them were fine-graded, while the other two were coarse-graded.
- The medium volume mixture group consisted of only three mixtures but with two types of aggregates (novaculite and limestone).
- 25 mm mixtures in the group of high volume, shown in Figure 21, contained different percentages of RAP materials (Table 6).
- In general, because of different binder type, aggregate type, and RAP percentage among different mixture groups, gradation analysis was conducted separately.

Figure 22 presents the correlations between the four gradation parameters and the IT strength test results for the 19 mm high volume mixtures considered. As shown in Figure 22, both intercepts a_{CA} and a_{FA} had a strong linear correlation with the IT strengths, especially for the intercept a_{FA} ($R^2=0.92$). The IT strengths increased with an increase in a_{CA} or a_{FA}. Similar correlation analyses were performed between slopes n_{CA} and n_{FA} and the IT strengths. The slope n_{CA} showed a moderate correlation with IT strength, whereas the slope n_{FA} possessed a poor correlation, as shown in Figure 22.

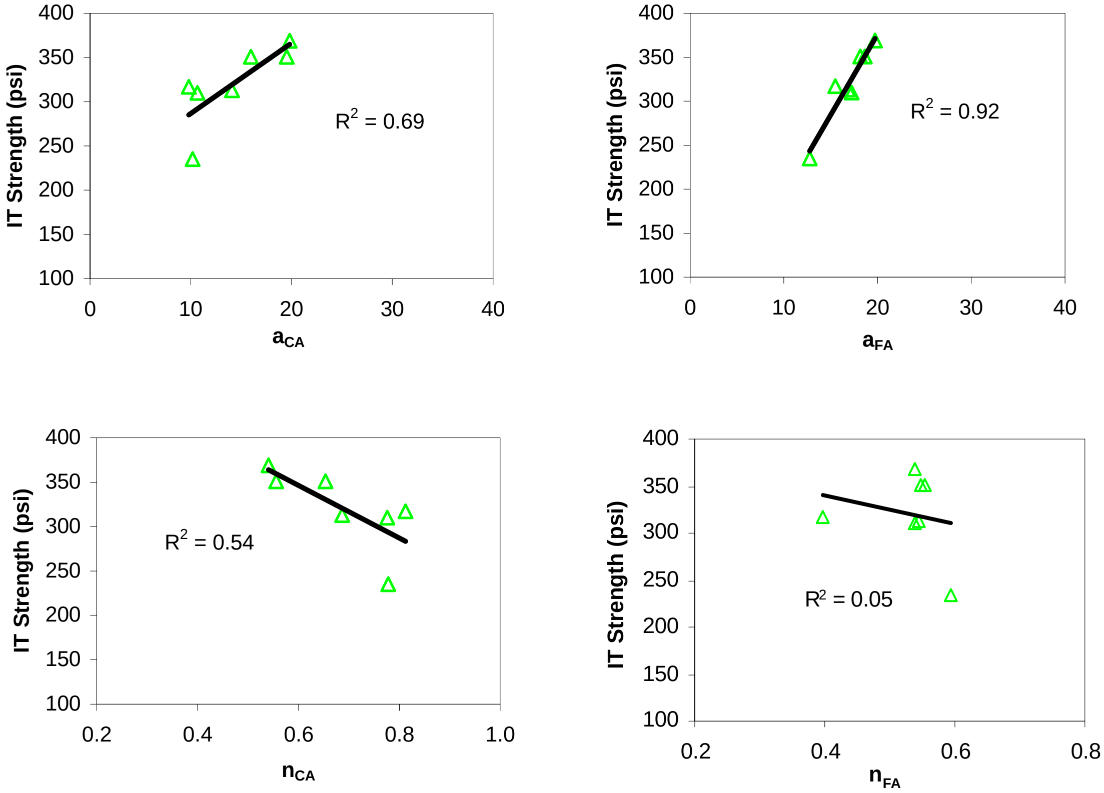


Figure 22
Gradation analysis on ITS test results for 19 mm high volume mixtures

In summary, the IT strength was fairly sensitive to the gradation intercept a_{FA} or a_{CA}. As the largest sieve size used in the fine aggregate portion regression was the 1.18mm sieve (smaller than the 2.36mm sieve), the a_{FA} intercept can be used as a parameter to approximate the total percentage of fine aggregates in a mixture. Thus, the IT strength increases with an increase in intercept a_{FA}, or the total percentage of fine aggregates in a mixture, as shown in Figure 22.

Indirect Tensile Resilient Modulus (Mr) Test

Figures 23-25 present the resilient modulus test results of the 18 Phase II Superpave mixtures at 5, 25, and 40^{o} C, respectively. The overall average of the IT M_r values for the low volume, medium volume, and high volume mixtures, respectively, were: 5,234 MPa (759.7 ksi), 4,742 MPa (688.3 ksi), and 4,395 MPa (637.9 ksi) at 5^{o} C; 4,187 MPa (607.7 ksi), 3,493 MPa (507.0 ksi), and 3,690 MPa (535.5 ksi) at 25^{o} C; and 2,744 MPa (398.3 ksi), 2,772 MPa (402.3 ksi), and 2,660 MPa (386.1 ksi) at 40^{o} C. It is noted that the average M_r values for the low volume Superpave mixtures appeared to be slightly greater than other traffic group mixtures at temperatures of 5 and 25^{o} C. However, this observation was based only on three mixtures (I-1, I-3, and I-4) in the low volume mixture group. In general, the indirect tensile resilient modulus test results indicate that the M_r values for high volume, medium volume, and low volume mixtures in this study essentially had similarly elastic characteristics at different test temperatures. The fact that polymer-modified binders were used in all mixtures may account for this similarity in elasticity.

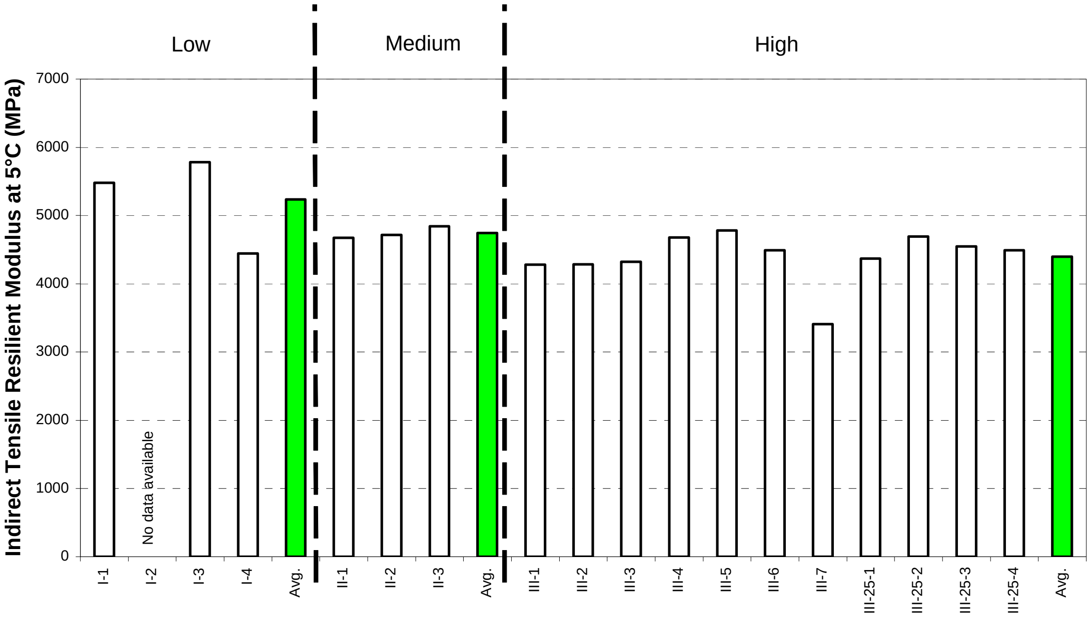


Figure 23
IT M_r test results at 5^oC

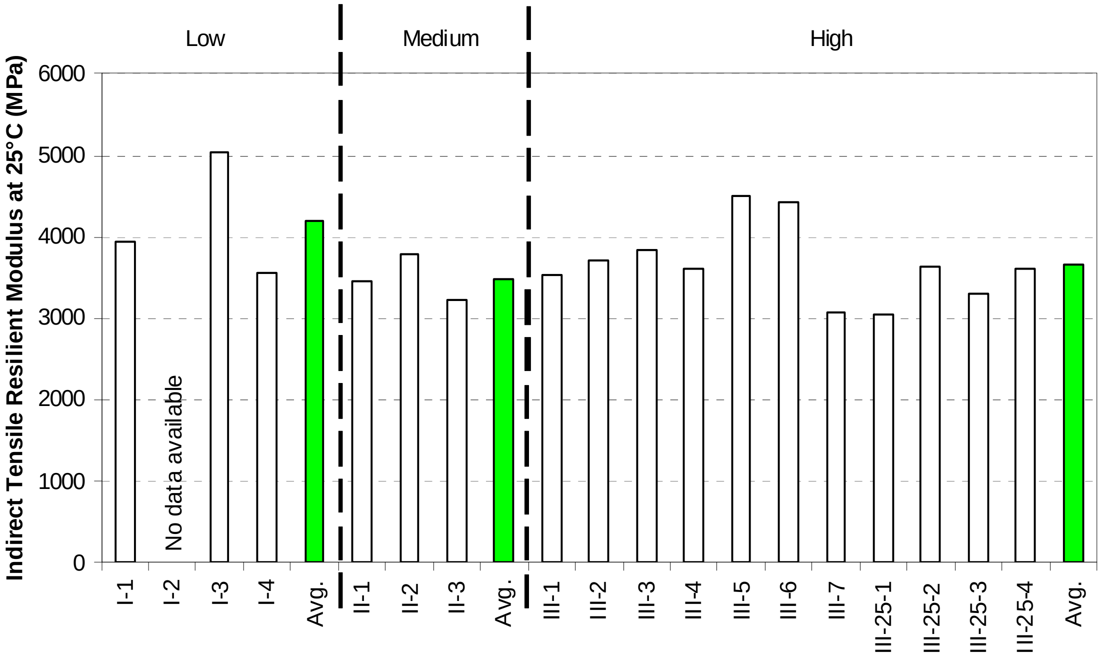


Figure 24
IT M_r test results at 25^{o}C

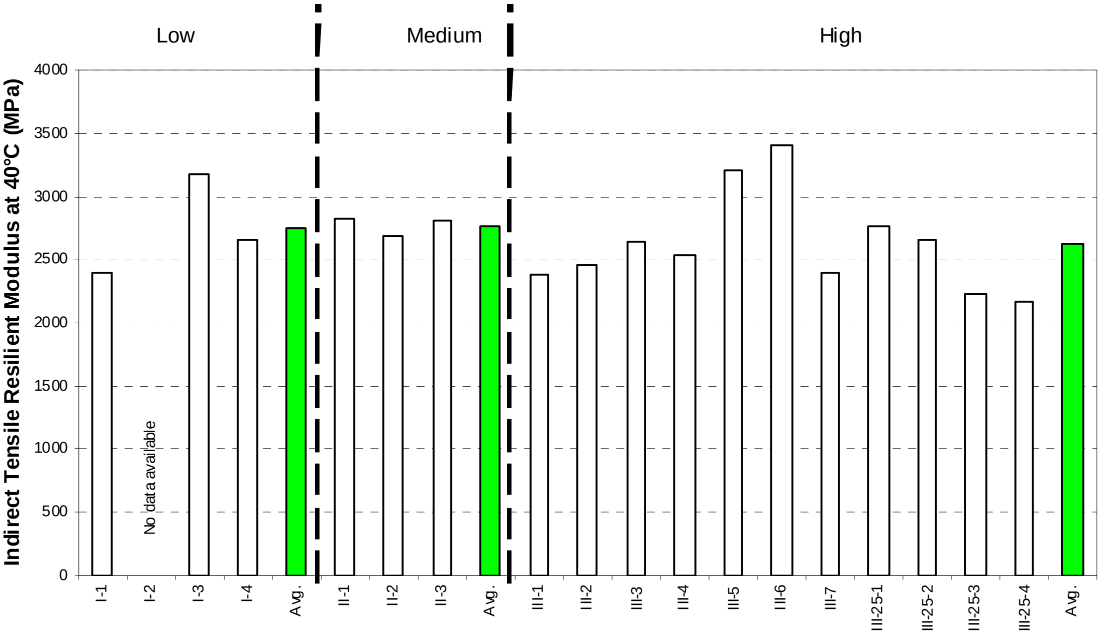


Figure 25
IT M_r test results at 40^{o}C

Gradation analysis was performed on the resilient modulus test results at different test temperatures. Regression results indicate that no significant correlations could be observed between the gradation parameters (a_{CA}, a_{FA}, $n_{CA,}$ and n_{FA}) and M_r values for any mixture group at any test temperatures. Figure 26 shows the variations between the M_r values at 40° C and the gradation parameters. A possible explanation is that, under the resilient modulus test conditions, the elasticity of binder plays a more dominant role in the elastic characteristic of a mixture than different aggregates and structures.

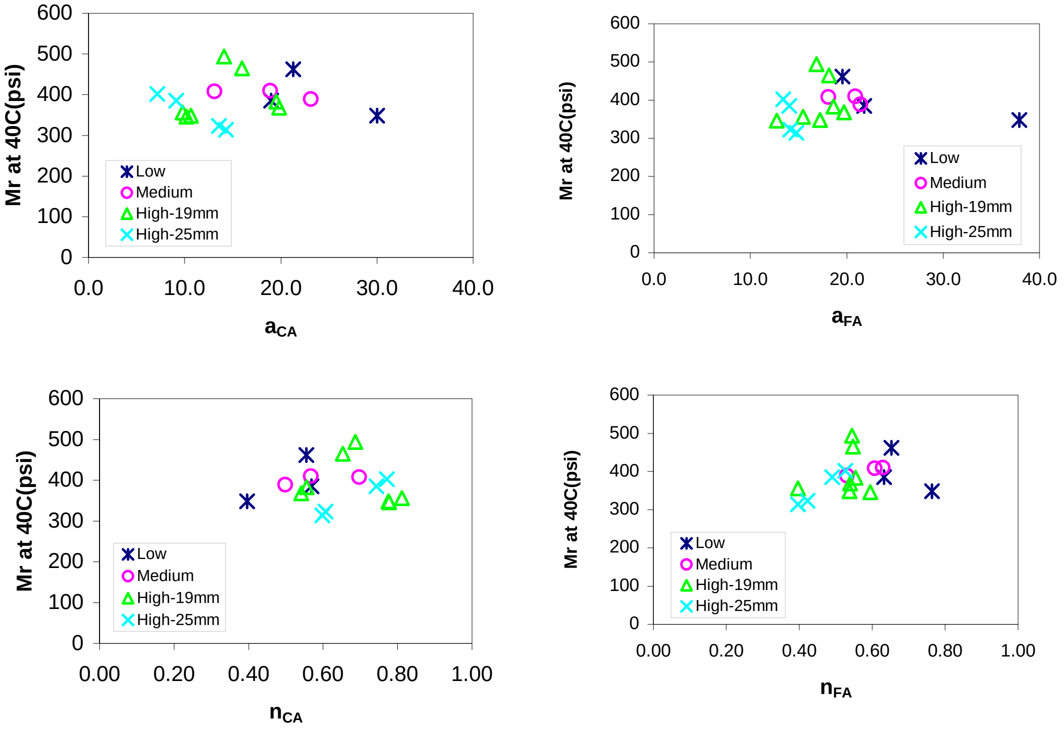


Figure 26
Gradation analysis on IT M_r test results at 40°C

Indirect Tensile (IT) Creep Test

Figure 27 presents the mean IT creep slope results of the 18 asphalt mixtures in the Phase II project. In this test, a lower creep slope is desired for rut resistant mixtures. Among the group, Mixture III-25-2 possessed the lowest IT creep slope, whereas Mixture I-3 had the highest. The overall average of the IT creep slope for the low volume, medium volume, and high volume mixtures was 0.37, 0.31, and 0.35 log-psi/log-sec, respectively. It is expected that high volume mixtures have lower creep slopes than low volume mixtures, indicating better rut resistance. However, no such observation can be made in this study, as shown in Figure 27.

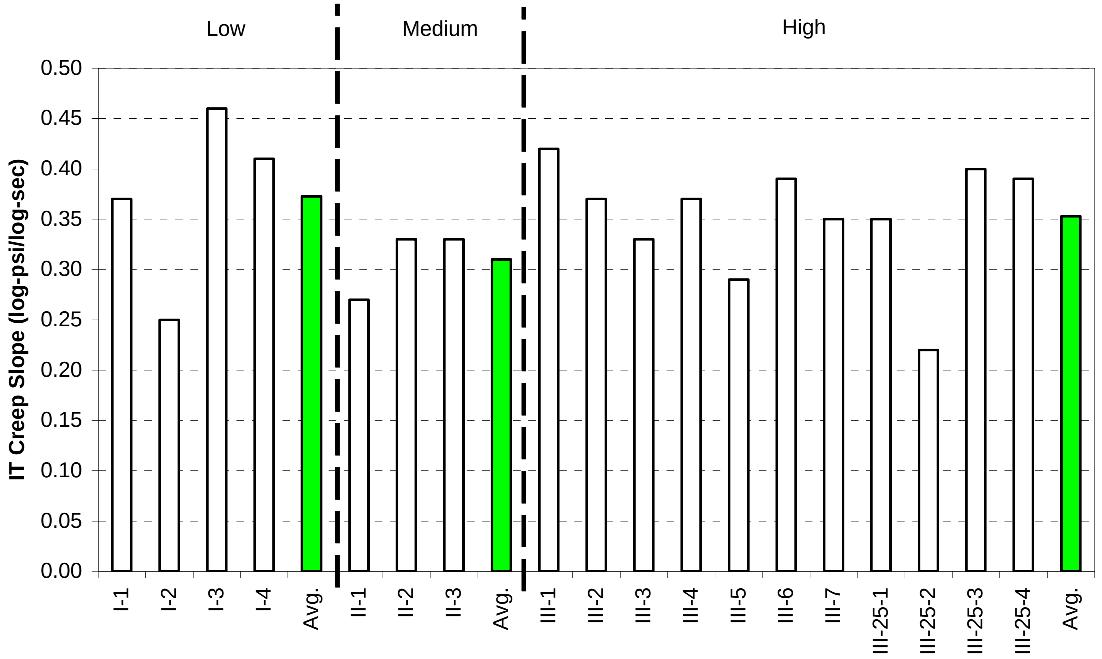


Figure 27
Indirect tensile creep test results

Figure 28 presents the variation of the slopes (n_{CA} and n_{FA}) and intercepts (a_{CA} and a_{FA}) of the Power-law gradation parameters with the creep slope of the high-volume 19 mm mixtures. A parabolic type of relationship was observed between creep slopes and all four gradation parameters (a_{CA}, n_{CA}, a_{FA}, and n_{FA}). The minimum value in this curve corresponds to the lowest creep slope, indicating an optimum value for each gradation parameter that yields a rut resistant mixture. From the previous section, the fact that an increase in intercepts a_{CA} or a_{FA} yielded an increase in the IT strength, as shown in Figure 26, may be noted. Thus, a proper selection of these parameters, such as a_{FA} or a_{CA}, has the potential of providing a balance between rut-resistant and durable mixtures. In summary, gradation parameters were found to be sensitive to the IT creep slope.

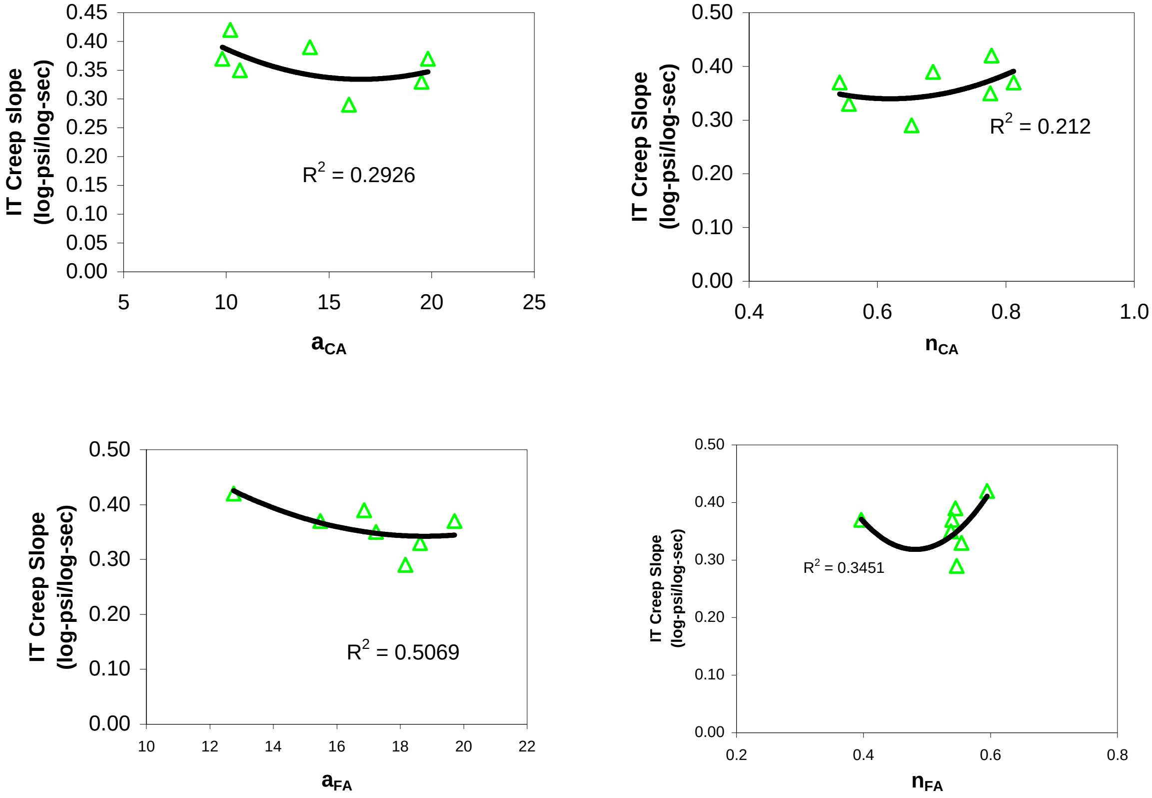


Figure 28
Gradation analysis on IDT creep slopes of 19 mm high volume mixtures

Axial Creep Test

Figure 29 presents the mean axial creep test results of the 18 mixtures considered. In this test, lower creep slope and higher creep stiffness are desired for a rut resistant mixture. As shown in Figure 29, Mixture I-4 had the lowest creep stiffness and highest creep slope. This indicates that I-4 is the least rut resistant mixture among the 18 mixtures considered. The overall average of the axial creep stiffness for the low-volume, medium-volume, and high-volume mixtures was 41.1 MPa (5,967 psi), 46.2 MPa (6,709 psi), and 46.7 MPa (6,775 psi), respectively, where the average creep slope for the low, medium, and high volume mixtures was 13.2×10^{-8} and 12.6×10^{-8} in./in.-sec., respectively. As expected, the majority of high volume mixtures showed lower axial creep slopes and higher stiffness. No explanation can be found at this stage as to why some low volume mixtures possessed even lower axial creep slopes than high volume mixtures.

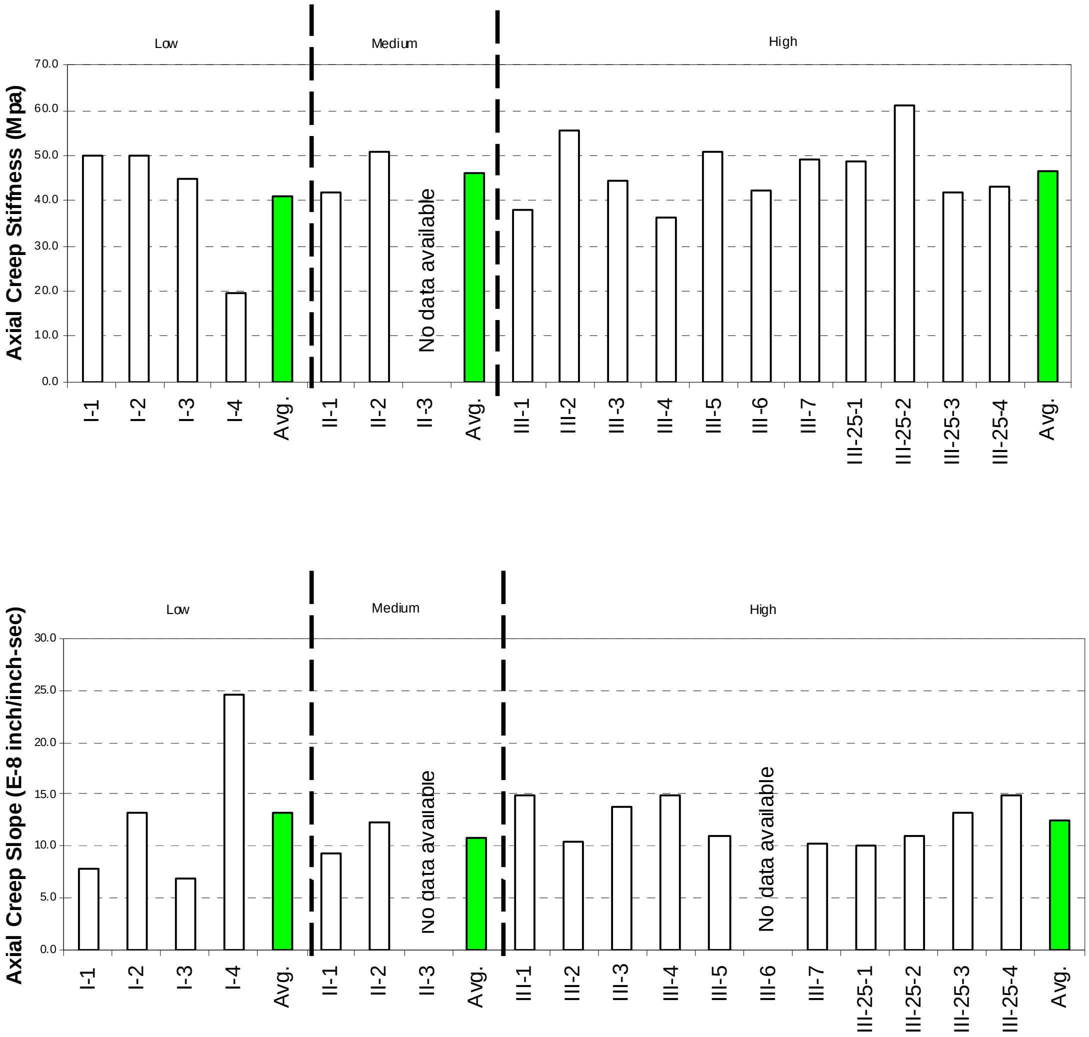


Figure 29
Axial creep test results

Figure 30 presents the variation of the slopes (n_{CA} and n_{FA}) and intercepts (a_{CA} and a_{FA}) of the Power-law gradation analysis with the axial creep slope for the high volume 19 mm mixtures. Similar to the IT creep slope analysis, a parabolic relationship was observed between creep slopes and all four gradation parameters (a_{CA}, n_{CA}, a_{FA}, and n_{FA}).

The best correlation was obtained between the axial creep slope and the intercept a_{FA} (R^2 =0.94). This observation confirms the parabolic correlations found in the IT creep tests and further indicates the sensitivity of gradation parameters on the creep properties of asphalt mixtures.

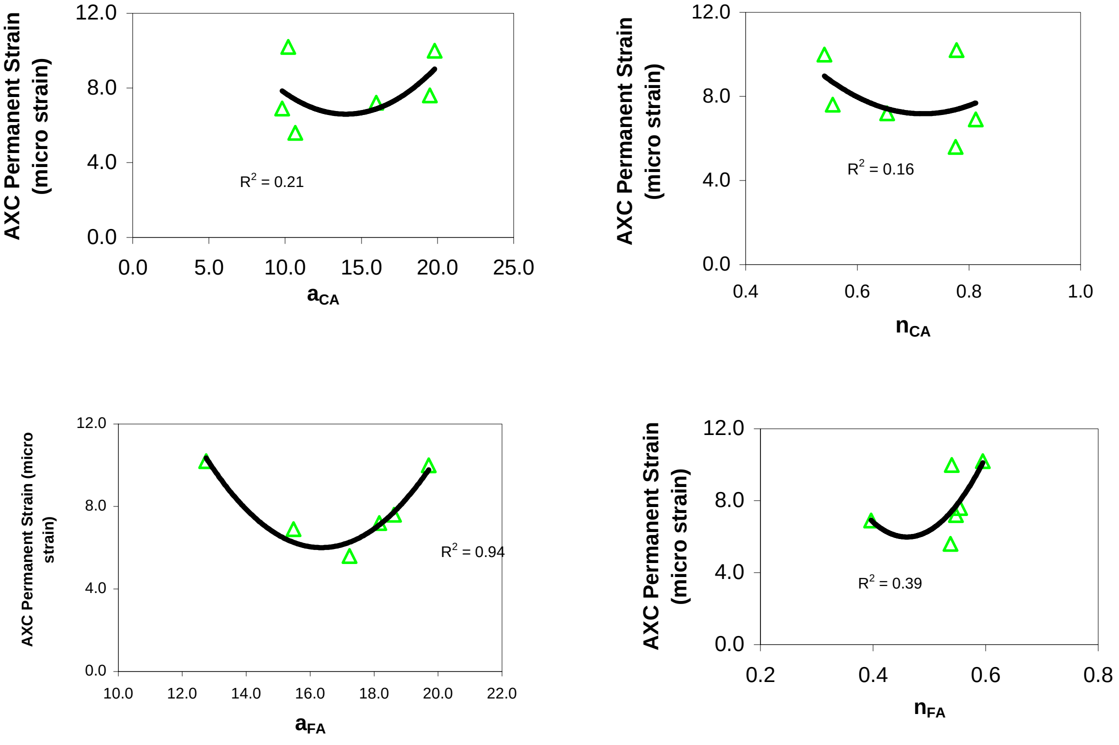


Figure 30
Gradation analysis on axial creep slopes of high volume mixtures

Frequency Sweep at Constant Height Test

Figure 31 presents the mean ratio of the complex shear modulus and phase angle G*/sin(δ) at 10 and 1 Hz, respectively. The complex shear modulus (G*) is defined as the ratio of the peak stress amplitude to the peak strain amplitude. It is a measure of the total stiffness of asphalt mixtures and is composed of elastic and viscous components. Phase angle (δ) is defined as the time lag between the application of a stress and the resulting strain. The property G*/sin(δ) is considered as an indicator of mixtures' susceptibility to permanent deformation. A higher G*/sin(δ) value is desired for rut resistant mixtures. As shown in Figure 31, the overall averages of the G*/sin(δ) values for the low volume, medium volume, and high volume mixtures, respectively, were:115.6 MPa (16.8 ksi), 100.7 MPa (14.6 ksi), and 126.0 MPa (18.3 ksi) at 10 Hz; and 50.6 MPa (7.3 ksi), 53.1 MPa (7.7 ksi), and 49.5 MPa (7.2 ksi) at 1 Hz. Although the rankings of G^*_{10Hz}/sin(δ) and G^*_{1Hz}/sin(δ) were slightly different, both tended to indicate slightly higher average moduli for high volume mixtures.

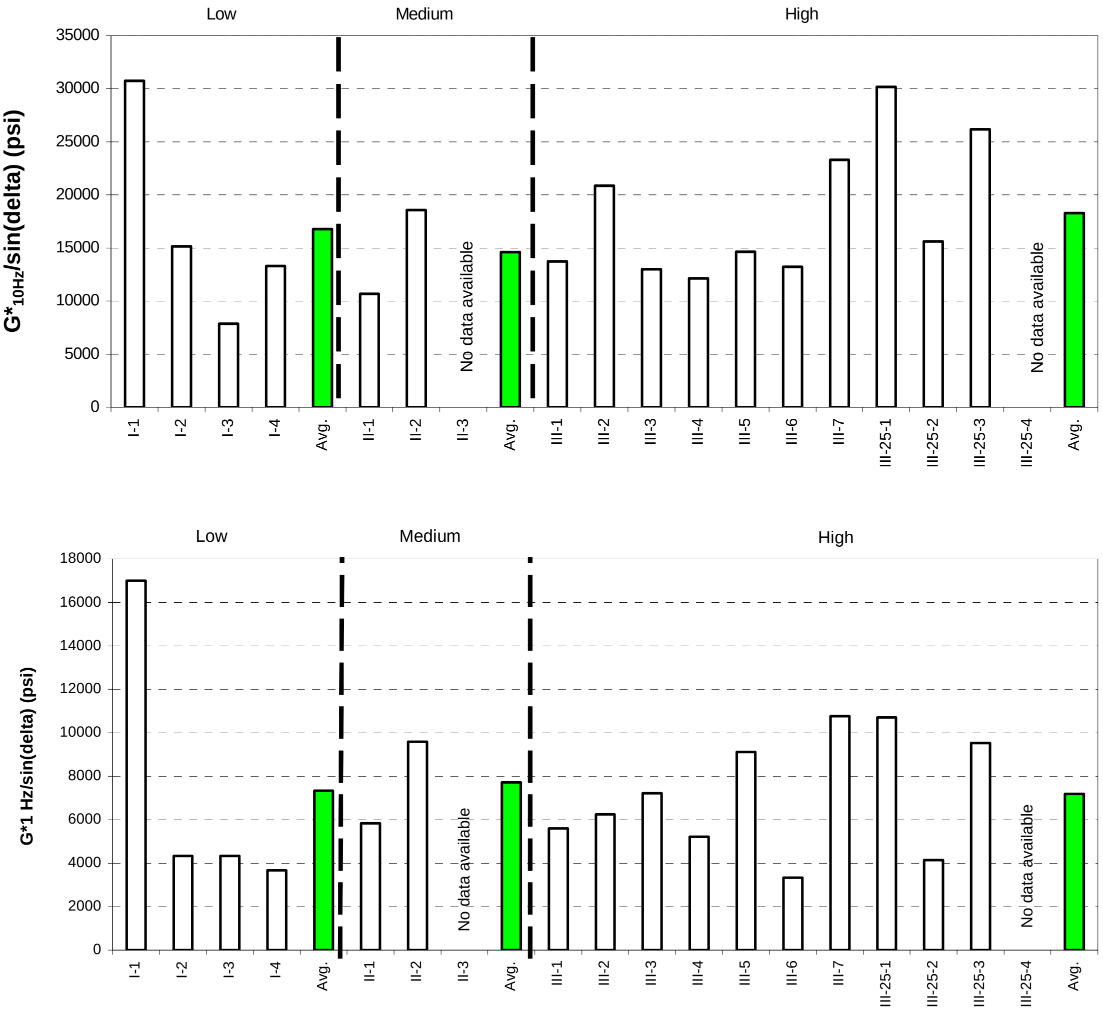


Figure 31
Complex shear modulus test results at 60°C

Figure 32 shows the variation of the slopes (n_{CA} and n_{FA}) of the Power-law gradation analysis with the property G*10Hz/sin(δ) for the high volume 19 mm mixtures. The property G*10Hz/sin(δ) increased with an increase in n_{CA} and a decrease in n_{FA}, as shown in Figure 32. This trend is consistent with the gradation parameters reported in Table 28 for the high volume mixture. As stated earlier, an increase in n_{CA} indicates a coarser coarse aggregate portion of the gradation curve, and a decrease in n_{FA} results in a coarser fine aggregate portion. Similar trends were obtained for G*/sin(δ) at 1 Hz and other frequencies.

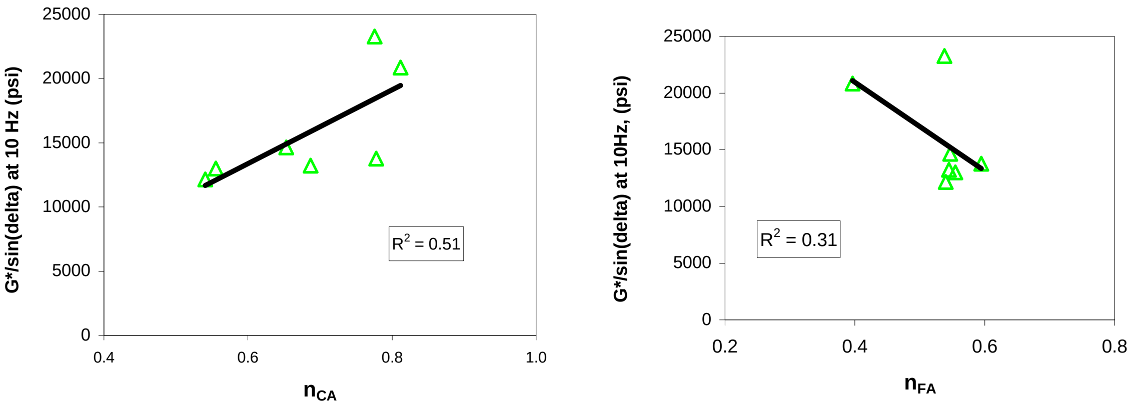


Figure 32
Gradation analysis on G^*_{10Hz} /sin (δ) of high-volume mixtures at 60°C

Repetitive Shear at Constant Height (RSCH) Test

Figure 33 presents the mean permanent shear strain results of the 18 mixtures considered. Lower permanent shear strain is desired for rut resistant mixtures. The permanent shear strains of all the mixtures were below the 5 percent limit at 5,000 cycles. The overall average of the permanent shear strains for the low volume, medium volume, and high volume mixtures was 2.6, 1.3, and 2.0 percent, respectively. Two medium volume mixtures had a relatively low permanent shear strain in this study. Significant variation of the measure permanent shear strains can be observed among low volume and high volume mixtures. Again, Mixture III-1 had the highest permanent shear strain in the high volume mixture group.

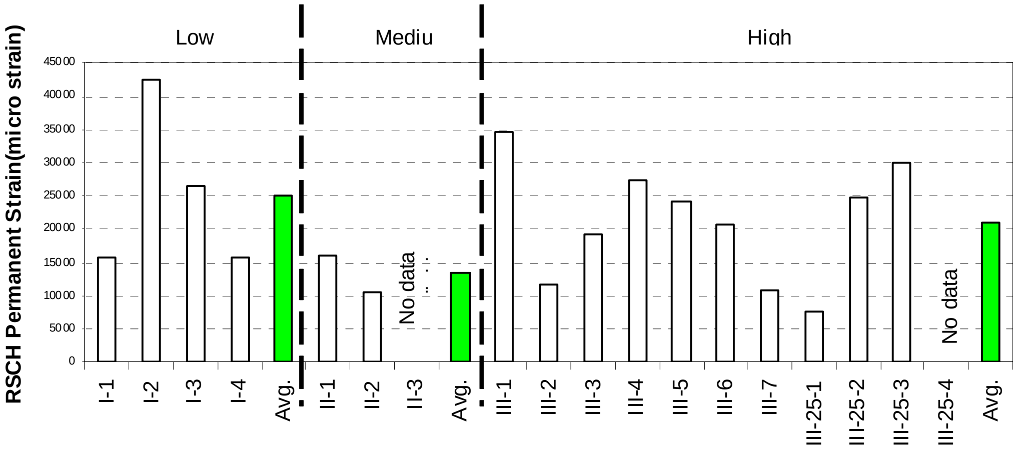


Figure 33
RSCH permanent shear strain test results at 60°C

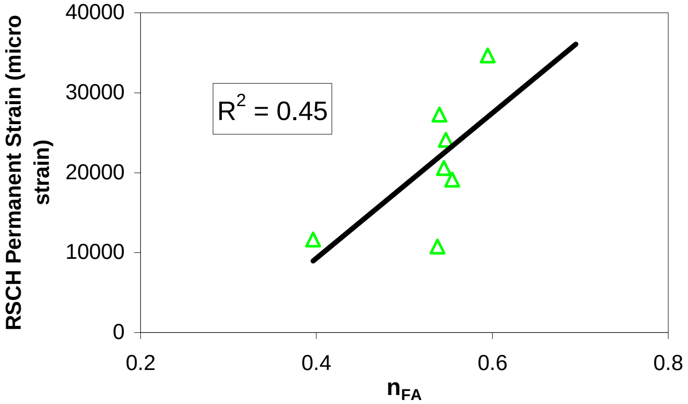


Figure 34
Gradation analysis on RSCH test results of high volume mixtures at 60°C

Figure 34 shows the variation of the slope n_{FA} of the Power-law gradation analysis with the permanent shear strain for the high volume 19 mm mixtures considered. The permanent strain increased with an increase in n_{FA}. This trend is consistent in performance with the one obtained from the FSCH results, i.e., lower G*/sinδ yields higher permanent shear strain as n_{FA} increases, as shown in Figure 32. Other gradation parameters did not provide good correlations with the RSCH test results. The results from the RSCH test are sensitive to the fine portion (FA) of the aggregate gradation. As the FA portion becomes coarser (increase in n_{FA}), more permanent shear strains are accumulated.

Simple Shear at Constant Height (SSCH) Test

Figure 35 presents the mean permanent shear strain of the SSCH test results for the 18 mixtures evaluated. Lower permanent shear strain is desired for rut resistant mixtures. The overall average of the permanent shear strains for the low volume, medium volume, and high volume mixtures was 2,938, 2,134, and 3,753 micro strains, respectively. As shown in Figure 35, significant variation of the measured permanent shear strains can be observed among low volume and high volume mixtures. High-volume mixtures are expected to show higher permanent shear strain in the SSCH tests than lower volume mixtures. As described earlier, in an SSCH test, the specified shear stress of 35 kPa is held constant for 10 seconds and then released (unloading 15 seconds) at a specific rate. Therefore, the significant test variation found in this study could be explained by the high testing temperature (60º C) and a very short unloading period. In other words, under a high temperature test condition, the unloading (releasing) time of 15 seconds may not be long enough for some of the high volume mixtures, as shown in Figure 35.

Figure 36 shows the variation of the two gradation parameters of coarse portion of the Power-law gradation analysis with the simple shear permanent shear strain for the high volume 19 mm mixtures. Similar to the IT creep slope analysis, parabolic relationships were obtained between simple shear permanent strain and a_{CA} and n_{CA}.

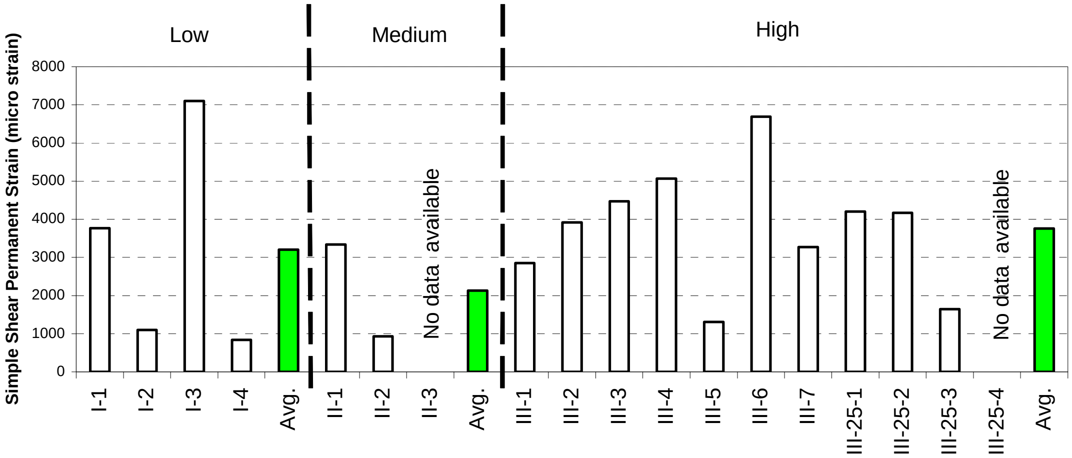


Figure 35
SSCH permanent shear strain test results at 60°C

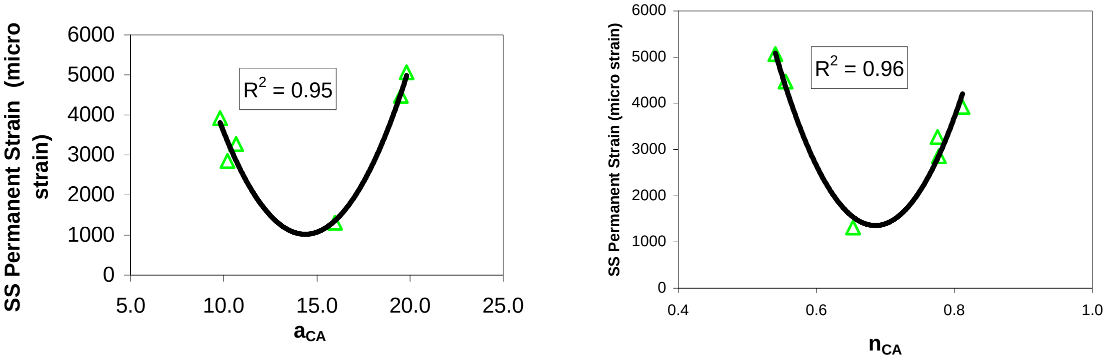


Figure 36
Gradation analysis on SSCH test results at 60°C of 19 mm high volume mixtures

APA Rut Test

Figure 37 presents the mean rut depths of the APA test results for the 18 mixtures evaluated. Lower APA rut depths are desired for rut resistant mixtures. The overall average of the APA rut depths for the low volume, medium volume, and high volume mixtures was 5.8, 2.4, and 3.5 mm, respectively. The medium volume and high volume mixtures are expected to have much lower mean rut depths than the low volume mixtures, which indicates better rut resistance. The exception is Mixture III-6, which is a 19 mm binder course mixture containing 20 percent RAP materials.

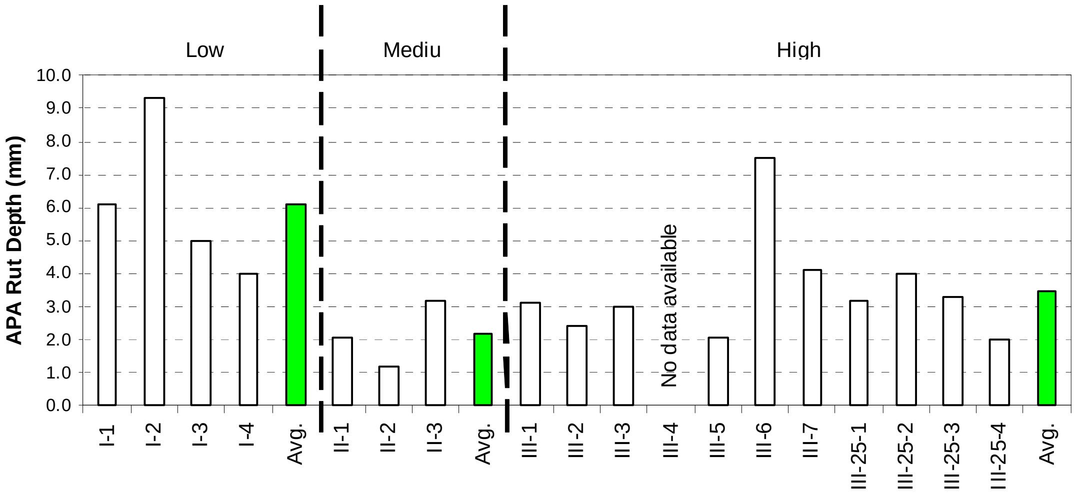


Figure 37
APA test results at 60°C

Figure 38 presents the variation of the four gradation parameters from the Power-law gradation analysis with the APA rut depths for the 18 Superpave mixtures evaluated. Regression results indicate that no strong correlations could be obtained between gradation parameters (a_{CA}, a_{FA}, n_{CA}, and n_{FA}) and APA rut depths for any mixture groups in this study. However, the influence trends of the gradation parameters to the rut susceptibility of asphalt mixtures were found consistent with other performance test results in this study, that is, parabolic trends for a_{CA} and a_{FA} to APA rut depths and linear trends for n_{CA} and n_{FA} to APA rut depths, respectively.

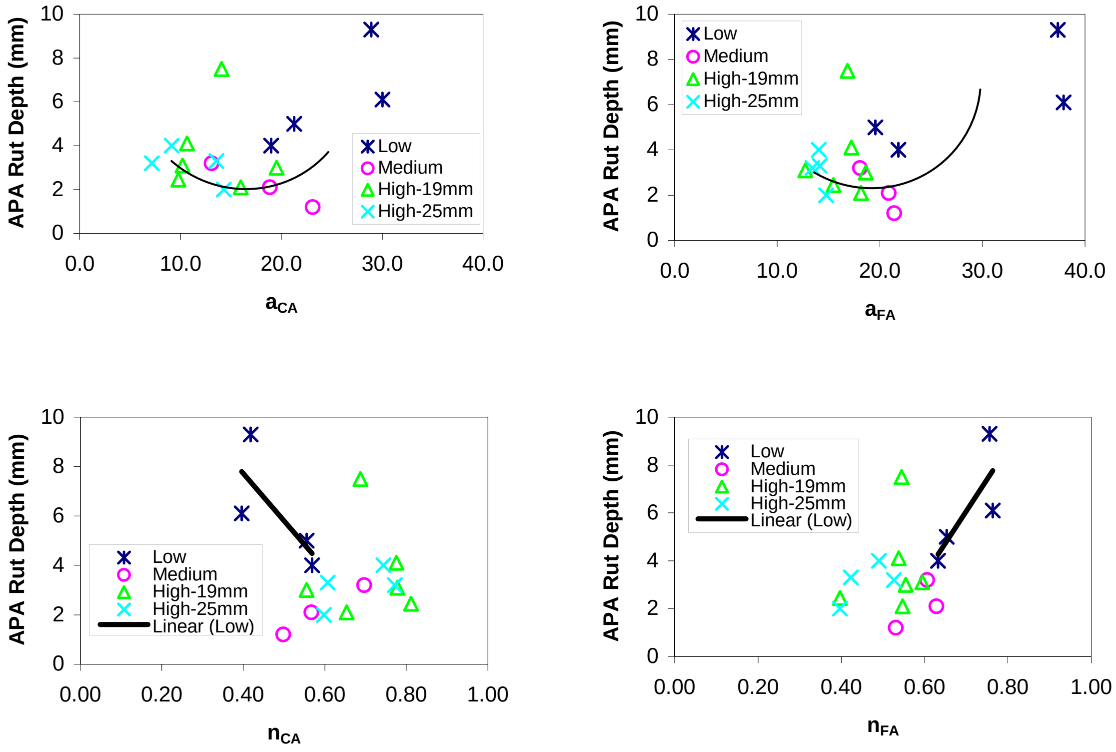


Figure 38
Gradation analysis on APA test results at 60°C of high volume mixtures

Variations of Volumetric Properties on Laboratory Test Results

Figures 39-40 present the variations of VMA and air voids with permanent shear strain of the RSCH test and $G^*_{10Hz}/\sin\delta$ of the FSCH test, respectively. These test properties do not appear to have been sensitive to variations in VMA and air voids for the mixtures evaluated. However, these properties were sensitive to parameters obtained from the gradation analysis described in the preceding section.

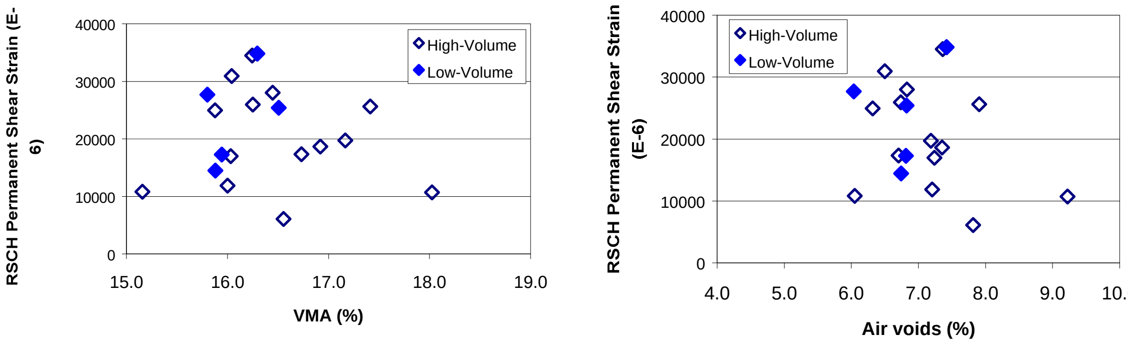


Figure 39
Variation of VMA and air voids with RSCH permanent shear strain at 60°C

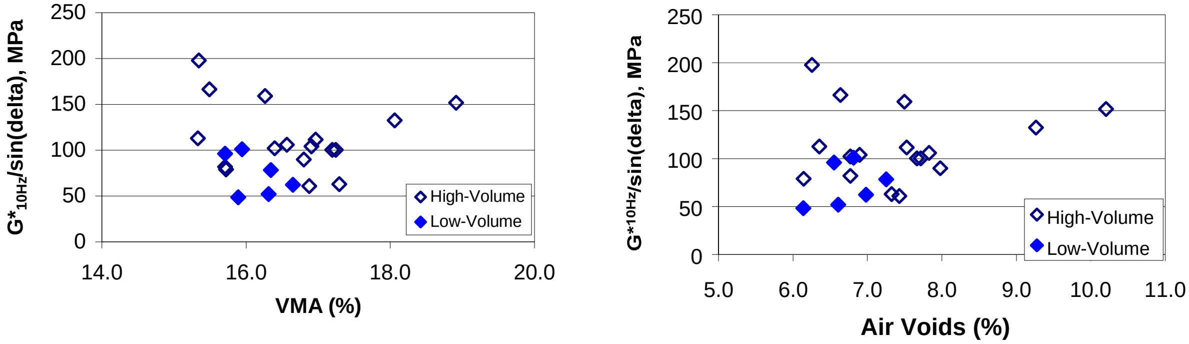


Figure 40
Variation of VMA and air voids with FSCH tests at 60°C properties

Figure 41 presents the relation between volumetric properties (VMA and air voids) and properties of IT strength and IT and axial creep tests. In general, these relationships were not strong, as measured by the coefficient of determination, R^2. A decrease in the IT strength was observed with an increase in VMA and air voids, whereas the creep slope (IT and axial) increased with an increase in VMA and air voids for the mixtures evaluated, as shown in Figure 41. This observation indicates that increasing VMA or air voids worsen the mixture quality as measured by those tests. The properties obtained from the IT and axial mode of testing showed trends of correlations, but no trends were observed in properties obtained from shear mode of testing, as shown in Figure 40.

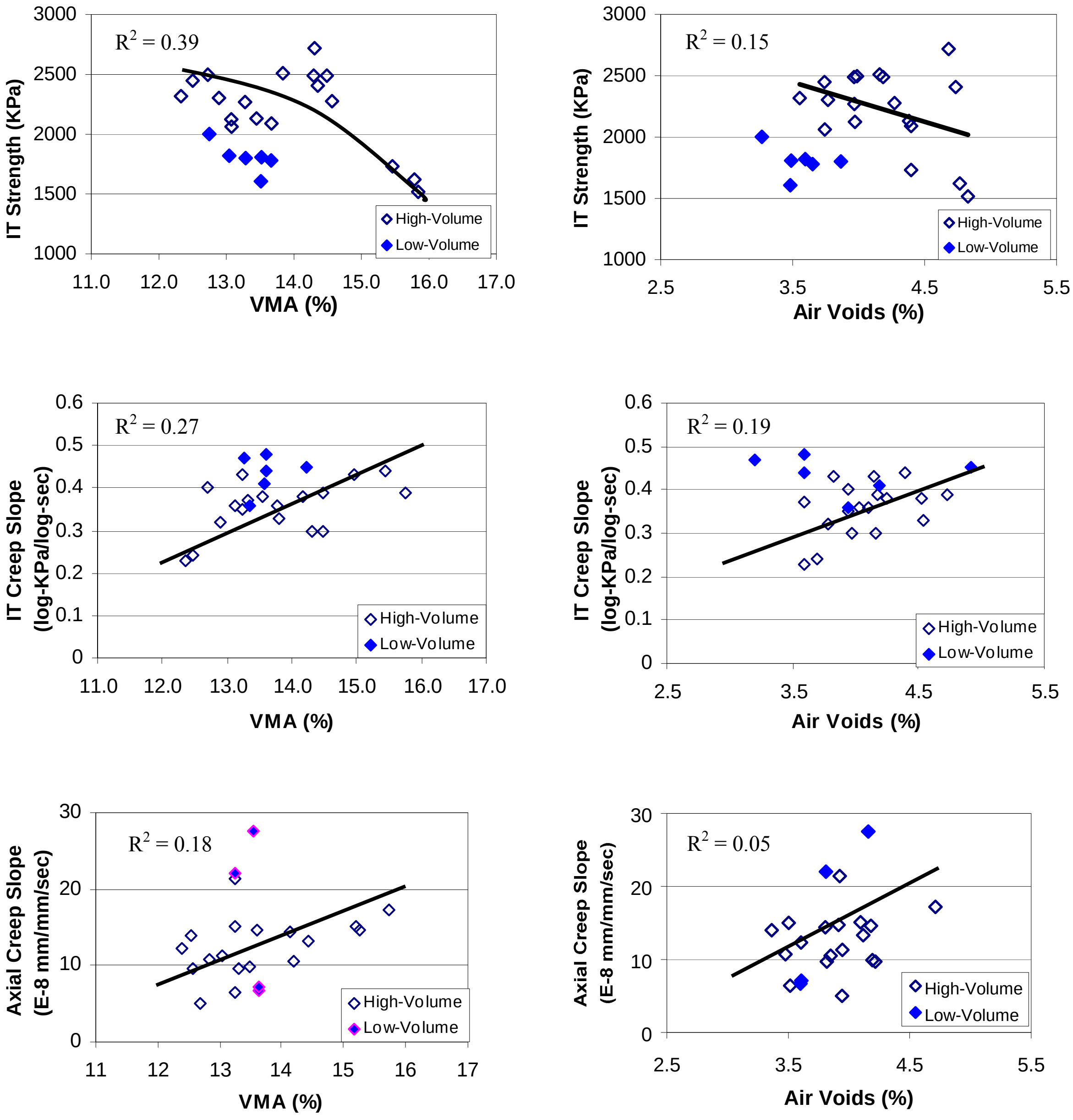


Figure 41
Variation of VMA and air voids with ITS at 25ºC, IT and axial creep at 40ºC test properties

Overall Ranking of Rutting Susceptibility

Similar to the overall ranking concept used among the Phase I mixtures (Tables 18-19), Tables 27-28 present the overall ranking of the rutting susceptibility of the 18 Superpave mixtures based on MTS and SST test results, respectively. Each mixture is ranked numerically from one to four within a comparison group for each performance test. Ranks that have smaller numbers tend to be less susceptible to rutting based on that particular item. In other words, a mixture ranking of one indicates less susceptibility to rutting than a ranking of two. Summing up all points of a mixture from all the tests, a total point is obtained. Consequently, a mixture with a lower ranking number is anticipated to resist rutting better than the ones that have higher ranking numbers.

As shown in Tables 29 and 20, the ranking of rutting susceptibility from the MTS test results is different from that from the SST test results. In general, the majority of mixtures in the Phase II study should be considered as rutting resistant mixtures, as indicated by the ranking of less than 2.0. The average ranking numbers based on the MTS tests were 2.5, 1.9, and 2.2, whereas, based on the SST tests, they were 2.4, 1.8, and 2.3 for low volume, medium volume, and high volume mixtures, respectively. The overall ranking further confirmed that higher volume mixtures generally had better rut resistance than low volume mixtures in this Phase II study. In addition, all mixtures evaluated in this study met the aggregate consensus properties, aggregate gradation, and mixture requirements. However, their laboratory performance was not similar. This demonstrates that meeting aggregate and mixture volumetric criteria does not ensure similar performances. Thus, the application of mechanical tests is necessary in the evaluation of mixture designs. The approach presented in this section provides a tool that correlates aggregate gradation analysis, based on Power-law, to mixture mechanical test properties.

Table 29
Ranking of rutting susceptibility from MTS test results—Phase II

Mix	I-1	I-2	I-3	I-4	II-1	II-2	II-3	III-1	III-2	III-3	III-4	III-5	III-6	III-7	III-25-1	III-25-2	III-25-3	III-25-4
IT Creep	2.88	1.38	4.0	3.38	1.63	2.38	2.38	3.50	2.88	2.38	2.88	1.88	3.13	2.63	2.63	1.0	3.25	3.13
Axial Creep	1.15	2.06	1.0	4.0	1.40	1.91	N/a	2.47	1.81	1.98	1.86	1.35	1.83	2.20	1.52	1.69	2.08	2.87
Average	2.01	1.72	2.5	3.69	1.51	2.14	2.38	2.98	2.34	2.18	2.37	1.61	2.48	2.41	2.07	1.35	2.66	3.0
Normalized	**1.86**	**1.48**	**2.48**	**4.0**	**1.22**	**2.02**	**2.32**	**3.10**	**2.28**	**2.06**	**2.31**	**1.34**	**2.45**	**2.36**	**1.93**	**1.0**	**2.69**	**3.12**

Table 30
Ranking of rutting susceptibility from SST test results—Phase II

Mix	I-1	I-2	I-3	I-4	II-1	II-2	II-3	III-1	III-2	III-3	III-4	III-5	III-6	III-7	III-25-1	III-25-2	III-25-3	III-25-4
FSCH	1.0	3.05	4.0	3.29	3.63	2.60	N/a	3.23	2.30	3.33	3.44	3.11	3.30	1.98	1.08	2.98	1.60	N/a
RSCH	1.71	4.0	2.64	1.71	1.72	1.24	N/a	3.29	1.34	1.98	2.67	2.40	2.10	1.26	2.89	1.0	2.02	N/a
SSCH	1.89	1.12	4.0	1.0	2.19	1.04	N/a	1.96	2.47	2.74	3.02	1.22	3.80	2.16	2.31	2.59	1.64	N/a
Average	1.53	2.72	3.55	2.0	2.51	1.63	N/a	2.83	2.04	2.68	3.04	2.25	3.07	1.80	2.09	2.19	1.76	N/a
Normalized	**1.0**	**2.77**	**4.0**	**1.69**	**2.46**	**1.14**	**N/a**	**2.93**	**1.75**	**2.71**	**3.25**	**2.06**	**3.28**	**1.40**	**1.83**	**1.98**	**1.33**	**N/a**

Rutting Susceptibility Ranking: 1 represents the lowest rutting susceptibility, 4 represents the highest. Therefore, the following scale was used to rank the mixtures:
1 = Excellent resistance to rutting
2 = Good resistance to rutting
3 = Fair resistance to rutting
4 = Marginal resistance to rutting

Summary of Findings of Phase II Study

The performance of the 18 Phase II Superpave mixtures was evaluated through laboratory mechanistic tests, aggregate gradation analysis, and field performance. The findings are summarized below:

- The results of the Power-law regression analyses showed that high volume mixtures were coarser than low volume mixtures considered in this study.

- High volume mixtures appeared to have higher IT strengths when compared to those of low volume mixtures. The IT strength was fairly sensitive to the gradation intercept a_{FA} or a_{CA}. Furthermore, the IT strength increases with an increase in intercept a_{FA}, or the total percentage of fine aggregates in a mixture.

- High volume mixtures exhibited lower creep slopes than low volume mixtures. Gradation parameters were found quite sensitive to the IT creep slope.

- Parabolic correlations were observed between the IT and axial creep tests and gradation analysis slopes and intercept. This indicates that gradation parameters are sensitive to the creep properties of asphalt mixtures.

- The property $G^*_{10Hz}/\sin(\delta)$ increased with an increase in n_{CA} and a decrease in n_{FA} slopes.

- The results from RSCH tests are sensitive to the fine portion (FA) of the aggregate gradation. More permanent shear strain was accumulated with an increase in the FA portion of the aggregate gradation (an increase in n_{FA}).

- $G^*_{10Hz}/\sin(\delta)$ and RSCH permanent shear strain were not sensitive to variations in VMA and air voids for the mixtures evaluated.

- A trend in decreasing IT strength and increasing IT and axial creep slope with an increase in VMA and air voids was observed.

Part III – Grouping and Correlation Analyses of Fundamental Engineering Properties of Superpave Mixtures

Grouping Analysis

Phase I and Phase II, altogether, included 30 Superpave mixtures. Those mixtures can be further grouped by three compaction design levels. Table 31 presents the grouping of those mixtures. The overall test results for those mixtures are summarized in Table 32 and Table 33. Specifically, Table 32 presents the average test results using MTS machine, while Table 33 provides the average test results using SST and APA devices.

Table 31
Groupings of Superpave mixtures

Superpave Mixtures									
Level-I	Level-II					Level-III			
N_{des}=75	N_{des}=96		N_{des}=100	N_{des}=109		N_{des}=125		N_{des}=126	
NMAS=19	NMAS=19	NMAS=25	NMAS=19	NMAS=19	NMAS=25	NMAS=19	NMAS=25	NMAS=19	NMAS=25
I-1 I-2 I-3 I-4	IBI22 IWI22 IBI121 IWI121 IBWI353	2BI4	II-1 II-2 II-3	1WII61	2BII61 2BII90	III-1 III-2 III-3 III-4 III-5 III-6 III-7	III-25-1 III-25-2 III-25-3 III-25-4	1WIIIwe	2BIIIwe 2BIII20

Table 32
Overall test results (by MTS)

Mixtures		NMS (mm)	Binder PG Grade	ITS		IT Mr (ksi)			IT Creep, 40°C		Axial Creep, 40°C	
				Strength (psi)	Strain (%)	5°C	25°C	40°C	Slope (log-psi/log-sec)	Intercept (log psi)	Stiffness (psi)	Slope (x10^{-8} in/in-sec)
Level I	I-1	19	PG70-22	260	0.75	795	573	348	0.37	11.25	7271	7.8
	I-2			294	0.6	N/a	N/a	N/a	0.25	12.40	7241	13.2
	I-3			251	0.59	839	733	462	0.46	10.80	6501	6..9
	I-4			272	0.56	645	517	385	0.41	11.60	2853	24.7
	Range			251~294	0.56~0.75	645~795	517~733	348~462	0.25~0.46	10.8~12.4	2853~7271	6.9~24.7
	Mean			269.3	0.63	759.7	607.7	398.3	0.4	11.5	5966.5	13.2
	Standard Deviation			18.6	0.09	101.7	112.1	58.2	0.1	0.7	2106.0	8.2
	Coefficient of Variation (%)			6.9	13.6	13.4	18.4	14.6	24.0	5..9	35.3	62.3
Level II	1BI$_{22}$	19	PG64-22	278	0.27	684	451	357	0.45	11.73	9618	7.6
	1WI$_{22}$			193	0.32	506	352	207	0.35	11.40	5319	16.5
	1BI$_{121}$			222	0.15	553	391	261	0.44	11.94	7837	12.1
	1WI$_{121}$			245	0.63	596	386	246	0.44	11.20	7126	10.1
	IBWI$_{353}$		PG70-22	225	0.87	559	349	195	0.43	11.12	6071	5.45
	2BI$_{4}$	25	PG64-22	148	0.64	426	325	181	0.54	10.76	5566	22.9
	II-1	19	PG76-22	344	0.38	678	502	410	0.27	11.36	6065	9.3
	II-2			285	0.43	684	550	389	0.33	11.94	7352	12.3
	II-3			279	0.48	703	469	408	0.33	11.34	N/a	N/a
	1WII$_{61}$		PG70-22	290	0.51	681	444	301	0.27	11.69	11935	4.3
	2BII$_{61}$	25		225	0.40	630	436	264	0.43	11.46	11408	7.5
	2BII$_{90}$			171	0.70	503	315	197	0.51	10.96	7605	6.2
	Range			148~344	0.15~0.87	426~703	315~550	197~410	0.27~0.54	10.76~11.94	5319~11935	4.3~16.5
	Mean			242.1	0.48	600.3	414.2	284.7	0.4	11.4	7809.3	10.4
	Standard Deviation			56.0	0.20	90.8	73.3	86.5	0.1	0.4	2264.1	5.4
	Coefficient of Variation (%)			23.1	41.8	15.1	17.7	30.4	22.1	3.2	29.0	52.5

Table 32
Overall test results (by MTS) (continued)

Mixtures		NMS (mm)	Binder PG Grade	ITS		IT Mr (ksi)			IT Creep, 40°C		Axial Creep, 40°C	
				Strength (psi)	Strain (%)	5°C	25°C	40°C	Slope (log-psi/log-sec)	Intercept (log psi)	Stiffness (psi)	Slope ($x10^{-8}$ in/in-sec)
Level III	III-1	19	PG76-22	235	0.37	621	513	346	0.42	10.85	5539	14.9
	III-2			317	0.41	622	537	356	0.37	11.70	8026	10.5
	III-3			351	0.47	627	557	383	0.33	11.83	6444	13.9
	III-4			369	0.43	679	523	368	0.37	11.27	5254	14.9
	III-5			351	0.35	694	652	465	0.29	12.07	7406	11.0
	III-6			313	0.46	652	643	494	0.39	11.80	6157	N/a
	III-7			310	0.69	495	446	348	0.35	11.18	7128	10.3
	III-25-1	25		342	0.26	634	444	402	0.35	11.27	7092	10.0
	III-25-2			324	0.36	681	529	385	0.22	11.27	8845	11.0
	III-25-3			N/a	N/a	660	479	323	0.40	11.12	6048	13.3
	III-25-4			359	0.32	652	524	314	0.39	11.42	6238	14.9
	$1WIII_{we}$	19	PG70-22	192	0.57	477	374	215	0.44	11.27	7300	11.25
	$2BIII_{we}$	25		230	0.88	652	454	315	0.41	11.50	7264	9.42
	$2BIII_{20}$			350	0.72	678	472	267	0.30	11.32	12583	4.46
	Range			192~369	0.26~0.88	477~694	374~652	215~494	0.22~0.44	10.85~12.07	5254~12583	4.46~14.9
	Mean			311.0	0.48	630.3	510.5	355.8	0.4	11.4	7237.4	11.5
	Standard Deviation			56.3	0.18	65.4	75.5	71.9	0.1	0.3	1816.1	2.9
	Coefficient of Variation (%)			18.1	37.5	10.4	14.8	20.2	16.4	2.9	25.1	25.3

Table 33
Overall test results (by SST and APA)

Mixtures		NMS (mm)	Binder PG Grade	FSCH G*/sinδ (psi)				RSCH*	SSCH*	APA*
				10Hz	1Hz	0.1Hz	0.01Hz	Perm. Strain (10^{-6})	Perm. Strain (10^{-6})	Rut Depth (mm)
Level I	I-1	19	PG70-22	30762	17003	11490	9741	15831	3768	6.1
	I-2			15146	4341	3113	2462	42435	1095	9.3
	I-3			7874	4340	3856	3989	26537	7105	5.0
	I-4			13312	3683	2511	9693	15866	842	4.0
	Range			7874~30762	3683~17003	2511~11490	2462~9741	15831~42435	842~7105	4.0~9.3
	Mean			16773.5	7341.7	5242.4	6471.3	25167.3	3202.5	6.1
	Standard Deviation			9823	6448	4201	3799	12566	2919.1	2.3
	Coefficient of Variation (%)			58.6	87.8	80.1	58.7	49.9	91.1	37.7
Level II	1BI$_{22}$	19	PG64-22	14984	6515	5495	5908	26756	3076	4.8
	1WI$_{22}$			21064	8067	4663	3774	14805	2947	2.9
	1BI$_{121}$			22782	7215	3912	3135	15347	1967	7.1
	1WI$_{121}$			16662	6671	4455	4127	11867	3771	4.6
	IBWI$_{353}$		PG70-22	47368	17533	9241	7463	5728	1088	2.1
	2BI$_{4}$	25	PG64-22	14841	5636	4542	4689	22210	3258	7.8
	II-1	19	PG76-22	10663	5842	4919	4386	16082	3334	2.1
	II-2			18565	9587	7702	7860	10510	934	1.2
	II-3			N/a	N/a	N/a	N/a	N/a	N/a	3.2
	1WII$_{61}$		PG70-22	13899	4562	3213	4205	15900	3857	5.9
	2BII$_{61}$	25		31298	10365	5173	4856	5939	1185	4.2
	2BII$_{90}$			23702	8800	5347	4090	14702	1305	4.1
	Range			10663~47368	4562~17533	3213~9241	3135~7463	5728~26756	934~3857	1.2~7.8
	Mean			21438.5	8253.9	5332.9	4953.9	14531.3	2429.3	4.2
	Standard Deviation			10323.9	3543.6	1716.5	1508.1	6229.4	1144.1	2.0
	Coefficient of Variation (%)			48.2	42.9	32.2	30.4	42.9	47.1	48.8

Table 33
Overall test results (by SST and APA) (continued)

Mixtures		NMS (mm)	Binder PG Grade	FSCH G*/sinδ (psi)				RSCH*	SSCH*	APA*
				10Hz	1Hz	0.1Hz	0.01Hz	Perm. Strain (10^{-6})	Perm. Strain (10^{-6}	Rut Depth (mm)
Level III	III-1	19	PG76-22	13760	5600	4135	4439	34664	2852	3.1
	III-2			20863	6246	4065	3890	11638	3917	2.5
	III-3			12995	7216	6295	6684	19145	4473	3.0
	III-4			12154	5224	3736	3360	27269	5068	N/a
	III-5			14630	9117	7744	8025	24095	1311	2.1
	III-6			13224	3344	2010	3708	20568	6696	7.5
	III-7			23286	10763	7249	6451	10755	3273	4.1
	III-25-1	25		30168	10699	5914	4150	7634	4202	3.2
	III-25-2			15646	4141	2803	2103	24682	4170	4.0
	III-25-3			26172	9530	5232	4198	2991	1643	3.3
	III-25-4			N/a	N/a	N/a	N/a	N/a	N/a	2.0
	$1WIII_{we}$	19	PG70-22	33799	12510	6594	5105	8632	1031	3.8
	$2BIII_{we}$	25		36197	13449	7619	5124	6165	1226	4.2
	$2BIII_{20}$			19009	7971	5889	5794	6390	1220	2.7
	Range			12154 ~ 36197	3344~ 13449	2010~ 7744	2103~ 8025	2991~ 34664	1031~ 6696	2.0~7.5
	Mean			20915.6	8139.3	5329.6	4848.4	17810.8	3160.1	3.5
	Standard Deviation			8362.3	3188.9	1846.6	1584.1	9821.8	1789.2	1.4
	Coefficient of Variation (%)			40.0	39.2	34.6	32.7	55.1	56.6	40.2

* 60º C

To examine the sensitivity of fundamental engineering properties, Superpave mixtures in this study were further grouped by nominal maximum aggregate size (NMAS), binder PG level, with/without RAP materials, and coarse or fine graded gradations. The effects of those grouping variables, including compaction levels on fundamental engineering properties, were studied, and details can be found in Appendix B. Examples of such sensitivity analyses were given in the following section for the Indirect Tensile Strength and Asphalt Pavement Analyzer (APA) tests.

Indirect Tensile Strength (ITS) Test

The IT strengths for the 30 Superpave mixtures tested in this study varied from 1,020 kPa (148 psi) to 2,545 kPa (369 psi), while the IT strains had a range from 0.15 to 0.88 percent, as shown in Table 34.

Figure 42 presents the mean IT strength test results for Superpave mixtures grouped at different compaction levels. The average IT strength for the Level I, Level II, and Level III mixtures was 1,857 kPa (269 psi), 1,670 kPa (242 psi), and 2,145 (311 psi), respectively. The statistical ranking presented in Table 34 indicates that the mean IT strength for Level III mixtures (ranked as an "A") is significantly higher than those for Level I and Level II mixtures (both ranked as a "B"). This could be attributed partly to both the stiffer binders (PG 76-22M) and the higher design gyratory compaction efforts used in the Level III mixture design. However, there was no statistically significant difference in the mean IT strains among mixtures compacted at different compaction levels, as shown in Table 35.

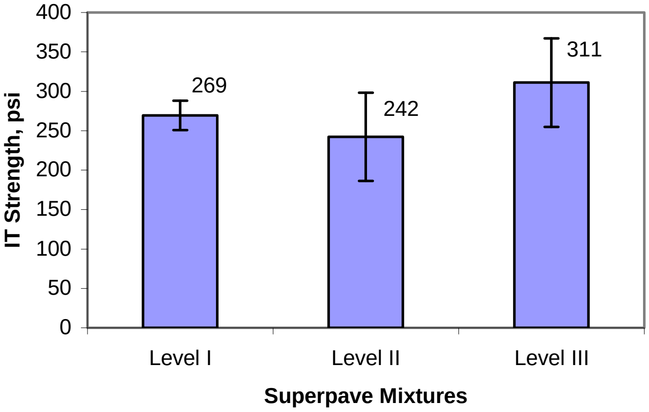


Figure 42
Mean IT strength test results of mixtures at different compaction levels

Table 34
The statistics of ITS test results on mixtures by level

Mix Type	Mean IT Strength, (psi)	STD (psi)	CV%	Max (psi)	Min (psi)	Statistic Grouping
Level-I	**269.3**	18.6	6.9	294.0	251.0	**B**
Level-II	**242.1**	56.0	23.1	344.0	148.0	**B**
Level-III	**311.0**	56.3	18.1	369.0	192.0	**A**
	Mean IT Strain, (%)	STD (%)	CV%	Max (%)	Min (%)	
Level-I	**0.63**	0.09	13.6	0.8	0.6	**A**
Level-II	**0.48**	0.20	41.8	0.9	0.2	**A**
Level-III	**0.48**	0.18	37.5	0.9	0.3	**A**

Figure 43 presents the mean IT strength results of those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively.

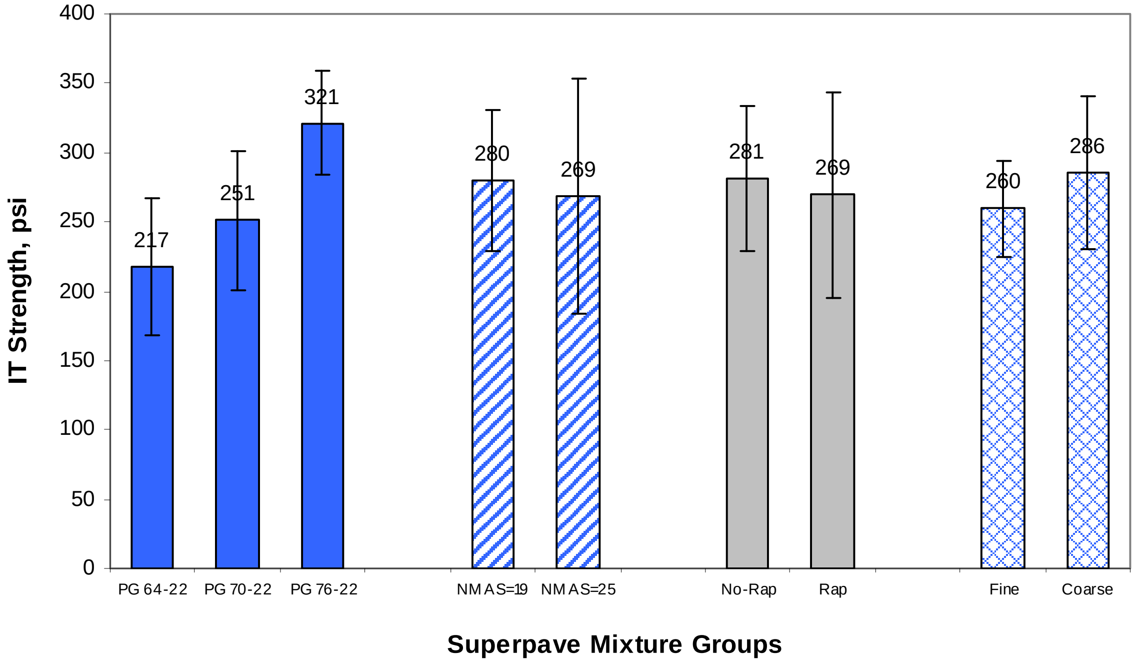


Figure 43
Mean IT strength test results of mixtures at different groups

Figure 43 shows that:

- Mixtures with higher PG binders tended to have higher IT strength values; in other words, $ITS_{(PG\ 76\text{-}22)} > ITS_{(PG\ 70\text{-}22)} > ITS_{(PG\ 64\text{-}22)}$. This indicates that the IT strength values for Superpave mixtures are sensitive to the binder PG types.
- As the NMAS increased from 19 mm to 25 mm, the IT strength tended to decrease, i.e., $ITS_{(19mm)} > ITS_{(25mm)}$. However, the difference in ITS between 19 mm and 25 mm Superpave mixtures was not statistically significant.
- Mixtures with no RAP appeared to have higher IT strengths than mixtures containing RAP, i.e., $ITS_{(no\text{-}RAP)} > ITS_{(RAP)}$. This is expected, as RAP materials contain aged binders that are less flexible in tension. However, the difference was not statistically significant.
- The mean IT strength for the coarse-graded Superpave mixtures appeared to be higher than that for the fine-graded, i.e., $ITS_{(coarse)} > ITS_{(fine)}$. This may be attributed to the difference in aggregate structure (interlocking) between coarse-graded and fine-graded mixtures. However, this difference in the mean ITS results was not statistically significant.

APA Rut Test

The APA rut depths for the 30 Superpave mixtures tested varied from 1.2 to 9.3 mm. The individual APA test results of the mixtures can be found in Table 35.

Figure 44 presents the mean APA test results for Superpave mixtures grouped at different compaction levels. The average APA rut depth for the Level I, Level II, and Level III mixtures was 6.1, 4.2, and 3.5 mm, respectively. The statistical ranking presented in Table 35 indicates that the mean APA rut depths for both Level II and Level III mixtures (both ranked as an "A") are significantly smaller than that for Level I mixtures (ranked as a "B"), indicating that Level II and Level III mixtures have better rut resistance than Level I mixtures. This implies that the APA rut test is fairly sensitive to Superpave gyratory compaction levels.

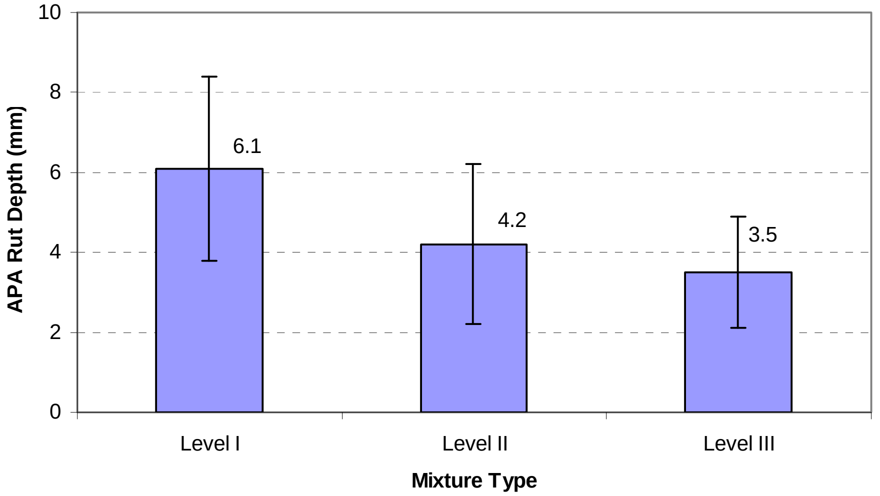


Figure 44
Mean APA rut depths of mixtures at different compaction levels

Table 35
The statistics of APA test results on mixtures by level

Mix by Level	Mean APA rut depth, (mm)	STD (mm)	CV%	Max (mm)	Min (mm)	Statistic Grouping
Level-I	6.1	2.3	37.7	9.3	4.0	B
Level-II	4.2	2.0	48.8	7.8	1.2	A
Level-III	3.5	1.4	40.2	7.5	2.0	A

Figure 45 presents the mean APA test results of those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively.

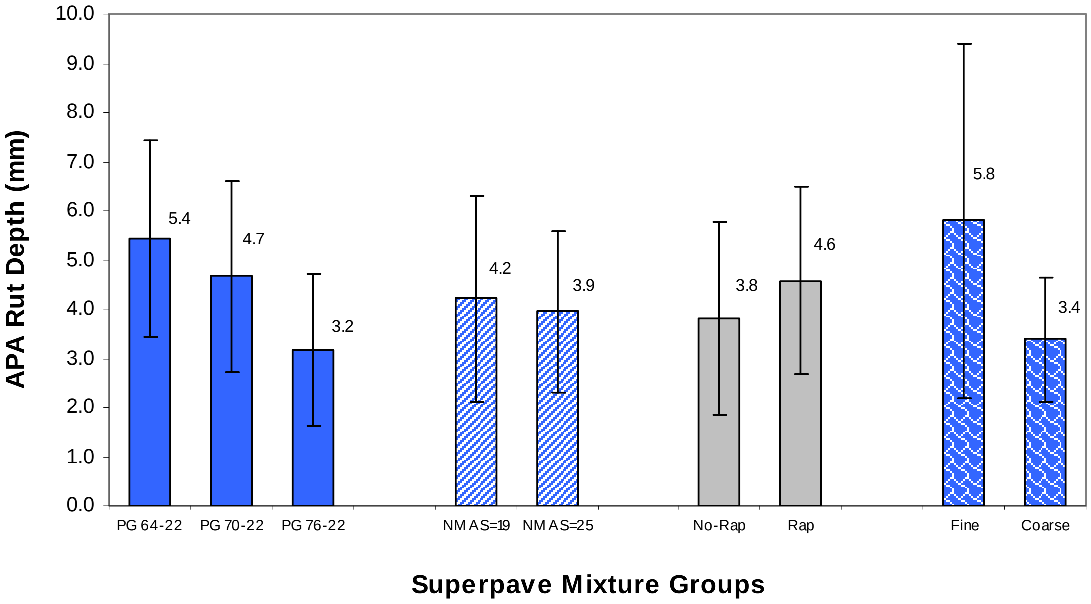


Figure 45
Mean APA rut depths of mixtures at different groupings

From Figure 45, the following observations can be made:

- Mixtures produced with higher PG binders tended to have lower APA rut depths than mixtures with lower PG binders, indicating that the APA test is very sensitive to the mixture binder types.
- There is no statistically significant difference in terms of APA rut depths among mixtures with two different NMAS of 19 and 25mm.
- Mixtures with RAP contents tended to have more APA rut depths than those without RAP contents.
- Coarse-graded mixtures seemed to be more rut resistant than fine-graded ones by having lower APA rut depths in this study.
- In general, the APA rut test was found to be fairly sensitive in capturing the rutting performance of Superpave mixtures considered in this study.

Based on the grouping analysis, the sensitivity of fundamental engineering properties on mixture grouping variables can be summarized and is presented in Table 36.

Table 36
Sensitivity of fundamental engineering test properties on Superpave mixture design variables

Mixture Grouping Variable	Fundamental Engineering Properties											
	ITS	IT Mr			IT Creep	Axial Creep	FSCH (G*/sinδ)			RSCH	SSCH	APA
	Strength	5C	25C	40C	Slope	Slope	10Hz	1Hz	0.1Hz	Perm Strain	Perm Strain	Rut Depth
N_{design} Level	☑	☑	✖	✖	✖	✖	☑	✖	✖	☑	✖	☑
Binder PG	☑	☑	☑	☑	☑	✖	✖	✖	✖	✖	✖	☑
NMAS (19 or 25mm)	☑	✖	✖	✖	✖	✖	☑	✖	✖	☑	☑	✖
RAP Usage	☑	☑	✖	✖	☑	✖	✖	✖	✖	✖	✖	✖
Gradation (Coarse or Fine)	☑	✖	✖	✖	☑	✖	☑	✖	✖	✖	☑	☑

Note: ☑ means "sensitive"; ✖ means "not sensitive"

The following observations can be made from Table 36:

- The IT strength test was sensitive to all five mixture grouping variables, which includes the design compaction effort, binder performance grade, nominal maximum aggregate size, RAP usage, and gradation curve shape.
- The IT M_r at 5^o C, IT creep slope, G*/sin(δ), and APA rut depth were observed to be sensitive to three of the five mixture grouping variables.
- The permanent deformations obtained from RSCH and SSCH tests were only sensitive to two grouping variables.
- Other fundamental engineering properties were not sensitive to any mixture grouping variables.

Correlations among Laboratory Test Results

A correlation study was performed to investigate any potential relationships among those mechanistic properties obtained from fundamental engineering tests in this study. Test results from all 30 Superpave mixtures were considered. Table 37 presents the correlation coefficient matrix for the selected mechanistic properties. In general, mixture properties obtained from different testing modes (SST or MTS) and testing temperatures generally did not correlate very well with each other. This is not unexpected because asphalt mixture consists of non-homogeneous, rate-temperature dependent materials. On the other hand, results from a single testing device tended to have stronger correlations with each other than those from different testing devices (MTS or SST). Furthermore, APA rut depth measurements in this study seemed to have no direct relationships with any of the other test results considered in Table 37, other than a poor correlation with the permanent strains measured from the RSCH tests.

Figure 46 presents the relationship between the APA rut depths and the permanent shear strain measured from the RSCH tests. As shown in Figure 46, a linear trend with $R^2= 0.18$ was observed between the two test results.

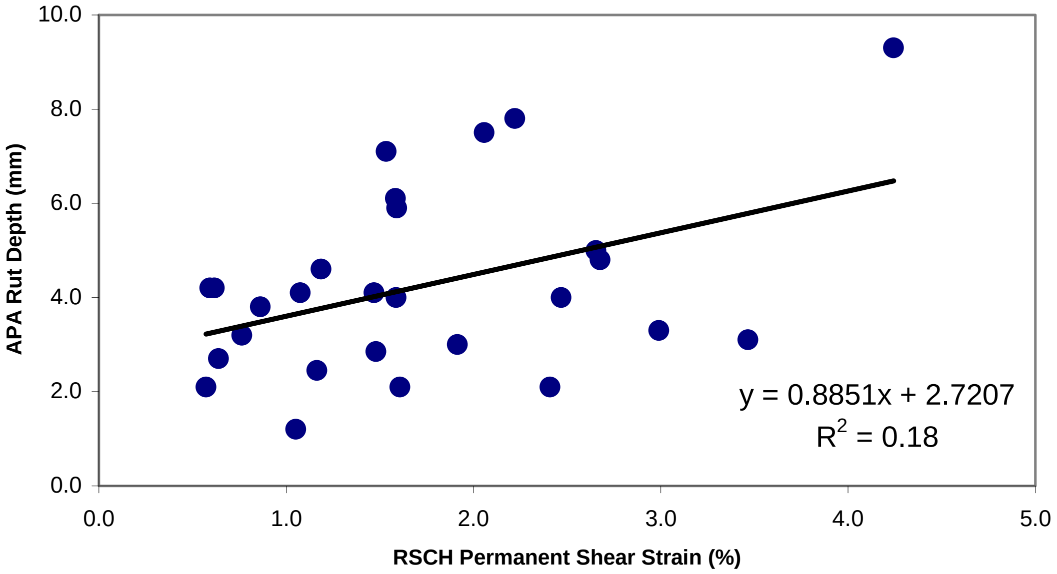


Figure 46
Relationship between APA and RSCH tests at 60°C

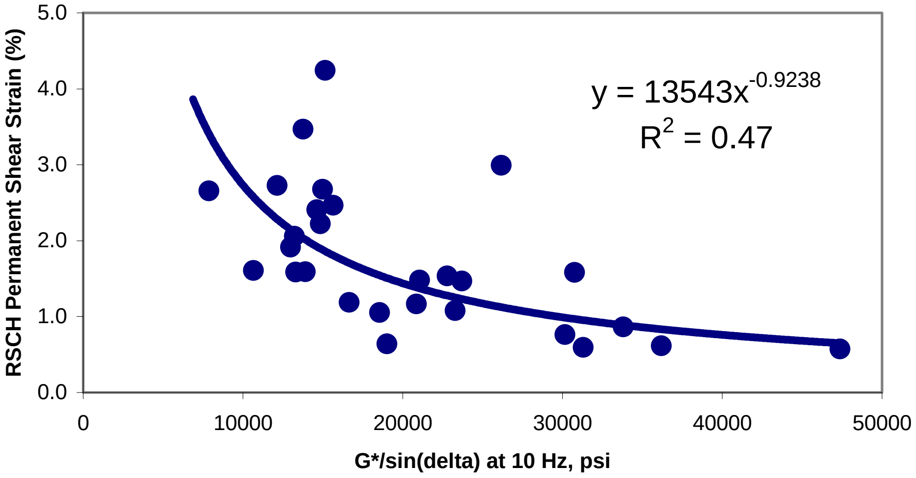
Table 37
Correlation coefficients for all test results in this study

	RUT	RCH	SCH	M1	M2	M3	ITCS	ITCI	ITS	ITSN	AXCS	AXCP	FCH1	FCH2	FCH3	FCH4
RUT	1.000	0.412	0.262	-0.118	-0.090	-0.115	0.175	0.176	-0.196	0.145	0.047	0.125	-0.200	-0.325	-0.365	-0.337
RCH	0.412	1.000	0.261	0.281	0.417	0.392	-0.136	0.122	-0.078	-0.356	-0.282	0.315	-0.590	0.545	-0.424	-0.312
SCH	0.262	0.261	1.000	0.379	0.502	0.489	-0.016	-0.212	0.270	-0.143	-0.138	-0.055	-0.468	-0.427	- 0.343	-0.325
M1	-0.118	0.281	0.379	1.000	0.782	0.700	-0.411	0.167	0.361	-0.090	0.163	-0.321	-0.297	-0.136	0.066	0.193
M2	-0.090	0.417	0.502	0.782	1.000	0.877	-0.365	0.279	0.449	-0.152	-0.098	-0.035	-0.489	-0.330	-0.0 73	0.187
M3	-0.115	0.392	0.489	0.700	0.877	1.000	-0.480	0.364	0.526	-0.264	-0.154	-0.001	-0.504	-0.376	-0.152	0.125
ITCS	0.175	-0.136	-0.016	-0.411	-0.365	-0.480	1.000	-0.509	-0.556	0.154	-0.261	0.173	0.246	0.188	0.056	0.061
ITCI	0.176	0.122	-0.212	0.167	0.279	0.364	-0.509	1.000	0.394	-0.213	0.182	0.012	-0.168	-0.203	-0.095	0.075
ITS	-0.196	-0.078	0.270	0.361	0.449	0.526	-0.556	0.394	1.000	0.093	0.166	-0.144	-0.355	-0.255	-0.042	0.105
ITSN	0.145	-0.356	-0.143	-0.090	-0.152	-0.264	0.154	-0.213	0.093	1.000	0.052	-0.230	0.308	0.360	0.380	0.332
AXCS	0.047	-0.282	-0.138	0.163	-0.098	-0.154	-0.261	0.182	0.166	0.052	1.000	-0.719	0.107	0.057	0.073	-0.157
AXCP	0.125	0.315	-0.055	-0.321	-0.035	-0.001	0.173	0.012	-0.144	-0.230	-0.719	1.000	-0.321	-0.356	-0.354	0.093
FCH1	-0.200	-0.590	-0.468	-0.297	-0.489	-0.504	0.246	-0.168	-0.355	0.308	0.107	-0.321	1.000	0.888	0.636	0.220
FCH2	-0.325	-0.545	-0.427	-0.136	-0.330	-0.376	0.188	-0.203	-0.255	0.360	0.057	-0.356	0.888	1.000	0.907	0.503
FCH3	-0.365	-0.426	-0.343	0.066	-0.073	-0.152	0.056	-0.095	-0.042	0.380	0.073	-0.354	0.636	0.907	1.000	0.655
FCH4	-0.337	-0.312	-0.325	0.193	0.187	0.125	0.061	0.075	0.105	0.332	-0.157	0.093	0.220	0.503	0.655	1.000

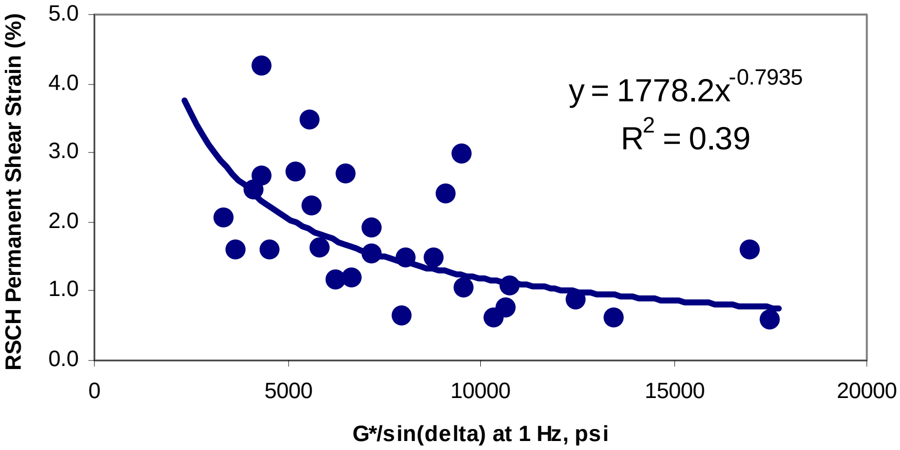
Note:

RUT-APA Rut Depth(mm); RCH-RSCH permanent shear strain; SCH-SSCH permanent shear strain; M1-IT Mr at 5C; M2-ITMr at 25C; M3-IT Mr at 40C; ITCS-IT creep slope; ITCI-IT creep intercept; ITS-IT strength; ITSN-IT strain at failure; AXCS-axial creep stiffness; AXCP-axial creep slope; FCH1-G*/sin(δ) at 10 Hz; FCH2-G*/sin(δ) at 1 Hz; FCH3-G*/sin(δ) at 0.1 Hz; FCH4-G*/sin(δ) at 0.01 Hz;

Figures 47 (a) and (b) presents the relationship between the RSCH permanent shear strain and the G*/sin(δ) at 10 Hz and 1 Hz, respectively. A power relationship was observed for both RSCH permanent shear strains vs. G*/sin(δ) at 10 Hz and RSCH permanent shear strains vs. G*/sin(δ) at 1 Hz.



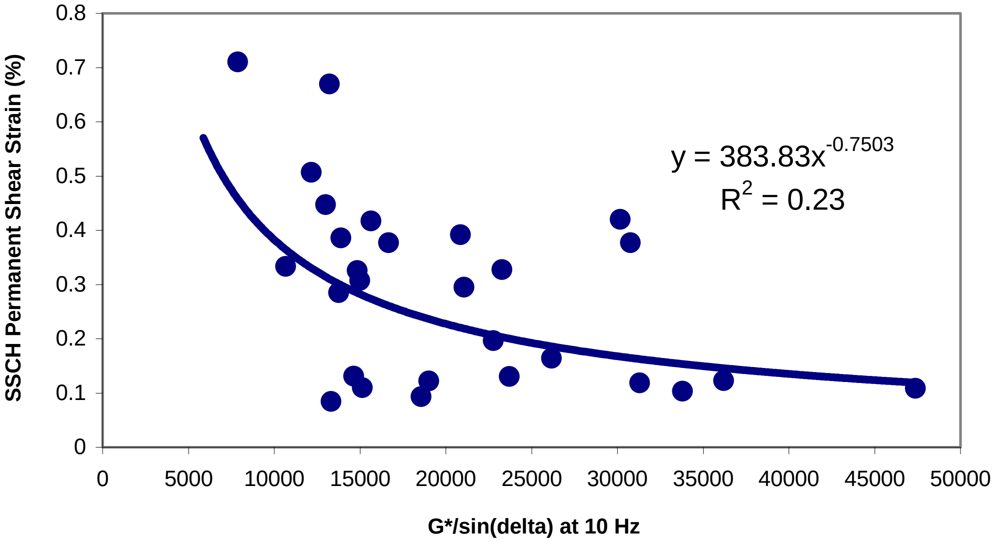
(a)



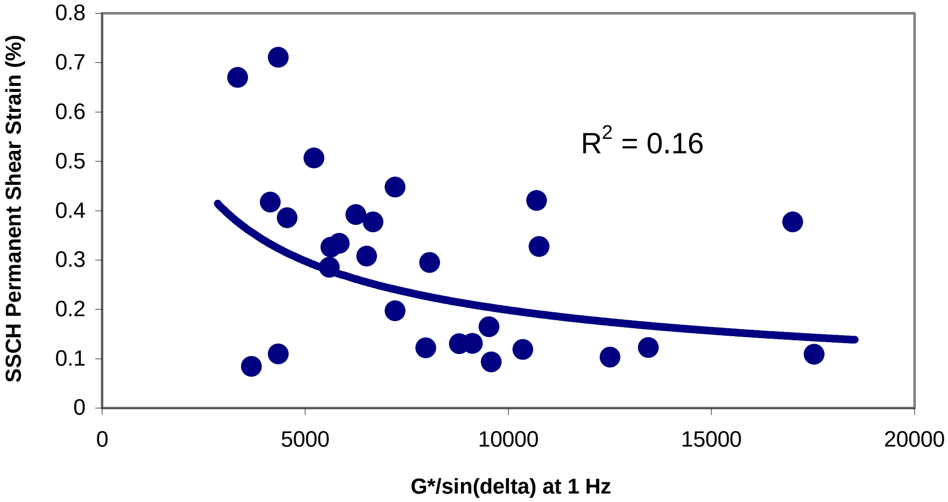
(b)

Figure 47
Relationships between RSCH and FSCH tests at 60ºC

As presented in Figures 48 (a) and (b), a power relationship was also observed between test results of SSCH and FSCH. However, the data are more scattered than those in Figure 48.



(a)



(b)

Figure 48
Relationships between SSCH and FSCH tests at 60ºC

Figure 49 presents the correlation between the cumulative permanent shear strain from RSCH tests and permanent shear strain from SSCH tests. Although both test parameters are supposed to be an indicator for the rutting susceptibility of Superpave mixtures, those two test results simply did not correlate very well in this study, as shown in Figure 49.

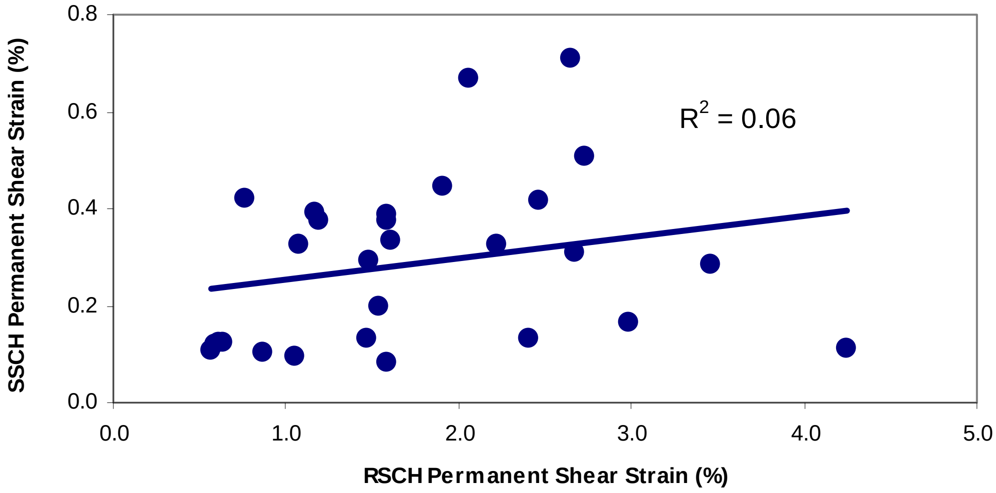


Figure 49
Relationship between SSCH and RSCH tests at 60ºC

Figure 50 presents a relationship between ITS and IT creep slopes. A linear correlation was obtained between the two mixture properties. As the ITS increased, the IT creep slope tended to decrease, implying better rut resistance for the Superpave mixture tested.

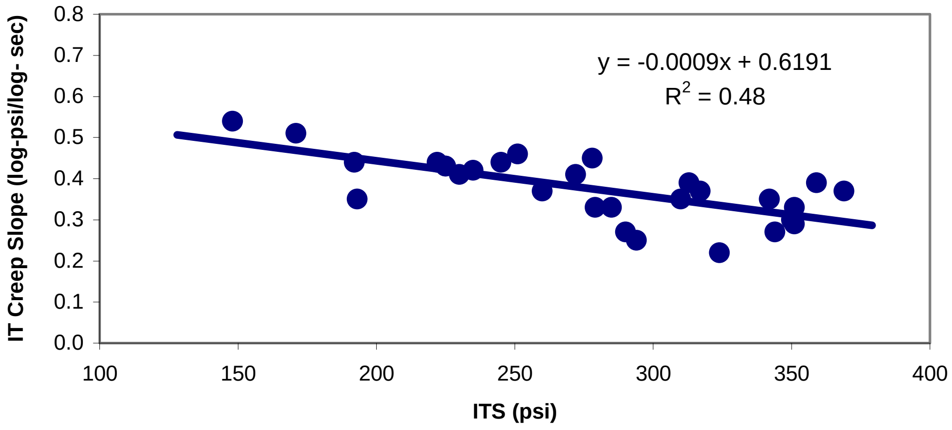
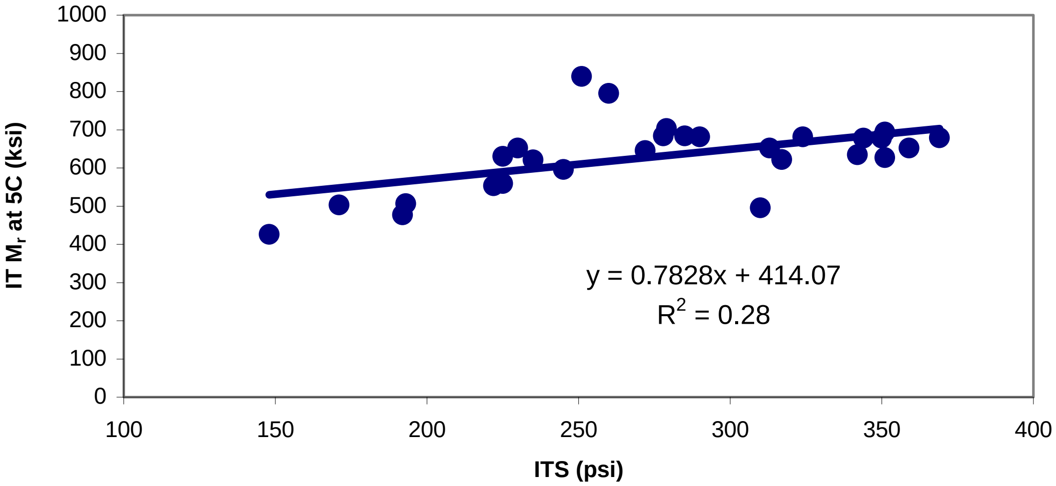


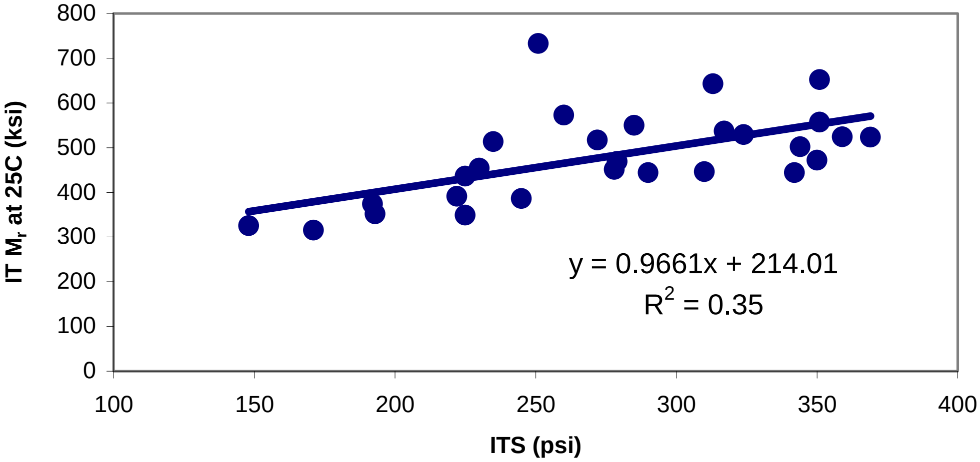
Figure 50
Relationship between ITS and IT creep tests

Figure 51 presents relationships between ITS and IT M_r test results at 5 º C, 25 º C, and 40º C, respectively. A general linear correlation could be obtained for ITS with IT M_r values at all three test temperatures tested. It is interesting to note that as the temperature goes from 5º C to 40º C, the linear ITS-IT M_r relationship tends to become stronger in terms of higher R-square values for this study.



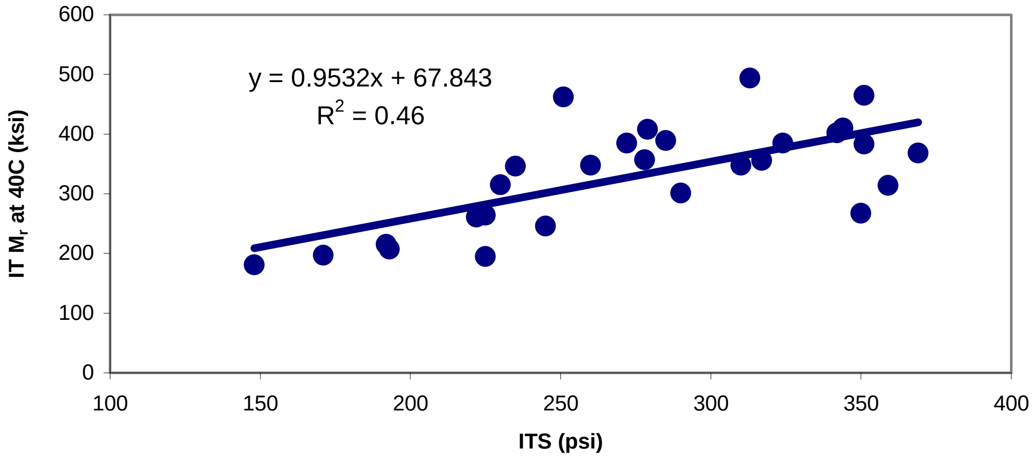
1000
900
800
700
600
500
400
300
200
100
0
IT M$_r$ at 5C (ksi)
100
150
200
250
300
350
400
ITS (psi)
y = 0.7828x + 414.07
R^2 = 0.28

(a)



800
700
600
500
400
300
200
100
0
IT M$_r$ at 25C (ksi)
100
150
200
250
300
350
400
ITS (psi)
y = 0.9661x + 214.01
R^2 = 0.35

(b)



(c)

Figure 51
Relationship between ITS and IT M_r tests

In summary, a linear trend was observed between the APA measured rut depth and the RSCH permanent shear strain. It is expected that the APA rut depth goes up as the RSCH permanent shear strain increases. However, this correlation was very poor in this study, with R^2=0.18.

The complex shear modulus measured from the FSCH test had a fair power relationship with the RSCH permanent shear strain. As the complex shear modulus increased, the RSCH permanent shear strain tended to decrease. Since both properties were obtained at 60° C, this indicates that both the FSCH and RSCH tests can be used to capture Superpave mixture's high temperature rutting performance.

The SSCH permanent shear strain did not have a fair correlation with either FSCH or RSCH test results, or any other test results in this study, indicating this test should not be used further for Superpave mixture performance characterization.

The indirect tensile strengths measured from ITS tests had a fair linear relationship with the IT creep slopes. As the ITS increased, the IT creep slope tended to decrease.

The indirect tensile strengths were also observed to have fair correlations with the IT M_r values. It is interesting to note that as temperature increased, the relationship between ITS and IT M_r became stronger.

Field Rutting Measurements

As stated earlier, the Superpave mixtures considered in this study (Phase I and Phase II) were obtained from 21 field implementation projects. At present, all project pavements have performed well and have less than 5.0 mm rut depths without any recordable cracking failure. Table 38 presents the early rutting data measurements of those field projects. The rut measurements reflect a trafficking of about two to five years. Based on an average 20 year design EASL number, a rut ratio (mm/million ESAL) was calculated for each pavement. The average rut ratio for each design level was then computed and presented in Figure 52. It is interesting to note that the Level III mixture has the lowest rut ratio, followed by the Level II and the Level I mixtures.

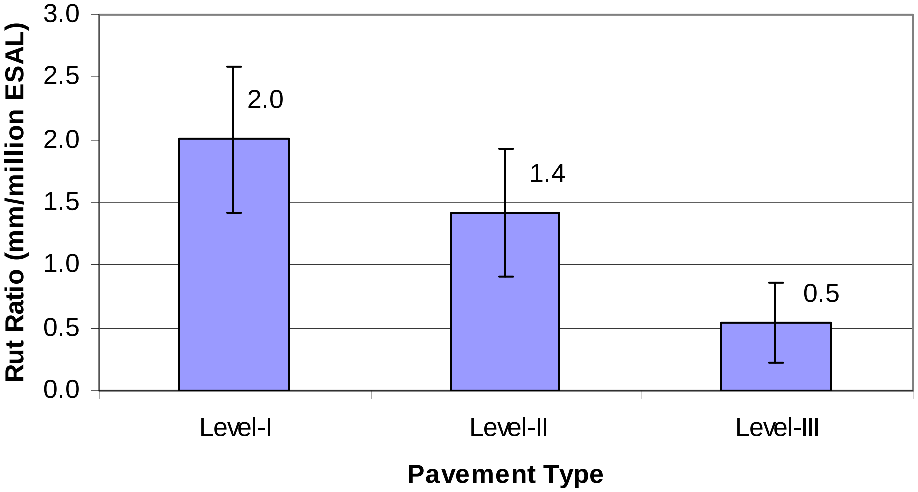


Figure 52
Field rutting measurements

It is interesting to note that the grouping analysis presented in Appendix A indicated that the APA rut depth ranking matched exactly with the field rutting ratio ranking. In addition, several fundamental test results considered in this study also provided similar rankings for Level I and Level III mixtures but with a different order for Level II mixtures. Those tests are ITS, IT Mr, Axial Creep, FSCH, and RSCH.

Table 38
Field rutting performance

Project	LA 361	LA 191	LA 874	LA 22	LA 121	LA 353	LA 4	LA 1	US 79	LA 29	US 61-1	US 61-2	US 90	I-10 (1)	I-10 (2)	I-12 (1)	I-10 (3)	I-49	I-12 (2)	West bank	I-20
Level	Level-I			Level-II										Level-III							
N_{design}	75			96				100			109			125						126	
Corresponding Mix	I-1	I-2	I-3	$1WI_{22}$	$1WI_{121}$	$1WI_{353}$	$2BI_4$	II-1	II-2	II-3	$1WII_{61}$	$2BII_{61}$	$2BII_{90}$	III-1	III-2	III-3	III-4	III-5	III-7	$2BIII_{we}$	$2BIII_{20}$
20 years ESALs (million)	3	3	3	6	6	6	6	10	10	10	10	10	10	30	30	30	30	30	30	30	30
Years on Service	3.5	3.3	3.6	5.1	4.8	4.7	4.7	3.8	2.8	3.6	4.8	4.7	4.5	2.5	2.0	2.0	3.0	2.0	3.0	5.0	5.0
Average Rut Depth (mm)	1.0	1.3	0.8	1.0	2.0	2.0	2.8	3.8	2.0	1.8	1.8	5.0	3.3	4.6	1.3	2.0	1.5	2.0	1.5	3.3	1.8
Rut ratio (mm/10^6 ESAL)	1.9	2.63	1.48	0.65	1.39	1.42	1.99	2.0	1.43	1.01	0.75	2.13	1.47	1.23	0.43	0.67	0.33	0.67	0.33	0.44	0.24
Average Rut ratio (mm/10^6 ESAL)	2.0			1.4										0.5							

CONCLUSIONS

Thirty Louisiana Superpave mixtures from twenty-one field implementation projects constructed between 1998 and 2000 were selected in the present study. After being open to traffic for two to five years, all project pavements were found to perform well and had less than 5.0mm rut depths, without any recordable cracking failure. The performance of those Superpave mixtures has been evaluated using a suite of laboratory fundamental engineering performance tests based on the ability of the mixture to resist tensile cracking and permanent deformation distresses. The fundamental engineering tests were conducted using three laboratory performance testers: Simple Shear Tester, Material Testing Machine, and Asphalt Pavement Analyzer. Based on the fundamental engineering test results, the following observations and conclusions were made:

- **Compaction Efforts (Design Gyratory Compaction Number)**
    - The design compaction efforts were observed to have a certain influence on Superpave mixture rut susceptibility. In Phase-I study, mixtures with Level I compaction effort (N_{design}=96) showed a higher rut susceptibility than Level II (N_{design}=109) and Level-III (N_{design}=126) mixtures. Similarly, high and medium Superpave mixtures in Phase-II study, which were designed at N_{design} of 125 and 100 gyrations, respectively, had better overall rut resistance than low volume mixtures at an N_{design} of 75 gyrations. This is evidenced by all fundamental engineering test results.
    - No significant difference was found in rut resistance between Phase-I mixtures compacted at N_{design} of 109 gyrations (Level II) and N_{design} of 126 gyrations (Level-III) or between Phase-II mixtures compacted at $N_{design}$of 100 gyrations (medium volume) and N_{design} of 125 gyrations (high volume).

- **Binder Performance Grade**
    - The effect of binder performance grade on mixture performance was not explicitly evaluated in this study because the usage of binder PG grade was generally associated with the design compaction effort in a Superpave mixture design; that is, the higher the compaction effort, the higher the performance grade of binder used.
    - Based on five Level-I mixtures in the Phase-I study, the overall laboratory performance of Mixture LA353 with PG 70-22 (PAC40) binder was found significantly superior to four other mixtures with PG 64-22 (PAC30 or AC 30) binders, including LA 22 binder/wearing and LA121 binder/wearing mixtures.

- **Design Volumetric Properties**
  - Asphalt mixtures in different air void groupings performed differently, but for mixtures within a certain air void group, the influence of the air void content was often minimal.
  - Concerning voids in the mineral aggregate VMA, no consistent trend was observed. Results from the stratified comparison produced very low coefficients of determination, whereas results from the multiple regression analysis identified this mix variable as one with high contribution on test results.
  - $G^*_{10Hz}/\sin(\delta)$ and RSCH permanent shear strain were not sensitive to variations in VMA and air voids for the mixtures evaluated.
  - A trend in decreasing IT strength and increasing IT and axial creep slope with an increase in the VMA and air voids was observed.
  - The nominal maximum aggregate size showed no discernable influence on rut susceptibility either from studying individual test results or from the multiple regression analysis.
  - The percent of aggregate passing the 0.075 mm sieve exhibited an inverse relationship with the rut susceptibility ranking. Mixtures containing lower values of this variable appeared to be more susceptible to rutting. This means that increasing the amount of fine dust (up to a certain limit) by a small amount made the asphalt cement/dust mixture act as a more viscous binder, thus increasing the stability. The percent of aggregate passing the 2.36 mm sieve, on the other hand, did not have an effect on the susceptibility to rutting.
  - Film thickness presented a strong, direct relationship with rut susceptibility. Mixtures with higher values of binder film thickness were more susceptible to permanent deformation. A possible explanation to this behavior is that, as those Superpave mixtures considered are usually coarser than pre-Superpave mixtures, they have lower aggregate surface areas to be coated with binder. Without a reduction in asphalt cement content, this causes thicker binder films, which have a negative effect on the resistance to permanent deformation.
  - Dust/AC ratio showed an inverse relation with rut susceptibility; that is, mixtures with lower dust/AC ratios appear to be more susceptible to rutting.

Gradation Analysis

- The results of the power law gradation analyses showed that high and medium volume mixtures were coarser (containing less finer aggregates) than low volume ones. This indicates that Superpave mixtures designed at a higher gyration level have to become coarser in order to achieve a certain VMA requirement.
- The IT strength was fairly sensitive to the gradation intercept a_{FA} or a_{CA}. The IT strength increases with an increase in intercept a_{FA}, or the total percentage of fine aggregates in a mixture.
- Gradation parameters were found to be quite sensitive to the IT and axial creep slopes. Parabolic correlations were observed between the IT and axial creep tests and gradation analysis slopes and intercept. This indicates that gradation parameters are sensitive to the creep properties of asphalt mixtures.
- The property $G^*_{10Hz}/\sin(\delta)$ increased with an increase in n_{CA} and a decrease in n_{FA} slopes.
- The results from the RSCH test are sensitive to the fine portion (FA) of the aggregate gradation. More permanent shear strain was accumulated with an increase in the FA portion of the aggregate gradation (an increase in n_{FA}).

- **Sensitivity Analysis of Fundamental Engineering Properties**
  - The IT strength test was sensitive to all five mixture grouping variables, which include the design compaction effort, binder performance grade, nominal maximum aggregate size, RAP usage, and gradation curve shape.
  - The IT Mr at 5°C, IT creep slope, $G^*/\sin(\delta)$, and APA rut depth were observed to be sensitive to three of five mixture grouping variables.
  - The permanent deformations obtained from RSCH and SSCH tests were only sensitive to two grouping variables.
  - Other fundamental engineering properties were not sensitive to any mixture grouping variables or were sensitive to only one of them.

- **Correlation among Fundamental Engineering Properties**
  - A linear trend was observed between the APA measured rut depth and the RSCH permanent shear strain. As expected, the APA rut depth goes up as the RSCH permanent shear strain increases. However, this correlation was found to be very poor in this study with $R^2 = 0.18$.
  - The complex shear modulus measured from the FSCH test had a fair power relationship with the RSCH permanent shear strain. As the complex shear modulus

increases, the RSCH permanent shear strain tends to decrease. As both properties were obtained at 60^{o}C, this indicates that both the FSCH and RSCH tests can be used to capture Superpave mixture's high temperature rutting performance.

- The SSCH permanent shear strain did not have fair correlation with either FSCH or RSCH test results or any other test results in this study, indicating that this test should not be further used for Superpave mixture performance characterization.
- The indirect tensile strengths measured from ITS tests had a fair linear relationship with the IT creep slopes. As the ITS increases, the IT creep slope tends to decrease.
- The indirect tensile strengths were also observed to have fair correlations with the IT Mr values. It is interesting to note that as temperature is increased, the relationship between ITS and IT Mr becomes stronger.

RECOMMENDATIONS

For QA/QC in plant production of Superpave mixtures, the indirect tensile strength test at 25 ^{o}C is recommended. The indirect tensile strength value for a Superpave mixture with 7 percent air voids shall be at least 150 psi (1.03 Mpa).

For durability/strength proof checking in laboratory Superpave mix design, the Asphalt Pavement Analyzer (APA) test at 64 ^{o}C is recommended. The average rut depths of three beams or six cylindrical SGC samples shall be less than 6.1, 4.2, and 3.5 mm, respectively, for Level-I (N_{design} = 75), Level-II (N_{design} = 100), and Level-III (N_{design} = 125) Superpave mixtures.

For permanent deformation properties of Superpave mixtures, the indirect tensile creep, frequency sweep at constant height, and repetitive shear at constant height tests are recommended.

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APPENDIX A

Fundamental Engineering Test Results

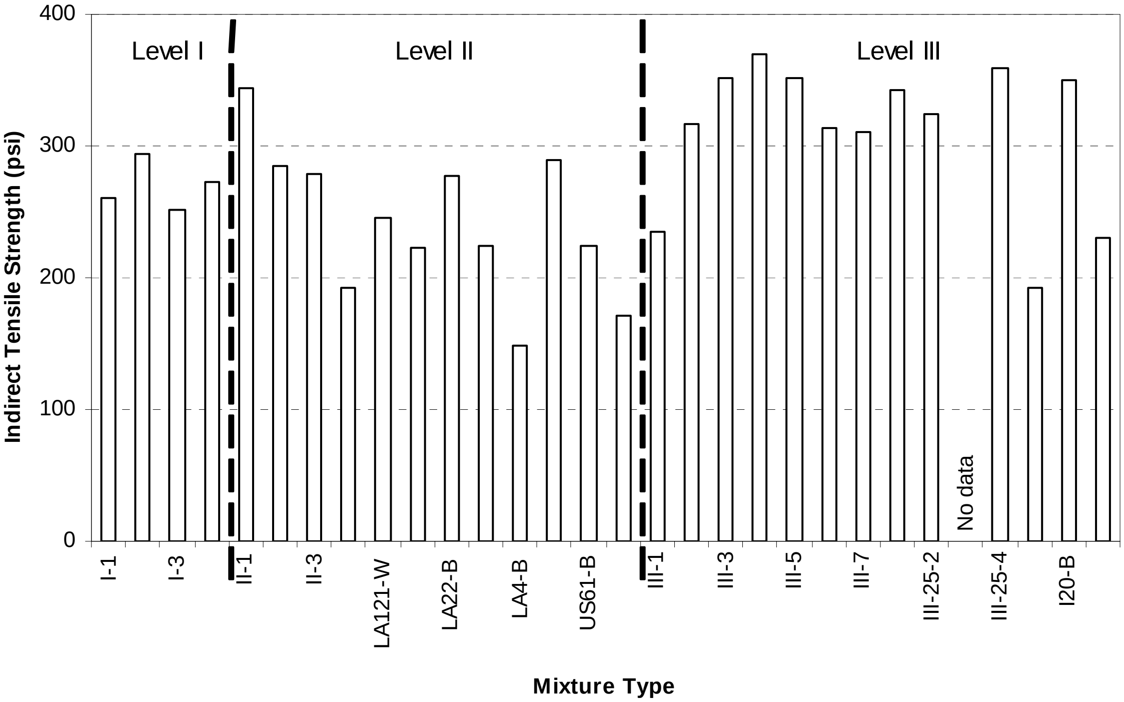


Figure A-1
Indirect tensile strength test results

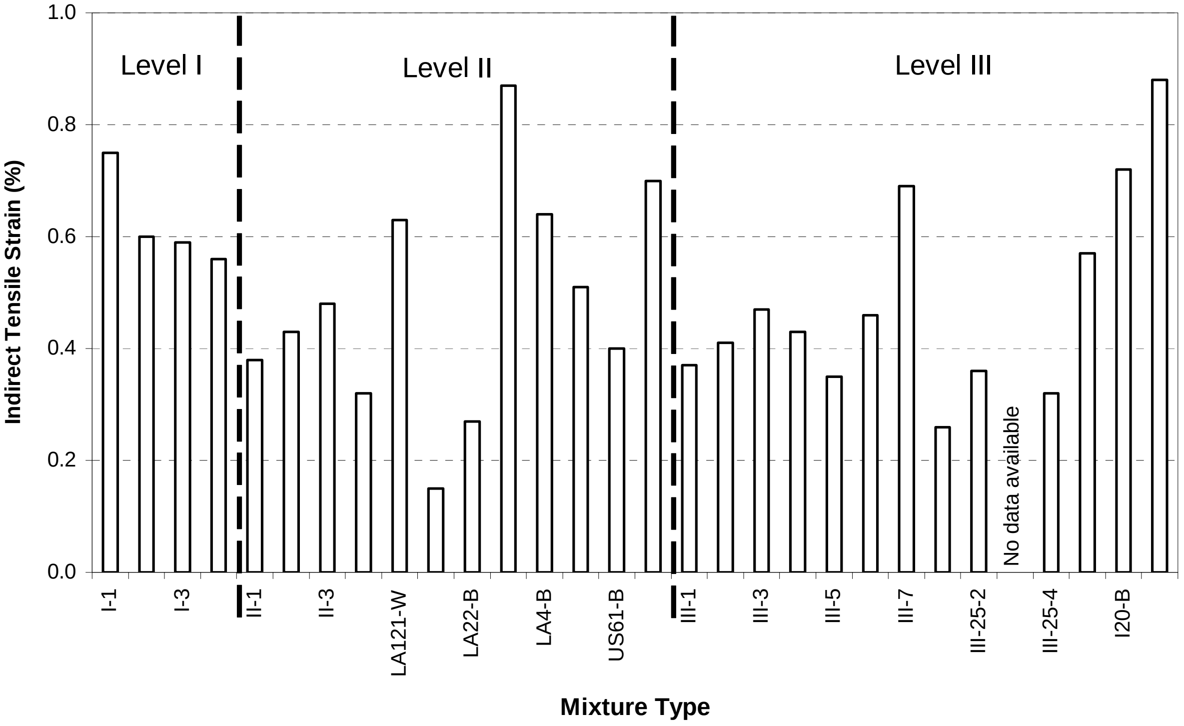


Figure A-2
Indirect tensile strength test results

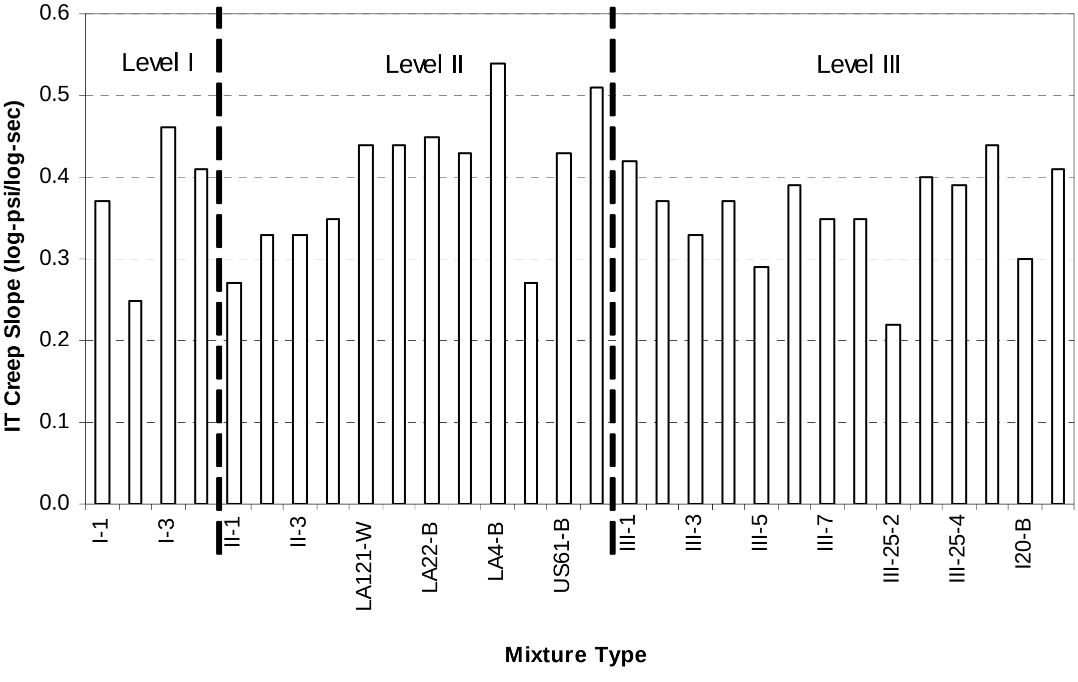


Figure A-3
Indirect tensile creep test results

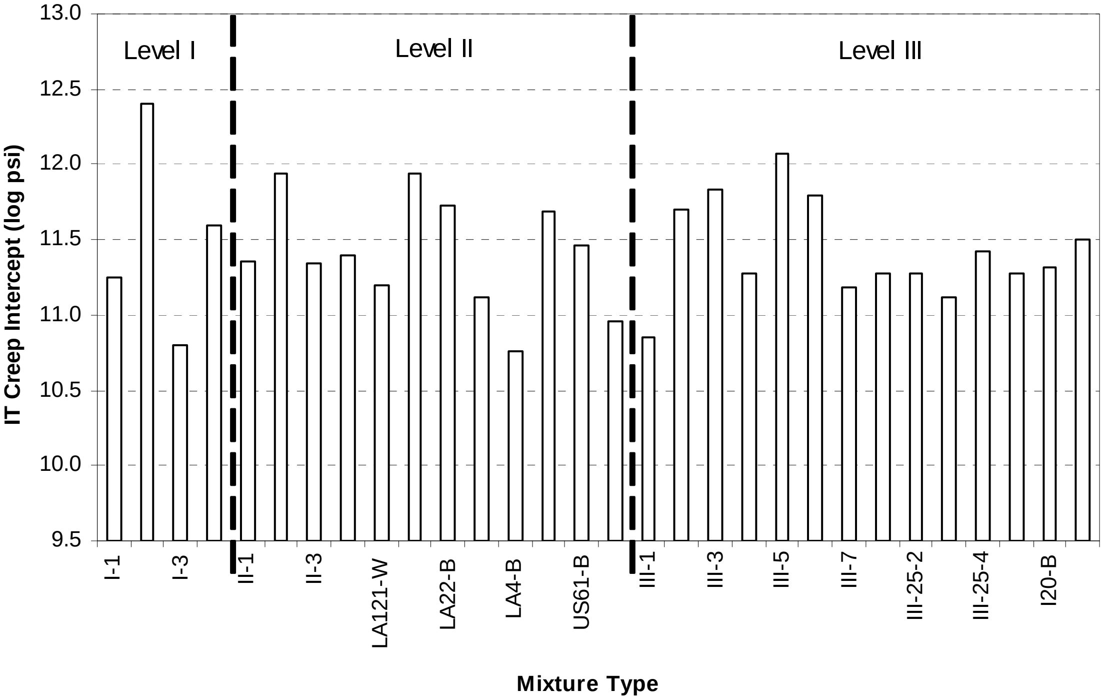


Figure A-4
Indirect tensile creep test results

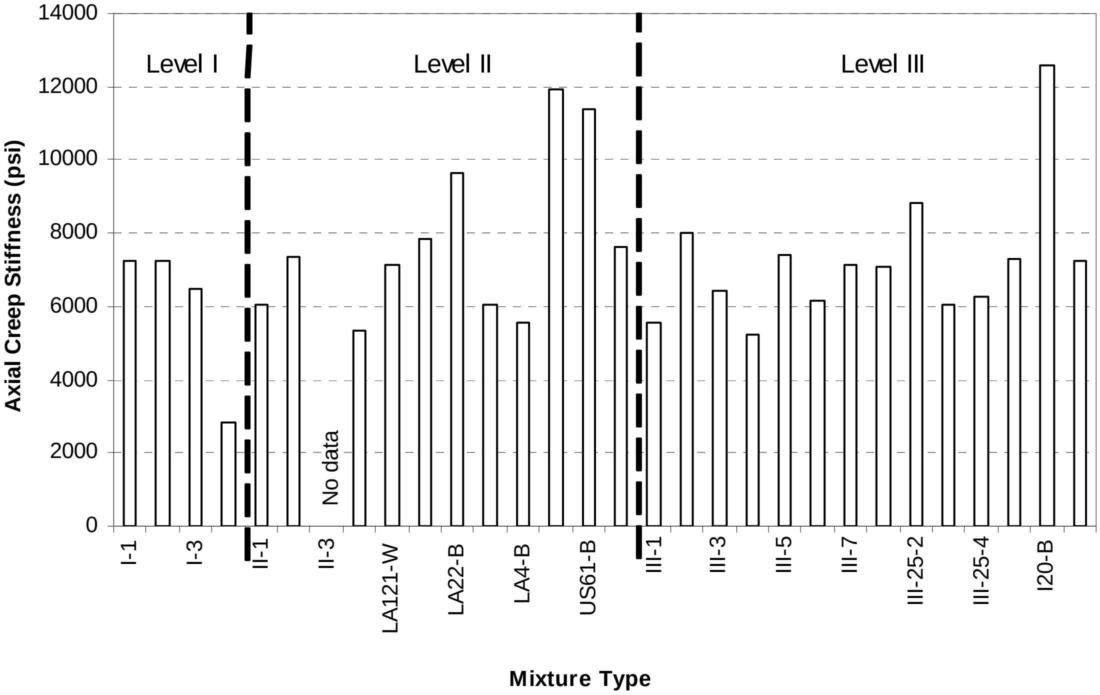


Figure A-4
Axial creep test results

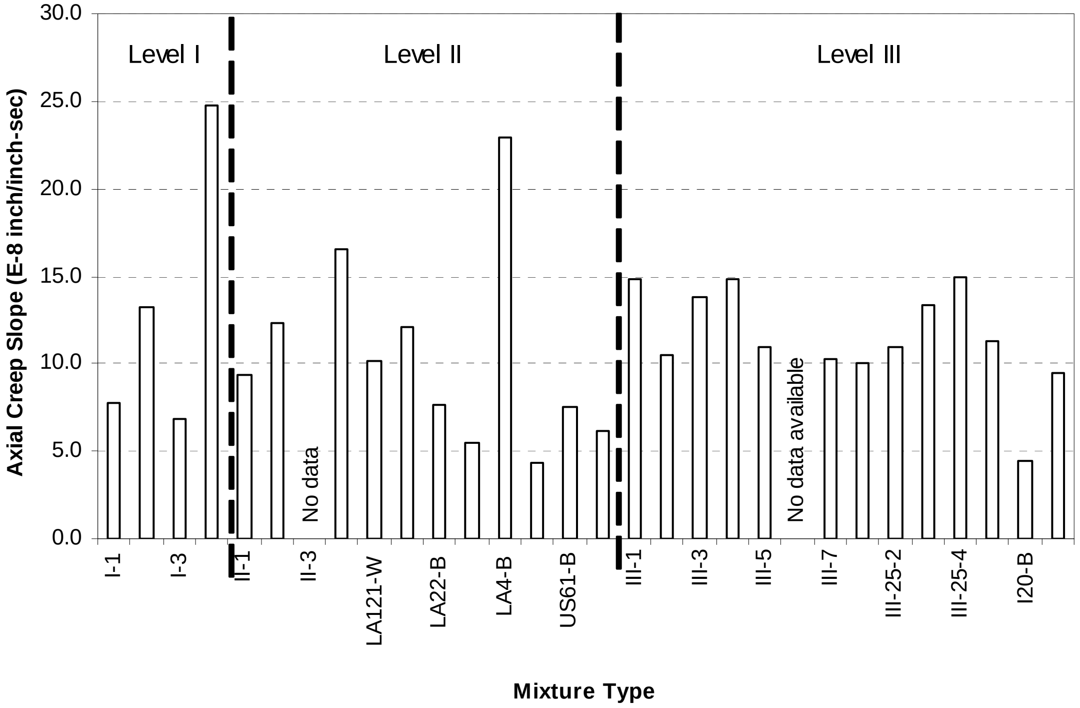


Figure A-5
Axial creep test results

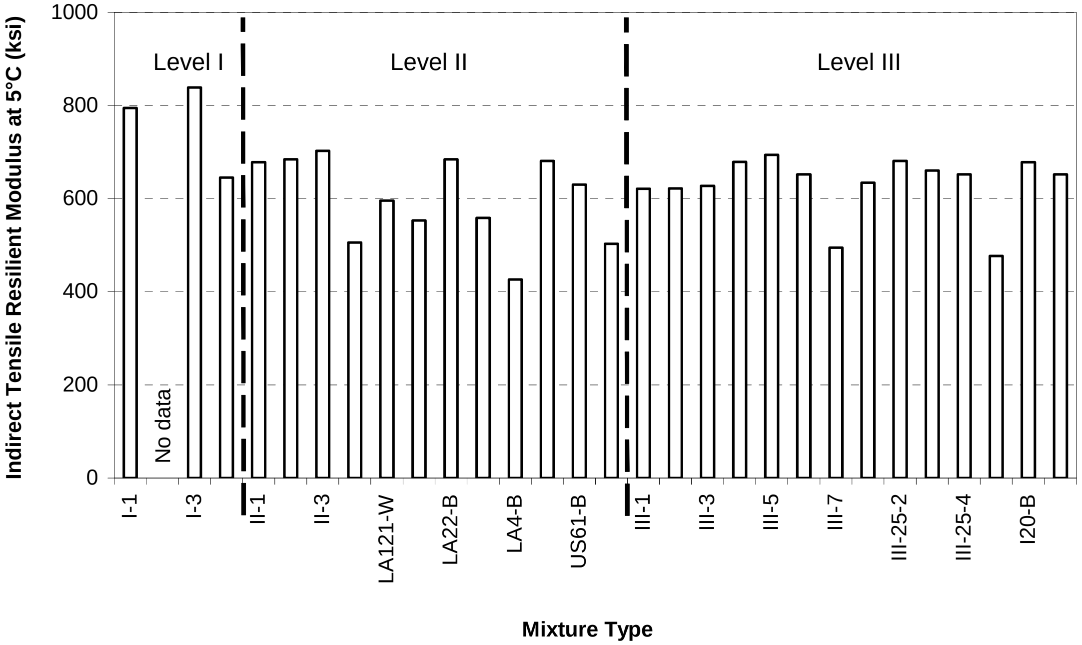


Figure A-6 1
Indirect tensile resilient modulus (5°C) test results

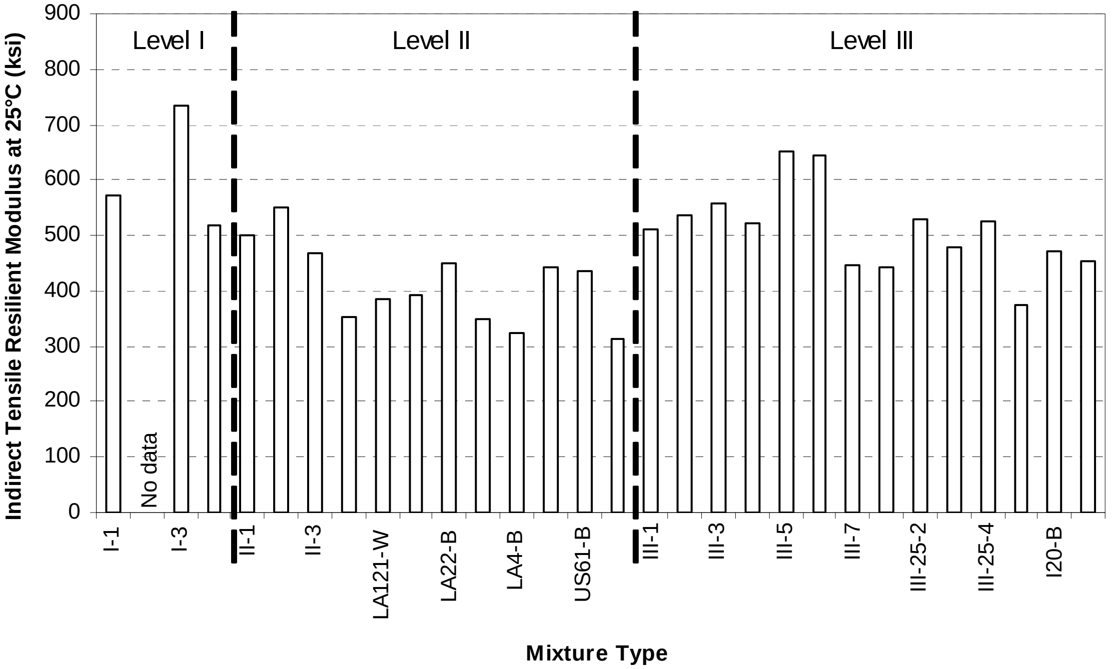


Figure A-7-0-1
Indirect tensile resilient modulus (25°C) test results

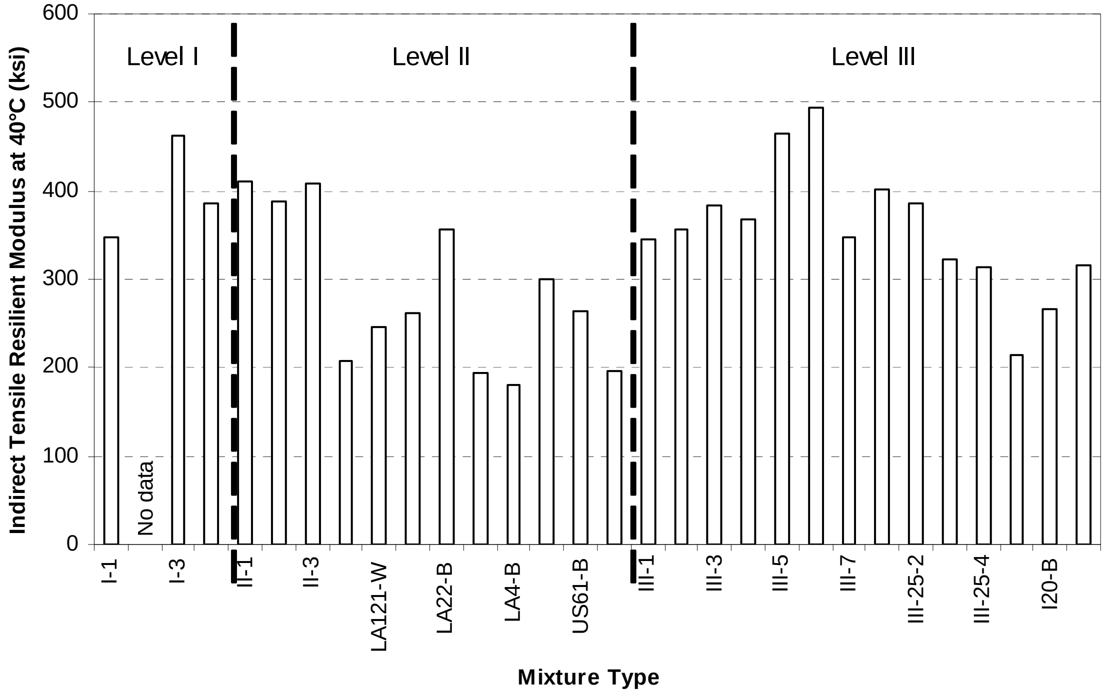


Figure A-8
Indirect tensile resilient modulus (40°C) test results

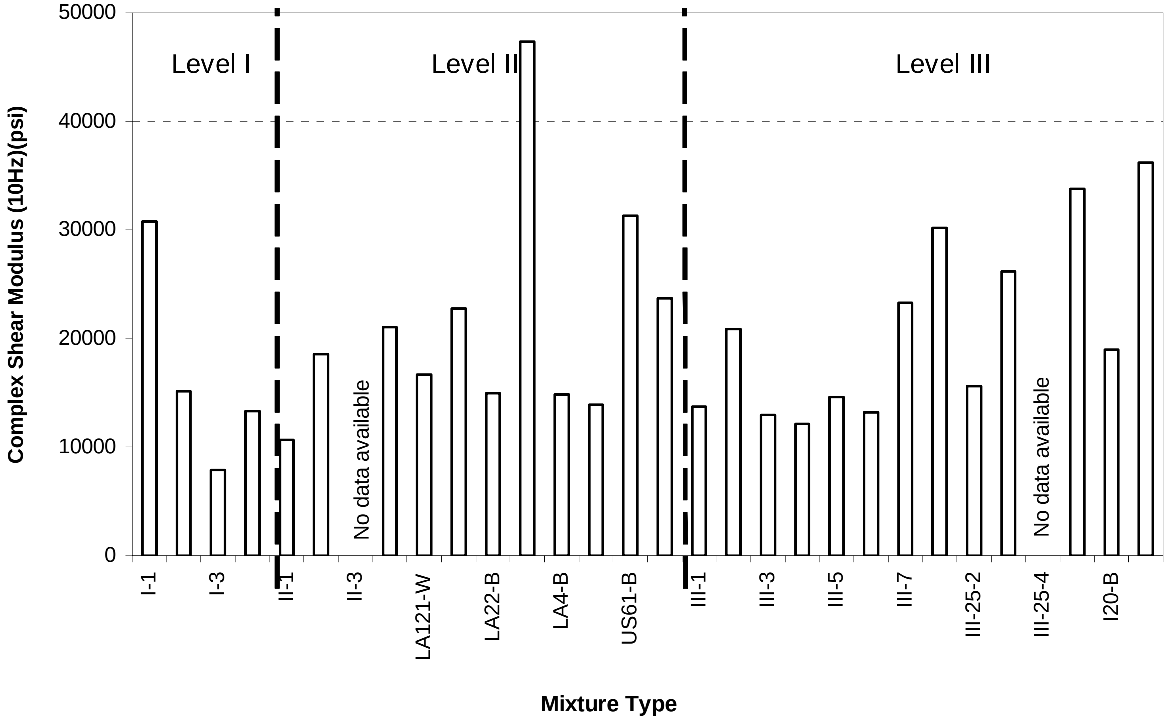


Figure A-9
Complex shear modulus test results

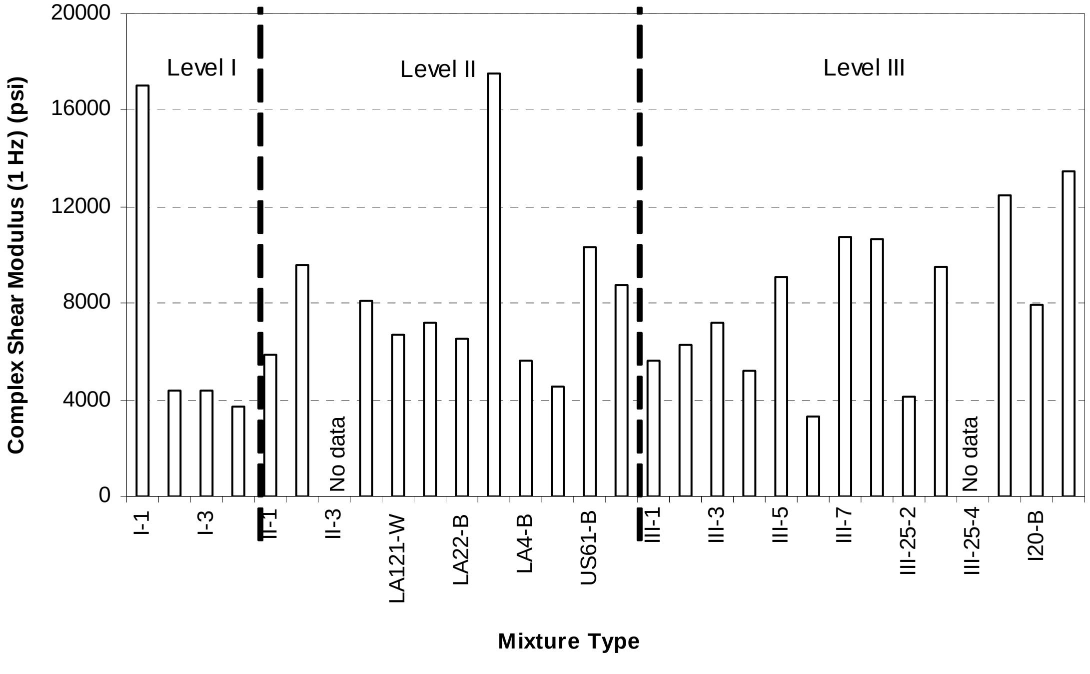


Figure A-10
Complex shear modulus test results

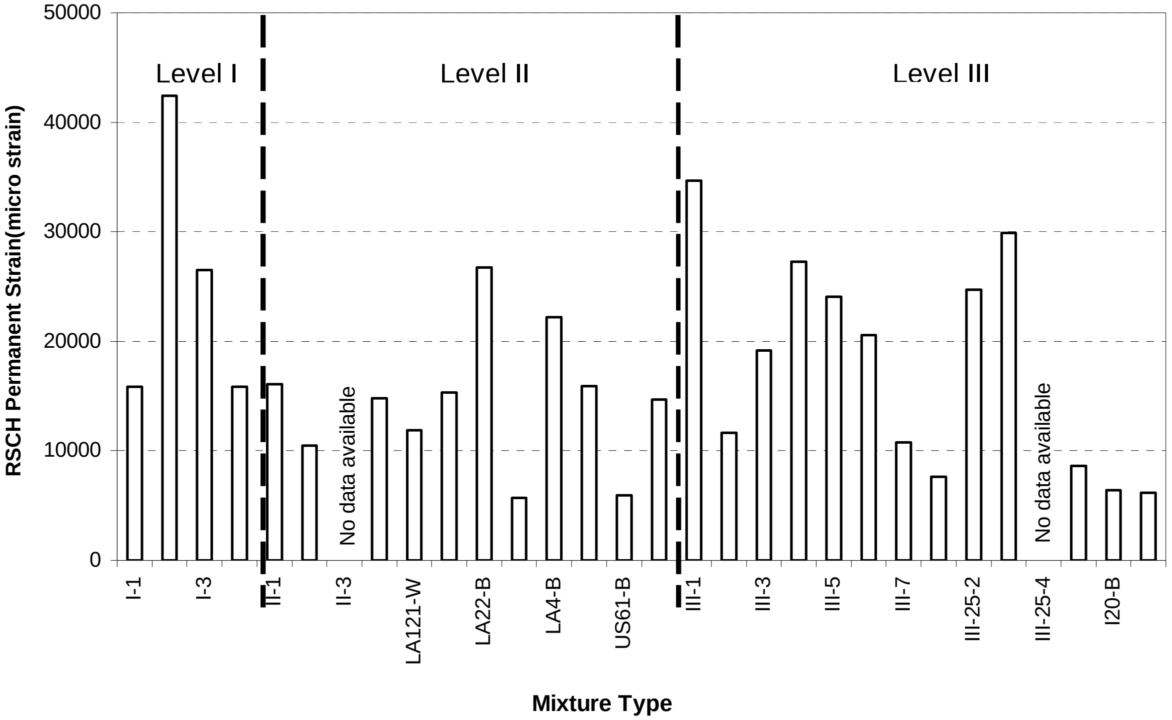


Figure A-11
RSCH permanent strain test results

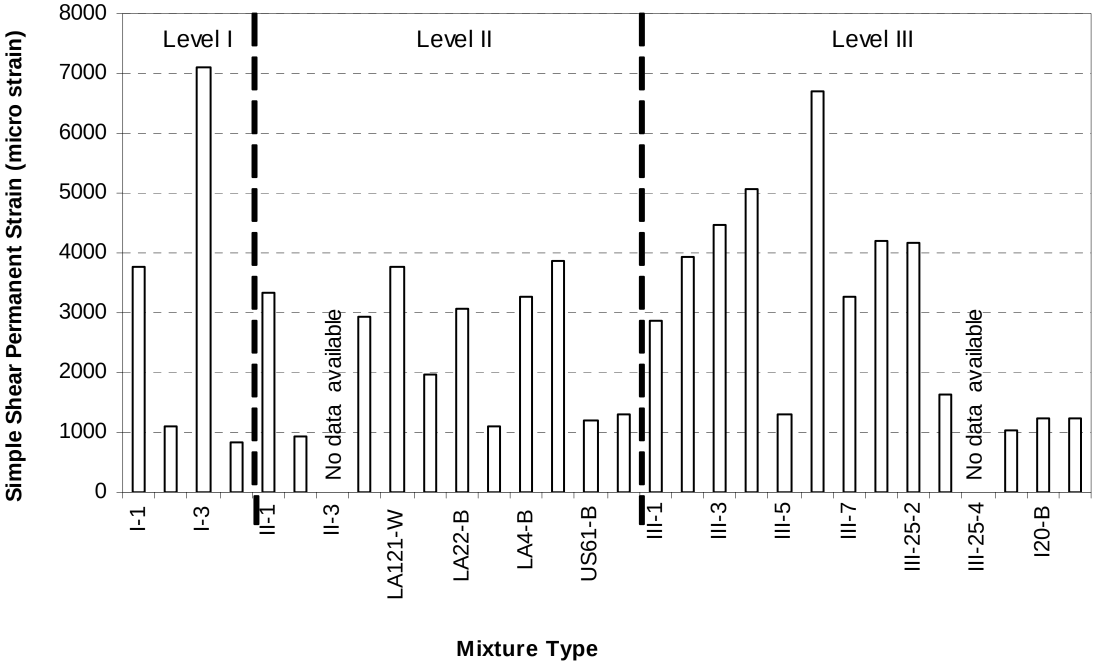


Figure A-12
Simple shear permanent strain test results

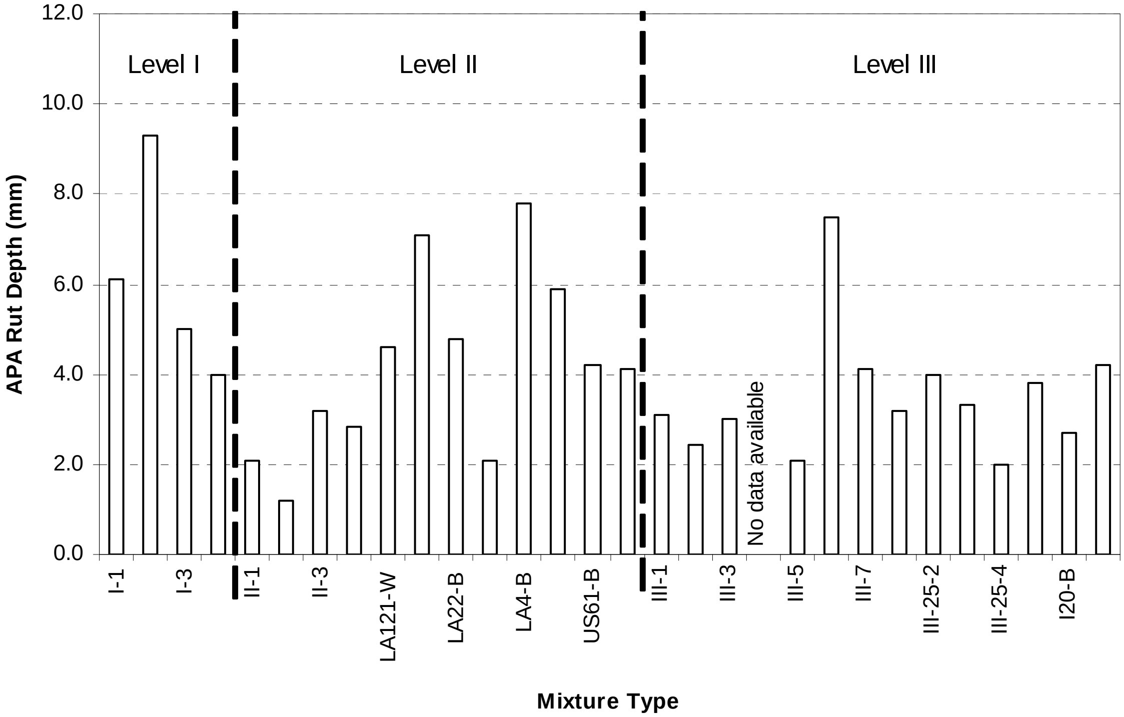


Figure A-13
Asphalt pavement analyzer test results

APPENDIX B

Grouping Analysis on Fundamental Engineering Properties of Superpave Mixture

In this part of the discussion, 30 Superpave mixtures were grouped by three mixture design levels (Table 31), two NMAS, three binder PG levels, with/without RAP materials, and coarse or fine graded gradations. The sensitivities of those grouping variables on mixture mechanistic properties were statistically analyzed for all fundamental engineering test results.

Indirect Tensile Strength (ITS) Test

The IT strengths for the 30 Superpave mixtures tested in this study varied from 1,020 kPa (148 psi) to 2,545 kPa (369 psi), while the IT strains had a range from 0.15 to 0.88 percent, as shown in Table B-1.

Figure B-1 presents the mean IT strength test results for Superpave mixtures grouped at different compaction levels. The average IT strength for the Level I, Level II, and Level III mixtures was 1,857 kPa (269 psi), 1670 kPa (242 psi), and 2,145 (311 psi), respectively. The statistical ranking presented in Table B-1 indicates that the mean IT strength for Level III mixtures (ranked as an "A") is significantly higher than those for Level-I and Level-II mixtures (both ranked as a "B"). This could be attributed partly to both the stiffer binders (PG 76-22M) and the higher design gyratory compaction efforts used in the Level-III mixture design. However, there was no statistically significant difference in the mean IT strains among mixtures compacted at different compaction levels, as shown in Table B-1.

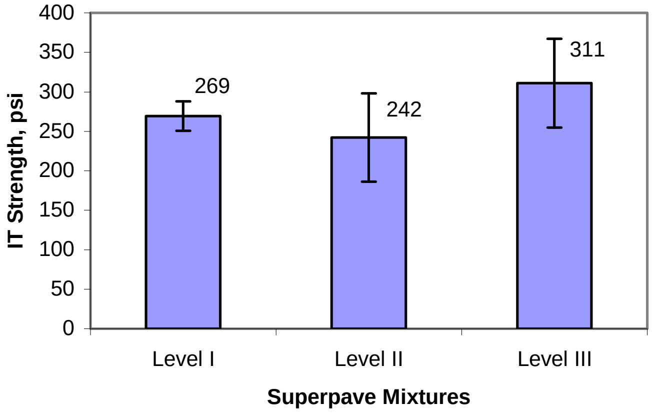


Figure B-1
Mean IT strength test results of mixtures at different compaction levels

Table B-1
The statistics of ITS test results on mixtures by level

Mix Type	Mean IT Strength, (psi)	STD (psi)	CV%	Max (psi)	Min (psi)	Statistic Grouping
Level-I	**269.3**	18.6	6.9	294.0	251.0	**B**
Level-II	**242.1**	56.0	23.1	344.0	148.0	**B**
Level-III	**311.0**	56.3	18.1	369.0	192.0	**A**
	Mean IT Strain, (%)	STD (%)	CV%	Max (%)	Min (%)	
Level-I	**0.63**	0.09	13.6	0.8	0.6	**A**
Level-II	**0.48**	0.20	41.8	0.9	0.2	**A**
Level-III	**0.48**	0.18	37.5	0.9	0.3	**A**

Figure B-2 presents the mean IT strength results of those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively.

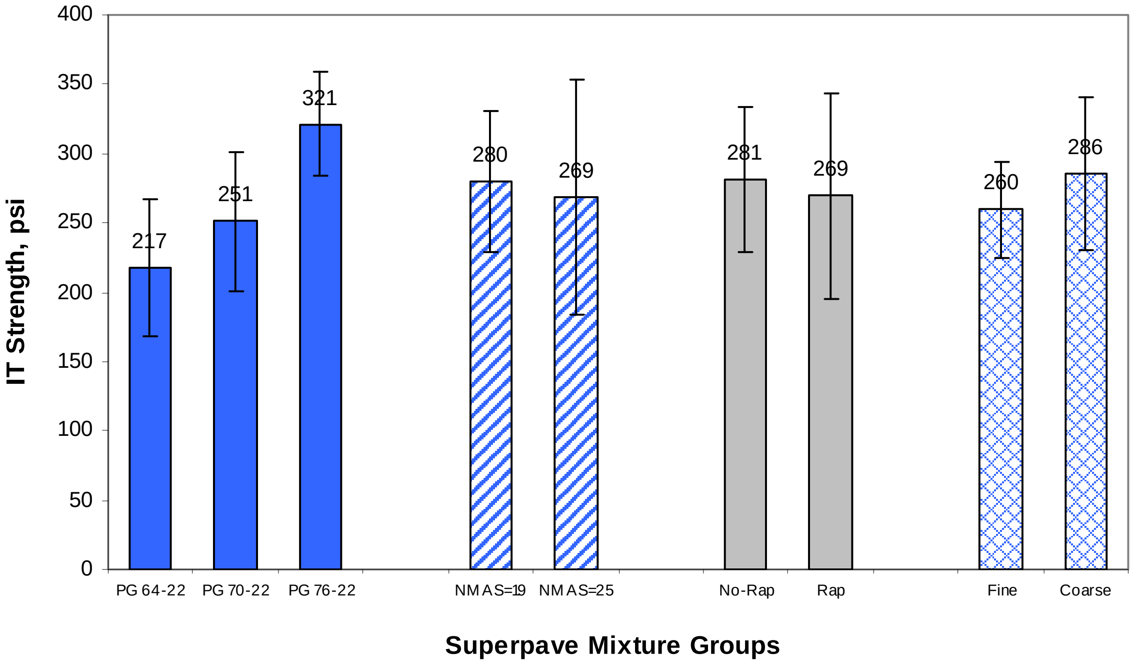


Figure B-2
Mean IT strength test results of mixtures at different groups

It can be observed from Figure B-2 that:

- Mixtures with higher PG binders tended to have higher IT strength values; in other words, $ITS_{(PG\ 76\text{-}22)} > ITS_{(PG\ 70\text{-}22)} > ITS_{(PG\ 64\text{-}22)}$. This indicates that the IT strength values for Superpave mixtures are sensitive to the binder PG types.

- As the NMAS increased from 19 mm to 25 mm, the IT strength tended to decrease; i.e., $ITS_{(19mm)} > ITS_{(25mm)}$. However, the difference in ITS between 19 mm and 25 mm Superpave mixtures was not statistically significant.

- Mixtures with no RAP appeared to have higher IT strengths than mixtures containing RAP; i.e., $ITS_{(no\text{-}RAP)} > ITS_{(RAP)}$. This is expected, as RAP materials contain aged binders that are less flexible in tension. However, the difference was not statistically significant.

- The mean IT strength for the coarse-graded Superpave mixtures appeared to be higher than that for the fine-graded; i.e., $ITS_{(coarse)} > ITS_{(fine)}$. This may be attributed to the difference in aggregate structure (interlocking) between coarse-graded or fine-graded mixtures. However, this difference in the mean ITS results was not statistically significant.

Indirect Tensile (IT) Creep Test

In an IT creep test, a lower creep slope and a higher creep intercept are desired for rut resistant mixtures. In this study, test results ranged from 0.22 to 0.54 log psi/log sec for IT creep slopes and from 10.76 to 12.40 log psi for IT intercepts.

Figure B-3 presents the mean IT creep slope results for Superpave mixtures grouped at different compaction levels. The average IT creep slope for the Level I, Level II, and Level III mixtures was 0.37, 0.40, and 0.36, respectively. The statistical ranking analysis presented in Table B-2 indicated that there was no significant difference in ranking for either IT creep slope results or IT strain results among different compaction levels. This indicates that Superpave mixtures classified at different compaction levels were not sensitive to an IT creep test condition.

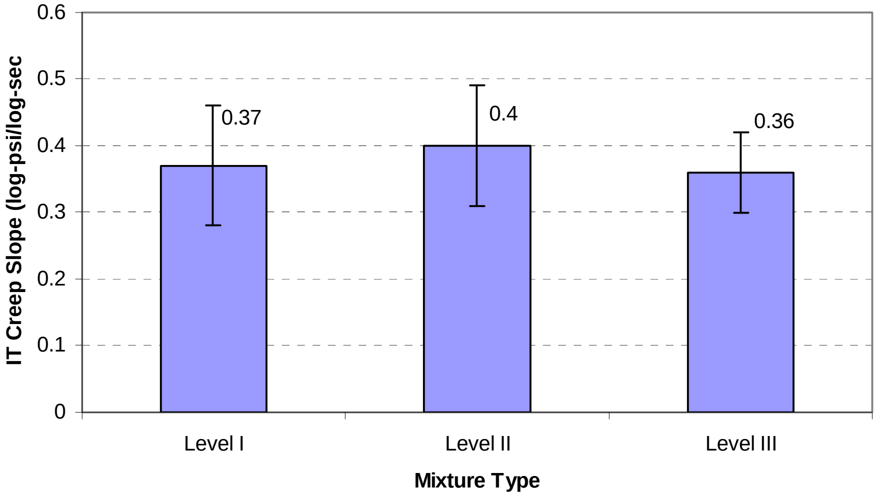


Figure B-3
Mean IT creep slopes of mixtures at different compaction levels

Table B-2
The statistics of IT creep test results on mixtures by level

Mix Type	Mean IT Creep Slope (log-psi/logsec)	STD (psi)	CV%	Max	Min	Statistic Grouping
Level-I	**0.37**	0.09	24.0	0.46	0.25	**A**
Level-II	**0.40**	0.09	22.1	0.54	0.27	**A**
Level-III	**0.36**	0.06	16.4	0.44	0.22	**A**
	Mean IT Creep Intercept (log psi)	STD (%)	CV%	Max	Min	
Level-I	**11.51**	0.68	5.9	12.40	10.80	**A**
Level-II	**11.41**	0.37	3.2	11.94	10.76	**A**
Level-III	**11.42**	0.33	2.9	12.07	10.85	**A**

Figure B-4 presents the mean IT creep slopes for those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively. The following two observations can be made from Figure B-4:

Mixtures that used higher PG binders tended to have lower IT creep slopes than mixtures with lower PG binders. Although this observation is not statistically significant, the numerical ranking of IT creep slopes was observed exactly in line with the binder's PG grades. This indicates that high PG binder Superpave mixtures have better rut resistance than lower PG binder mixtures. It also implies that the IT creep slopes are sensitive to binder's performance grades.

Mixtures with a smaller NMAS (19 mm), containing no RAP and coarse-graded, seemed to be more rut resistant than those mixtures having a larger NMAS (25mm) with RAP and fine-graded. However, this observation was not statistically significant.

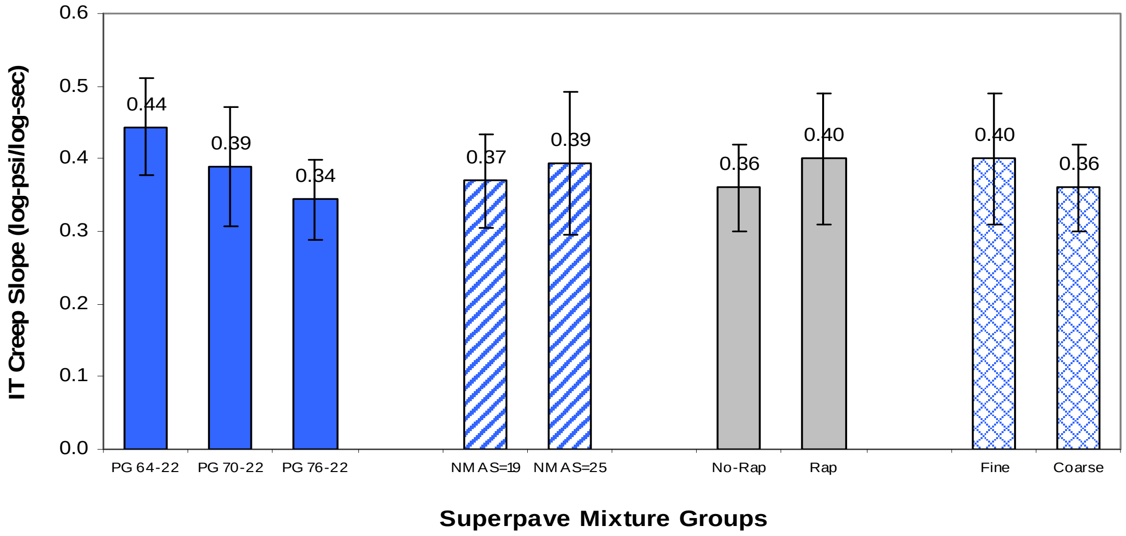
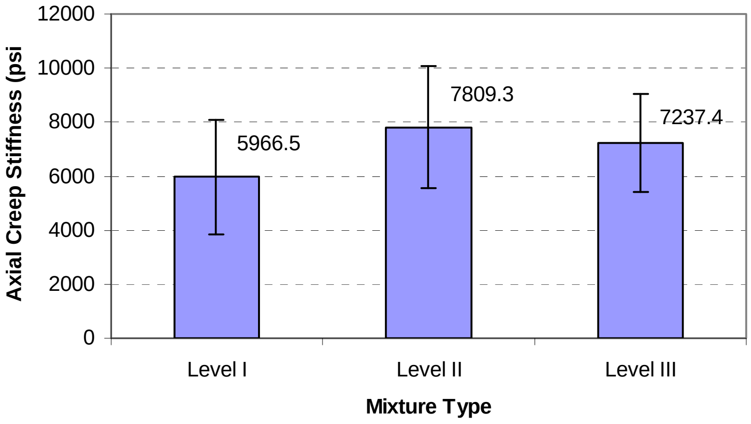


Figure B-4
Mean IT creep slopes of mixtures at different groups

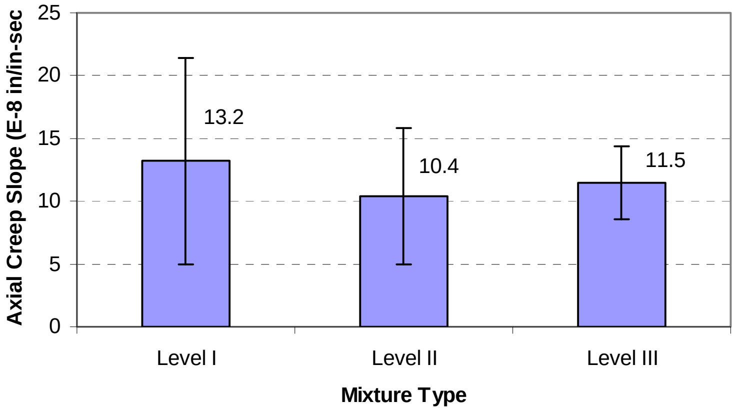
Axial Creep Test

In an axial creep test, a low creep slope and high creep stiffness are desired for rut resistant mixtures. In this study, test results ranged from 4.3 × 10^{-8} to 24.7 ×10^{-8} in/in-sec for axial creep slopes and from 2,853 to 12,583 psi for axial creep stiffness values.

Figure B-5 presents the mean axial creep stiffness and slope values for mixtures grouped at different compaction levels. The average axial creep test results for the Level I, Level II, and Level III mixtures were 5,966.5, 7,809.3, and 7,237.4 psi, respectively, for axial creep stiffness, and 13.2 ×10^{-8}, 10.40 × 10^{-8}, and 11.5 ×10^{-8} in/in-sec, respectively, for axial creep slopes. From those average axial creep test results, both Level II and Level III seemed to have better rut resistance than the Level I mixtures. However, statistical grouping analysis presented in Table B-3 indicates that there was no statistically significant difference among those axial creep test results (axial creep stiffness or creep slopes) for mixtures grouped at different compaction levels.



(a) Mean Axial Creep Stiffness



(b) Mean Axial Creep Slopes

Figure B-5
Mean axial creep test results at different compaction levels

Table B-3
The statistics of axial creep test results on mixtures by compaction level

Mix Type	Mean Axial Creep Stiffness (log-psi/log-sec)	STD	CV%	Max	Min	Statistic Grouping
Level-I	**5967**	2106	35.3	7271	2853	**A**
Level-II	**7809**	2264	29.0	11935	5319	**A**
Level-III	**7237**	1816	25.1	12583	5254	**A**
	Mean Axial Creep Slope (E^{-8} in/in-sec)	STD (%)	CV%	Max	Min	
Level-I	**13.2**	8.2	62.3	24.7	6.9	**A**
Level-II	**10.4**	5.5	52.5	22.9	4.3	**A**
Level-III	**11.5**	2.9	25.3	14.9	4.5	**A**

Figure B-6 presents the mean axial creep slopes and stiffness results for those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively.

From Figure B-6, the following observations can be made:

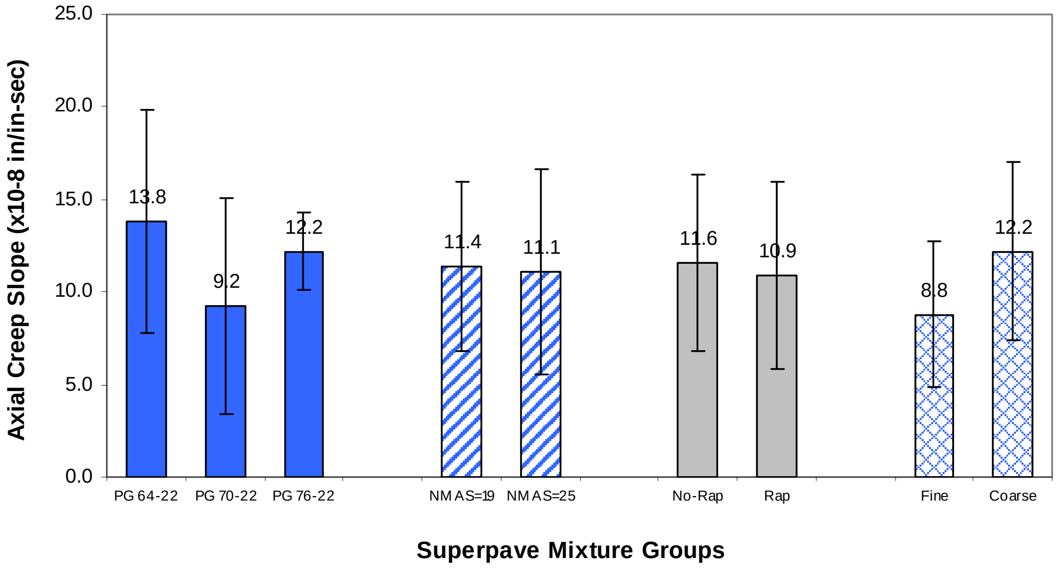
- Mixtures produced with PG 70-22 binders seemed to have lower axial creep slopes and higher axial creep stiffness than mixtures with other PG binders. However, there is no statistically significant difference among those values.

- There is no statistically significant difference in terms of axial creep slope and creep stiffness among mixtures with two different NMAS of 19 and 25 mm.

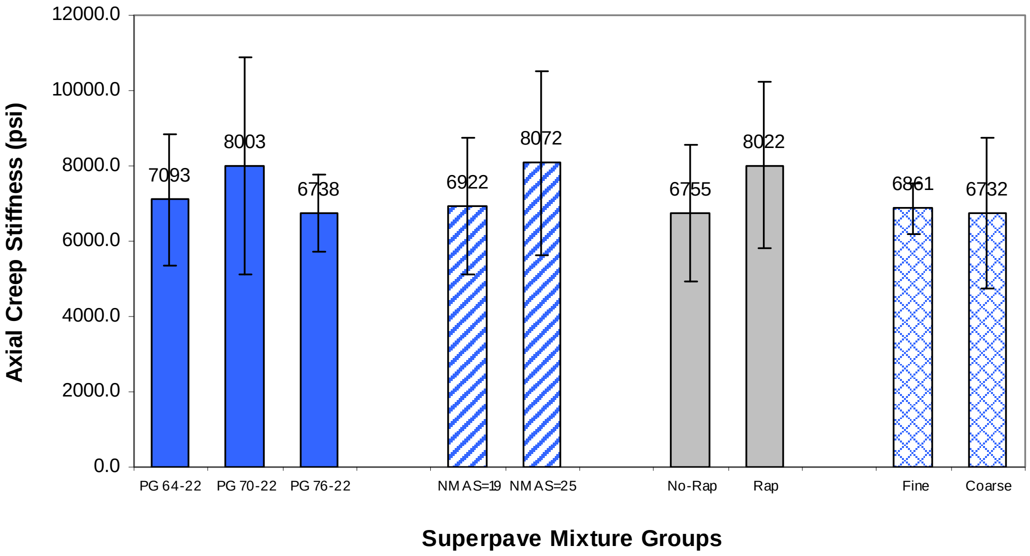
- Similarly, there is no statistically significant difference in terms of axial creep slope and creep stiffness among mixtures with or without RAP contents.

- However, fine-graded mixtures appeared to have lower creep slopes than coarse-graded ones, although both had similar creep stiffness values. This indicates that fine-graded Superpave mixtures seemed to have better rut resistance than coarse-graded mixtures. Obviously, this contradicts the IT creep test results.

- In general, axial creep test results were found not to be very sensitive in capturing the rutting performance of Superpave mixtures considered in this study.



(a) Axial Creep Slopes



(b) Axial Creep Stiffness

Figure B-6
Mean axial creep test results of mixtures at different groups

Indirect Tensile (IT) Resilient Modulus (M_r) Test

Figure B-7 presents the mean IT M_r test results at three test temperatures (5, 25, and 40° C) and three different compaction levels. In general, the resilient moduli were decreased as the test temperature was increased. This is expected because asphalt mixtures are stiffer at lower temperatures due to the higher binder stiffness.

The average IT M_r values for the Level I, Level II, and Level III mixtures were 760, 600, and 630 ksi, respectively, at 5 °C; 608, 414, and 511 ksi, respectively, at 25° C; and 398, 285, and 356 ksi, respectively, at 40° C. The statistical ranking presented in Table B-4 indicates that, at the low and medium temperatures (5 and 25°C), the IT M_r at Level I are statistically higher than those at Level 2 and Level 3. However, at 40° C, there is no significant difference among the IT M_r of mixtures at different compaction levels. This implies that at all three test temperatures, the Level I mixture had similar or higher IT M_r properties than mixtures at Level II and Level III.

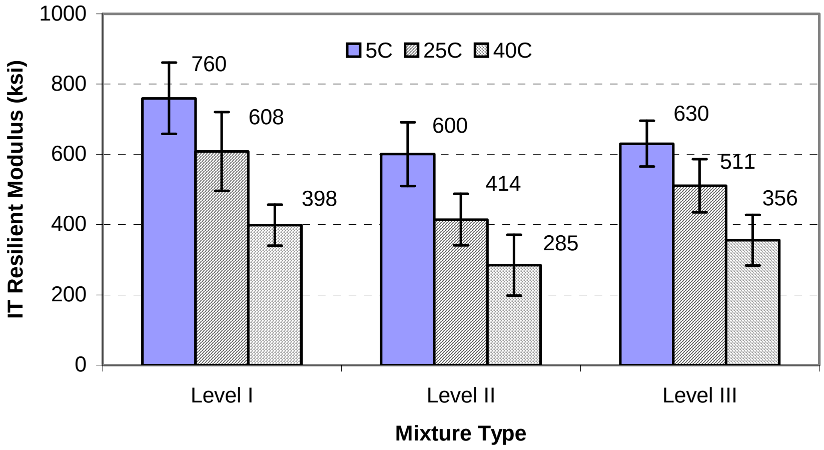


Figure B-7
Mean IT resilient moduli of mixtures at different compaction levels

Table B-4
The statistics of IT M_r test results on mixtures by level

Mix Type	Mean IT Modulus at 5C, (ksi)	STD (psi)	CV%	Max (psi)	Min (psi)	Statistic Grouping
Level-I	**760**	102	13.4	839	645	**A**
Level-II	**600**	91	15.1	703	426	**B**
Level-III	**630**	65	10.4	694	477	**B**
	Mean IT Modulus at 25C, (ksi)	STD (%)	CV%	Max (%)	Min (%)	
Level-I	**608**	112	18.4	733	517	**A**
Level-II	**414**	73	17.7	550	315	**B**
Level-III	**511**	75	14.8	652	374	**A/B**
	Mean IT Modulus at 40C, (ksi)	STD	CV%	Max	Min	
Level-I	**398**	58	14.6	462	348	**A**
Level-II	**285**	96	30.4	410	181	**A**
Level-III	**356**	72	20.2	494	215	**A**

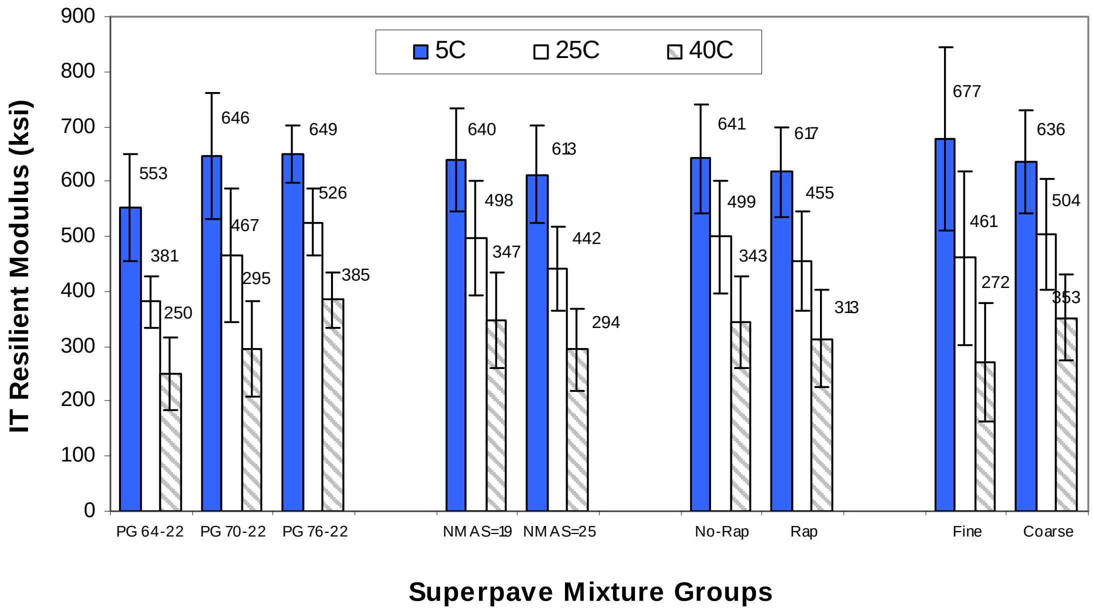


Figure B-8
Mean IT resilient moduli of mixtures at different groups

Figure B-8 presents the mean IT M_r test results of Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively. The following observation can be made:

Mixtures produced with higher PG binders had a tendency to possess higher IT M_r values than mixtures with lower PG binders at all three temperatures: 5, 25, and 40^{o} C. In addition, mixtures with PG 76-22 had statistically significant higher IT M_r values than those with PG 64-22, indicating that the IT M_r test is fairly sensitive to binder PG types used in a Superpave mixture.

Mixtures with 19 mm NMAS and no RAP content tended to have higher IT M_r values at all three test temperatures than those with 25 mm NMAS and RAP contents. However, the differences were not statistically significant.

Fine-graded mixtures tended to have higher IT M_r values at 5 ^{o} C and lower IT M_r values at both 25 and 40 ^{o} C than coarse-graded mixtures. Again, those differences were not statistically significant.

Frequency Sweep at Constant Height Test

As stated earlier, the complex shear modulus (G*) is defined as the ratio of the peak stress amplitude to the peak strain amplitude. It is a measure of the total stiffness of asphalt mixtures and is composed of elastic and viscous components. Phase angle (δ) is defined as the time lag between the application of a stress and the resulting strain. The property G*/sin(δ) is considered as an indicator of mixtures' susceptibility to permanent deformation. Higher G*/sin(δ) value is desired for rut resistant mixtures. In this study, the property of G*/sin(δ) at 60^{o}C ranged from 7,874 to 47,368 psi at 10Hz, from 3,683 to 17,533 psi at 1Hz, from 2,010 to 11,490 psi at 0.1Hz, and from 2,103 to 9,741 psi at 0.01 Hz, as shown in Table 33.

Figures B-9 and B-10 present the mean G*/sin(δ) at 10 and 0.1 Hz, respectively, for mixtures grouped at three compaction levels. The mean G*/sin(δ) values for Level I, Level II, and Level III mixtures are 16,774, 21,439, and 20,916 psi, respectively, at 10Hz and 5,242, 5,333, and 5,330 psi, respectively, at 0.1Hz. The statistical ranking presented in Table B-5 indicated that the $G^*/\sin(\delta)_{10Hz}$ for Level-II and Level-III are significantly higher than that for Level-I. However, at 0.1 Hz, all three levels of mixtures possessed similar G*/sin(δ) values.

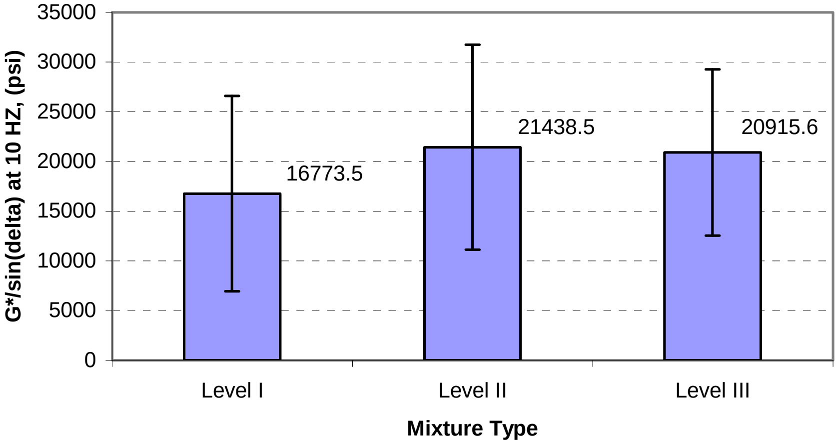


Figure B-9
Mean G*/sin(δ) at 10 Hz of mixtures at different compaction levels

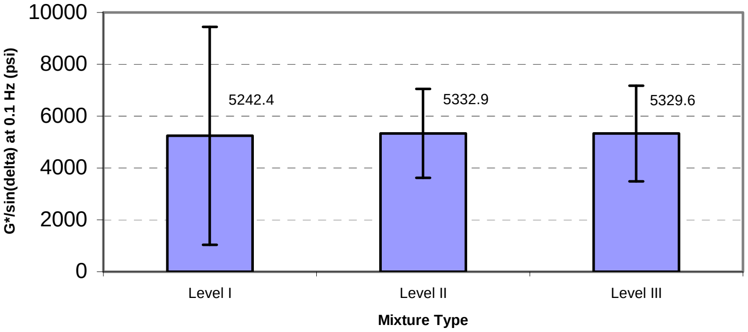


Figure B-10
Mean G*/sin(δ) at 0.1 Hz of mixture at different compaction levels

Table B-5
The statistics of FSCH test results on mixtures by level

Mix Type	Mean G*/sin(δ) at 10 Hz, psi	STD (psi)	CV%	Max	Min	Statistic Grouping
Level-I	**16773.5**	9823.4	58.6	30761.8	7874.5	**B**
Level-II	**21438.5**	10323.9	48.2	47367.8	10663.2	**A**
Level-III	**20915.6**	8362.3	40.0	36197.3	12153.9	**A**
	Mean G*/sin(δ) at 0.1Hz, psi	STD (%)	CV%	Max	Min	
Level-I	**5242.4**	4201.2	80.1	11489.9	2511.0	**A**
Level-II	**5332.9**	1716.5	32.2	9240.8	3212.7	**A**
Level-III	**5329.6**	1846.6	34.6	7744.2	2010.1	**A**

Figure B-11 presents the mean G*/sin(δ) test results at 10, 1, and 0.1Hz for Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively. The following observations can be made from Figure B-11:

Fine-graded mixtures tended to have higher G*/sin(δ) values at different frequencies than coarse-graded ones. However, the differences might be not statistically significant.

Mixtures produced with higher PG binders had a tendency of having higher G*/sin(δ) values than mixtures with lower PG binders with an exception of mixtures with PG 76-22 at 10Hz. However, those differences were not statistically significant.

Mixtures with 19 mm NMAS and without RAP content showed a tendency of having lower G*/sin(δ) values. Again, those differences were not statistically significant.

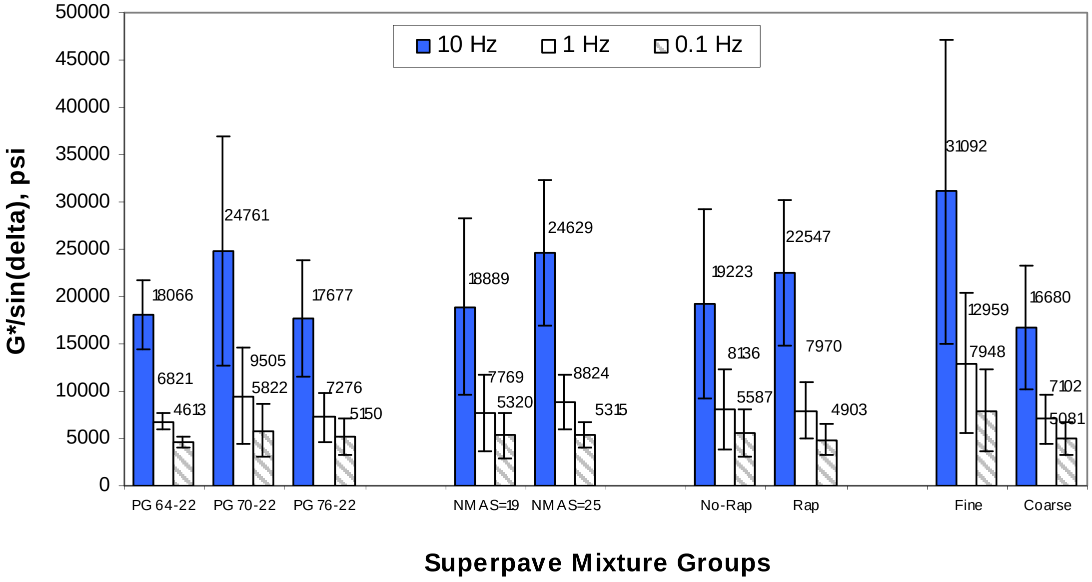


Figure B-11
Mean G*/sin(δ) of mixtures at different groupings

Repetitive Shear at Constant Height (RSCH) Test

Lower permanent shear strains from an RSCH test are desired for rut resistant mixtures. In this study, the measured RSCH permanent shear strains range from 0.3 percent to 4.2 percent, as shown in Table 33. This means that the permanent shear strains for all the mixtures met the Superpave limit of below 5 percent at 5,000 cycles, implying that all Superpave mixtures in this study are considered as rut resistant mixtures.

Figure B-11 presents the mean RSCH permanent shear strain test results for mixtures grouped at different compaction levels. The average RSCH permanent shear strain for the Level I, Level II, and Level III mixtures was 2.5, 1.5, and 1.8 percent, respectively. The statistical ranking presented in Table B-6 indicates that the mean permanent shear strain for Level II and Level III mixtures (both ranked as an "A") is significantly higher than that for Level I (ranked as a "B"). This indicates that Level II and Level III mixtures had better rut resistance than the Level I.

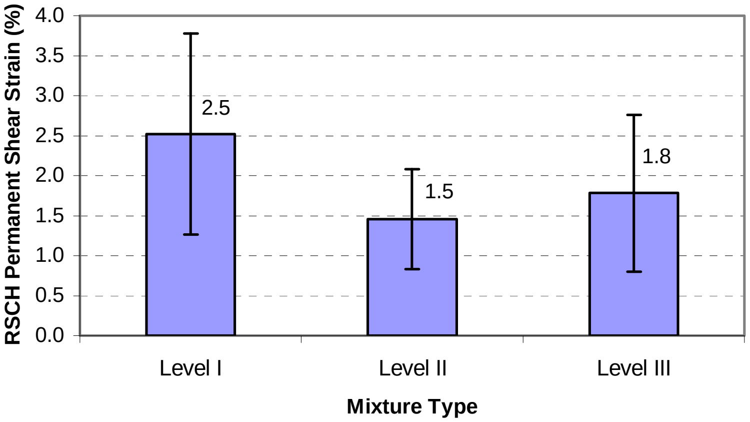


Figure B-11
Mean RSCH permanent shear strain of mixtures at different compaction levels

Table B-6
The statistics of RSCH test results on mixtures by level

Mix Type	Mean Permanent Shear Strain (%)	STD	CV%	Max	Min	Statistic Grouping
Level-I	**2.5**	1.25	49.9	4.24	1.58	**B**
Level-II	**1.5**	0.62	42.9	2.68	0.57	**A**
Level-III	**1.8**	0.98	55.1	3.47	0.62	**A**

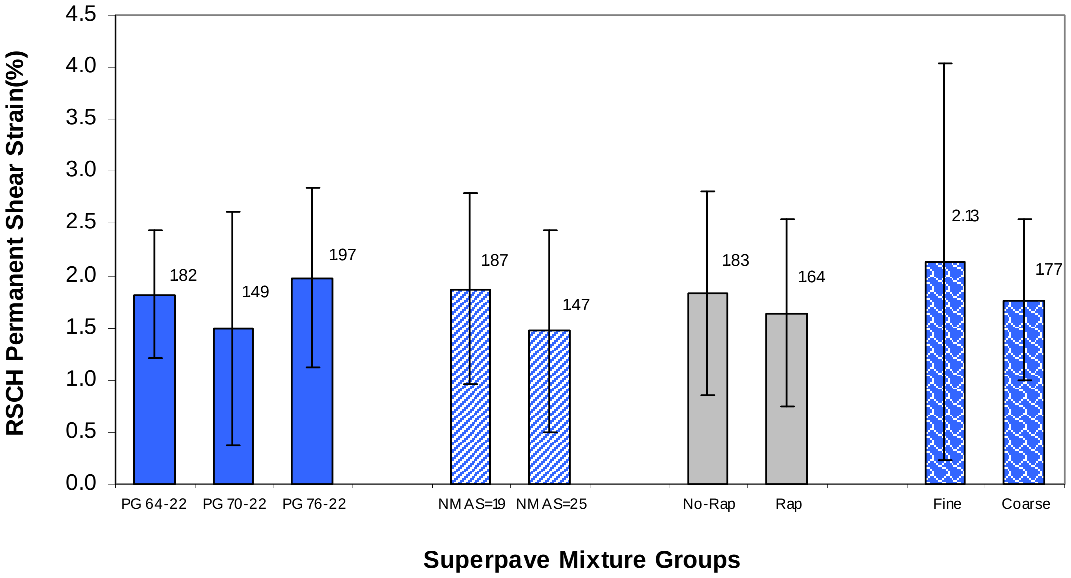


Figure B-13
Mean RSCH permanent shear strain of mixtures at different groupings

Figure B-13 presents the mean RSCH results of those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse-/fine-graded, respectively. The following observations can be made from Figure B-13:

Mixtures produced with different PG binders seemed to have similar permanent shear strains. This indicates that the RSCH test is not very sensitive to the binder PG types.

As the NMAS increases from 19 mm to 25 mm, the permanent shear strain tended to decrease, indicating that 25mm Superpave mixtures may have better rut resistance than 19 mm ones.

Both mixtures with no RAP content and mixtures with fine-graded gradations appeared to have higher permanent shear strain or be more rut susceptible than mixtures with some RAP contents or coarse-graded gradations. However, those differences in RSCH permanent shear strain values were not statistically different.

Simple Shear at Constant Height (SSCH) Test

Similar to the RSCH test, lower permanent shear strains from an SSCH test are desired for rut resistant mixtures. The measured SSCH permanent shear strains ranged from 0.08 percent to 0.7 percent for all 30 Superpave mixtures considered, as shown in Table 33.

Figure B-14 presents the mean SSCH permanent shear strain test results for mixtures grouped at different compaction levels. The average SSCH permanent shear strain for the Level I, Level II, and Level III mixtures was 0.32, 0.24, and 0.32 percent, respectively. The statistic ranking presented in Table B-7 indicates that the mean permanent shear strains of all three compaction level mixtures are statistically similar, implying that the ranges of the mean permanent shear strain from SSCH tests are not able to separate the rutting performance of Superpave grouped at different compaction levels in this study.

Figure B-15 presents the mean SSCH results of those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-Rap, and coarse/fine graded, respectively.

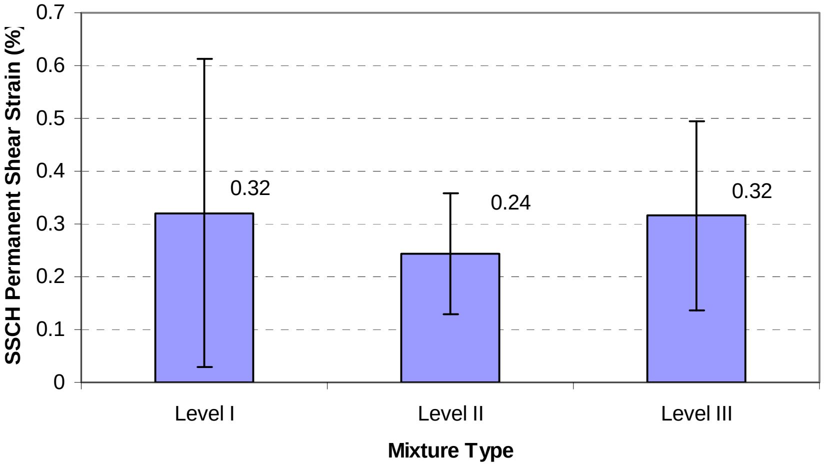


Figure B-14
Mean SSCH permanent shear strain of mixtures at different compaction levels

Table B-7
The statistics of SSCH test results on mixtures by level

Mix by Level	Mean SSCH Permanent Shear Strain, (%)	STD	CV%	Max	Min	Statistic Grouping
Level-I	0.32	0.29	91.1	0.71	0.08	A
Level-II	0.24	0.11	47.1	0.39	0.09	A
Level-III	0.32	0.18	56.6	0.67	0.10	A

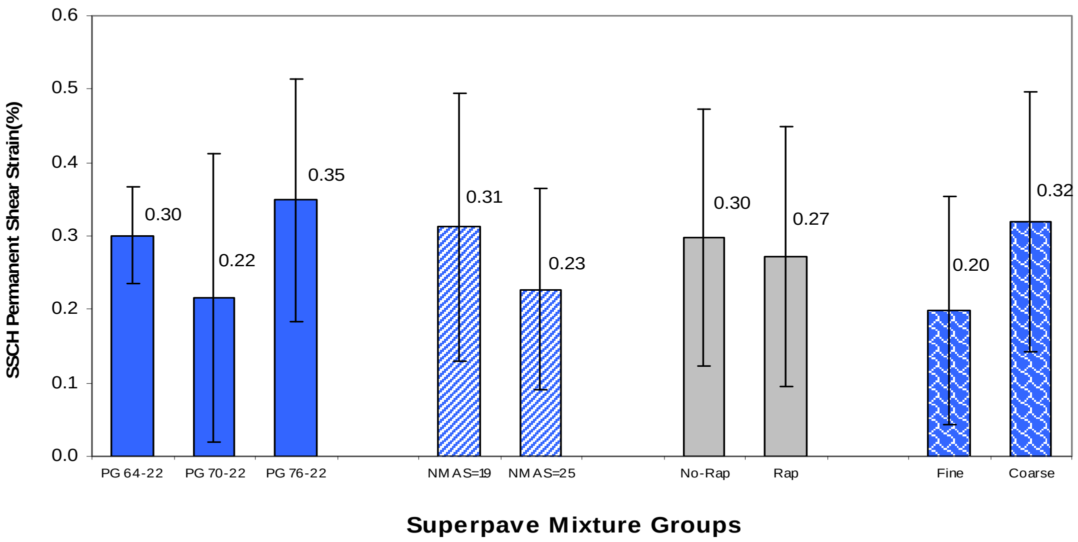


Figure B-15
Mean SSCH permanent shear strain of mixtures at different groupings

The following observations can be made from Figure B-15:

- Similar to RSCH permanent shear strain results, mixtures produced with different PG binders seemed to have similar SSCH permanent shear strains. This indicates that the SSCH test is not very sensitive to the binder PG types.

- As the NMAS increased from 19 mm to 25 mm, the permanent shear strain tended to decrease, indicating that 25mm Superpave mixtures may have better rut resistance than 19 mm ones. This is consistent with the RSCH test results.

- Mixtures with no RAP contents appeared to have higher SSCH permanent shear strain or be more rut susceptible than mixtures with some RAP contents. Again, this is consistent to the RSCH test results.

- Mixtures with fine-graded gradations seemed to have lower SSCH permanent shear strain or be more rut resistant than mixtures with coarse-graded gradation. However, this trend is not consistent with the RSCH test results.

APA Rut Test

The APA rut depths for the 30 Superpave mixtures tested varied from 1.2 to 9.3 mm. The individual APA test result of mixtures can be found in Table 33.

Figure B-16 presents the mean APA test results for Superpave mixtures grouped at different compaction levels. The average APA rut depth for the Level-I, Level-II, and Level-III mixtures was 6.1, 4.2, and 3.5 mm, respectively. The statistic ranking presented in Table B-8 indicates that the mean APA rut depths for both Level-II and Level-III mixtures (both ranked as an “A”) are significantly smaller than that for Level-I mixtures (ranked as a “B”), indicating that Level-II and Level-III mixtures have better rut resistance than Level-I mixtures. This implies that the APA rut test seemed to be sensitive to Superpave gyratory compaction levels.

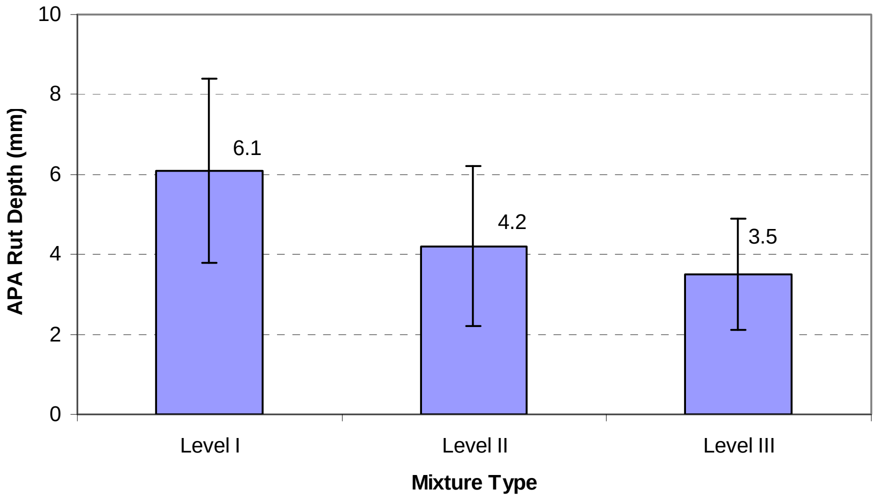


Figure B-16
Mean APA rut depths of mixtures at different compaction levels

Table B-8
The statistics of APA test results on mixtures by level

Mix by Level	Mean APA rut depth, (mm)	STD (mm)	CV%	Max (mm)	Min (mm)	Statistic Grouping
Level-I	6.1	2.3	37.7	9.3	4.0	B
Level-II	4.2	2.0	48.8	7.8	1.2	A
Level-III	3.5	1.4	40.2	7.5	2.0	A

Figure B-17 presents the mean APA test results of those Superpave mixtures grouped at different NMAS, binder PGs, RAP/No-RAP, and coarse/fine graded, respectively.

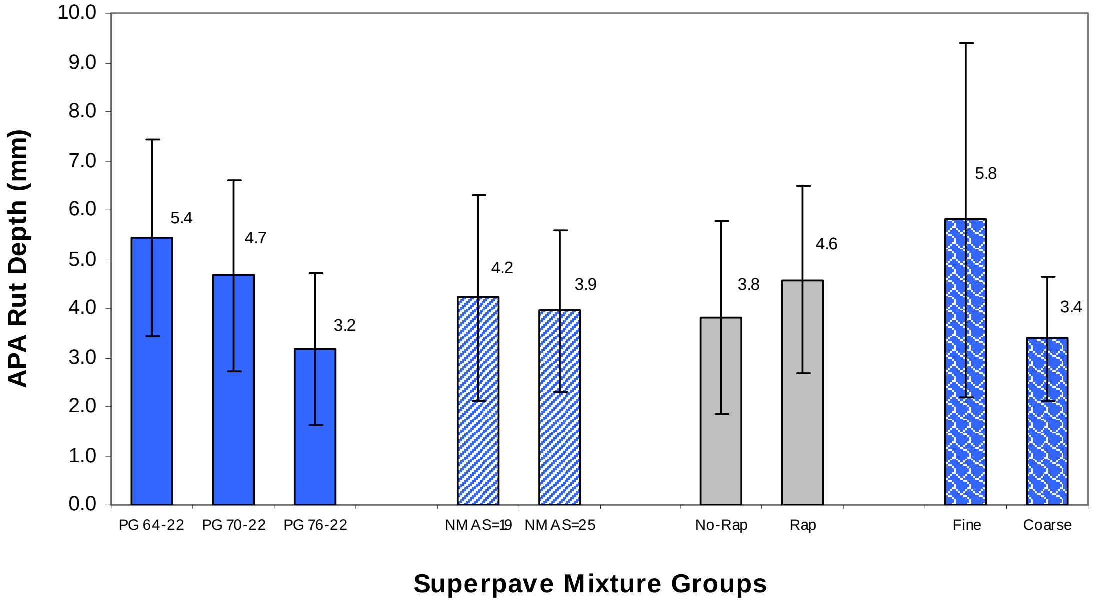


Figure B-17
Mean APA rut depths of mixtures at different groupings

From Figure B-17, the following observations can be made:

- Mixtures produced with higher PG binders tended to have lower APA rut depths than mixtures with lower PG binders, indicating that the APA test is very sensitive to the mixture binder types.

- There is no statistically significant difference in terms of APA rut depths among mixtures with two different NMAS of 19 and 25mm.

- Mixtures with RAP content tended to have more APA rut depths than those without RAP content.

- Coarse-graded mixtures seemed to be more rut resistant than fine-graded ones, as they were found to have lower APA rut depths in this study.

- In general, the APA rut test was found to be fairly sensitive in capturing the rutting performance of Superpave mixtures considered in this study.

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