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Assessment of Asphalt Concrete QA Specifications

An Assessment of WSDOT's Hot-Mix Asphalt Quality Control and Assurance Requirements

by

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16. ABSTRACT

This report assesses various elements of the Washington State Department of Transportation (WSDOT) hot-mix quality assurance (QA) specification.

Current WSDOT QA specifications contain measures of in-place density, asphalt content, and aggregate gradation for contractor pay and special provisions allow for additional pay factor items based on volumetric properties. Data from production paving projects suggests that use of the original pay items are adequate in determining the quality of hot-mix asphalt (as opposed to pay items based on volumetric mix properties). Additionally, the option of increasing the minimum compaction level (currently 91 percent of theoretical maximum density) is recommended to increase quality.

In addition, a contractor quality control (QC) program is recommended for consideration by WSDOT.

17. KEY WORDS
Specification, statistics, hot mix asphalt, HMA, asphalt concrete, pay factor, precision, Superpave, compaction, quality control, quality assurance

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INTRODUCTION

INTRODUCTION TO THE CHAPTERS

Hot Mix Asphalt (HMA) is the major paving material for WSDOT which purchased almost 1.5 million tons per year over a five year period (from 2002 through 2006 (WSDOT, 2006a)). How the quality of this material is assured is a critical issue for any State DOT.

During the last two decades, there has been a trend in the highway construction industry toward the use of statistically based specifications. This continues an evolution from traditional, method-based specifications that have been used in the industry for nearly a century. The focus of this study is on Quality Assurance (QA) specifications for hot mix asphalt (HMA). Contractor quality control (QC) programs are also examined. This is the third and final report for this study and it will be used to focus on the WSDOT QA specification with specific emphasis on issues relating to Superpave implementation. The first report provided an overview of State DOTs and their QA specifications and QC programs (Mahoney and Backus, 1999). The second report dealt with statistical risks built into hot mix QA specifications (Muench and Mahoney, 2001). This third and final report was originally drafted by the authors and reviewed by WSDOT during 2004. Over the past two years the implementation of the Superpave mix system has been completed along with new HMA field tests and pay factors. As such, the final report is used to recognize and assess these changes.

Interest in designing asphalt concrete mixtures with the Superpave system has grown within the Washington State Department of Transportation (WSDOT) and nationwide. Within Washington State, the first Superpave-designed mixes were placed in 1997 with the number of Superpave mixes increasing each year.

To conduct this review of WSDOT’s current and evolving QA and QC requirements, the information is organized into seven chapters. These chapters reflect some of the emerging issues that face WSDOT and its Contractors with respect to HMA specifications. As such, this report covers several separate but related topics.

Chapter 1 contains this introduction and selected terminology.

Chapter 2 is a literature review and assessment. It largely draws on national and local studies with a specific focus on mix volumetrics.

Chapter 3 contains a review of WSDOT mix volumetrics that are based on actual field projects. Some of the projects reviewed, although Superpave-designed, were constructed with WSDOT’s customary asphalt concrete QA program that includes pay factors for asphalt content, aggregate gradation, and in-place density. During the 2001 construction year, three projects were constructed with volumetric-based pay factors that include pay for asphalt content, voids in mineral aggregate (VMA), gyratory-compacted air voids (V_a), specified sieve sizes for gradation, and in-place density. During the 2002 construction year, 12 projects were constructed with volumetric pay factors. This chapter will be used to provide an early assessment of whether mix volumetric (VMA, V_a) pay factors result in improved HMA. The projects that were evaluated with the volumetric pay factors during the 2001 and 2002 construction seasons were compared with the previous Superpave projects constructed from 1997 to 2002. This evaluation included the volumetric properties, gradation, asphalt content, and in-place density.

In Chapter 4, mixes that have been designed via the Superpave system have been compared to WSDOT's Class A mix (both are dense-graded mixtures). This provides an assessment of whether the Superpave mixes are producing a better quality mix than the traditional Hveem-designed Class A mix. With respect to field performance, the Superpave mixes were compared with Class A mixes, aggregate gradation, asphalt content, and in-place densities were used for the assessment.

In Chapter 5, an examination of in-place densities was done to evaluate the current WSDOT HMA compaction specification.

In Chapter 6, Contractor QC programs are examined and discussed.

Finally, Chapter 7 is used to present a summary and relevant conclusions.

TERMINOLOGY

Precision statements for various hot mix tests are of interest in this study and report. Thus, a few definitions are in order (from American Society for Testing and Materials (ASTM) C 670 and E 177):

- "The precision of a measurement process…is a generic concept related to the closeness of agreement between tests results obtained under prescribed like conditions from the measurement process being evaluated. … The greater the dispersion or scatter of the test results, the poorer the precision."
- "One-sigma limit (1S)—the fundamental statistic underlying all indexes of precision is the standard deviation of the population of measurements characteristic of the method when the latter is applied under specifically prescribed conditions (a given system of causes). The terminology 'one-sigma limit' is used in Recommended Practice E 177 to denote the estimate of the standard deviation or sigma that is characteristic of the total statistical population."
- "Single operator one-sigma limit—the one-sigma limit for single operator precision is a quantitative estimate of the variability of a large group of individual test results when the tests have been made on the same material by a single operator using the same apparatus in the same laboratory over a relatively short period of time."
- "Multi-laboratory one-sigma limit—the one-sigma limit for multi-laboratory precision is a quantitative estimate of the variability of a large group of individual test results when each test has been made to make the test portions of the material as

nearly identical as possible. Under normal circumstances the estimates of one-sigma limit for multi-laboratory precision are larger than those for single operator precision, because different operators and different apparatus are being used in different laboratories for which the environment may be different."

- "Field versus laboratory tests—precision indexes for ASTM methods are normally based on results obtained in laboratories by competent operators using well-controlled equipment on test portions of materials for which precautions have been taken to assure that they are as nearly alike as possible. Such precautions and the same level of competence may not be practicable for the usual quality control or routine acceptance testing. Therefore, the normal testing variation among laboratories engaged in quality control and acceptance testing of commercial materials may be larger than indicated by the relationship derived from the one-sigma limit for multilaboratory precision. In this case it is recommended that studies be made to determine the one-sigma limit for tests made under field conditions and realistic adjustments in specification tolerances be made accordingly."
- "Two Standard Deviation Limits (2s) – Approximately 95% of *individual* test results from laboratories similar to those in an interlaboratory study can be expected to differ in absolute value from their average value by less than 1.960 s (about 2 s). [This index is known as repeatability.]"
- "Difference Two Standard Deviation Limit (d2s) – Approximately 95% of *all pairs* of test results from laboratories similar to those in the study can be expected to differ in absolute value by less than $1.960\sqrt{2}$ s (about $2\sqrt{2}$ s) = 2.77 s (or about 2.8 s). This index is also known as the 95% limit on the difference between two test results [or reproducibility]."

CHAPTER 2
LITERATURE REVIEW AND ASSESSMENT

INTRODUCTION

This chapter is organized by six topics that are: (1) testing variability, (2) variability of Superpave Gyratory Compactors (SGC), (3) HMA bulk density measurements, (4) volumetric parameters and HMA performance, (5) trial mixes, and (6) initial WSDOT Superpave assessment.

TESTING VARIABILITY

The current effect of testing variability on volumetric properties, according to Hand and Epps (2000), was unacceptable for field management operations. Using the ASTM and American Association of State Highway and Transportation Officials (AASHTO) precision and bias statements, they ran a Monte Carlo simulation to determine the precision for air voids in a SGC compacted mix. It was determined that the multi-laboratory d2s range was ± 3.7 percent and the single operator d2s range was ± 1.8 percent. WSDOT broadband tolerances for air voids are 3.0 to 5.0 percent with a target of 4.0 percent for laboratory compacted specimens (for the volumetric pay based projects, the target air voids are 4.5 percent with the tolerances set at 3 to 6 percent). The Hand and Epps single operator results come close to current WSDOT limits. Their multi-laboratory results exceed the allowable tolerance for air voids.

D’Angelo, et al. (2001) performed an evaluation of the volumetric properties during HMA production in 16 states from 1995 to 1999. Of the 16 projects, ten were analyzed to examine the relationship between both V_a and VMA and the changes in asphalt content (AC) and gradation. Nine of the ten projects were coarse-graded (i.e., below the maximum density line and restricted zone). FHWA personnel performed the sampling and testing of the hot-mix in two of their mobile labs (for multi-laboratory comparisons). To reduce the variability within the AASHTO and ASTM test methods, the tests were performed with identical methods for sampling, preparation, and testing along with routine maintenance and calibration of the test equipment. From the analysis of the ten projects, it was determined that the multi-laboratory precision (one-sigma limit) was ± 1.6 percent for V_a.

D’Angelo, et al. performed a multiple linear regression on the gyratory compacted specimens for air voids and VMA (dependent variables) in relation to the change from sample to sample of the percent asphalt content and the percent passing various sieve sizes for the ten projects. They found that the key independent variables in predicting gyratory air voids and VMA are the asphalt content and the sieve sizes ranging between the No. 16 and No. 200. The relative magnitudes of the regression constants, not the t-statistics, were used to determine the key independent variables. The percent asphalt content, No. 200 sieve, and the No. 100 sieve most influenced V_a, while the percent asphalt content, No. 100 sieve, and the No. 50 sieve most influenced VMA.

Analysis of the data indicated that both VMA and air voids in gyratory compacted specimens are directly related to the changes in the asphalt content and the gradation during hot mix production. The air voids, especially, are directly related to the changes in asphalt content. D'Angelo, et al. (2001) recommended that tolerances for gyratory compacted air voids should be ± 1.4 percent while those for VMA should be ± 1.0 percent. They also found that the upper and lower specification limits should be set at ± 2 standard deviations for establishing reasonable production limits.

VARIABILITY OF SGC COMPACTORS

Buchanan and Brown (2001) studied the effect that the Superpave Gyratory Compactor (SGC) has on the compacted HMA density. They note that there is variability associated within and between laboratories and variability within and between the types of gyratory compactor being used. When compacting HMA samples with the gyratory compactor, a number of factors contribute to the variability in the bulk specific gravity (G_{mb}). Among these factors are the sampling procedures, the operator (both experience and technique), type of equipment, calibration of equipment, and the temperature.

Buchanan and Brown examined the data obtained from the Southeast Superpave Center gyratory compactor proficiency samples and the NCHRP 9-9 study. During the span of one year, the proficiency samples were sent out three times with three different SGCs. The results showed that the variability (one-sigma limit) decreased over time, most likely due to familiarity with the gyratory compactor, with the overall variability for G_{mb} at 0.0094 for a single operator and 0.0132 for multi-laboratory. They note that this variability is better than the Marshall hammer precision, but also recognize that if there are to be advances in the design and construction of HMA pavements, the degree of variability must be within acceptable tolerances.

In the NCHRP 9-9 study, which was done to validate the gyratory levels in the N design table, two SGCs were used. It was found that one of the compactors always provided a higher bulk specific gravity than the other and that the average difference in air voids ranged from 0.6 to 1.6 percent. It was also noted that coarse-graded mixes had greater differences in air voids. The study also included an evaluation of six field projects where the samples were compacted at different times in both gyratory compactors to determine the variability associated with aging effects. Of the sixteen sampling times, twelve were found to have a statistically significant difference between the bulk specific gravity values of the specimens produced from the two gyratory compactors (air void difference ranged from 0.6 to 1.9 percent). In the four cases with no statistically significant difference, the difference in air voids ranged from 0.3 to 0.5 percent. The average air void difference of all 16 samples from five different mixes was 0.8 percent.

Buchanan and Brown (2001) also noted that a difference between two SGCs could result in conflicts between the Contractor and the State agency. Differences between gyratory compactors can result in a difference in the optimum asphalt content and volumetric properties. Observed bulk specific gravity differences could result in a change in optimum asphalt content of approximately 0.3 percent and an approximate 1 percent change in the calculated VMA.

To evaluate the effects of different gyratory compactors, Buchanan and Brown (2001) used a target air void value of 4 ± 1 percent with an assumed standard deviation of 0.75 percent. When the percent within limits were calculated based on three replicates and for the assumed standard deviation, approximately 40 percent of the air void results fell outside the specification tolerance range of 3 to 5 percent.

A major factor that influences SGC compacted specimens is the angle of gyration. A SPS-9 project in Arizona showed that a change in the angle of 0.25 degrees resulted in an air void difference of 4 percent (McGennis, et al., 1997). The gyration angle for many compactors can be measured in the loaded and unloaded conditions. Research has shown that the gyration angle decreases during compaction depending on the mix characteristics (Dalton, 1999). The angle changes with all types of compactors, but can be significant with some. Because of this, the gyration angle must be determined during mix compaction, not in the unloaded condition.

Hinrichsen (2001) performed an evaluation of four Superpave gyratory compactors to determine if the devices would produce comparable results. The four SGCs used were Troxler model 4140, Test Quip Brovold, Pine model AFGC 125X, and an Interlaken Model 1. There were a total of four different plant-produced mixtures tested (three of which were coarse-graded) in the four SGCs.

The first item performed in that study (Hinrichsen, 2001) was the calibration of the equipment according to the manufacturer's recommendations. Hinrichsen (2001) noted some of the difficulties and errors that could be produced in the calibration process.

- The Pine SGC uses dial gauges and a mounting device to calibrate the angle, which the technicians found difficult to mount properly and read.
- The Pine and the Interlaken SGCs have two methods of calibration: with and without a load.
    - Both SGCs calibrated without the load did not yield an accurate angle calibration. The observed error for the Pine was less than the 0.02^{o} tolerance, but the Interlaken produced an error of 0.12^{o} between the two methods.
- The Troxler and Interlaken SGCs use simple height calibration procedures that include a spacer block, two papers, and the mold plates.
- The Pine SGC uses several spacer blocks that must be inserted and stacked in a certain order to calibrate the height. This procedure calibrates the measuring device but does not calibrate the displayed height (the device performs calculations based on an assumed thickness of the mold plates and papers when it displays the height of the specimen).
- The Test Quip SGC required a caliper to measure from the top seat to the ram. This procedure also calibrates the height but not the displayed height.
- Because of these differences and the fact that none of these SGCs measure the final height after the leveling load or dwell gyrations are applied, the height was measured

after each specimen was cooled. The final height is used in the backcalculation of N_{des}.
- There were no noted difficulties with the pressure and speed of rotation calibrations.

It is noted that the independent measurements of the angle during the compaction operation showed that the Troxler and Interlaken held the angle between 1.24^o and 1.26^o. The Test Quip held the angle between 1.25^o and 1.26^o, but the Pine was not measurable during compaction because of a spinning cage around the mold. The technicians did note, however, that the Interlaken occasionally showed an angle of 1.10^o for several gyrations prior to returning to the proper reading.

After the calibration process was complete, the specimens were compacted in each of the SGCs. An analysis of the results showed that the Pine SGC was consistently higher than the average G_{mb} (G_{mb} deviation was always less than 0.020 for all the values) and the Interlaken was consistently lower than the average (5 of 12 G_{mb} results deviated by greater than 0.020). It was also noted that coarse-graded mixtures were more sensitive and variable than the fine-graded mixture, which showed the smallest standard deviations.

WSDOT performed a similar study in 2001 (Molohon, 2001) to compare the G_{mb} from the different SGCs owned by WSDOT. There were five samples, all Superpave ¾-inch PG 64-22, compacted in each of the six SGCs. The SGCs tested included two from Interlaken, two from Pine, and two from Troxler. One person performed all the testing, so these tests can be viewed as single operator precision for each SGC and multi-operator precision between each SGC and brand of SGC. Table 1 shows the G_{mb} that was determined for each sample tested in each SGC and the standard deviation associated with each SGC evaluated. The overall standard deviation is also shown. The single operator range for each SGC is within the limit of AASHTO recommendations (single operator range for AASHTO T 166 is 0.020). The largest difference between two sample results is 0.026 (ASTM D2726 multi-laboratory range is 0.076), which results in an air void difference of 1.0 percent (Table 2). This air void difference of 1.0 percent was a result of each SGC within the acceptable tolerance limits of bulk specific gravity according to AASHTO T 166 and ASTM D2726. One maximum theoretical density (G_{mm}) and aggregate bulk specific gravity (G_{sb}) was used to calculate the air void content and VMA results (Table 3), so this difference of 1.0 percent in air voids only represents the error introduced by the sample preparation and the measurement of the bulk specific gravity.

Table 1. Results of WSDOT Bulk Specific Gravity Comparison Between Different SGCs.

Gmb							
	Interlaken (ITC)		Pine		Troxler (4140)		
Sample	North Central	Olympic	AFGB1A	AFGC125XA	Mats Lab	Mats Lab Van	Total
1	2.451	2.429	2.455	2.440	2.443	2.452	
2	2.447	2.442	2.440	2.444	2.432	2.446	
3	2.447	2.444	2.439	2.442	2.443	2.443	
4	2.443	2.442	2.450	2.445	2.434	2.451	
5	2.441		2.438	2.444	2.440	2.448	
Average	2.446	2.439	2.444	2.443	2.438	2.448	2.443
Standard Deviation	0.004	0.007	0.008	0.002	0.005	0.004	0.006
Range	0.010	0.015	0.017	0.005	0.011	0.009	
Avg. Range	0.007		0.001		0.010		
Largest Range w/in Brand	0.022		0.017		0.020		
Largest Range							0.026

Table 2. Results of WSDOT Air Void Comparison Between Different SGCs.

Air Voids							
	Interlaken (ITC)		Pine		Troxler (4140)		
Sample	North Central	Olympic	AFGB1A	AFGC125XA	Mats Lab	Mats Lab Van	Total
1	3.1	4.0	2.9	3.5	3.4	3.0	
2	3.2	3.4	3.5	3.4	3.8	3.3	
3	3.2	3.4	3.6	3.4	3.4	3.4	
4	3.4	3.4	3.1	3.3	3.8	3.1	
5	3.5		3.6	3.4	3.5	3.2	
Average	3.3	3.5	3.3	3.4	3.6	3.2	3.4
Standard Deviation	0.2	0.3	0.3	0.1	0.2	0.1	0.2
Range	0.4	0.6	0.7	0.2	0.4	0.4	
Avg. Range	0.3		0.1		0.4		
Largest Range w/in Brand	0.9		0.7		0.8		
Largest Range							1.0

Table 3. Results of WSDOT VMA Comparison Between Different SGCs.

VMA							
	Interlaken (ITC)		Pine		Troxler (4140)		
Sample	North Central	Olympic	AFGB1A	AFGC125XA	Mats Lab	Mats Lab Van	Total
1	12.1	12.9	11.9	12.5	12.4	12.0	
2	12.2	12.4	12.5	12.3	12.8	12.2	
3	12.2	12.3	12.5	12.4	12.4	12.4	
4	12.4	12.4	12.1	12.3	12.7	12.1	
5	12.4		12.5	12.3	12.5	12.2	
Average	12.3	12.5	12.3	12.4	12.5	12.2	12.3
Standard Deviation	0.1	0.2	0.3	0.1	0.2	0.1	0.2
Range	0.359	0.538	0.610	0.179	0.395	0.323	
Avg. Range	0.2		0.1		0.3		
Largest Range w/in Brand	0.8		0.6		0.7		
Largest Range							0.9

BULK DENSITY MEASUREMENT METHODS

Hall, et al. (2001) examined the operator variability for three methods of measuring the bulk specific gravity of HMA. The three methods were AASHTO T-166, AASHTO T-

275, and vacuum sealing (via the CoreLok®). Statistically significant differences were noted between all three methods, but the CoreLok® method exhibited a lower degree of variability than the other two methods used, based on the standard deviation of the test results obtained by different operators. In direct comparison with AASHTO T-166, the CoreLok® exhibited a lower variability in 81 percent of the cases. With the AASHTO T-166 method, there is a "tendency for different operators to obtain results that are dissimilar when performing testing on the same materials, using the same equipment, and following the same procedures." These differences can be related to the interconnected voids in the core where water may infiltrate differently into the submerged core and drain differently.

WSDOT (Willoughby, et al., 2003) evaluated the CoreLok® device in a comparison with AASHTO T-166, Method C. There were 96 core samples obtained from seven different projects within Washington, with mix types of WSDOT Class A, Superpave ½-inch, and Superpave ¾-inch. Findings show that the difference in air voids between the two methods can vary significantly. This difference in air voids varied for the Class A, Superpave ½ inch and Superpave ¾-inch mixes that were tested. The Class A gradations follow the maximum density line (i.e., fine-graded), while the Superpave gradations (both the ½- and ¾-inch) fall below the maximum density line and restricted zone (i.e., coarse-graded).

The density results show that the Class A mixes on average, follow the line of equality (Figure 1), but around 12 percent air voids, the CoreLok® tends to have higher results than AASHTO T-166. The Superpave ½-inch mixes, shown in Figure 2, begin to deviate from the line of equality around 8 percent air voids and the Superpave ¾-inch mixes (Figure 3) are all above the line of equality (i.e., the CoreLok® results are always higher than the AASHTO T-166 results).

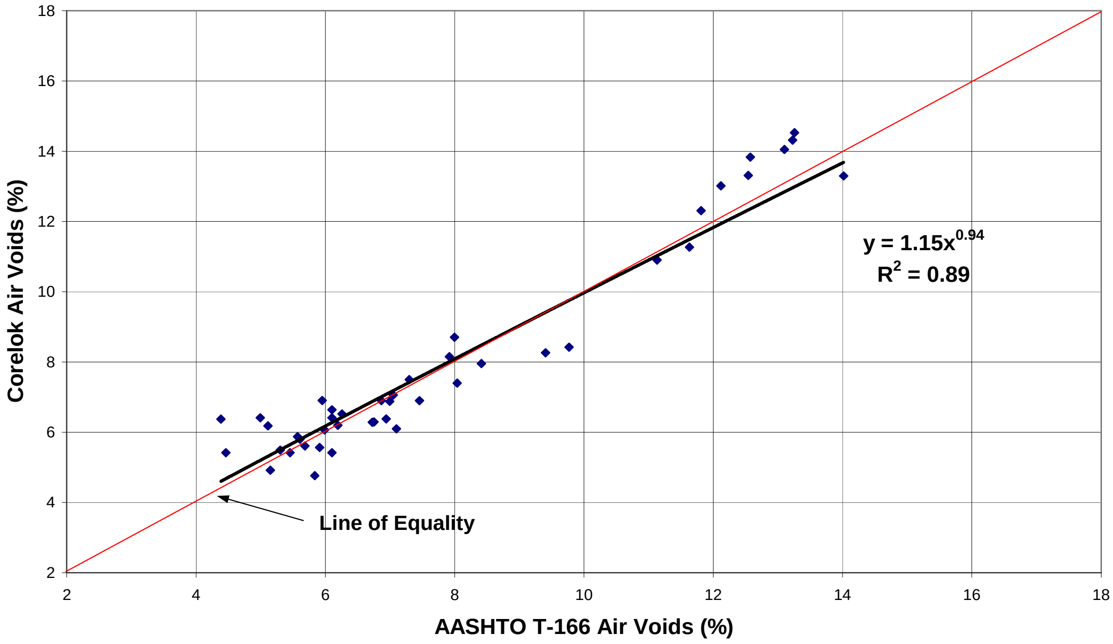

Figure 1. Class A comparison of AASHTO T-166 and CoreLok® air voids.

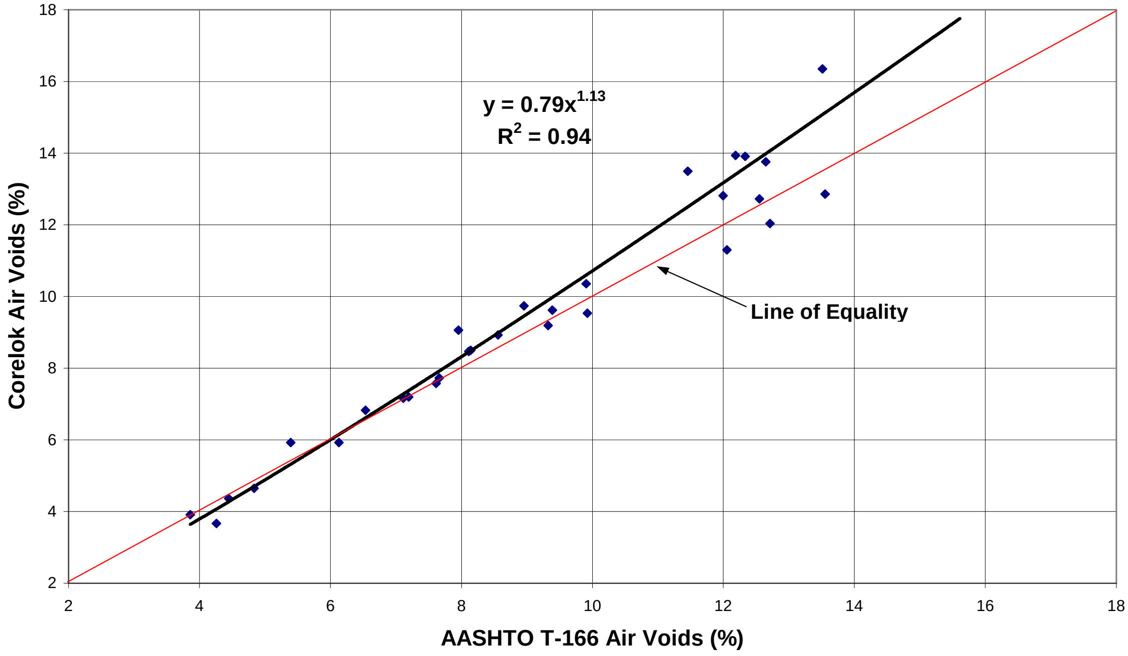

Figure 2. Superpave ½-inch comparison of AASHTO T-166 and CoreLok® air voids.

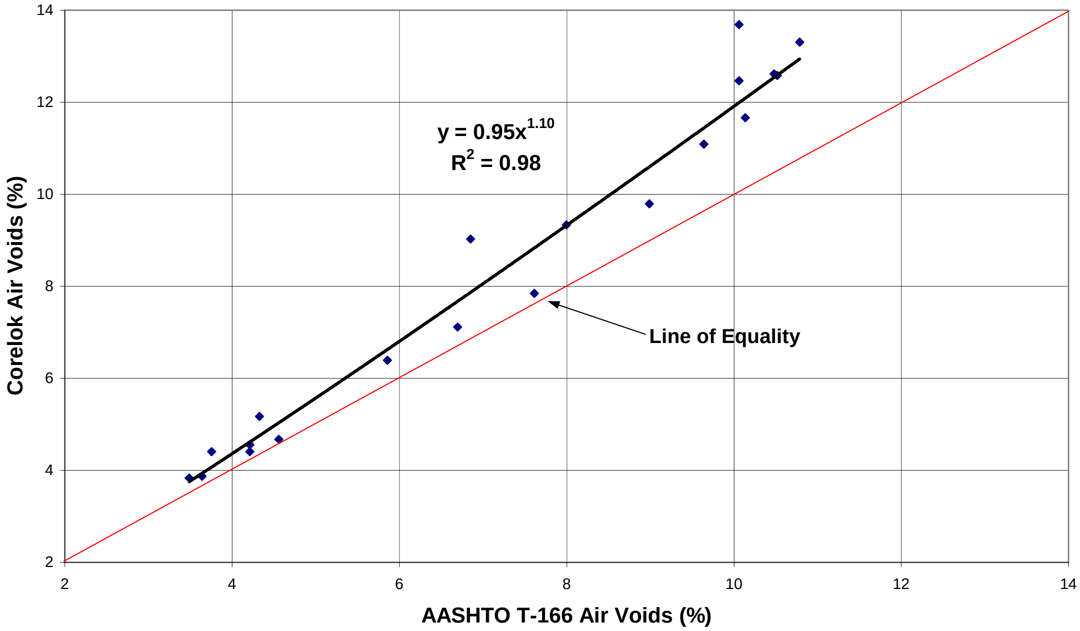

Figure 3. Superpave ¾-inch comparison of AASHTO T-166 and CoreLok® air voids.

These three figures illustrate the difference in air voids that can occur when different test methods are used for fine- and coarse-graded mixes. The results directly relate to the amount of interconnected voids present in the different types of mixes over a wide range of air voids. For instance, when the air voids are less than 8 percent, the difference between the CoreLok® and AASHTO T-166 air voids are very similar for the Class A and Superpave ½-inch mixes, while the Superpave ¾-inch mixes differ by about a half percent (Table 4). When the air voids are 12 percent or greater, the results show that, on average, the Superpave ¾-inch mixes can vary by 2 percent depending on the test method used. Again, the amount of interconnected voids and surface voids can drastically affect the SSD testing within AASHTO T-166. Of the 96 cores sampled, 46 were tested for absorption, and 85 percent of these core samples (which had air voids ranging from 4.5 to 15.6 percent) exceeded 2.0 percent absorption. The CoreLok® better represents the G_{mb} at higher air void levels due to the incorrect use of AASHTO T-166 (water absorption greater than 2.0 percent).

Table 4. Average Difference between CoreLok® and AASHTO T-166 Air Voids.

Air Voids	**Class Mix**		
	A	**½ inch**	**¾ inch**
<8 %	0.11	0.08	0.55
8 - <12%	-0.37	0.45	0.69
≥ 12 %	0.79	1.69	1.99

PERMEABILITY, COMPACTION, AND LIFT THICKNESS

Roberts, et al. (1996) and other studies have shown that dense-graded mixes should have an initial in-place air void content between 3 to 8 percent. Low in-place air voids (below 3 percent) can result in rutting, shoving, and bleeding, while high air voids (greater than 8 percent) can increase the potential for moisture damage, oxidation, raveling, and cracking. Previous research by Zube (1962) and Brown, et al. (1989) confirmed that a minimum of 92 percent of theoretical maximum density is needed for the in-place density of dense-graded mixes, but with the increased use of coarse-graded Superpave mixes (gradation passing below the maximum density line and restricted zone), 92 percent may not be adequate to combat permeability issues. Stevens (1959) and Zube (1962) have suggested that the time of construction can also affect permeability characteristics. Pavements constructed during summer months can “seal up” due to traffic consolidation and reduce the permeability of the pavement, whereas pavements constructed during the fall do not have the opportunity to “seal up” prior to the winter and can lead to permeability problems.

It has been shown by several studies including Zube (1962), Brown, et al. (1989), Choubane, et al. (1998), Mallick, et al. (1999), Westerman (1998), and Maupin (2000) that pavement density and permeability are directly related, both of which are related to the durability of the pavement. Mallick, et al. (1999) and Musselman, et al. (1998) have shown that the lift thickness can also affect the density and permeability. Mallick, et al. (1999), Cooley, et al. (2001), and Maupin (2000) have shown that the Nominal Maximum Aggregate Size (NMAS) can significantly affect the relationship between density and permeability. A lift thickness to NMAS ratio (t/NMAS) recommendation of 4 is preferred, but a minimum t/NMAS of 3 can be used. Cooley, et al. (2002) used 23 hot-mix asphalt construction projects to evaluate the relationship of permeability, in-place air voids, lift thickness, and NMAS.

The 23 projects used to test the relationship between density, permeability, lift thickness, and NMAS were all coarse-graded Superpave mixes (for this study, coarse-graded consisted of a gradation passing below the maximum density line at the No. 8 sieve). Four classes of mixes were used: 3/8-inch, ½-inch, ¾-inch, and 1-inch NMAS. A critical field permeability of $100\text{x}10^{-5}$ cm/sec was used to determine if a mix was excessively permeable. It was found that the 3/8-inch and ½-inch mixes have similar permeability characteristics and become excessively permeable above an in-place air void content of 7.7 percent. For the ¾-inch and 1-inch mixes, the critical in-place air void content is 5.5 percent and 4.4 percent, respectively.

EFFECTS OF MIX CONDITIONING

Musselman, et al. (2001) performed an evaluation of the field conditioning (holding the mixture at compaction temperature for a specified period) of Superpave asphalt mixes. They compared condition times of 1, 2, and 3 hours for the bulk and maximum specific gravities to the roadway conditions (samples taken on the roadway after haul). Analysis of the maximum specific gravity (G_{mm}) for the seven mixes tested indicated that a postproduction conditioning time that was closest to the actual haul time of the mix appears to correlate well with roadway data. AASHTO PP 2-01, Standard Practice for Conditioning HMA (current test method has been changed to AASHTO R30), for plant-produced samples that required no conditioning time does not correlate well with roadway samples. For the mix design phase, the 3-hour conditioning best correlates with the roadway conditions for maximum specific gravity, but the 2-hour conditioning best correlates with the roadway conditions for the bulk specific gravity and the air voids. Their recommendations were to continue to use the 2-hour aging/conditioning period for the mix design process (which is the current requirement contained in AASHTO R30) and a 1-hour conditioning period before testing during production (samples should be covered).

VOLUMETRIC PARAMETERS AND PERFORMANCE

In NCHRP Report 409 (Cominsky, et al. (1998)), a detailed assessment of various performance-oriented tests was conducted for various levels of mixture proportions and volumetric properties. The goal was to see whether laboratory changes in mixture components resulted in significant mixture property changes (volumetric and mechanical). The samples were tested via the SGC for volumetric properties and the Superpave Shear Tester (SST) for mechanical properties. Specifically, the experiment examined changes in the following independent variables:

- Asphalt content,
- Coarse aggregate content (material retained on the No. 4 sieve),
- Intermediate aggregate gradation (material passing the No. 4 sieve and retained on the No. 50 sieve),
- Fine aggregate gradation (material passing the No. 50 sieve), and
- Ratio of natural to crushed sands.

The SGC and SST were used to evaluate the effects of the above changes of various response variables, as will be illustrated.

The mix evaluated was a Superpave ¾-inch composed of crushed limestone (coarse and fine aggregate) and natural sand. The optimum binder content was 4.7 percent by weight of total mix. Low and high binder levels were set at ± 0.5 percent (or 4.2 and 5.2 percent, respectively). The aggregate gradations were varied as well. Specimens for mechanical properties were prepared in the SGC at an air void content of 7 percent with a tolerance of ± 0.5 percent (to reflect an air void content expected in the field following compaction). The tolerance was increased to ± 1.0 percent due to the difficulty in producing the specimens. Seventeen different blends with various combinations of high and low factors of asphalt content, gradation, and natural and crushed fines were produced for further testing.

The results of the mechanical property tests for the various blends will be discussed since the results provide insight into the efficacy of volumetric mix properties. Some of the results are summarized as follows:

- A comparison of permanent shear strain at 5000 cycles (via the SST repeated shear test - constant height) showed that:

  - Blend 1 (the “standard” with optimal proportions) had a VMA of 13.7 percent and V_a of 4.2 percent. Blend 12 (asphalt content at the HIGH level, fine aggregate at the HIGH level, and coarse aggregate at the LOW level) had similar VMA (14.3 percent) and V_a (3.6 percent); however, Blend 12 had twice as much permanent shear strain (4.2 percent for Blend 1 and 7.8 percent for Blend 12).
  - Blends 6, 7, 8, 13, and 14 that had V_a ranging from a low of 1.9 percent to a high of 8.6 percent, all had permanent shear strains within ± 0.5 percent of Blend 1. These same blends had VMA ranging from a low of 10.2 percent to a high of 18.3 percent.
  - From NCHRP Report 409, “There are two observations that can be made regarding the results of the repeated shear test. First, the most significant effect appears to be the interaction of asphalt content and coarse aggregate gradation. This effect is relatively insignificant in the analysis of the volumetric and densification properties.”
- A comparison of final shear strains (from the SST simple shear - constant height conducted at 79°F) showed that:
  - Final shear strains were about the same as Blend 1 or less (Blends 4, 6, 8, 11, 13, 14, 15, 16, and 17) and had V_a percentages that ranged from a low of 1.9 percent to a high of 8.2 percent. The corresponding VMA percentages ranged from a low of 10.2 percent to a high of 15.9 percent. Out of the nine blends noted above, seven were at the LOW asphalt content level.
  - These results suggest that V_a and VMA can vary substantially without detrimental shear properties.
- A comparison of the complex shear modulus (G*) at 10 Hz and 79°F showed that:
  - The complex shear moduli were about the same as Blend 1 or higher (Blends 6, 8, 11, 13, 14, 15, 16, and 17) and had V_a percentages that ranged from a low of 1.9 percent to a high of 9.4 percent. The corresponding VMA percentages ranged from a low of 10.2 percent to a high of 17.6 percent.
  - These results suggest that V_a and VMA can vary substantially without detrimental effects on complex shear moduli.
- The interaction of the asphalt content and the fine gradation (No. 50 minus) appears to have the most significant effect on all the volumetric properties.
  - Of these two variables, the asphalt content has the most significant effect on the volumetric properties. (The effect of the interaction of asphalt content and fine aggregate on volumetric mix properties is supported by the D’Angelo, et al. (2001) study.)

The results shown above support the view offered in the Conclusions section of NCHRP Report 409: “Volumetric…properties appear to perform adequately in estimating mixture mechanical properties but may not be absolutely reliable.” The quote might be a bit understated.

Cominsky, et al. (1998) also outlined the criticality of quality control (QC) performed by the Contractor. The concept behind quality control is to keep the process in control, quickly determine when it goes out of control, and respond to bring the process back into control. On the other hand, the objective of acceptance sampling and testing is to determine a purchase action (accept, reject, or penalize).

AIR VOIDS AND PERFORMANCE

Linden, et al. (1989) performed a literature review, a state highway agency (SHA) survey, and a review of three Washington State projects to illustrate how compaction (i.e., air voids) influences the performance of dense-graded HMA. The literature review was comprised of research dealing with fatigue cracking and aging, two terms indicative of HMA performance.

Fatigue Cracking

There have been several authors (Finn and Epps (1980); Epps and Monismith (1971); and Puangchit, et al. (1982)) that have shown fatigue life (the time from original construction to significant fatigue cracking) of HMA is reduced approximately 10 to 30 percent for each 1 percent increase over normal air voids. Normal air voids are generally considered around 7 percent immediately after construction, so if a mix were constructed with 10 percent air voids, the result would be a loss of pavement surfacing life of a minimum of 30 percent.

Finn and Epps (1980) also demonstrated that the effective thickness of a HMA layer decreases as the air voids increase. Evaluation of a 4-inch and a 6-inch HMA layer was performed by Finn and Epps (1980), both of which had a starting air void content of 7 percent. What they found is illustrated in Table 5. In essence, a 4-inch and a 6-inch layer constructed at 12 percent air voids effectively lasts as long as a 2-inch layer and a 4-inch layer, respectively.

Table 5. Effective Thickness of a HMA Layer In Relation to Increasing Air Voids.

Percent Air Voids in HMA	Effective Thickness of HMA (inches)	
	Example 1	Example 2
7	4.0	6.0
8	3.5	5.0
9	3.0	4.5
10	2.5	4.0
12	2.0	4.0

Aging

Aging, in this case, was judged by the asphalt penetration of the binder and then related to the in-place air voids of the pavement. Goode and Owings (1961) showed that the asphalt penetration is reduced by about 6 percent for each 1 percent increase in air voids for HMA mixtures 4 years after construction. They were able to demonstrate that the binder retains about 75 percent of its original penetration at an air void level of 6 percent, but if the air voids are 12 percent, the asphalt penetration is only about 30 percent of its original penetration. The lower the asphalt penetration, the more susceptible the mixture is to cracking, as established by Hubbard and Gollomb (1937), who showed that an asphalt penetration of 30 or less at 77°F generally leads to distressed HMA. What was found corroborates the findings of Finn, et al. (1978) concerning the maximum desirable air void levels for HMA construction (Table 6).

Table 6. Maximum Air Void Levels for HMA Construction.

HMA Layer	**Maximum Air Voids (%)**	
	Light Traffic	**Moderate to Heavy Traffic**
Upper 1-1/2”-2” of HMA	8	7
HMA deeper than 2”	7	6

SHA Survey

A questionnaire (Linden (1987)) was prepared and sent out in 1987 to the materials engineer in each of the 50 SHAs. The purpose was to review the practices and gather opinions of the SHAs in the control of air voids in HMA pavements. The questions covered mix design methods, construction compaction control and tests, field density limits, average asphalt content, pavement air voids, primary mode of pavement failure, and the effect of increasing air voids on pavement life. Forty-eight of the 50 SHAs responded to the questionnaire.

Questions:

1. Asphalt concrete mix design procedure?
   Marshall – 34 agencies (71%)
   Hveem – 10 agencies (21%)
   Both – 2 agencies (4%)
   Other – 2 agencies (4%)

2. Field results used to verify the adequacy of HMA mix designs?
   Yes – 39 agencies (81%)
   No – 9 agencies (19%)
   Agencies that responded yes typically use field results to verify air voids, aggregate gradation, asphalt content, and so on.

3. Construction compaction requirement?
   Percent of lab-compacted density – 18 agencies (38%)
   Percent of theoretical maximum density (TMD) – 21 agencies (44%)
   Percent of control strip – 6 agencies (12%)
   Other – 3 agencies (6%), which reported percent of Marshall field density

4. Construction compaction control tests?
   Nuclear gauge – 18 agencies (38%)
   Core samples – 12 agencies (25%)
   Other – 18 agencies (38%), which reported using both methods

5. (a) Does the Agency have a maximum field density limit?

Yes – 12 (25%)
No – 36 (75%)
Of the agencies that responded yes, the limits are shown below.

Specification Limit	*# Agencies*
96% of TMD	2
97% of TMD	6
98% of TMD	1
101% of Marshall	1
102% of control strip	1
105% of control strip	1

5. (b) What do you normally do if a contractor exceeds your maximum compaction requirements?
Price adjustment – 2 agencies
Price adjustment or remove and replace – 2 agencies
Penalty system – 2 agencies
Removal if severe – 1 agency
No incentive payment – 1 agency
Adjust job mix formula – 1 agency
Adjust rolling procedure – 1 agency
New control strip – 1 agency
No answer – 1 agency

5. (c) Does the Agency have a minimum field density limit?
Yes – 48 agencies (100%)
No – 0 agencies (0%)
Of the agencies that responded yes, the limits are shown below.

Specification Limit	*# Agencies*
90% of TMD	1
91% of TMD	1
92% of TMD	12
92.5% of TMD	2
93% of TMD	5
93% of Marshall density	1
95% of Marshall density	9
96% of Marshall density	2
97% of Marshall density	1
95% of Marshall field density	2
98% of Marshall field density	1
95% of control strip density	1
97.5% of control strip density	1
98% of control strip density	4
95% of Hveem density	1
95% of other lab density	1

98% of other lab density	1
No answer	2

5. (d) What do you normally do if a contractor does not meet your minimum compaction requirements?
Price adjustment – 17 agencies
Price adjustment or remove and replace – 13 agencies
Penalty system – 5 agencies
Re-evaluate compaction procedure of mix design – 3 agencies
Require additional compaction – 5 agencies
Reject below 92% of TMD – 1 agency
Assess liquidated damages – 1 agency
No answer – 3 agencies

5. (e) Has the Agency recently changed or is it considering a change in its compaction requirements?
Yes – 23 agencies (48%)
No – 25 agencies (52%)

5. (f) At what minimum compacted course thickness does the Agency require compaction control?

Minimum Thickness (in.)	*# Agencies*
¾	5
1	13
1 1/8	1
1 ¼	5
1 ½	10
2	2
No minimum	8
No answer	4

6. What is the average asphalt content you use in your normal HMA surfacing mixes (percent by weight of total mix)?
The range reported was 4.6 to 6.7 percent, with an average of 5.7 percent. 52 percent of the agencies reported an average asphalt content between 5.5 and 6.0 percent.

7. What is the range and average of field air voids in pavement constructed in the past 5 years?
This question was not uniformly interpreted, but the averages and ranges that were reported are as follows.

	Average Air Voids (%)	*Air Void Range (%)*
Maximum	9.9	5-15
Minimum	3.5	1-6
Average	6.5	2.8-10

8. (a) What is the typical 'life' of a HMA surfacing course in your state? ('Life' is defined as the time between construction and the time when the next overlay or rehabilitation is needed.)
   Of the 46 responding agencies, 34 (74%) reported an average pavement life of 10 to 15 years. Six agencies reported a longer life and six reported a shorter life. The overall average for all responding agencies was 12.5 years.

8. (b) What is the principal mode of failure at the end of a HMA surfacing course life (i.e., fatigue cracking, rutting, etc.)?
   Some agencies reported more than just the principal failure mode, so all modes are reported below.

Mode	*# Agencies*
Fatigue cracking	20
Rutting	14
Cracking (non-specific)	12
Thermal cracking	6
Stripping	5
Weathering	4
Raveling	3
Reflective cracking	2
Base failure	2
Shrinkage cracking	1
Wear	1
Variable modes	5
No response	1

8. (c) What is your experience or opinion of the effect of field air voids on HMA pavement life?
   Forty-six agencies responded to this question and the comments are grouped into three categories.

   Air Void Significance

   All 46 respondents said that air voids play a significant role in the performance and life of HMA. Fourteen (30%) described the role as:

   - Critical [to have an acceptable range]
   - Significantly influencing the life of the pavement
   - Playing a tremendous part in performance
   - Very critical (four agencies used this description)
   - All important
   - Very important
   - Having a dramatic effect
   - The most important item relative to life
   - The single most important property affecting durability
   - One of the most important criteria
   - Extremely important

Minimum Air Voids

Twenty of the respondents (44%) commented that too few air voids cause a reduction in pavement life due to rutting, shoving, and bleeding. Eight of the 20 respondents indicated a minimum field air void content to avoid this distress. The specified minimum air void level and the number of agencies reporting that level are listed below.

1-2 percent – 1 agency
2 percent – 2 agencies
3 percent – 3 agencies
4 percent – 2 agencies

One agency commented that low air voids in the surface mix are more likely than raveling to cause pavements to fail.

Maximum Air Voids

Of the 46 respondents, 44 indicated that increasing or excessive air voids adversely affect pavement performance and life. Opinions ranged widely, however, on the level of air voids at which performance and life begin to be affected. Fourteen agencies (30%) reported the following levels.

3 percent – 1 agency
4 percent – 1 agency
5 percent – 1 agency
6 percent – 5 agencies
7 percent – 1 agency
8 percent – 3 agencies
10 percent – 1 agency
11 percent – 1 agency

9. (d) In your opinion, what is the effect of increasing air voids on HMA life, expressed as a percentage of design life, for the following field (as constructed) air void contents:
4%___5%___6%___7%___8%___9%___10%___11%___12%___
(Normally, 4 to 6 percent air voids would constitute 100 percent of design life.)
Twenty-eight respondents (58%) addressed this question. The opinions varied widely, but suggest that air void levels above about 6 percent will decrease the HMA life by about 7 percent for each 1 percent increase in air voids.

	Percent of Design Life	
Air Void Content (%)	*Range*	*Average*
4	20-120	97
5	30-120	97
6	70-120	98
7	50-100	93
8	40-100	87
9	30-100	79
10	20-100	73
11	10-95	62
12	0-90	54

The bottom line from the survey is that based on the opinions of 48 State Highway Agencies, an increase in as-constructed air voids has a negative effect on the pavement life (approximately 7 percent decrease in life for every 1 percent over a nominal 6 percent air voids).

Air Void Effects on Pavements in Washington State

Data from the Washington State Pavement Management System (WSPMS) supports the results of the questionnaire survey and the literature review. The WSPMS tracks survey and distress data for the entire state system and rates the projects for cracking (longitudinal, alligator, and transverse cracking), rutting, and ride. The pavement structural condition measures cracking and patching, but is weighted towards tracking fatigue cracking.

In addition to performing surveys, resurfacing investigations take place for over 100 projects per year. These investigations examine the performance and demonstrate that a combination of factors can contribute to the particular performance of each project. A single cause can almost never be attributed to the shortened service life of a pavement, but of the several factors that can cause reduced pavement life, air voids are consistently one of the most significant.

Three projects have been chosen for evaluation, which are typical of those that have high air void contents in the wearing and leveling courses that caused early fatigue failure. All three projects were constructed in Eastern Washington, which is a dry-freeze environment and more prone to performance problems associated with void content and moisture sensitivity. In all three cases, the original as-constructed air void levels were in the 11 to 12 percent range for the wearing and leveling courses. The following is the approximate pavement structure for each of these projects:

1.8 inches	Class B HMA (dense-graded wearing course)
1.2 inches	Class B HMA (dense-graded leveling course)
4.2 inches	Class E HMA (dense-graded base course)
3.0 inches	Crushed surfacing top course (unstabilized)
6.0 inches	Gravel base (unstabilized)

A summary of pertinent data is shown in Table 7. The ‘Life to PCR=40’ represents the time it took for this pavement to reach a pavement condition rating (PCR) of 40 (equivalent to about 10 percent fatigue cracking). The percent loss column illustrates the percent reduction in pavement life as compared to the average in Washington State of 12 ½ years (The average HMA surface life was as of 1987 when that work was performed; subsequently, the average HMA life has increased.).

Table 7. Summary of Contract Data.

State Route	Contract Number	Construction Year	Life to PCR=40 (years)	Percent Loss
2	8602	1970	7.0	42
82	8672	1971	8.5	29
395	8004	1968	5.0	58
Average			**6.8**	**43**

For all three projects, the fatigue cracking was confined to the wearing and leveling courses. No fatigue cracking was found in the base course (Class E), which had air void contents in the 6 to 9 percent range. During the recycling process, the binder recovered from the wearing and leveling courses showed penetrations in the range of 7 to 16 and 140°F absolute viscosities of 50,000 to 250,000 poise. The binder used in the SR 395 project was 85-100 penetration grade, while the binder for the later projects (SR 2 and SR 82) was AR4000W, which has a penetration in the range of 100-115. Observations suggest that the high air void content increased the rate of hardening of the binder and decreased the fatigue resistance of the pavement.

The findings of the literature review, SHA survey, and WSPMS data are summarized in Table 8. All three sources of information confirm that the air void content affect pavement performance. The rule-of-thumb that emerges is that each 1 percent increase in air voids (over a base level of 7 percent) results in about a 10 percent loss in pavement life (or about 1 year less).

Table 8. Effect of Compaction of Pavement Performance.

Air Voids (%)	Pavement Life Reduction (%)		
	Literature[a]	SHA Survey[b]	WSPMS
7	0	7	0
8	10	13	2
9	20	21	6
10	30	27	17
11	40	38	-
12	50	46	36

[a] Lower bound of range.

[b] Average.

TRIAL MIXES

Cominsky, et al. (1998) stated that the Contractor must provide the Laboratory Trial Mix Formula (LTMF) to the State Highway Agency for verification. Once the LTMF is approved, the burden of producing this mix goes back to the Contractor. It is recommended that the Contractor be responsible for setting the HMA plant to produce the hot-mix within the LTMF tolerances (standard deviations) specified in Table 9 for the mix composition and gyratory-compacted mix properties. The tolerances listed in Table

9 are for one sample; if more than one sample is being tested the standard deviation is determined by Equation 1.

Once the Contractor can prove that they can produce the hot-mix to LTMF within tolerances, the Contractor can proceed to field verification. The field verification consists of the test strip that allows the Contractor to establish the compaction pattern and verify that the equipment and processes are satisfactory. The hot-mix placed in the test strip must meet an acceptable quality level of 90 percent within the LTMF limits for asphalt content, gradation, and volumetric properties according to Table 9.

Table 9. Superpave LTMF Tolerances Based on Standard Deviations (Cominsky, et al. (1998))

Mix Composition Property	**Ignition Furnace**	**Cold Feed**
Asphalt Content	± 0.13	---
Gradation Passing No. 4 and Larger Sieves	± 3	± 3
Gradation Passing No. 8 to No. 100 Sieves	± 2	± 2
Gradation Passing No. 200 Sieve	± 0.7	± 0.7
Maximum Theoretical Gravity (G_{mm})	± 0.015	
Gyratory Compacted Mix Properties		
Air Voids (V_a)	± 1	
Voids in Mineral Aggregate (VMA)	± 1	
Voids Filled with Asphalt (VFA)	± 5	
Bulk Specific Gravity (G_{mb})	± 0.022	

$$s_{\bar{x}} = \frac{s}{\sqrt{n}} \qquad \text{(Equation 1)}$$

Where $s_{\bar{x}}$ = standard deviation of the sample means of sample size n
s = standard deviation from Table 5
n = sample size

The Contractor must also test the in-place density through nondestructive test methods. It was recommended that the in-place density should have a minimum requirement of 93 percent of maximum theoretical gravity (G_{mm}) and the maximum should be 98 percent of G_{mm}. If the lay down and compaction process does not meet the control limits (93 to 98 percent), the Contractor must modify the process to reduce the variability.

Cominsky, et al. (1998) also recommended that the design air voids for all traffic levels should be 4 percent. The acceptable values for the VMA at 4 percent air voids are based on the nominal maximum size aggregate and are shown in Table 10.

Table 10. Superpave VMA Requirements.

Nominal Maximum Size	Minimum VMA (%)
3/8 inch	15.0
½ inch	14.0
¾ inch	13.0
1 inch	12.0

INITIAL WSDOT SUPERPAVE ASSESSMENTS

Leahy, et al. (1999) performed an evaluation of the Superpave mix design criteria on 1994 WSDOT Hveem-designed mixes. Of 147 mixes used during 1994, 72 percent failed to meet the Superpave gradation criteria, mainly because of the restricted zone (a requirement that AASHTO dropped). WSDOT and other states indicated that a violation of the restricted zone did not necessarily yield poor performance. However, it was found that a gradation passing through the restricted zone at a severe angle is more likely to result in rutting. The Superpave requirement for coarse aggregate angularity was not met by 33 percent of the Hveem-designed mixes. Nearly 75 percent of the mixes that failed the coarse aggregate angularity had design ESALs greater than 10 million. From this, WSDOT now specifies 90 percent fractured faces (WSDOT (2006)). WSDOT adopted the original Fine Aggregate Angularity (FAA) specification from Superpave, along with the flat and elongated particle requirement (the FAA requirement was changed with the 2006 Standard Specifications to 40 or 44 percent voids depending on Design ESAL level). The sand equivalency, LA Abrasion, and aggregate soundness specifications that WSDOT currently uses meet or are similar to the Superpave specifications.

The testing requirements for the specific gravity of aggregate and the G_{mm} were modified from the Hveem procedures. The Hveem-designed mixes use ½-inch to 3/8-inch aggregate to determine the aggregate specific gravity (G_{sb}), while Superpave uses the material retained on the No. 4 sieve for the determination of the coarse G_{sb} and passing the No. 4 sieve for the fine G_{sb}. The coarse and fine G_{sb} are combined by weight of the stockpile/mix design to determine the combined G_{sb} for the mix. It was found that there is very little difference between the two methods when comparing the Hveem method to the coarse G_{sb} for Superpave-designed mixes. In general, the VMA and VFA are higher with the Hveem-calculated G_{sb} than with the Superpave-calculated G_{sb}. For the determination of the maximum theoretical density, it was found that there was no difference between the different types of pycnometers used. The difference in results generally came from the field samples, where the mix is placed in boxes and reheated, then tested. It was also noted that the values from the reheated samples had consistently higher values for G_{mm}.

During 2003-2004, a follow-up Superpave assessment was reported by Willoughby, et al (2004). The study concluded that Superpave mixes in Washington State were performing as well or slightly better than the prior, conventional HMA (Class A mixes). Further, the costs of Superpave and the previously used Class A mixes were about the same.

CHAPTER SUMMARY

Based on a review of the literature contained in this chapter, the following points are significant:

- Typical specification bands (such as V_a in SGC specimens) and test precision are uncomfortably close.
- Volumetric mix properties can be partially characterized by tests such as asphalt content and aggregate gradation.
- The Superpave gyratory compactor and its associated variability need to be considered with respect to mix volumetric measures.
- Measurement of the bulk specific gravity of the aggregates can affect mix volumetric results.
- The same or similar volumetric properties and strength characteristics can be attained with very different gradations and asphalt content based on a recent NCHRP study. The implication is that volumetric mix properties are not "absolute" measures of mix performance.
- The rule-of-thumb that emerges with respect to air void effects on pavement performance is that each 1 percent increase in air voids (over a base level of about 7 percent) results in approximately a 10 percent loss in pavement life.
- Superpave permeabilities are strongly influenced by lift thickness and compaction requirements. The recommended compaction requirement (as a percent of theoretical maximum density) is higher for ¾-inch Superpave mixes as compared to ½-inch mixes. The critical in-place air void level is 5.5 percent for ¾-inch mixes and 7.7 percent for ½-inch mixes. The mat thickness should be at least three times larger than the nominal maximum aggregate size.

CHAPTER 3
WSDOT VOLUMETRIC EVALUATION

INTRODUCTION

This chapter is used to examine by use of data from constructed Superpave projects: (1) volumetric mix measures such as VMA, V_a, and VFA and relationships with measures of gradation and asphalt content, (2) an early assessment of Superpave pay factors based on volumetric and non-volumetric measures, and (3) an examination of gradation broadband tolerances.

The data summarized was obtained from the WSDOT QA database. The regression analyses that follow were based on the 32 Superpave projects available following the 2001 construction year. More Superpave projects were constructed during 2002 but those were not available when this specific analysis was done. The regression analyses are used to examine relationships between VMA and V_a and traditional mix tests such as asphalt content and gradation.

Subsequent analyses of projects that were constructed with non-volumetric and volumetric pay factors are also contained in this chapter. These analyses include projects constructed through 2002.

REGRESSION ANALYSES

In order to examine WSDOT Superpave volumetric mix properties and any relationships with traditional mix measures, each mix was first placed into one of two mix categories: ½-inch (12.5 mm) or ¾-inch (19.0 mm). There were 23 Superpave ½-inch mixes (21 contracts) and 9 Superpave ¾-inch mixes. One of the ¾-inch mixes did not have all the required data for evaluation and was not used.

The next step for each class of mix was an evaluation via multiple linear regressions with the dependent variables being VMA, V_a, and VFA. The purpose of this was to examine how well traditional mix tests (such as asphalt content and gradation) predict volumetric mix properties. This is a similar process as those reported in D'Angelo, et al. and Cominsky, et al. Test samples were obtained from box samples obtained from truck beds. Each box was separated into representative samples for binder content, gradation, maximum theoretical density, and material for one SGC sample. Regression equations were developed for three separate data categories (or datasets).

- **General Field results** – independent variables were binder content and measures of gradation associated with a SGC sample for VMA, V_a, and VFA.
- **Sample-to-sample differences** – independent variables were sample-to-sample differences for binder content and measures of gradation associated with SGC sample differences for VMA, V_a, and VFA. The sample "differences" were calculated for sequentially prepared samples within a project.

- **Field samples compared to JMF** – independent variables were differences between each sample and project JMF for binder content and measures of gradation associated with the SGC sample differences for VMA, V_a, and VFA.

The basic formula for multiple linear regression using asphalt content and gradation sieve sizes (percent passing) is:

$$Y = \beta + a(AC) + b(3/4") + c(1/2") + d(3/8") + e(\#4) + f(\#8) + g(\#16) + h(\#30) + i(\#50) + j(\#100) + k(\#200)$$

Where: Y is the dependent variable (VMA, V_a, or VFA)
β is the y-intercept
a-k are the coefficients of the independent variables
( ) are the independent variables in percent
*Note that the ¾-inch independent variable is not used for the Class Superpave ½-inch mix.

The results are summarized in tables 11 and 12 for the ½-inch and ¾-inch Superpave mixes, respectively. The coefficients and the t-statistics are shown for each of the regression results. For each regression, superscripts of A through D indicate the significance of the coefficients and the t-statistics, with A being the most significant.

For the Superpave ½-inch mixes across all three datasets, the most significant independent variables (in order of significance) for predicting VMA, V_a, and VFA are:

VMA

- *Based on the t-statistics*
  - ✓ Percent passing the No. 30 sieve
  - ✓ Percent passing the No. 200 sieve
- *Based on the regression coefficients*
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 30 sieve
  - ✓ Percent asphalt content

V_a

- *Based on the t-statistics*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 30 sieve
  - ✓ Percent passing the No. 200 sieve
- *Based on the regression coefficients*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 30 sieve

VFA

- *Based on the t-statistics*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 30 sieve
- *Based on the regression coefficients*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 30 sieve

For the Superpave ¾-inch mixes across all three datasets, the most significant independent variables (in order of significance) for predicting VMA, V_a, and VFA are:

VMA

- *Based on the t-statistics*
  - ✓ Percent passing the No. 4 sieve
  - ✓ Percent passing the No. 8 sieve
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
- *Based on the regression coefficients*
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 8 sieve
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 4 sieve

V_a

- *Based on the t-statistics*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 4 sieve
  - ✓ Percent passing the No. 8 sieve
- *Based on the regression coefficients*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 50 sieve

VFA

- *Based on the t-statistics*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 4 sieve
- *Based on the regression coefficients*
  - ✓ Percent asphalt content
  - ✓ Percent passing the No. 200 sieve
  - ✓ Percent passing the No. 50 sieve

To examine which independent variables best-predicted volumetric mix parameters, additional regression equations were developed (see tables 13 and 14). The data were obtained from individual projects. The difference between these regressions and those summarized in tables 11 and 12 is that a specific regression equation was developed for each individual project. For the Superpave ½-inch mixes, the independent variables included the percent asphalt content and the percent passing the No. 30 and No. 200 sieves. For the Superpave ¾-inch mixes, the independent variables included the percent asphalt content and the percent passing the No. 4, No. 8 and No. 200 sieves. The dependent variables were VMA and V_a. VFA was not used since it is directly calculated from VMA and V_a. Each dependent variable (VMA or V_a) was regressed against each independent variable separately for every contract. If there were enough observations for a specific contract, the dependent variables were also run against any possible combination of the three or four independent variables for Superpave ½-inch and ¾-inch mixes, respectively.

The results from one dependent variable regressed against one independent variable did not provide much insight. Therefore, for Superpave ½-inch mixes, each dependent variable (V_a and VMA) was regressed against the combination of percent asphalt content, percent passing the No. 30 sieve, and percent passing the No. 200 sieve as independent variables. Each dependent variable for the Superpave ¾-inch mixes was regressed against the independent variables of percent asphalt content, percent passing the No. 4 sieve, percent passing the No. 8 sieve, and percent passing the No. 200 sieve. Each contract dataset resulted in a different order of importance for the independent variables. From this process, the order of importance for the independent variables is shown in tables 13 and 14.

Table 11. Superpave ½-inch Mix Results.

1/2 inch		**Intercept**	**AC**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.600**	**0.300**	**0.150**	**0.075**	**Adjusted**	**Standard**	**Number of**
				1/2"	**3/8"**	**#4**	**#8**	**#16**	**#30**	**#50**	**#100**	**#200**	**R^2**	**Error**	**Observations**
Field results															
VMA	Coeff.	23.95	0.20	-0.09	0.07	-0.03	0.13	0.01	-0.57^{B}	0.41^{C}	0.01	-0.77^{A}	0.30	1.34	634
	t stat	*8.629*	*1.732*	*-2.533*	*3.151*	*-0.902*	*2.308*	*0.080*	*5.923*^{A}	*4.096*^{C}	*0.095*	*-5.292*^{B}			
Va	Coeff.	26.01	-0.53^{B}	-0.15	0.02	0.10	-0.04	-0.08	-0.41^{C}	0.36	-0.13	-0.71^{A}	0.36	1.34	634
	t stat	*9.357*	*-4.650*^{B}	*-4.060*	*0.848*	*3.285*	*-0.676*	*-0.990*	*-4.285*^{C}	*3.567*	*-0.896*	*-4.896*^{A}			
VFA	Coeff.	-56.99	3.75^{A}	0.92	-0.02	-0.59	0.15	0.91	1.27	-1.30^{C}	0.74	2.69^{B}	0.31	7.21	634
	t stat	*-3.814*	*6.147*^{A}	*4.585*^{B}	*-0.200*	*-3.521*^{C}	*0.500*	*1.990*	*2.436*	*-2.408*	*0.970*	*3.440*			
Sample to sample differences															
VMA	Coeff.	-0.01	-0.23^{C}	0.08	0.03	0.08	-0.08	0.06	-0.32^{B}	-0.02	-0.22	-0.38^{A}	0.35	1.02	610
	t stat	*-0.261*	*-1.405*	*3.004*	*1.826*	*3.212*^{C}	*-1.958*	*1.143*	*-4.440*^{A}	*-0.201*	*-2.383*	*-3.505*^{B}			
Va	Coeff.	0.00	-2.14^{A}	0.09	0.04	0.09	-0.11	0.06	-0.37^{C}	0.03	-0.24	-0.46^{B}	0.43	1.27	610
	t stat	*-0.013*	*-10.456*^{A}	*2.693*	*1.821*	*2.996*	*-2.110*	*0.890*	*-4.154*^{B}	*0.292*	*-2.077*	*-3.426*^{C}			
VFA	Coeff.	0.00	13.40^{A}	-0.28	-0.29	-0.36	0.35	-0.02	1.44^{C}	0.05	1.26	1.66^{B}	0.37	7.29	610
	t stat	*-0.001*	*11.361*^{A}	*-1.452*	*-2.597*^{C}	*-2.013*	*1.165*	*-0.062*	*2.795*^{B}	*0.085*	*1.928*	*2.141*			
Field samples compared to JMF															
VMA	Coeff.	0.72	0.31^{C}	0.13	0.06	-0.04	0.02	0.26	-0.43^{B}	-0.10	-0.76^{A}	0.12	0.50	1.18	634
	t stat	*10.408*	*1.947*	*3.716*	*3.196*	*-1.947*	*0.496*	*5.738*^{C}	*-7.477*^{B}	*-1.244*	*-10.872*^{A}	*1.280*			
Va	Coeff.	0.61	-1.25^{A}	0.07	0.03	0.00	0.15	0.14	-0.56^{B}	-0.06	-0.42^{C}	-0.20	0.36	1.35	634
	t stat	*7.670*	*-6.750*^{B}	*1.628*	*1.323*	*0.032*	*3.104*	*2.758*	*-8.530*^{A}	*-0.671*	*-5.105*^{C}	*-1.847*			
VFA	Coeff.	-1.78	7.94^{A}	-0.13	-0.17	-0.04	-0.73	-0.30	2.28^{B}	0.18	1.32^{C}	1.01	0.24	7.62	634
	t stat	*-3.964*	*7.590*^{A}	*-0.575*	*-1.261*	*-0.259*	*-2.716*	*-1.004*	*6.113*^{B}	*0.346*	*2.884*^{C}	*1.663*			

* Most significant independent variable – A
Second most significant independent variable – B
Third most significant independent variable – C

Table 12. Superpave ¾-inch Mix Results.

3/4 inch		**Intercept**	**AC**	**19.0** **3/4"**	**12.5** **1/2"**	**9.5** **3/8"**	**4.75** **#4**	**2.36** **#8**	**1.18** **#16**	**0.600** **#30**	**0.300** **#50**	**0.150** **#100**	**0.075** **#200**	**Adjusted R^2**	**Standard Error**	**Number of Observations**
Field results																
VMA	Coeff.	8.32	1.37^{A}	0.00	0.03	-0.03	0.21	-0.26^{C}	0.21	-0.49^{B}	0.11	0.01	-0.19	0.60	0.94	259
	t stat	*2.153*	*11.714*^{A}	*-0.043*	*1.144*	*-1.439*	*7.387*^{B}	*-4.050*^{D}	*2.391*	*-5.456*^{C}	*1.078*	*0.113*	*-1.192*			
Va	Coeff.	5.28	-0.56^{A}	0.05	0.02	-0.01	0.22	-0.22	-0.04	-0.39^{C}	0.33	-0.15	-0.55^{B}	0.57	0.97	259
	t stat	*1.324*	*-4.647*^{B}	*0.988*	*0.557*	*-0.370*	*7.358*^{A}	*-3.331*^{D}	*-0.400*	*-4.250*^{C}	*2.993*	*-1.286*	*-3.327*			
VFA	Coeff.	43.51	5.63^{A}	-0.26	0.03	-0.04	-0.93	0.84	0.52	1.67	-1.82^{C}	0.94	3.54^{B}	0.60	5.24	259
	t stat	*2.016*	*8.621*^{A}	*-0.985*	*0.228*	*-0.294*	*-5.743*^{B}	*2.364*	*1.055*	*3.337*^{D}	*-3.054*	*1.500*	*3.951*^{C}			
Sample to sample differences																
VMA	Coeff.	0.00	0.12	0.03	0.05	-0.01	0.20	-0.21^{C}	0.10	-0.04	0.03	-0.23^{B}	-0.79^{A}	0.39	0.83	252
	t stat	*-0.080*	*0.566*	*0.961*	*2.190*	*-0.433*	*5.366*^{A}	*4.294*^{C}	*1.288*	*-0.507*	*0.380*	*-2.277*^{D}	*-5.059*^{B}			
Va	Coeff.	0.02	-1.42^{A}	0.03	0.06	0.01	0.21	-0.21	0.01	-0.03	0.17	-0.30^{C}	-1.02^{B}	0.38	1.09	252
	t stat	*0.240*	*-5.152*^{A}	*0.663*	*2.007*	*0.131*	*4.351*^{C}	*-3.260*^{D}	*0.087*	*-0.358*	*1.513*	*-2.345*	*-5.025*^{B}			
VFA	Coeff.	-0.13	10.13^{A}	-0.03	-0.31	-0.04	-0.92	0.89	0.01	0.24	-0.92	1.70^{C}	5.16^{B}	0.37	6.20	252
	t stat	*-0.328*	*6.453*^{A}	*-0.111*	*-1.751*	*-0.156*	*-3.390*^{C}	*2.418*^{D}	*0.012*	*0.469*	*-1.481*	*2.300*	*4.454*^{B}			
Field samples compared to JMF																
VMA	Coeff.	0.67	-0.41	0.05	-0.18	0.12	0.42^{C}	-0.44^{B}	-0.13	0.01	0.10	-0.21	-0.46^{A}	0.50	0.93	221
	t stat	*6.729*	*-1.620*	*0.961*	*3.957*^{C}	*2.780*^{D}	*8.383*^{A}	*-5.860*^{B}	*-1.188*	*0.112*	*0.777*	*-1.600*	*-2.152*			
Va	Coeff.	0.38	-1.33^{B}	0.10	0.00	-0.02	0.23	-0.21	-0.11	0.01	0.26^{C}	0.00	-1.35^{A}	0.47	0.86	221
	t stat	*4.105*	*-5.601*^{B}	*2.127*	*0.046*	*-0.583*	*4.918*^{C}	*-2.991*^{D}	*-1.021*	*0.097*	*2.135*	*-0.015*	*-6.748*^{A}			
VFA	Coeff.	-1.48	8.29^{A}	-0.56	-0.29	0.33	-0.62	0.24	0.67	0.05	-1.71^{C}	-0.12	8.22^{B}	0.40	5.20	221
	t stat	*-2.658*	*5.799*^{B}	*-1.971*	*-1.159*	*1.335*	*-2.195*^{D}	*0.569*	*1.072*	*0.086*	*-2.365*^{C}	*-0.169*	*6.825*^{A}			

* Most significant independent variable – A
Second most significant independent variable – B
Third most significant independent variable – C
Fourth most significant independent variable – D

Table 13. Independent Variables Associated with Prediction of Volumetric Properties - Superpave ½ inch Mix Results For Individual Contracts.

V_a versus Percent Asphalt Content and Percent Passing No. 30 and No. 200 Sieves			
Order of Importance	*1*	*2*	*3*
Field Results	Percent asphalt content	Percent passing No. 30	Percent passing No. 200
Sample-to-sample differences	Percent passing No. 30	Percent asphalt content	Percent passing No. 200
VMA versus Percent Asphalt Content and Percent Passing No. 30 and No. 200 Sieves			
Order of Importance	*1*	*2*	*3*
Field Results	Percent passing No. 30	Percent passing No. 200	Percent asphalt content
Sample-to-sample differences	Percent passing No. 30	Percent passing No. 200	Percent asphalt content

Table 14. Independent Variables Associated with Prediction of Volumetric Properties - Superpave ¾-inch Mix Results For Individual Contracts.

V_a versus Percent Asphalt Content and Percent Passing No. 4, No. 8, and No. 200 Sieves				
Order of Importance	*1*	*2*	*3*	*4*
Field Results	Percent passing No. 200 and Percent asphalt content		Percent passing No. 4	Percent passing No. 8
Sample-to-sample differences	Percent passing No. 200	Percent asphalt content	Percent passing No. 4 and Percent passing No. 8	
VMA versus Percent Asphalt Content and Percent Passing No. 4, No. 8, and No. 200 Sieves				
Order of Importance	*1*	*2*	*3*	*4*
Field Results	Percent passing No. 4	Percent passing No. 200	Percent passing No. 8	Percent asphalt content
Sample-to-sample differences	Percent passing No. 200 and Percent passing No. 4		Percent passing No. 8	Percent asphalt content

Tables 13 and 14 reflect the "averaged" results of the individual contract regressions. Tables 15a, 15b, 16a, and 16b are the regression results for all projects combined (similar results reported in tables 11 and 12 but only for significant independent variables). Table 15a shows the results of all the Superpave ½-inch contracts for field results and Table 15b is the sample-to-sample differences for ½-inch mixes. Table 16a shows the results of all the Superpave ¾-inch contracts for field results and Table 16b is the sample-to-sample differences for ¾-inch mixes. For either class of Superpave mix, the V_a versus each independent variable has R^2 values ranging from 0.00 to 0.24. The VMA versus each independent variable has the same range of R^2 (0.00 to 0.24).

These R^2 values are low. The R^2 increases somewhat for the dependent variable (V_a or VMA) versus <u>all</u> the significant independent variables—as would be expected.

Superpave ½-inch mixes:

- V_a versus percent asphalt content and percent passing the No. 30 and No. 200 sieves:
  - ✓ Field results – R^2 of 0.32
  - ✓ Sample-to-sample differences – R^2 of 0.39
- VMA versus percent asphalt content and percent passing the No. 30 and No. 200 sieves:
  - ✓ Field results – R^2 of 0.25
  - ✓ Sample-to-sample differences – R^2 of 0.30

Superpave ¾-inch mixes:

- V_a versus percent asphalt content and percent passing the No. 4, No. 8, and No. 200 sieves:
  - ✓ Field results – R^2 of 0.50
  - ✓ Sample-to-sample differences – R^2 of 0.36
- VMA versus percent asphalt content and percent passing the No. 4, No. 8, and No. 200 sieves:
  - ✓ Field results – R^2 of 0.52
  - ✓ Sample-to-sample differences – R^2 of 0.37

Table 15a. Superpave ½-inch Field Results.

All contracts	Va vs. individual independent variable		Va vs. AC, #30, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	-0.789	0.00	-5.372	0.32
No. 30	-14.074	0.24	-13.904	
No. 200	-8.795	0.11	-6.982	
All contracts	VMA vs. individual independent variable		VMA vs. AC, #30, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	4.587	0.03	1.512	0.25
No. 30	-12.955	0.21	-10.809	
No. 200	-8.071	0.09	-6.017	

Table 15b. Superpave ½-inch Sample-to-Sample Differences.

All contracts	Va vs. individual independent variable		Va vs. AC, #30, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	-11.131	0.17	-8.747	0.39
No. 30	-11.131	0.17	-6.736	
No. 200	-13.348	0.23	-6.464	
All contracts	VMA vs. individual independent variable		VMA vs. AC, #30, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	-1.761	0.00	1.864	0.30
No. 30	-13.797	0.24	-7.055	
No. 200	-14.066	0.24	-7.103	

Table 16a. Superpave ¾-inch Field Results.

All contracts	Va vs. individual independent variable		Va vs. AC, #4, #8, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	-5.166	0.09	-4.513	0.50
No. 4	2.394	0.02	10.795	
No. 8	-0.193	0.00	-9.037	
No. 200	-8.189	0.20	-6.192	
All contracts	VMA vs. individual independent variable		VMA vs. AC, #4, #8, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	8.489	0.22	10.705	0.52
No. 4	7.125	0.16	9.938	
No. 8	4.808	0.08	-7.404	
No. 200	0.611	0.00	-2.584	

Table 16b. Superpave ¾-inch Sample-to-Sample Differences.

All contracts	Va vs. individual independent variable		Va vs. AC, #4, #8, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	-3.739	0.05	-4.963	0.36
No. 4	-1.050	0.00	7.490	
No. 8	-4.751	0.08	-4.167	
No. 200	-8.156	0.21	-7.198	
All contracts	VMA vs. individual independent variable		VMA vs. AC, #4, #8, and #200	
Independent Variable	t-statistic	R^2	t-statistic	R^2
AC	2.758	0.03	0.772	0.37
No. 4	3.446	0.04	8.404	
No. 8	-0.751	0.00	-4.813	
No. 200	-6.048	0.12	-7.195	

For both classes of mix and the dependent variable V_a, the independent variables for the combined regression all have significant t-statistics (greater than 4). This implies that for Superpave ½-inch mixes, the percent asphalt content, percent passing the No. 30 sieve, and percent passing the No. 200 sieve are all significant independent variables. For the Superpave ¾-inch mixes, the percent asphalt content, percent passing the No. 4 sieve, percent passing the No. 8 sieve, and percent passing the No. 200 sieve are all significant independent variables. With the dependent variable VMA, the percent asphalt content is not as significant as the other independent variables (three of the four AC t-statistics are less than 2).

In summary, the general trends show that the results of the volumetric mix properties (VMA, V_a, and VFA) are most affected by the percent asphalt content and specific sieve sizes for each class of mix evaluated. Volumetric mix properties are most significantly affected by the percent passing the fine sieves (No. 4 minus) and the percent asphalt content. This was shown in the WSDOT volumetric evaluation and in previous studies (Cominsky, et al. (1998) and D'Angelo, et al. (2001)). Table 17 presents the results of the most significant items of gradation or asphalt content for each class mix and volumetric property, in order of significance.

Table 17. Significance of Gradation and/or Asphalt Content for Predicting Volumetric Properties of Superpave Mixes.

<table>
<tr><th colspan="4">Superpave ½-inch mixes</th></tr>
<tr><th>Order of Significance</th><th>VMA</th><th>V_a</th><th>VFA</th></tr>
<tr><td>1</td><td>Percent passing No. 30 sieve</td><td>Percent asphalt content</td><td>Percent asphalt content</td></tr>
<tr><td>2</td><td>Percent passing No. 200 sieve</td><td>Percent passing No. 30 sieve</td><td>-</td></tr>
<tr><td>3</td><td>Percent asphalt content</td><td>Percent passing No. 200 sieve</td><td>-</td></tr>
<tr><th colspan="4">Superpave ¾-inch mixes</th></tr>
<tr><th>Order of Significance</th><th>VMA</th><th>V_a</th><th>VFA</th></tr>
<tr><td>1</td><td>Percent passing No. 4 sieve</td><td>Percent passing No. 200 sieve</td><td>Percent asphalt content</td></tr>
<tr><td>2</td><td>Percent passing No. 200 sieve</td><td>Percent asphalt content</td><td>-</td></tr>
<tr><td>3</td><td>Percent passing No. 8 sieve</td><td>Percent passing No. 4 sieve</td><td>-</td></tr>
<tr><td>4</td><td>Percent asphalt content</td><td>Percent passing No. 8 sieve</td><td>-</td></tr>
</table>

Overall, the R^2 values reported here for prediction of volumetric mix properties from material proportions are low. The results listed in Table 17 could aid in the determination of weighting factors for pay.

NON-VOLUMETRIC AND VOLUMETRIC PAY FACTOR PROJECTS

Two types of Superpave projects are described in this section – those constructed with non-volumetric based pay factors and those with volumetric based pay factors. The goal is to see how these projects are similar or different with respect to basic mix measures and whether such differences have implications for mix performance. The non-volumetric pay factor projects are based on Superpave projects constructed from 1997 through 2002 (a total of 43). The volumetric based projects were built during the 2001 and 2002 construction years (three in 2001 and 12 in 2002 for a total of 15). The tables and figures that follow are divided into two categories: Superpave ½-inch and Superpave ¾-inch mixes, respectively. The results are organized into the following subsections: (1) basic statistics for pay factor projects, and (2) field results compared to JMF.

Basic Statistics for Projects

The initial comparisons of projects constructed with the two different pay factor schemes are based on means and standard deviations for VMA, V_a, and VFA. Table 18 shows the overall means and standard deviations for four categories: (1) Superpave ½-inch non-volumetric pay factor mixes (NVPF), (2) Superpave ½-inch volumetric pay factor mixes (VPF), (3) Superpave ¾-inch non-volumetric pay factors mixes (NVPF), and (4) Superpave ¾-inch volumetric pay factor mixes (VPF). These results are for all Superpave projects constructed from 1997 through 2002 (NVPF projects) and all 2001 and 2001 VPF projects. Overall, the differences in means are small. The standard deviations are a bit smaller for the VPF projects.

Table 18. Superpave Non-Volumetric and Volumetric Summary for VMA, Va, and VFA for all Projects Constructed from 1997 through 2002.

		Weighted Average			Weighted St Dev			Number of Samples
		Va	VMA	VFA	Va	VMA	VFA	
Superpave 1/2" mixes	Non-volumetric	4.56	15.65	71.27	1.30	1.02	6.64	995
	Volumetric	4.21	14.98	72.44	0.99	0.71	5.53	310
Superpave 3/4" mixes	Non-volumetric	4.46	15.05	70.48	1.17	0.81	6.66	427
	Volumetric	4.45	15.62	71.73	0.98	0.76	5.14	244

Tables 19 through 22 show means and standard deviations for NVPF and VPF projects constructed during 2002 for VMA, V_a, and VFA. This data allows for mix comparisons with the assumption that both WSDOT and Contractors have learned how to better design and construct Superpave mixes during 2002 as opposed to earlier projects. These tables also include a weighted average and standard deviation for all the projects listed in that specific table (with exceptions as listed). The weighted average and standard deviation simply take into account the number of samples tested per project.

Table 19. Superpave ½-inch Volumetric Properties of Non-Volumetric Projects Constructed During 2002.

NON-VOLUMETRIC PROJECTS			Va	VMA	VFA
Contract	6115	Avg	4.01	15.65	74.69
Sample Size	55	*St Dev*	*1.39*	*1.18*	*7.66*
Contract	6220	Avg	4.96	15.45	69.03
Sample Size	68	*St Dev*	*1.05*	*0.66*	*6.64*
Contract	6251	Avg	4.97	13.66	63.80
Sample Size	25	*St Dev*	*0.78*	*0.62*	*4.31*
Contract	6275	Avg	5.13	15.16	66.27
Sample Size	15	*St Dev*	*1.03*	*2.44*	*6.08*
Contract	6332	Avg	3.46	14.46	76.13
Sample Size	30	*St Dev*	*0.52*	*0.30*	*3.20*
Contract	6338	Avg	2.97	13.91	80.19
Sample Size	10	*St Dev*	*1.98*	*1.66*	*10.16*
Contract	6339	Avg	5.10	16.02	68.46
Sample Size	33	*St Dev*	*1.36*	*0.98*	*6.63*
Contract	6381	Avg	4.68	16.39	71.17
Sample Size	17	*St Dev*	*1.00*	*0.72*	*5.02*
	Weighted Average		**4.51**	**15.26**	**70.93**
	Weighted St Dev		**1.15**	**1.04**	**6.43**

Note: Target air voids are 4.0%.

Table 20. Superpave ½-inch Volumetric Properties of the Volumetric Projects Constructed During 2002.

VOLUMETRIC PROJECTS			Va	VMA	VFA
Contract	6296	Avg	3.84	14.26	73.75
Sample Size	33	*St Dev*	*1.02*	*0.67*	*6.07*
Contract	6310	Avg	4.23	15.77	73.30
Sample Size	3	*St Dev*	*0.23*	*0.38*	*0.87*
Contract	6311	Avg	4.90	16.35	70.18
Sample Size	22	*St Dev*	*0.86*	*0.70*	*4.24*
Contract	6318	Avg	4.08	14.44	75.07
Sample Size	29	*St Dev*	*1.17*	*0.62*	*5.72*
Contract	6333	Avg	5.18	15.29	66.12
Sample Size	12	*St Dev*	*0.35*	*0.38*	*2.03*
Contract	6340	Avg	3.90	15.14	74.70
Sample Size	32	*St Dev*	*1.42*	*1.03*	*8.02*
Contract	6370	Avg	2.71	15.38	82.50
Sample Size	32	*St Dev*	*0.98*	*0.80*	*5.86*
Contract	6372	Avg	4.84	14.11	65.86
Sample Size	23	*St Dev*	*0.91*	*0.78*	*5.32*
Contract	6404	Avg	4.45	14.66	69.88
Sample Size	22	*St Dev*	*0.79*	*0.49*	*4.41*
	Weighted Average		4.08	14.92	73.32
	Weighted St Dev		1.03	0.74	5.76
Excluding Contract 6333 & 6370	**Weighted Average**		**4.27**	**14.80**	**72.06**
	Weighted St Dev		**1.08**	**0.75**	**5.92**

Note: Target air voids are 4.5%, except Contracts 6333 and 6370.

Table 21. Superpave ¾-inch Volumetric Properties of the <u>Non-Volumetric Projects</u> Constructed During 2002.

NON-VOLUMETRIC PROJECTS			Va	VMA	VFA
Contract	6115	Avg	4.26	15.19	72.21
Sample Size	19	*St Dev*	*1.14*	*0.98*	*6.80*
Contract	6158	Avg	5.41	15.95	66.09
Sample Size	8	*St Dev*	*0.70*	*0.29*	*4.11*
Contract	6238	Avg	5.10	14.48	64.83
Sample Size	31	*St Dev*	*0.70*	*0.41*	*4.24*
Contract	6369	Avg	4.07	14.08	71.13
Sample Size	37	*St Dev*	*0.75*	*0.34*	*4.86*
	Weighted Average		**4.56**	**14.59**	**68.87**
	Weighted St Dev		**0.82**	**0.55**	**5.07**

Note: Target air voids are 4.0%.

Table 22. Superpave ¾-inch Volumetric Properties of the <u>Volumetric Projects</u> Constructed During 2002.

VOLUMETRIC PROJECTS			Va	VMA	VFA
Contract	6308	Avg	5.31	17.65	70.09
Sample Size	71	*St Dev*	*1.11*	*0.82*	*5.02*
Contract	6326	Avg	3.69	14.40	74.47
Sample Size	32	*St Dev*	*0.59*	*0.49*	*3.57*
Contract	6349	Avg	4.12	13.75	70.45
Sample Size	26	*St Dev*	*1.11*	*0.85*	*6.66*
	Weighted Average		**4.67**	**16.06**	**71.25**
	Weighted St Dev		**1.04**	**0.80**	**4.87**

Note: Target air voids are 4.5%.

Based on the 24 Superpave projects constructed during 2002, the four tables reveal similarities in means and standard deviations. The VMA is higher, on average, for VPF projects when compared to NVPF projects for ¾-inch Superpave mixes but lower for the ½-inch mixes. Individual project standard deviations for all the volumetric parameters are within the same range for both NVPF and VPF projects. The project means for V_a deviate from target for both NVPF and VPF projects with no consistent trends apparent. Note that the target V_a is 4.5 percent for VPF projects (except contracts 6333 and 6370) and 4.0 percent for NVPF projects. The design air void content for contracts 6333 and 6370 were lowered after the mix design was issued, so the target air void content was different for these two projects. Therefore, the bottom of Table 20 shows the volumetric results for the VPF projects without these two contracts. The difference in V_a for the Superpave ½-inch and ¾-inch VPF and NVPF projects is minimal (4.5% (NVPF) and 4.3% (VPF) for Superpave ½-inch and 4.6% (NVPF) and 4.7% (VPF) for Superpave ¾-inch).

The ranges based on the mean project values are shown in Table 23. In general, the ranges of project mean values are higher for the VPF projects implying more project-to-project variation.

Table 23. Ranges (Max – Min) Based on Projects Constructed During 2002 for V_a, VMA, and VFA.

Mix	Number of Projects	Va	VMA	VFA
½ inch Superpave NVPF	8	2.2%	2.7%	16.4%
½ inch Superpave VPF	9	2.5%	2.2%	16.6%
¾ inch Superpave NVPF	4	1.3%	1.9%	7.4%
¾ inch Superpave VPF	3	1.6%	3.9%	4.4%

Field Tests Compared to JMF

Figures 4 and 5 are used to summarize differences between actual field results and the JMFs for the various projects. The test parameters shown include V_a, VMA, VFA, asphalt content (AC), and the percent passing various sieve sizes (3/4-inch, ½-inch, and 3/8-inch, No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves). Figure 4 shows the average differences (field results minus the JMF) for ½-inch mixes and Figure 5 for ¾-inch mixes. Figures 6 and 7 are for the same sequence of mixes but show the standard deviations for each test parameter.

From figures 4 and 5, a comparison of volumetric and non-volumetric projects shows that the gyratory air voids and VMA volumetric properties are similar. The VFA shows a very different trend for NVPF and VPF mixes. The AC contents are about the same.

The gradations generally show differences between the volumetric and non-volumetric projects with a few exceptions. There are no significant differences between the volumetric and non-volumetric projects on the ¾-inch, No. 4, and No. 100 sieves for the ½-inch mixes. For the ¾-inch mixes, no significant difference is observed for the No. 4 sieve. Overall, there are more deviations from the JMF for ½-inch VPF projects than NVPF projects. The reverse is true for ¾-inch projects.

The weighted average differences (reported in figures 4 and 5) and weighted standard deviations (figures 6 and 7) were calculated as follows:

- The field results were subtracted from the JMF (original JMF and each change in the JMF, except that the air voids were all set to 4.0 percent for both VPF and NVPF to get a true comparison of the air voids) then the average of these numbers were taken.
- From the average differences for each contract, the weighted average was calculated from the number of samples in each contract multiplied by the average difference divided by the total number of samples for all the contracts in the group, hence a *weighted* average difference.
- The same type of calculation was done for the weighted standard deviation, except that the formula is the square root of each of the sample sizes minus 1 times the square of the standard deviation from each contract divided by each of the sample sizes minus 1.

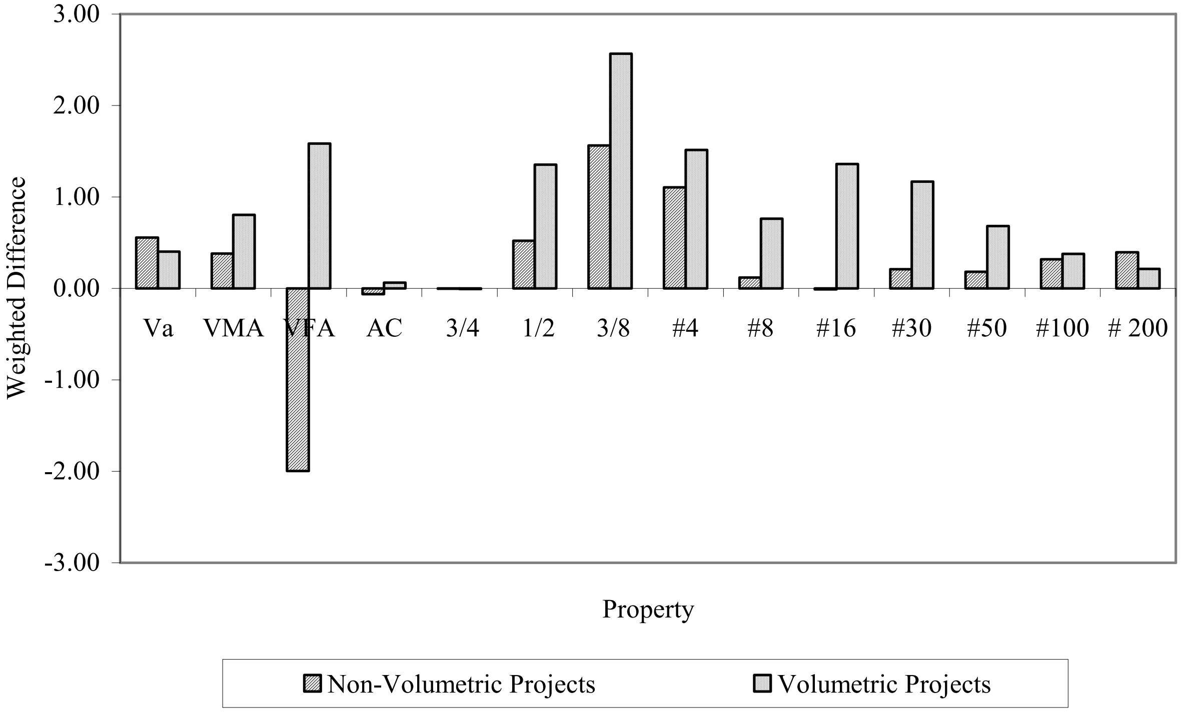

Figure 4. Average Percent Difference (Field Result minus the JMF) for the Superpave ½-inch Mixes.

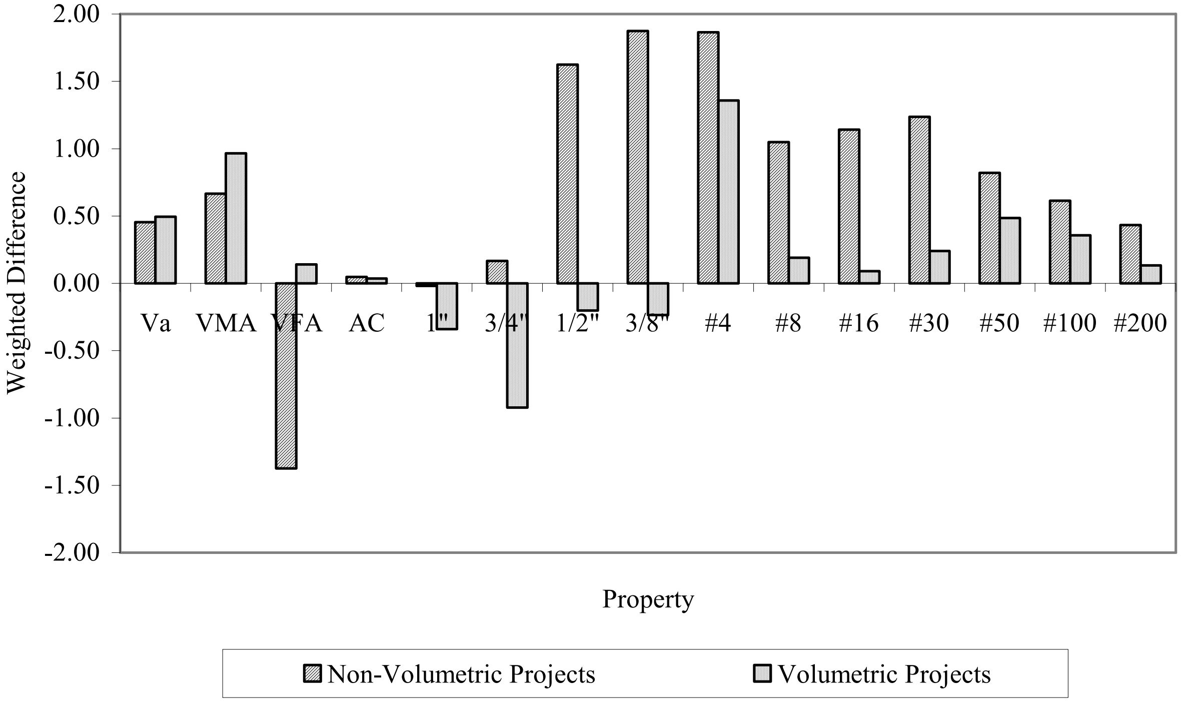

Figure 5. Average Percent Difference (Field Result minus the JMF) for the Superpave ¾-inch Mixes.

For figures 6 and 7, the standard deviations show that:

- All gradation measures have approximately the same variation regardless of NVPF or VPF for the ½- and ¾-inch mixes.
- The V_a is approximately the same for NVPF and VPF mixes.
- The VMA and VFA are about the same with respect to NVPF and VPF for the ¾-inch mixes but different for the ½-inch mixes. The VMA is lower for the ½-inch NVPF mixes by a factor of two but a bit higher on VFA.

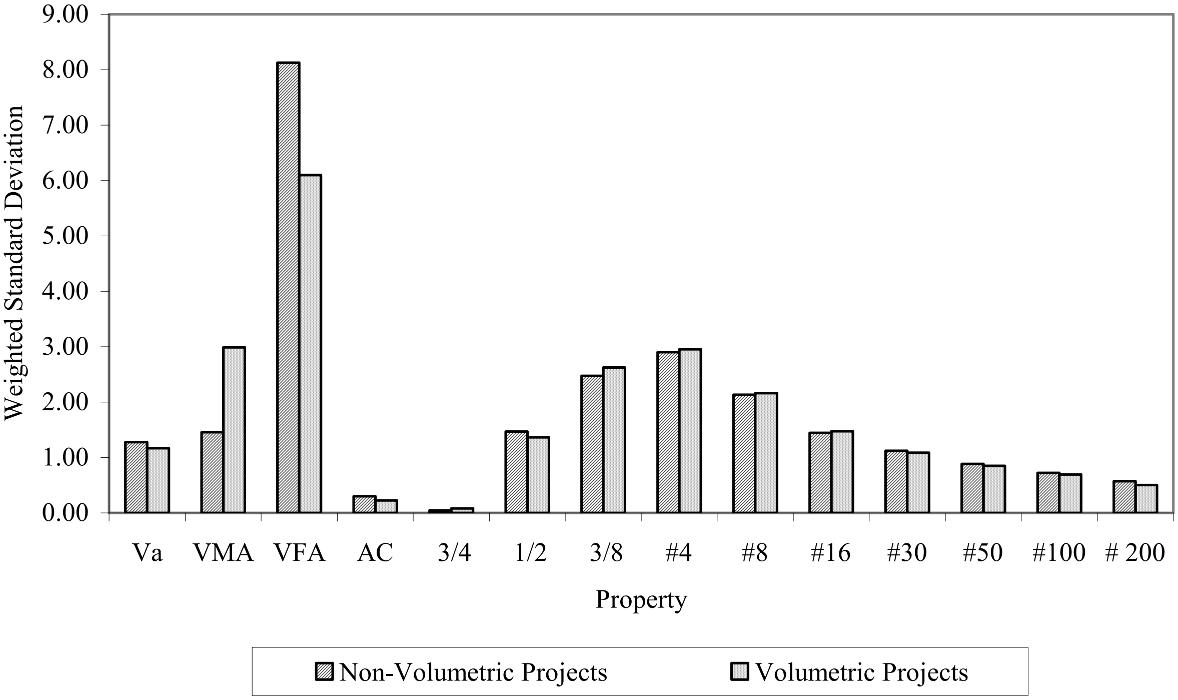

Figure 6. Standard Deviation Percentages for Superpave ½-inch Mixes.

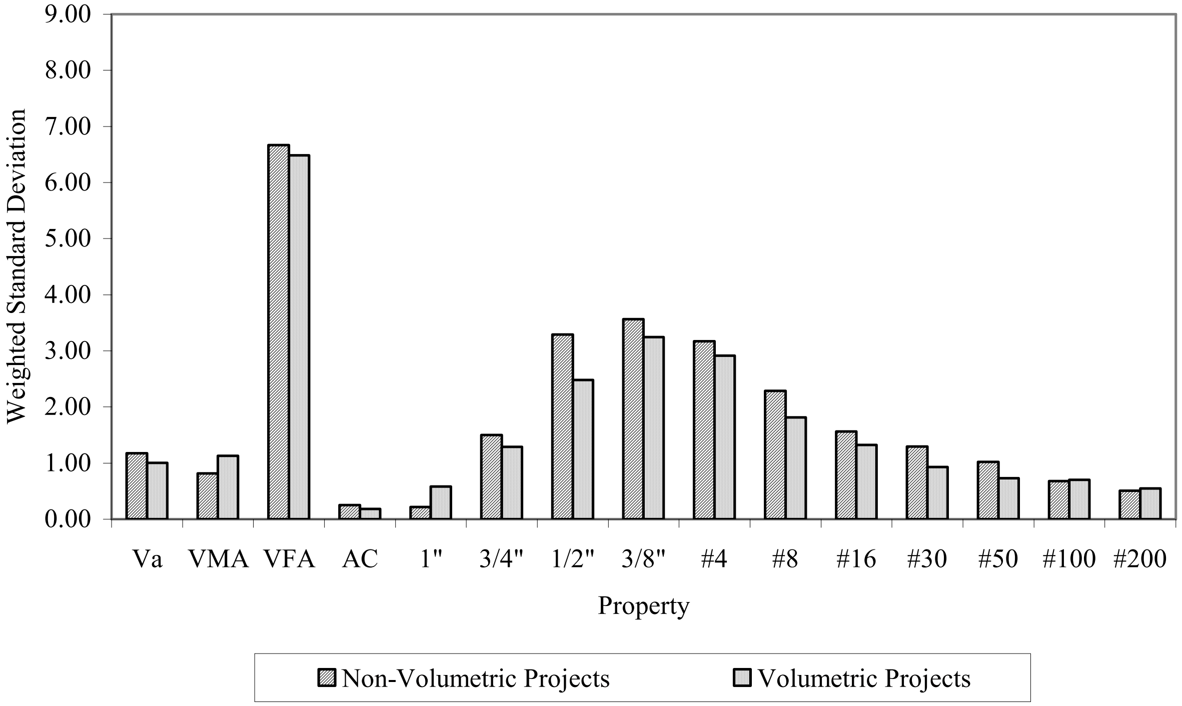

Figure 7. Standard Deviation Percentages for Superpave ¾-inch Mixes.

PRECISION AND IMPACTS ON PAY FACTORS

As noted earlier, the reported multi-laboratory d2s range values for V_a from the well-controlled FHWA experiment was ± 1.6 percent. This implies that when more than one operator is performing the tests using different equipment but the same sampling and testing procedures, the range between two samples should be about the same as reported by FHWA. With the Monte Carlo simulation that Hand and Epps (2000) performed, they found that the multi-laboratory range was ± 3.7 percent and the single operator range was ± 1.8 percent. The Hand and Epps work shows that V_a results can vary widely from ASTM and AASHTO published precision statements (Table 24). D'Angelo, et al. (2001) recommended that the SGC V_a tolerance limit (two standard deviations) be set at ± 1.4 percent.

For V_a, the published ranges from AASHTO for the single operator and multi-laboratory conditions are lower than the published results from D'Angelo, et al. (2001) and Hand and Epps (2000). Using AASHTO's precision statements for multi-laboratory, the acceptable precision and range for determination of V_a is greater than virtually all of the precisions and ranges for the determination of extracted aggregate. Further, the estimated multi-laboratory precision for the VMA is greater than all the precision statements for the determination of extracted aggregate.

Table 24. AASHTO/ASTM Precision Standards in Published Test Methods.

AASHTO/ASTM Test Method Procedure	Test Method		Single Operator Limit		Multi-laboratory Limit	
			1s	d2s	1s	d2s
Extracted Aggregate (percent passing)	T 30					
40% ≤ Test Result < 95% (typical #4 sieve)			1.06	3.00	1.24	3.50
25% ≤ Test Result < 40% (typical #8 sieve)			0.65	1.80	0.84	2.40
10% ≤ Test Result < 25% (typical #30 sieve)			0.46	1.30	0.81	2.30
5% ≤ Test Result < 10% (typical #200 sieve)			0.29	0.80	0.56	1.60
Bulk Specific Gravity - Fine (dry)	T 84		0.011	0.032	0.023	0.066
Bulk Specific Gravity - Coarse (dry)	T 85		0.009	0.025	0.013	0.038
Compacted Bulk Specific Gravity	T 166		-	0.020	-	-
	D2726	1/2"	0.008	0.023	0.015	0.042
		3/4"	0.013	0.037	0.015	0.042
Theoretical Specific Gravity	T 209		0.0040	0.011	0.0064	0.019
Determination of Asphalt Content (%)	T 308		0.040	0.110	0.060	0.170
Determination of Air Voids (%)	T 312	1/2"	0.3	0.9	0.6	1.7
		3/4"	0.5	1.4	0.6	1.7
	T 269		0.51	1.44	1.09	3.08
Determination of Voids in Mineral Aggregate (%)			0.59*	-	1.26*	-

* Estimate based on average values from WSDOT Superpave mix designs and published values of standard deviations for Equation 2. (The d2s limits listed are the acceptable range between two test results.)

The 2006 WSDOT Standard Specifications sets target air voids at 4.0 percent with a range of 2.5 to 5.5 percent and the VMA tolerance at the design value minus 1.5 percent with no upper limit. The V_a is dependent on the asphalt content and to some extent, the gradation (especially the fine aggregate). The VMA is also dependent on the asphalt content and gradation (mostly fine aggregate). According to the published AASHTO precision statements (Table 24), the asphalt content and fine aggregate sieve sizes have about the same precision limits than the V_a or VMA.

The V_a and VMA are calculated values (based on two and three variables, respectively) and accumulate the variability of each of the variables. The VMA calculation depends on the bulk specific gravity for the total aggregate (G_{sb}), which is calculated in the design phase of the mix design process. It is typically not recalculated when the percentages of the stockpiles change or the gradation changes to attempt to meet the volumetric properties. For example, using the Superpave data obtained from the WSDOT mix designs and Equation 2, a change in the stockpile percentages of 10 percent results in a blended G_{sb} that could vary from the original by 0.003 to 0.023. This change in the G_{sb} correlates to a change in the VMA of 0.3 to 0.8 percent. The P_s, G_{sb}, G_{mb}, and G_{mm} are the inputs into the VMA and V_a calculations. The P_s (percent stone, which is 100 minus the asphalt content), G_{sb} (bulk specific gravity, fine and coarse), G_{mb} (compacted bulk specific gravity), and G_{mm} (theoretical maximum specific gravity) precision statements are listed in Table 24. Conversely, the gradation and asphalt content are determined directly from the test results and are not dependent on test results obtained in the mix design phase.

$$VMA = 100 - \left[\frac{G_{mb} \times P_s}{G_{sb}} \right]$$ (Equation 2 – The Asphalt Institute MS-2)

$$V_a = 100 \times \left[\frac{G_{mm} - G_{mb}}{G_{mm}} \right]$$ (Equation 3 – The Asphalt Institute MS-2)

$$VFA = 100 \times \left[\frac{VMA - V_a}{VMA} \right]$$ (Equation 4 – The Asphalt Institute MS-2)

Where: G_{mb} = bulk specific gravity of the compacted mixture
G_{mm} = maximum theoretical specific gravity of the paving mixture
G_{sb} = bulk specific gravity for the total aggregate
P_s = aggregate content, percent by total weight of mixture

V_a and VMA are both affected by the asphalt content and the gradation. Pay factors based on V_a or VMA and asphalt content and/or gradation have the possibility of changing the alpha and beta risks for both WSDOT and the Contractor (Muench and Mahoney (2001)). For example, if WSDOT pays the Contractor for meeting the gyratory-compacted air voids and percent asphalt content, WSDOT could be paying the Contractor twice for meeting the tolerance on asphalt content. On the other hand, the Contractor could be penalized twice for not meeting the tolerance on asphalt content simply because the gyratory-compacted air voids are partially dependent on the percent asphalt content (see Muench and Mahoney (2001) for more information regarding risk). A rule of thumb presented by Cominsky, et al. (1998) is that if the asphalt content changes by 1 percent, the air voids change by approximately 2.5 percent.

In summary, the multi-laboratory precision for V_a ranges from ± 1.09 to ± 3.7 percent and WSDOT is currently allowing ± 1.5 percent for projects with pay based on volumetric properties. The multi-laboratory precision for VMA is estimated at ± 1.26 percent and WSDOT currently allows the design VMA minus 1.5 percent for projects with pay based on volumetric properties.

The FHWA suggests that the upper and lower specification limits should be set at ± 2 standard deviations for establishing reasonable production limits. This information, along with the standard deviations calculated from production paving published in tables 19 through 22 can be used to set reasonable tolerance limits on volumetric properties.

SIEVE BROADBAND TOLERANCES

A related topic to volumetric properties of Superpave mixes and how pay factors are established are sieve broadband tolerances. The current WSDOT Superpave gradation requirements are based on modified AASHTO M323-04 Gradation Control Points as shown below (Table 25). If requirements beyond Gradation Control Points are needed, the subsequent data and analysis will provide guidance on suitable tolerances.

Table 25. WSDOT Gradation Control Points (WSDOT (2006)).

Sieve Size	¾-inch Superpave (% passing)		½-inch Superpave (% passing)	
	Min	Max	Min	Max
1 inch	100	-	-	-
¾ inch	90	100	100	-
½ inch	-	90	90	100
3/8 inch	-	-	-	90
No. 8	23	49	28	58
No. 200	2	7 (8)*	2	7 (10)*

*(x) indicates values from AASHTO M323-04

The data from the QA database was used to calculate the standard deviation of the differences between the field results and JMF for:

- Class A, Superpave ½-inch, and Superpave ¾-inch mixes prior to 2002
- Superpave ½-inch and Superpave ¾-inch mixes categorized by VPF or NVPF projects

In addition to the WSDOT data reported in Table 26 are standard deviations from previous research for comparison purposes. For WSDOT data, a random check for normality was made for each sieve size and the asphalt content – and normality was found for the cases checked.

Table 26. Standard Deviations for Class A, Superpave ½-inch, and Superpave ¾-inch Mixes Based on Production Results and Data From Previous Research

Sieve Sizes	Class A Pre-2002 Projects	Superpave 1/2 inch mixes			Superpave 3/4 inch mixes			WA data (1993)[1]	Freeman and Grogan[2]
		Pre-2002 Projects	2002 Non-Volumetric	2002 Volumetric	Pre-2002 Projects	2002 Non-Volumetric	2002 Volumetric		
3/4"	0.1				1.6	1.5	1.3	1.6	2
1/2"	1.9	1.3	1.7	1.4	3.5	3.3	2.5	1.6	2
3/8"	3.1	2.4	2.7	2.7	3.9	3.6	3.3	2.5	2
1/4"	3.5								
No. 4		2.8	3.1	3.0	3.5	3.2	2.9	3.0	4
No. 8		2.0	2.3	2.2	2.3	2.3	2.8	2.4	3
No. 10	2.6								
No. 16		1.5	1.4	1.5	1.7	1.7	1.3		3
No. 30		1.2	1.0	1.1	1.4	1.3	0.9		2
No. 40	1.8								
No. 50		0.9	0.8	0.9	1.2	1.0	0.7	1.6	2
No. 100		0.8	0.6	0.7	0.8	0.7	0.7		1
No. 200	0.8	0.6	0.5	0.5	0.5	0.5	0.6	0.5	1
AC	0.2	0.2	0.4	0.2	0.3	0.3	0.2	0.24	0.25

[1] As reported in Hughes (1996).

[2] As reported in Freeman and Grogan (1996).

Currently, there are no WSDOT broadband tolerances on the No. 16, No. 30, No. 50, and No. 100 sieves. Recall that the FHWA recommends upper and lower specification limits be set at ± 2 standard deviations for establishing reasonable production limits. Table 27 includes the current tolerance limits for specified sieve sizes and asphalt content as well as a suggestion for modifying the tolerance limits (based on the production standard deviations listed in Table 26).

Table 27. Current and Suggested Modification of the Tolerance Limits for Gradation and Asphalt Content.

Sieve Sizes	Current Tolerance Limits	2s (Standard Deviation) Limits*	Suggested Tolerance Limits**
3/4”	± 6.0%	± 2.3%	± 3.0%
1/2”	± 6.0%	± 4.5%	± 4.5%
3/8”	± 6.0%	± 6.2%	± 6.0%
No. 4	± 5.0%	± 6.2%	± 6.0%
No. 8	± 4.0%	± 4.6%	± 4.5%
No. 16		± 3.0%	± 3.0%
No. 30		± 2.3%	± 2.5%
No. 50		± 1.8%	± 2.0%
No. 100		± 1.4%	± 1.5%
No. 200	± 2.0%	± 1.1%	± 1.5%
AC	± 0.5%	± 0.5%	± 0.5%

*Based on the average of standard deviations summarized in Table 26 (excluding referenced works).

**If used as a pay factor.

CHAPTER 4
COMPARISON OF SUPERPAVE AND CLASS A MIXES

As noted earlier in this report, WSDOT has been designing mixes by the Superpave method since 1997, so the oldest projects are nine years old; however, when the original project data was analyzed, the oldest projects were six years old. The WSDOT QA database was queried for all projects that were designed as Superpave ½-inch, Superpave ¾-inch, and Class A mixes through the 2001 construction year (the 2002 projects were not available when this specific analysis was done). The results were obtained only from mixes that were used as production paving. The gradation and asphalt content averages and standard deviations are reported in Table 28 for all three mix types (the sample sizes are also listed). Table 29 contains the differences in the QA test results when compared to the Job Mix Formula (JMF).

Table 28. Quality Assurance Test Results for Class A, Superpave ½-inch, and Superpave ¾-inch mixes.

	Class A			Class Superpave 1/2 inch			Class Superpave 3/4 inch		
	Average	Standard Deviation	Sample Size	Average	Standard Deviation	Sample Size	Average	Standard Deviation	Sample Size
3/4"	100.00	0.11	7092				97.59	1.90	259
1/2"	95.59	2.20	7107	95.90	2.07	634	86.48	5.54	259
3/8"	83.91	3.54	7112	82.96	4.37	634	75.29	6.17	259
1/4"	66.21	3.96	7103						
No. 4				52.23	4.64	634	52.66	10.24	259
No. 8				33.67	3.50	634	34.62	6.86	259
No. 10	35.37	3.10	7100						
No. 16				22.62	3.05	634	22.44	3.76	259
No. 30				16.02	2.50	634	15.47	2.23	259
No. 40	15.85	2.23	7102						
No. 50				11.05	1.42	634	11.11	1.66	259
No. 100				7.71	0.97	634	8.07	1.21	259
No. 200	5.61	0.93	7103	5.50	0.76	634	5.58	0.72	259
AC	5.25	0.43	7078	5.53	0.51	634	5.15	0.56	259

Table 29. Differences in Quality Assurance Test Results When Compared to the JMF for Class A, Superpave ½-inch, and Superpave ¾-inch Mixes.

	Class A			Class Superpave 1/2 inch			Class Superpave 3/4 inch		
	Average	Standard Deviation	Sample Size	Average	Standard Deviation	Sample Size	Average	Standard Deviation	Sample Size
3/4"	0.004	0.111	7038				0.357	1.576	221
1/2"	-0.129	1.891	7049	0.259	1.579	634	1.860	3.328	221
3/8"	-0.482	3.109	7059	2.097	3.097	634	2.127	3.625	221
1/4"	-0.329	3.518	7050						
No. 4				1.228	3.544	634	1.367	3.651	221
No. 8				0.269	2.435	634	1.090	2.782	221
No. 10	0.335	2.586	7042						
No. 16				-0.079	2.123	634	1.140	2.295	221
No. 30				0.067	1.687	634	1.475	2.019	221
No. 40	0.120	1.768	7044						
No. 50				0.157	1.301	634	1.118	1.594	221
No. 100				0.380	1.120	634	0.579	0.852	221
No. 200	-0.234	0.808	7046	0.379	0.747	634	0.321	0.595	221
AC	-0.059	0.241	7024	-0.091	0.343	634	0.047	0.297	221

Note 1: Averages based on Field result minus the JMF

Table 28 shows that the average and standard deviation of the Superpave ½-inch mix are similar to the Class A statistics for gradation and asphalt content. Overall, the Superpave ½-inch has fewer fines in the mix (approximately 52 percent passing the No. 4 sieve) compared to the Class A (approximately 66 percent passing the ¼-inch sieve). The Superpave ½-inch mix has approximately 0.28 percent more asphalt than the Class A.

The Superpave ¾-inch mix has a similar gradation to the ½-inch mix, except that the ¾-inch mix has approximately 25 percent retained on the 3/8-inch sieve while the ½-inch mix only has 17 percent retained on the 3/8-inch sieve. The percent asphalt content comparison between the ¾-inch mix and ½-inch mix shows about 0.4 percent less than the ½-inch mix. Also of interest are the standard deviations of the ¾-inch mix. The large standard deviations for the ¾-inch sieve to the No. 8 sieve are likely due to the design of this type of mix. The ¾ mix allows for a wide variation in the design because of the recommended control points for Superpave mixes. There are some ¾-inch mixes that were designed as "coarse" mixes (larger amount of material retained on the No. 4 sieve) while others were not, hence the large standard deviations.

Table 29 shows the differences from the design JMF values to the actual gradations and asphalt content produced in the field (field result minus the JMF). On average, all three types of mix have similar means and standard deviations.

A comparison of in-place density is provided for Superpave-designed and Hveem-designed Class A mixes. Table 30 shows the average and standard deviation for the in-place density (as a percent of maximum theoretical density) for both types of mix for projects that were greater than 12,000 tons (12,000 tons was used to exclude small paving jobs, pavement repair quantities, material used as prelevel, etc.). The results are similar even though there is a large difference in sample sizes.

Table 30. Comparison of Superpave and Class A In-Place Density (Projects greater than 12,000 tons).

	Class A mixes	**Superpave mixes**
	Percent	**Percent**
Average	92.99	92.97
Standard Deviation	1.45	1.39
Sample Size (tests)	23870	6370

Table 31 also shows a comparison of all mixes in the QA database (Class A, B, E, F, G, and SMA), Class A mixes, and Superpave mixes with no restriction on tonnage. The percentages less than or greater than the theoretical maximum density (TMD) levels shown were calculated for the means and standard deviations shown in the table and use of a normal distribution. A normal distribution was used since the sample sizes are quite large and approach being three separate "populations." The same percentages were calculated based on actual test results (as opposed to a statistical basis as used in the table) and there are generally small differences. For example, the Superpave mixes had 7.8, 14.5, 23.7, and 36.3 percent less than 91.0, 91.5, 92.0, and 92.5 percent of TMD from the QA database. The modest differences can be attributed to various reasons but none are proven.

Table 31. In-Place Density Comparison for All Classes of Mix Combined, Class A (only), and All Superpave Mixes (No Restriction on Project Tonnage) as of June 2001.

Lower or Upper Specification Limit	Percent of Test Results Less Than (or Greater Than) Specification Limit		
	All Classes of Mix (%)	Class A Mixes (%)	Superpave Mixes (%)
Less than 91.0 %	9.5	10.2	7.8
Less than 91.5 %	16.1	16.8	14.5
Less than 92.0 %	24.8	26.1	23.7
Less than 92.5 %	35.9	37.5	36.3
Less than 93.0 %	48.0	49.8	50.3
Greater than 96 %	3.3	2.9	1.6
Greater than 97 %	0.7	0.6	0.2
Mean	93.08	93.01	92.99
Standard Deviation	1.59	1.58	1.40
Sample Size (Number of Tests)	73615	46445	7220

All classes of mix include WSDOT Classes A, B, E, F, G, and SMA (the SMA has a minimum density of 94 percent).

CHAPTER 5
HMA IN-PLACE DENSITY

This chapter will be used to overview the current WSDOT HMA in-place density specification with specific emphasis on the lower specification limit.

The current WSDOT specification for in-place density is a minimum of 91.0 percent of maximum theoretical density. Pay factors are calculated from the average and standard deviation of five random tests for each sublot. Table 31 in the previous chapter provides a summary of the percent of densities that are less than the specified percent of G_{mm}. For example, Class A mixes had approximately 25 percent of the random densities fall below 92.0 percent of G_{mm}, 17 percent are below 91.5 percent, and 10 percent below 91.0 percent.

A reasonable goal of field densification is to achieve approximately 7 percent air voids in the compacted mat. This is based on numerous studies that show a reduction in fatigue life and durability for in-place air voids greater than 7 percent (Linden, et al., 1989). A study on HMA permeability by Cooley, et al. (2002) states that Superpave ½-inch and ¾-inch mixes have critical air void contents of 7.7 percent and 5.5 percent, respectively. A more recent NCAT/NCHRP study by Brown, et al (2004) recommended that the in-place air voids should be 6 to 7 percent or less to preclude significant HMA permeability. Additionally, Brown, et al (2004) reconfirmed important lift thickness criteria in NCHRP 531. Their recommendations are quite clear for achieving improved HMA compactability: (1) fine-graded mixes should have t/NMAS ratios ≥ 3.0, and (2) coarse-graded and SMA mixes should have t/NMAS ratios ≥ 4.0. As shown in Table 31, about 50 percent of the random tests have in-place densities less than 93.0 percent of G_{mm}.

Table 32 is an example of how the average density might change if the allowable density limit is modified. The data in Table 32 was created from the contracts in the QA database as of June 2001. The average density for all readings is 93.08 percent, which includes tests for all classes of mix excluding pavement repair, prelevel, etc. For the "Greater than __%" cases, the average and standard deviation includes all the density readings from the QA database greater than the percent listed. Lastly, for the "Range of Allowed Densities", all the readings that fell between the ranges listed were used to obtain the average and standard deviations. If, for example, the minimum allowable density was raised to 91.5 percent, the average density (based on the densities in the QA database) would increase to about 93.4 percent and the standard deviation would decrease (the actual average and standard deviation would be different due to values below 91.5 percent in actual field operations). If the recommendations by Cominsky et al. (1998) were followed (93 to 98 percent) and assuming that all the densities would fall between 93 and 98 percent, the average density would increase to 94.3 percent with a standard deviation of 1.05 percent. Again, because actual field operations can produce material that falls outside of the tolerances, the actual average and standard deviation would be different than shown.

Several authors have shown the effect that air voids can have on the loss in pavement life (especially the report by Linden, et al. (1989)). The general rule-of-thumb is that a 1 percent increase in air voids over a base air void level of 7 percent tends to produce about a 10 percent loss in pavement life (Linden, et al. (1989)). Currently, there is no link between design, construction, and pavement performance within WSDOT, so a thorough evaluation of current data is difficult, but if the systems developed by the University of Washington (i.e., HMA View, WSPMS View, and HMA Design) were to be utilized, this evaluation will become relatively straightforward. Ultimately, these systems will utilize a global positioning system (GPS) that will be able to link specific construction and performance data.

Table 32. Average and Standard Deviation of Density with Varying Limits of Allowable Density.

All Classes of mix	Average	Standard Deviation	Range of Allowed Densities	Average	Standard Deviation
All readings	93.08	1.59			
Greater than 91.0%	93.23	1.45	91.0% - 96.0%	93.07	1.25
			91.0% - 97.0%	93.17	1.37
			91.0% - 98.0%	93.22	1.42
Greater than 91.5%	93.45	1.36	91.5% - 96.0%	93.28	1.15
			91.5% - 97.0%	93.38	1.27
			91.5% - 98.0%	93.43	1.33
Greater than 92.0%	93.70	1.27	92.0% - 96.0%	93.52	1.03
			92.0% - 97.0%	93.64	1.16
			92.0% - 98.0%	93.68	1.23
Greater than 92.5%	94.00	1.18	92.5% - 96.0%	93.80	0.92
			92.5% - 97.0%	93.93	1.06
			92.5% - 98.0%	93.98	1.14
Greater than 93.0%	94.33	1.10	93.0% - 96.0%	94.10	0.80
			93.0% - 97.0%	94.24	0.96
			93.0% - 98.0%	94.31	1.05

*All classes of mix include WSDOT Classes A, B, E, F, G, and SMA
(The SMA has a minimum density of 94 percent).

A comparison of the current minimum allowable density (91 percent of G_{mm}) to a higher minimum (91.5 and 92 percent of G_{mm}) was made. First, an estimate of pavement life lost due to an increase in the in-place air voids above the target value of 7 percent was made. Shook, et al. (1982) presented an equation that allows the calculation of fatigue based on the volume of asphalt and volume of air voids that are present in the pavement (Equation 5).

$$N = 18.4C\left[4.325 \cdot 10^{-3}(\varepsilon_t)^{-3.291}\left(\left|E^*\right|\right)^{-0.854}\right] \qquad \text{(Equation 5)}$$

Where N = number of 18 kip equivalent single axle loads

ε_t = tensile strain in the asphalt layer (in/in or mm/mm)

$|E^*|$ = asphalt mixture stiffness modulus, psi

C = function of air voids and asphalt volume (Equations 6 and 7)

$$C = 10^M \qquad \text{(Equation 6)}$$

Where $$M = 4.84\left[\frac{V_b}{V_v + V_b} - 0.69\right] \qquad \text{(Equation 7)}$$

Where V_b = volume of asphalt

V_v = volume of air voids

The volume of asphalt was determined using the average percent asphalt found in Superpave ½-inch mixes (Table 28) and the average specific gravities of the asphalt and the aggregate from all Superpave mixes (Appendix B).

- Average percent asphalt was 5.53 percent
- Average asphalt specific gravity was 1.028
- Average aggregate specific gravity was 2.694

From this data, the volume of asphalt was found to be 13.3 percent. The volume of air voids was varied from 7 percent (target) to 9 percent (percentage relating to 91 percent minimum density). Using these values, the C coefficient was calculated as follows:

- 7 percent air voids: C = 0.676
- 8 percent air voids: C = 0.479
- 9 percent air voids: C = 0.355

Using the C value at 7 percent air voids as the target and comparing the C values of 8 and 9 percent air voids, the estimated loss of life due to the increase in air voids is 20 to 30 percent. Additionally, the rule of thumb presented by Linden, et al. (1989) of a 1 percent increase in air voids relates to a 10 percent loss of pavement life provides a lower bound. A loss of life estimate was made using 10 to 30 percent as a lower and upper bound. From this, an estimation of the percentage of densities that would fall below the current average of 93.08 and assumed increased averages due to an increase in the minimum density was made.

The average density and standard deviation that was retrieved from all WSDOT classes of mix in the QA database was 93.08 percent with a standard deviation of 1.59. The assumed increase in average density is 0.5 percent for every 0.5 percent increase in the minimum allowable density. Another assumption is that the standard deviation is constant with an increase in the minimum allowable density. The evaluation was performed with the following averages and standard deviations:

- Average of 93.08, Standard deviation of 1.59 (minimum of 91.0 percent of G_{mm})
- Average of 93.58, Standard deviation of 1.59 (minimum of 91.5 percent of G_{mm})
- Average of 94.08, Standard deviation of 1.59 (minimum of 92.0 percent of G_{mm})

The percentage of densities that fall below 93 percent (based on the target value of 7 percent air voids) for the three scenarios presented above are:
- Average of 93.08, Standard deviation of 1.59 – 48 percent fall below 7 percent air voids
- Average of 93.58, Standard deviation of 1.59 – 36 percent fall below 7 percent air voids
- Average of 94.08, Standard deviation of 1.59 – 25 percent fall below 7 percent air voids

The estimated loss of life due to densities below the average is:
- Average of 93.08 – range is 7 to 22 percent (average of 15 percent)
- Average of 93.58 – range is 5 to 15 percent (average of 10 percent)
- Average of 94.08 – range is 3 to 9 percent (average of 6 percent)

For every ½ percent increase in the minimum density, the pavement life could increase by 5 percent.

WSDOT's current compaction pay factor is based on the average and standard deviation of five random tests per sublot. The average of the five tests must be above the minimum of 91 percent and must have a relatively small standard deviation to receive 100 percent of the unit price. Individual tests can fall below the minimum. For example, a bonus (Pay Factor greater than 1.0) can be achieved with the following averages and standard deviations for a sublot of five random tests:
- Average of 91.5 percent, standard deviation up to 0.55 percent
- Average of 92.0 percent, standard deviation up to 1.1 percent
- Average of 93.5 percent, standard deviation up to 2.8 percent
- Average of 95.5 percent, standard deviation up to 3.7 percent

This shows that low variability within a sublot can overcome less than desirable average densities and still achieve a bonus.

By comparison, if the minimum density were changed to 91.5 percent, a bonus could be achieved with the following averages and standard deviations for a sublot of five random tests:
- Average of 92.0 percent, standard deviation up to 0.6 percent
- Average of 93.5 percent, standard deviation up to 2.5 percent
- Average of 95.5 percent, standard deviation up to 3.4 percent

Along with an increased minimum allowable density, a change to include a maximum allowable density of 98 percent will also decrease the amount of deviation within a sublot as follows:
- Average of 92.0 percent, standard deviation up to 0.55 percent
- Average of 93.5 percent, standard deviation up to 2.1 percent
- Average of 95.5 percent, standard deviation up to 2.6 percent

These standard deviations are the maximum values along with the listed averages that would allow the Contractor to achieve a bonus. The same could be done with a minimum density of 92 or 93 percent. The purpose of this example is twofold: (1) illustrate the deviations from the average density that is allowed under the current WSDOT specifications, and (2) demonstrate the outcome on density average and standard deviation if the upper and/or lower specification limits are changed.

Figure 8 illustrates a standard normal curve with WSDOT's current density mean and standard deviation of 93.1 percent and 1.59 (refer to Table 32) and a curve with the same standard deviation but an increased mean. This graph shows that approximately 9.3 percent of the density results could fall below 91 percent of TMD (the shaded area under the black curve on the left side of the graph). If the average is shifted to 93.6 percent (this assumes that the minimum in-place density is increased by 0.5 percent and the standard deviation is held the same), the percent of tests below 91 percent TMD is reduced to 5.2 percent.

A concern with an increase in the minimum density is an increase in the number of tests with excessively low in-place air voids (less than 2 percent, or greater than 98 percent TMD). With WSDOT's current average of 93.1 percent TMD, approximately 0.1 percent of the random tests are above 98 percent TMD. With a shift in the average up to 93.6 percent, there could be 0.3 percent of the tests above 98 percent TMD.

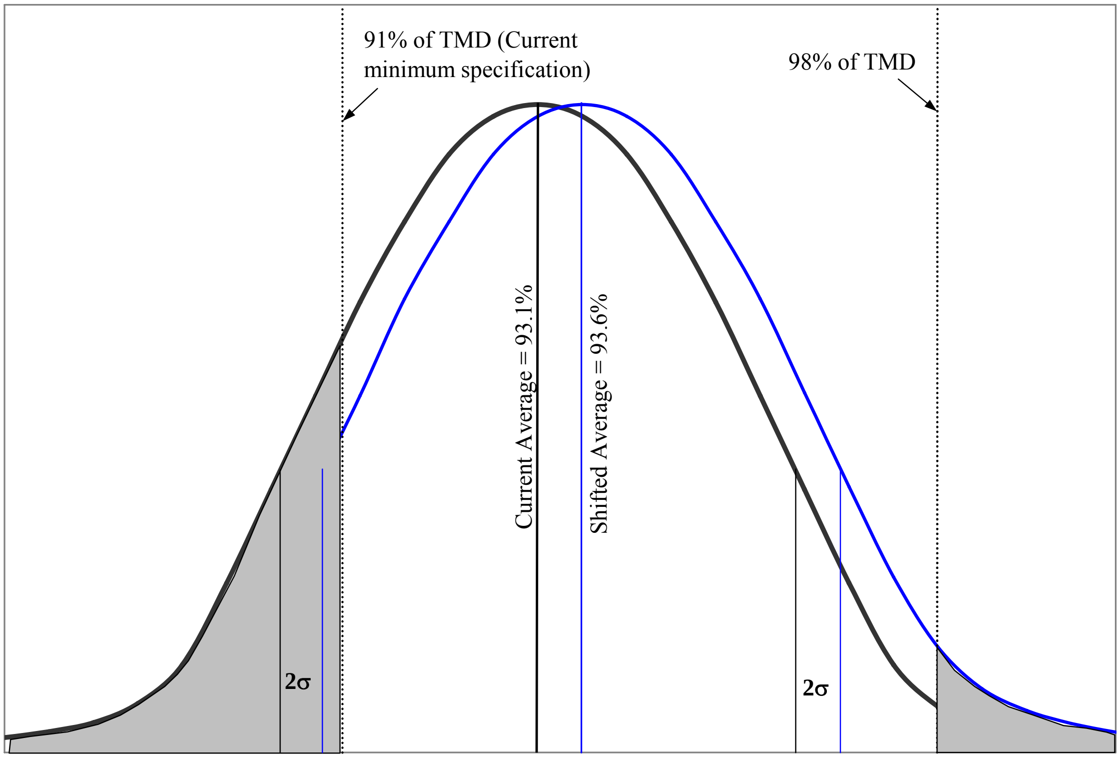

Figure 8. Comparison of WSDOT Current In-Place Density Average and Standard Deviation to a Shifted Average with the Same Standard Deviation

For comparison, Table 33 shows the minimum density requirements expressed as a percentage of maximum theoretical density to receive 100 percent of the unit price (Mahoney and Backus, (1999); Mahoney and Economy, (2001); FHWA (2006)). A handful of states have the same minimum density requirement as WSDOT, but the majority of the states listed have a minimum density requirement that is higher than what WSDOT currently requires. However, it is important to understand how the minimum density is actually applied via state specific QA specifications. Cominsky, et al. (1998) recommends that the minimum requirement for in-place density should be 93 percent of maximum theoretical gravity and the maximum should be 98 percent. These recommendations are generally confirmed in other studies – minimum requirements for in-place density during construction in the 92 to 93 percent range and the final density not exceeding 97 percent density (Brown, 1990; Brown and Cross, 1991; Cooley, et al., 2001).

Table 33. Minimum Density Requirements for Other States.

State	Density Requirement		Roadway Type
	Minimum	Maximum	
Alabama	92.0		
Alaska	92.0	98.0	
Arkansas	92.0	96.0	
Colorado	92.0	96.0	
Connecticut	92.0	97.0	
Florida	93.0		Coarse-graded
	90.0		Fine-graded
Georgia	92.2		
Hawaii	91.0		
Idaho	92.0	95.0	
Illinois	92.0	96.0	75-blow Marshall
	93.0	97.0	50-blow Marshall
Indiana	92.0		
Iowa	92.0		
Kentucky	92.0		
Louisiana	92.0		
Maine	93.0	98.0	50 gyration mixes
	92.5	97.5	75+ gyration mixes
Maryland	92.0	97.0	
Michigan	92.0		
Minnesota	92.0		Wearing surface
	93.0		Non-wear surface, shoulders
Mississippi	92.0	95.0	
Missouri	92.0	96.0	
Nebraska	92.4		
Nevada	92.0	96.0	
New Mexico	92.0	98.0	
New York	92.0	97.0	Interstate
	96.0	103.0	Low-volume
North Dakota	91.0		
Ohio	93.0		Surface
	92.0		Intermediate
Oklahoma	92.0	97.0	
Oregon	91.0		Low to medium volume roads
	92.0		High volume roads
Pennsylvania	92.0	97.0	RPS
	90.0	97.0	Standard
Puerto Rico	93.5		Coarse-graded
	93.0		Fine-graded
South Carolina	92.0		New Construction/Interstate
	91.4		Other
Tennessee	92.0		
Texas	91.0	95.0	
Utah	93.5		
	92.5		<2” thick
West Virginia	92.0	96.0	
Western Federal Lands	91.0		
Wisconsin	91.5		<3 million ESALs
	92.0		≥3 million ESALs
Wyoming	92.0		

CHAPTER 6
CONTRACTOR QUALITY CONTROL

WSDOT does not generally require a contractor quality control (QC) program; however, WSDOT and Contractor's have taken steps towards implementation in the North Central Region. WSDOT placed three projects in 2003 that implemented contractor quality control and subsequent projects in 2004, 2005, and 2006. Based on the 2003 projects, the quality control program required that the Contractor perform asphalt content and gradation testing every 800 tons of mix placed. With the 2003 pilot projects, the Contractor had more control of the asphalt content and gradation (which, in turn, helped to minimize the variation in the volumetric properties). Overall, the weighted standard deviation for the QC projects was lower than the volumetric and non-volumetric projects, but the weighted average for air voids and VMA was farther from the target.

In an earlier study report (Mahoney and Backus, 2000) and more recently in a survey of hot mix specifications of the western states (Mahoney and Economy, 2001), most states now require contractor QC programs. The results of the surveys are summarized in tables 34 and 35. Further, NCHRP Report 409 (Cominsky, et al. (1998)) supports and presents elements of contractor QC specifically tailored for Superpave.

Responses to questions about quality control programs were similar among the SHAs. About 83 percent of the respondents (15 out of 18 states reporting) require contractors to perform quality control on various attributes of the hot mix and in-place pavement. Table 34 shows the QC tests that contractors are expected to perform. Essentially all of the states with contractor QC programs require testing of aggregate gradation, binder content, and in-place density. Increasingly, measures of mixture volumetrics are being required.

Ten of the 15 states (or 67 percent) with contractor QC reported that their programs either increased or greatly increased HMA quality. Florida and Ohio reported that their QC programs specifically increased contractor knowledge of materials and specifications and/or increased consistency. Several of the SHAs responded that the level of increase in quality varied from contractor to contractor depending on the level of commitment. Table 35 provides state comments on the impact of QC programs.

If WSDOT chooses to require contractor QC, at least three types of information will assist in developing the necessary details (such as the types of required tests, personnel qualifications, etc.). These are:

- The QC information summarized for the 18 State DOTs that responded to the QA specification survey. The summary is shown as Table 34.
- The information on contractor QC programs recommended for Superpave hot mix. This is contained in NCHRP Report 409—Chapter 2 (Cominsky, et al. (1998)).
- ASTM, AASHTO, and NAPA publications:
  - ✓ ASTM D 3666-05a—Standard Specification for Minimum Requirements for Agencies Testing and Inspecting Road and Paving Materials

- ✓ ASTM D 4561-96—Practice for Quality Control Systems for Organizations Producing and Applying Bituminous Paving Materials
- ✓ ASTM D5506-98 Standard Practice for Organizations Engaged in the Certification of Personnel Testing and Inspecting Bituminous Paving Materials
- ✓ AASHTO R18-06—Standard Recommended Practice for Establishing and Implementing a Quality System for Construction Materials Testing Laboratories
- ✓ NAPA Quality Improvement Series 97—Quality Control for Hot Mix Asphalt Operations.

Table 34. Contractor Quality Control Requirements.

State	QC Program Required?	Aggregate Gradation	Binder Content	In-place Density	Mixture Volumetrics	Other
Alaska	Yes	Yes	Yes	Yes	No	
Arkansas	Yes	Yes	Yes	Yes	Air Voids, VMA	
Arizona	Yes	Yes	Yes	Yes		Va in field compacted specimens
California	Yes[1]	Yes	Yes	Yes		Yes, V_a in field compacted specimens, Sand Equivalent, Stability, and Air Voids (Voids only at start up evaluation)
Florida	Yes	Yes	Yes	Yes	Air Voids	
Hawaii	No					
Indiana	Yes	Yes	Yes	Yes	Air Voids, VMA	
Kansas	Yes	Yes	Yes	Yes	Air Voids, VMA	
Kentucky	Yes	Yes	Yes	Yes	Air Voids, VMA	
Nevada	Yes[2]	Yes	Yes	Yes		V_a in field compacted specimens
Ohio	Yes	Yes	Yes	Yes[3]		
Oregon	Yes	Yes	Yes	Yes	VMA, VFA, V_a (field compacted)	Percent moisture in the mix
Rhode Island	No					
South Carolina	Yes	Yes	Yes			
Washington	No					
Western Federal Lands	Yes	Yes	Yes	Yes		Sand Equivalent, Fractured Faces on Gravel Sources
Wisconsin	Yes	Yes	Yes	Yes	Air Voids	
Wyoming	Yes	Yes		Yes		Note 4

Notes: 1) California: QC required for projects with 10,000 tonnes or greater. 2) Nevada: Contractor QC required on certain projects. 3) Ohio: Contractor option. 4) Mix design verification (asphalt content, air voids, VMA, etc.) during startup and then 1 each 20,000 tons.

Table 35. Impact of Contractor QC Programs.

State	Impact on Quality of Work
Alaska	No Noticeable Increase
Arkansas	Increase
Arizona	Increased Quality
California	Increased Quality
Florida	Increase
Hawaii	No Program Required
Indiana	Increase/Great Increase
Kansas	Great Increase
Kentucky	Increase
Nevada	No Noticeable Increase
Ohio	Other
Oregon	Do Not Know
Rhode Island	No Program Required
South Carolina	Unknown
Washington	No Program Required
Western Federal Lands	Increased Quality
Wisconsin	Great Increase
Wyoming	Increase

Cominsky et al. (1998) in NCHRP Report 409 provided details for a QC/QA program to control the production of Superpave mixes. They note that "Quality cannot be tested or inspected into the Superpave mix; it must be 'built in'…it is imperative that the Contractor have a functional, responsive QC plan." Further, they stated that the primary method of field QC would need to employ the use of the SGC and evaluation of the volumetric properties of the mix. Other points made about contractor and agency roles and responsibilities include:

- Basic Roles and Responsibilities
    - "The SHA will verify the Superpave volumetric mix designs, inspect plants, and monitor control of the operations…"
    - "The Contractor shall be responsible for development and formulation of the Superpave mix design, which will be submitted to the SHA for verification."
    - "…the Contractor shall be responsible for the process control of all materials during the handling, blending, mixing, and placing operations."
    - "The Contractor's QC procedures, inspections, and tests shall be documented and shall be available for review by the SHA for the life of the contract."
- Superpave Mix Design and Production
    - It is noted in NCHRP Report 409 that "control of volumetric properties is performed primarily on laboratory-compacted specimens of plant mix. Volumetric properties (i.e., air void content, VMA, and VFA) take precedence over material proportions. Therefore, if asphalt content and gradation meet the design mixture but air voids do not, adjustments must be made to either asphalt content or gradation to bring air voids, VMA, and VFA into line."

  - "The Contractor shall develop a Superpave LTMF [Laboratory Trial Mix Formula] for the HMA paving courses by the Superpave mix design process employing the volumetric mix design concept with the gyratory compactor."
  - "At least 1 month before the start of construction (or when the construction materials are available), the Contractor shall verify in the laboratory that the paving mixes prepared from the asphalt binder, coarse and fine aggregate, and mineral filler, when necessary, planned for use in the pavement construction yield mix composition and gyratory-compacted (AASHTO Standard Method TP4) properties within the LTMF tolerances listed in [Table 9]."
  - "The Contractor shall report to the SHA the results of [the] laboratory verification and any actions necessary in the Contractor's judgment to bring the paving mixes produced with the materials planned for use in the pavement construction into conformance with the LTMF Superpave tolerances."
  - "At the beginning of the project, the Contractor shall produce a minimum of 500 tons but not exceed a day's production of HMA of uniform composition and shall verify that the plant-produced HMA is within the Superpave LTMF tolerances shown in [Table 9]."
  - "The 500 ton lot of Superpave mix must meet an acceptable quality level of 90 percent within the LTMF limits for each of the following characteristics: asphalt content, aggregate gradation, and volumetric properties identified in [Table 9]."
- Sampling and Testing
  - "The QC Plan recognizes that the LTMF generally is not representative of the HMA that is produced in the field. The target values developed from the field verification of the plant-produced HMA and the control strip will become the control values."
  - "The QC Plan is based on a concept of continuous sampling of Superpave HMA at the plant. Lots and sublots are considered in the QC Plan only for in-place compaction. The QC sampling will progress continuously as long as the target values are within the LTMF tolerances and do not change values substantially as monitored by the control chart values. The objective of sampling and testing associated with this QC Plan is to ensure conformance of the mean properties of the 'plant-produced' mix with the 'target' mix and to minimize variability in the HMA."
- QC Activities
  - "The primary method of field QC makes use of the SGC and the volumetric properties of the HMA."
  - The Contractor shall develop and implement a plan approved by the SHA to control the compaction of the HMA and ensure its compliance with the project specification….The Contractor shall measure and record a daily summary of the following: the amount of HMA delivered to the paver; the temperature of the HMA in each truck of the surface of the load; and the temperature of the mat at the approximate start of the compaction process."

The report (NCHRP 409) also provides a description of a model QA plan.

The items recommended in NCHRP 409 vary from today's WSDOT/Contractor practices. As recommended in NCHRP 409, the contractor must conduct a rigorous QC program. The activities associated with contractor QC include:

- Contractor determines Laboratory Trial Mix Formula (LTMF) that is verified by the agency
- Contractor verifies LTMF at plant lab with the plant materials that will be actually used on the project.
- Contractor verifies LTMF via field production.
- With the first 100 tons of field mix, laboratory tests are performed by the contractor as follows:
  - Asphalt cement content
  - Percent passing various sieve sizes
  - G_{mm}
  - G_{mb} (measured)
  - V_a at $N_{initial}$, N_{design}, and N_{max} and in-place
  - Compare results to LTMF tolerances.
  - If the measured properties fall within the allowable tolerances, the continuous QC process begins. Samples are taken from the plant and the mat. For the plant samples, the SGC is used and corrected G_{mb} values are determined. In-place densities are taken from the mat.
- If the mix varies outside of allowable tolerances, adjustments are made to the mix.

The above represents a substantial increase in contractor testing and control (actually more than "substantial" since WSDOT does not require a contractor QC program). The real question is the efficacy of this NCHRP recommended testing program or some subset of the recommended tests. Based on the preceding information presented in this report, there is not a clear-cut answer to that question. In fact, the efficacy of QC tests for volumetric mix properties is unclear even though NCHRP Report 409 is clear in its fundamental recommendation – that is – volumetric properties control over mix proportions. The bottom line is whatever testing is done should enhance mix performance. At this point, it is logical that WSDOT work with contractors to start contractor conducted QC testing. Initially, that should include measures of asphalt content, gradation, and in-place density. Whether volumetric mix properties should be included in contractor QC can await further evaluation – such information can come from in state or out of state experience. Adding volumetric tests for a field situation has a large impact on testing personnel, qualifications, and test equipment. Any related decisions should be carefully made.

CHAPTER 7
SUMMARY AND CONCLUSIONS

SUMMARY

The focus of this study was on the WSDOT specification for HMA and was conducted, in part, to aid in the implementation of the Superpave mix design system. A literature review was conducted along with extensive use of WSDOT HMA field data. During the study, WSDOT tested the concept of using volumetric mix parameters as a partial basis for Contractor pay. Field results from these projects were compared to "traditional" pay factor projects to allow an initial assessment.

Literature Review

The literature review is summarized as follows:

- Typical specification bands (such as V_a in SGC specimens) and test precision are uncomfortably close.
- Volumetric mix properties can be partially characterized by tests such as asphalt content and aggregate gradation.
- The Superpave gyratory compactor and its associated variability need to be considered with respect to mix volumetric measures.
- Measurement of the bulk specific gravity can affect mix volumetric results. The CoreLok® measurement system provides improved density results.
- The same or similar volumetric properties and strength characteristics can be attained with very different gradations and asphalt contents based on a NCHRP study. The implication is that volumetric mix properties are not "absolute" measures of mix performance.
- In-place density (air voids) strongly impact pavement performance. The general rule-of-thumb is that a 1 percent increase in air voids over a base air void level of 7 percent tends to produce about a 10 percent loss in pavement life.
- Permeabilities are strongly influenced by lift thickness and compaction requirements, especially coarse-graded Superpave mixtures. The recommended compaction requirement (as a percent of theoretical maximum density) is higher for coarse-graded ¾-inch Superpave mixes as compared to ½-inch mixes. The critical in-place air void levels are about 6 percent for ¾-inch mixes and 7 percent for ½-inch mixes. The mat thickness for improved compactability based on t/NMAS should be: (1) fine-graded mixes, t/NMAS ratios ≥ 3.0, and (2) coarse-graded and SMA mixes, t/NMAS ratios ≥ 4.0.

Study Analyses

Several types of analyses were done to examine the current WSDOT HMA specification. These included:

- Regression analyses were used to examine the relationship between volumetric mix properties (V_a, VMA, and VFA) and asphalt content and measures of gradation.

- A comparison of WSDOT field produced HMA examined non-volumetric and volumetric Contractor pay. This included:
  - Basic statistics
  - Field tests compared to JMF requirements
  - Test precision impacts
  - Sieve broadband tolerances
- A comparison of WSDOT Superpave and Class A projects
- WSDOT HMA in-place densities, and
- Contractor QC

All of the above topics are related and relevant for WSDOT and its associated Contractors. A short summary for each of the items listed follows.

Regression Analyses

Regression analyses for WSDOT Superpave mixes showed that V_a and VMA are correlated to certain sieve sizes and the asphalt content; however, the R^2 values are generally low. For Superpave ½-inch mixes, the percent asphalt content, and the percent passing the No. 30 and No. 200 sieves have the largest effect on predicting V_a and VMA. For the Superpave ¾-inch mixes, the percent asphalt content, and the percent passing the No. 4, No. 8, and No. 200 sieves have the largest effect on predicting V_a and VMA.

Non-Volumetric and Volumetric Contractor Pay Projects

The examination of non-volumetric pay factor projects were based on Superpave projects constructed from 1997 through 2002 (a total of 43). The volumetric based pay projects were built during the 2001 and 2002 construction seasons (three in 2001 and 12 in 2002 for a total of 15). The results can be summarized by: (1) basic statistics and (2) field results compared to JMF requirements.

The means and standard deviations for V_a, VMA, and VFA are similar for projects that span the 1997 to 2002 time period; however, in general, the variation is a bit smaller for the volumetric pay projects. Based on the 24 Superpave projects constructed during 2002, similar means and standard deviations are observed for both types of projects (non-volumetric and volumetric).

Overall, there are more deviations from the JMF for ½-inch volumetric pay projects than non-volumetric pay projects. The reverse is true for ¾-inch projects. For standard deviations, all gradation measures have approximately the same variation regardless of whether non-volumetric or volumetric pay was used. This applies to both the ½- and ¾-inch mixes. The V_a is approximately the same for NVPF and VPF mixes.

Comparison of WSDOT Superpave and Class A Mixes

The average and standard deviation of the Superpave ½-inch mixes are similar to the Class A for gradation and asphalt content; however, the Superpave ½-inch mix has, on average, approximately 0.28 percent more asphalt binder than Class A.

The differences from the design JMF values to the gradations and asphalt content produced in the field (field result minus the JMF) were compared. On average, all three types of mixes (Superpave ¾-inch, ½-inch, and Class A) have similar means and standard deviations.

A comparison of Superpave and Class A mixes showed that the level of compaction (based on the percent of theoretical maximum density) is quite similar (the overall average is about 93 percent of TMD with a slightly smaller standard deviation for the Superpave mixes).

Though not discussed in Chapter 5, research reported by several states shows that Performance Graded (PG) binders can significantly influence HMA performance.

WSDOT HMA In-Place Densities

The current WSDOT specification for in-place density is a minimum of 91.0 percent TMD. The percent of Superpave mix densities that are less than the specified percentages of G_{mm} were calculated. Approximately 50 percent of the densities were below 93 percent of G_{mm}, 36 percent below 92.5 percent, 24 percent below 92.0 percent, 15 percent below 91.5 percent, and 8 percent below 91.0 percent. Based on several cited studies for ½-inch NMAS mixes, the in-place air voids should not exceed 7 percent. This air void level is exceeded by about 50 percent on all field results.

By use of HMA fatigue cracking estimates, for every ½ percent increase in the minimum density, the pavement life increases by 5 percent.

Contractor QC

WSDOT does not currently require a contractor quality control (QC) program; however, specific WSDOT Regions and Contractors are taking steps towards implementation. Most states now require contractor QC programs.

CONCLUSIONS

Based on the literature reviewed and the analysis of available WSDOT field data, the following conclusions are made:

Based on Literature

Coarse-graded Superpave ¾-inch mixes require a higher level of density than current WSDOT standards to keep mix permeability at low, acceptable levels. The work at NCAT showed that in-place air void levels higher than 5.5 percent had excessive mix permeability. Further, a thickness to NMAS ratio of 4 or greater is recommended by NCAT resulting in a minimum layer thickness of 3.0 inches. If a higher density standard and sufficient lift thickness are not possible, a second option is not to use ¾-inch coarse-graded Superpave mixes as wearing courses.

Superpave Gyratory Compactors must be carefully checked for gyration angle. Otherwise, mix density variability can result. WSDOT has been proactive in doing so.

The CoreLok® method for measurement of bulk specific gravity provides improved estimates of density when the sample air voids exceed eight percent. WSDOT should consider its adaptation. WSDOT-specific results support this conclusion.

There are currently two approaches used by WSDOT for field QA tests and calculation of Contractor pay factors: (1) use of in-place density, asphalt content, and gradation (2) use of in-place density, AC, VMA, V_a, and selected measures of gradation (1/2 inch, 3/8 inch, No. 4, No. 8, and No. 200). WSDOT is in the process of assessing which of the two approaches it will use for Superpave projects. Based on NCHRP 409 (a laboratory study that showed a wide range of volumetric properties resulted in similar mix performance), a positive link between typical volumetric pay factors and enhanced performance is uncertain. Mix volumetric measures are an important aid to the mix design process and should be considered for use in making test section JMF adjustments.

WSDOT Volumetric Assessment

A comparison of Superpave non-volumetric and volumetric pay factor projects (43) in general did not reveal significant differences between the two pay processes to suggest enhanced mix performance.

Volumetric field testing is more complicated and subject to greater operator error than testing for binder content and gradation. QA testing for mix volumetric measures will be more expensive based on current testing frequencies.

Pay factors, if possible, should not be based on multiple items that are correlated, such as volumetric mix properties and gradation/asphalt content.

Though the initial assessment of volumetric-based pay factors is, at best, neutral, there is no evidence from the available data to suggest that volumetric pay factors are less effective in achieving reasonable quality HMA.

A recent report for the California Department of Transportation (Popescu and Monismith (2007)) supports the view that mix and pavement structure characteristics that most affect HMA performance are: (1) for rutting prediction asphalt content, degree of compaction, and aggregate gradation (P200 fraction) are significant, and (2) for fatigue prediction the degree of compaction, pavement thickness, and asphalt content are significant. This work is part of a study examining the feasibility of moving to performance based pay factors.

Comparison of Superpave and Class A Mixes

WSDOT Superpave and Class A mixes have similar mix characteristics and in-place densities. Even though no laboratory or field accelerated testing exists within

Washington State on which to base a conclusion, it is unreasonable to expect that a major improvement in HMA performance will occur based on Superpave mix principles alone. However, full implementation of the Superpave system is desirable for other reasons. A paper published by Willoughby, et al (2004) concluded that Superpave mixes in Washington State were performing as well or slightly better than the prior, conventional HMA (Class A mixes). Further, in the 2003-2004 timeframe, the costs of Superpave and the previously used Class A mixes were about the same.

Research from other states strongly suggests that the proper selection of PG binders can significantly improve HMA performance.

WSDOT HMA In-Place Densities

Consideration should be given to raising the minimum level of TMD. This will result in increased HMA field densities. However, any increase in the minimum TMD must be viewed along with other possible mix changes.

Contractor QC

An assessment is underway by WSDOT as to the efficacy of the 2003 to 2006 North Central Region Contractor QC projects. Once this assessment is complete, WSDOT should decide on whether to develop and implement a Contractor QC program for the whole state. Studies and data reviewed via this study strongly suggest that Contractor QC will enhance HMA performance.

Implementation of Changes

All changes to the WSDOT HMA specification should be fully discussed within the agency and with paving Contractors. This is straightforward to achieve since existing committees exist for this purpose. Major specification changes should be put into an implementation plan prior to execution.

The impacts and interactions of multiple HMA specification changes should be considered. To do this, all potential changes should be summarized and potential impacts examined.

REFERENCES

AASHTO (2006). "*Standard Specifications for Transportation Materials and Methods of Sampling and Testing – Part I Specifications and Part II Tests*," American Association of State Highway and Transportation Officials, Washington, D.C.

American Society for Testing and Materials (2000). "*Annual Book of ASTM Standards, Volume 04.03 – Road and Paving Materials; Pavement Management Technologies,"* West Conshohocken, PA.

Asphalt Institute (1995). "*Mix Design Methods For Asphalt Concrete and Other Hot-Mix Types – MS-2," Sixth Edition*. Lexington, KY.

Brown, E. Ray (1990). *"Density of Asphalt Concrete – How Much is Needed?,"* NCAT Report 90-03, National Center for Asphalt Technology, Auburn, AL.

Brown, E. Ray and Cross, S. A. (1991). *"Comparison of Laboratory and Field Density of Asphalt Mixtures,"* NCAT Report 91-1, National Center for Asphalt Technology, Auburn, AL.

Brown, E. Ray, Collins, R., and Brownfield, J. A. (1989). "*Investigation of Segregation of Asphalt Mixtures in the State of Georgia*," Transportation Research Record 1217, Transportation Research Board, Washington, DC.

Brown, E. Ray et al (2004), *"Relationship of Air Voids, Lift Thickness, and Permeability of Hot Mix Asphalt Pavements,"* NCHRP Report 531, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Buchanan, Shane M., and Brown, Ray E. (2001). *"Effect of Superpave Gyratory Compactor Type on Compacted Hot-Mix Asphalt Density,"* Transportation Research Record No. 1761, Transportation Research Board, Washington, D.C.

Choubane, B., Page, G. C., and Musselman, J. A. (1998). "*Investigation of Water Permeability of Coarse Graded Superpave Pavements*," Association of Asphalt Paving Technologists, Volume 67.

Cominsky, Ronald J., Killingsworth, Brian M., Anderson, R. Michael, Anderson, David A., and Crockford, William W. (1998). "*Quality Control and Acceptance of Superpave-Designed Hot-Mix Asphalt*," Report 409, National Cooperative Highway Research Program Report, Transportation Research Board, Washington, D.C.

Cooley, Jr., L. A., Brown, E. R., and Maghsoodloo, S. (2001). "*Development of Critical Field Permeability and Pavement Density Values for Coarse Graded Superpave Pavements*," Journal of the Transportation Research Board 1761, Transportation Research Board, Washington, DC.

Cooley, Jr., L. Allen, Prowell, Brian D., and Brown, E. Ray. (2002). "*Issues Pertaining to the Permeability Characteristics of Coarse-Graded Superpave Mixes*," NCAT Report No. 2002-06, National Center for Asphalt Technology, Auburn, Alabama.

Dalton, E. F. (1999). *"Superpave Gyratory Compactors – Angle Problems?"* Report 1999-03. Pine Instrument Company, Grove City, Pa.

D'Angelo, John, Harman, Thomas P., and Paugh, Charles W. (2001). "*Evaluation of Volumetric Properties and Gyratory Compaction Slope for the Quality Control of Hot-Mix Asphalt Production*," Proceedings, Annual Meeting of the Association of Asphalt Paving Technologists.

Epps, J. A. and Monismith, C. L. (1971). *Fatigue of Asphalt Concrete Mixture – Summary of Existing Information.* Special Technical Publication 508. ASTM, Philadelphia, PA.

FHWA National Highway Specifications website, http://fhwapap04.fhwa.dot.gov/nhswp/index.jsp. Accessed December 27, 2006.

Finn, F. N., Nair K., and Hilliard J. M. (1978). *NCHRP Report 195: Minimizing Premature Cracking in Asphaltic Concrete Pavement.* TRB, National Research Council, Washington, D.C.

Finn, F. N. and Epps, J. A. (1980). *Compaction of Hot Mix Asphalt Concrete.* Research Report 214-21. Texas Transportation Institute, Texas A&M University, College Station.

Freeman, R. and Grogan, W. (1996). "*Statistical Analysis and Variability of Pavement Materials*," Draft Technical Report GL-97-XX, US Army Corps of Engineers.

Goode, J. F. and Owings, E. P. (1961). A Laboratory-Field Study of Hot Asphaltic Concrete Wearing Course Mixtures. *Public Roads*, Vol. 31, No. 11.

Hall, Kevin D., Griffith, Frances T., and Williams, Stacy G. (2001). *"Examination of Operator Variability for Selected Methods for Measuring Bulk Specific Gravity of Hot-Mix Asphalt Concrete,"* Transportation Research Record No. 1761, Transportation Research Board, Washington, D.C.

Hand, A.J. and Epps, A.L. (2000). "*Effects of Test Variability on Mixture Volumetrics and Mix Design Verification*," Proceedings, Annual Meeting of the Association of Asphalt Paving Technologists.

Hinrichsen, John. (2001). *"Comparison of Four Brands of Superpave Gyratory Compactors,"* Transportation Research Record No. 1767, Transportation Research Board, Washington, D.C.

Hubbard, P. and Gollomb, H. (1937). The Hardening of Asphalt with Relation to Development of Cracks in Asphalt Pavements. In *Proceedings of the Association of Asphalt Paving Technologists*, Vol. 9.

Hughes, C. (1996). "*Variability in Highway Pavement Construction*," Synthesis of Highway Practice 232, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

Leahy, Rita B., and Briggs, Robert N. (1999). "*Superpave – Washington DOT's Assessment and Status,"* Research Report WA-RD 486.1, Washington State Department of Transportation, Olympia, WA, December 1999.

Linden, R. N. (1987). *The Effect of Air Voids on Asphalt Concrete Pavement Performance.* M.S. research report. University of Washington, Seattle, WA.

Linden, Robert N., Mahoney, Joe P., and Jackson, Newton C. (1989). "*Effect of Compaction on Asphalt Concrete Performance,"* Transportation Research Record No. 1217, Transportation Research Board, Washington, D.C.

Mahoney, Joe P., and Backus, Andrew W. (1999). "*QA Specification Practices,"* Research Report 498.1, Washington State Department of Transportation, Olympia, WA, August 2000.

Mahoney, Joe P., and Economy, Lisa G. (2001). "*Results of the PCCAS Questionnaire on State Highway and Federal Agency Quality Control/Quality Assurance Programs for Asphalt Concrete,"* Draft Report for Presentation and Discussion at the Pacific Coast Conference on Asphalt Specifications (September 11-12, 2001). Reno, NV.

Mallick, R. B., Cooley, Jr., L. A., and Teto, M. (1999). "*Evaluation of Permeability of Superpave Mixes in Maine*," Final Report, Technical Report ME-001.

Maupin, Jr., G. W. (2000). "*Asphalt Permeability Testing in Virginia*," Transportation Research Record 1723, Transportation Research Board, Washington, DC.

McGennis, R.B., Perdomo, D., Kennedy, T.W., and Anderson, V.L. (1997). *"Ruggedness Evaluation of AASHTO TP4 the Superpave Gyratory Compactor,"* Journal of the Association of Asphalt Paving Technologists, Volume 67, pp. 277-311.

Molohon, Rob. (2001). *"Results of Statewide Gyratory Comparison Study,"* Washington State Department of Transportation, Materials Laboratory, Tumwater, WA – Not published.

Muench, Steve T., and Mahoney, Joe P. (2001). "*A Quantification and Evaluation of WSDOT's Hot-Mix Asphalt Concrete Statistical Acceptance Specification,"* Research Report 517.1, Washington State Department of Transportation, Olympia, WA, June 2001.

Musselman, J. A., Choubane, B., Page, G. C. and Upshaw, P. B. (1998). "*Superpave Field Implementation: Florida's Early Experience*," Transportation Research Record 1609, Transportation Research Board, Washington, DC.

Musselman, James A., Page, Gale C., and Sholar, Gregory A. (2001). *"Field Conditioning of Superpave Asphalt Mixes,"* Transportation Research Record No. 1761, Transportation Research Board, Washington, D.C.

Popescu, L. and Monismith, C. (2007), "*Performance-Based Pay Factors for Asphalt Concrete Construction; Comparison with a Currently Used Experience-Based Approach*," Draft Report, Client Reference No. 3.1.5, California Department of Transportation (Division of Construction), January 12, 2007.

Puangchit, P., Hicks, R. G., Wilson, J. E., and Bell C. A. (1982). *Impact of Variation in Material Properties on Asphalt Pavement Life.* Report FHWA-OR-82-3. Oregon Department of Transportation, Salem, OR.

Roberts, F. L., Kandahl, P. S., Brown, E. R., Lee, D. Y., and Kennedy, T. W. (1996). Hot Mix Asphalt Materials, Mixture Design, and Construction. Second Edition. NAPA Education Foundation, Lanham, MD.

Shook, J.F., Finn, F.N., Witczak, M.W., and Monismith, C.L. (1982). *"Thickness Design of Asphalt Pavements – The Asphalt Institute Method,"* Proceedings of the Fifth International Conference on the Structural Design of Asphalt Pavements. Delft University of Technology, The Netherlands.

Stevens, D. E. (1959). "*Raveling*," Association of Asphalt Paving Technologists, Volume 28.

WSDOT (2006a), "Cross-Cutting Management Issues—Hot Mix Asphalt," Measures, Markers, and Mileposts, Washington State Department of Transportation, Olympia, Washington, September 30, 2006.

WSDOT (2006b), "Standard Specifications for Road, Bridge, and Municipal Construction—2006," Manual 41-10, Washington State Department of Transportation, Olympia, Washington.

Westerman, J. R. "*AHTD's Experience with Superpave Pavement Permeability*," Accessed at http://www.utexas.edu/research/superpave/articles/jrw10a.html on January 21, 1998.

Willoughby, Kim A., and Weston, Jim. (2003). *"Evaluation of the CoreLok Device and AASHTO T-166 Test Methods for Measuring Bulk Specific Gravity,"* Washington State Department of Transportation, Materials Laboratory, Tumwater, WA – Not published.

Willoughby, K., Pierce, L., Weston, J., and Mahoney, J. (2004), "*Comparison of Performance and Cost Between Superpave and Conventional Hot-Mix Asphalt in Washington State*," Journal of the Transportation Research Board No. 1869, Transportation Research Board, Washington, D.C.

Zube, E. (1962). "*Compaction Studies of Asphalt Concrete Pavements as Related to the Water Permeability Test*," Highway Research Board, Bulletin 358.

APPENDIX A
CONTRACT EXAMPLES

CONTRACT EXAMPLES

Appendix A contains a comparison of WSDOT Class A, G, and E mixes as well as three Superpave ½-inch project field results, three Superpave ¾-inch project field results, one SMA project field results, and the three volumetric projects constructed during in 2001. Table A1 shows a comparison between Class A and G from the same pit source, Class A and E from the same pit source, and Classes A, G, and E from the same pit source. Within each pit source, the classes of mix that are shown have different gradations (depending on the class of mix) and the resulting bulk and rice specific gravities at the same asphalt content. This data was taken directly from the mix design information contained in the WSDOT SmartWare database. With the Class A and G comparisons, the maximum theoretical densities are the same. The Class A and E comparison also has the same rice density at the same asphalt content. When Classes A, G, and E are compared, the rice densities are very similar at the same asphalt content. These results show that the G_{mm} is almost completely dependent on the asphalt content. It is known that when the asphalt content increases, the G_{mb} will increase and the G_{mm} will decrease. The opposite is also true. If a sample is coarser (i.e., has more coarse aggregate retained on the No. 4 sieve), the G_{mb} will increase.

Tables A2 through A4 contain the three Superpave ½ mix field results. A contract-by-contract evaluation of this data shows that two samples within one contract that have the same gradation and asphalt content can have very different G_{mm} and G_{mb} results. Conversely, for field sample results that have different asphalt contents, we should expect that the G_{mm} value would change. For instance, Table A2 contains the field sample results from Contract 5544 paved in 1999. After the revision of the JMF, there are only two samples outside the tolerances for V_a and one outside the VMA tolerance. If we examine Samples 8 and 9 (Sample 8 is out of the volumetric specifications), the gradation and asphalt content are the same, yet the bulk specific gravity changed by 0.015. We can also compare the G_{mm} and G_{mb} from Samples 21 and 23. We can expect that the G_{mm} will decrease when the asphalt content increases and the G_{mb} to decrease, but the changes here are larger than expected, -0.014 and 0.012 for the G_{mm} and G_{mb}, respectively. Overall, this contract met the volumetric properties. Evaluation of the average gradation and asphalt content along with the standard deviations at the bottom of the table show that the contractor met the JMF and the standard deviations are small. The same evaluation can be done with any of the contracts randomly chosen and included in tables A2 through A4. Below are a few points from tables A3 and A4.

- Table A3: Samples 1 and 3; Sample 3 has more fines (percent passing the No. 4 sieve) than Sample 1, but the G_{mm} changes by 0.044. Typically, the G_{mm} changes by approximately 0.02 with a 0.5 percent change in asphalt content.
  - Samples 6 and 9 have the same gradation and asphalt content, but the G_{mm} and G_{mb} change by 0.011 and 0.035, respectively.
  - Samples 12 and 13 have the same gradation but the asphalt content increases by 0.2 percent. With an increase in asphalt content, the G_{mb} should increase and the G_{mm} should decrease. The G_{mm} and G_{mb} both increase.
- Table A4: Samples 1 and 2 after the revised JMF have approximately the same gradation and the same asphalt content, the G_{mm} is very similar, but the G_{mb} changes by 0.035.
  - Samples 9 and 10 after the revised JMF again have the same gradation and asphalt content, but the G_{mb} changes by 0.017.

- Samples 22 and 23 after the revised JMF have the same gradation and asphalt content, but the G_{mb} changes by 0.037.

The same evaluation can be done for the Superpave ¾-inch mixes, the SMA, and the volumetric projects. It is important to note that when no significant change has occurred to the gradation, and the asphalt content is similar (within 0.1 percent), the G_{mm} and G_{mb} values should be at least within the single operator precision according to AASHTO (assuming that the same operator is performing the work, which is what typically occurs on WSDOT Superpave projects).

Table A1. Comparisons of Class A, G, and E for Gradation, Asphalt Content, and Densities

Mix ID	G8308	G8309	G9180	G9181	G9093	G9091	G8985	G8986	G8988	G9728	G9724	G9727
Class Mix	G	A	G	A	A	E	G	A	E	G	A	E
Pit #	I-102		M-132		AD-121		F-160			A-464		
1 1/4"						100			100			100
1"						98			98			99
3/4"		100		100	100			100			100	
5/8"						79			81			81
1/2"	100	97	100	96	95	70	100	95	69	100	95	66
3/8"	98	83	98	85	85		99	84		97	85	
1/4"	83	67	82	67	68	55	82	65	49	82	68	44
#10	46	37	40	35	35	31	48	36	34	44	38	27
#40	18	16	16	15	14	15	18	15	15	19	17	12
#200	6.0	5.3	5.5	5.5	5.5	5.9	4.5	4.7	4.0	6.3	5.0	3.0
AC	5.0	5.0	5.0	5.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Bulk	151.5	154.7	145.4	149.7	148.2	144.2	145.3	149.1	152.2	147.8	148.6	152.6
Rice	158.0	158.0	156.9	156.9	159.3	159.3	155.9	156.2	154.8	154.5	154.6	155.6

Table A2. Contract 5544 Superpave ½-inch Mix Field Results

5544	**Sieve Size (mm)**	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.600**	**0.300**	**0.150**	**0.075**	**AC**	**Gmb**	**Gmm**	**Va**	**VMA**	**VFA**	**D/A Ratio**
G9186	**JMF**	*100*	*97*	*83*	*51*	*32*	*22*	*16*	*12*	*8*	*5.8*	*5.2*	*2.361*	*2.457*	*4.1*	*14.4*	*71.1*	*0.8*
	Tolerance Limits	*99 - 100*	*91 - 100*	*77 - 89*	*46 - 56*	*28 - 36*	*20 - 24*	*14 - 18*	*10 - 14*	*6 - 10*	*3.8 - 7.0*	*4.7 - 5.7*			*3.0 - 5.0*	*14.0 Min*	*65 - 75*	*0.6 - 1.6*
Test #	**Date**																	
TS 1	8/17/1999	100	98	85	53	35	24	17	13	9	6.0	5.1	2.464	2.321	5.8	15.4	62.3	1.4
TS 2	8/17/1999	100	98	85	53	35	24	17	13	9	6.2	5.2	2.491	2.333	6.3	15.1	58.3	1.6
TS 3	8/17/1999	100	96	86	54	34	23	17	13	9	6.1	5.2	2.444	2.321	5.0	15.6	67.9	1.3
TS 4	8/17/1999	100	97	86	55	36	25	18	13	10	6.8	5.1	2.447	2.321	5.1	15.4	66.9	1.5
	REVISED JMF	*100*	*97*	*83*	*51*	*32*	*22*	*16*	*12*	*8*	*5.8*	*5.5*			*4.1*	*14.4*	*71.1*	*0.8*
	Tolerance Limits	*99 - 100*	*91 - 100*	*77 - 89*	*46 - 56*	*28 - 36*	*20 - 24*	*14 - 18*	*10 - 14*	*6 - 10*	*3.8 - 7.0*	*5.0 - 6.0*			*3.0 - 5.0*	*14.0 Min*	*65 - 75*	*0.6 - 1.6*
1	8/19/1999	100	96	82	48	31	21	16	12	9	5.9	5.0	2.441	2.337	4.3	14.8	70.9	1.3
2	8/19/1999	100	96	84	52	34	23	17	12	9	5.9	5.3	2.433	2.333	4.1	15.2	73.0	1.2
3	8/20/1999	100	98	87	55	36	24	17	13	9	6.1	5.6	2.336	2.429	3.8	15.3	75.2	1.2
4	8/20/1999	100	97	85	53	34	23	17	12	9	5.7	5.5	2.340	2.429	3.7	15.1	75.5	1.1
5	8/20/1999	100	96	82	49	31	21	15	11	8	5.3	5.3	2.344	2.432	3.6	14.8	75.7	1.1
6	8/20/1999	100	97	85	52	33	22	16	12	8	5.3	5.5	2.330	2.437	4.4	15.5	71.6	1.1
7	8/23/1999	100	98	88	56	36	24	18	13	9	6.1	5.7	2.347	2.424	3.2	15.1	78.8	1.2
8	8/23/1999	100	96	84	50	33	22	16	12	8	5.6	5.4	2.371	2.432	2.5	13.9	82.0	1.1
9	8/23/1999	100	97	83	50	32	22	16	12	8	5.6	5.4	2.356	2.430	3.0	14.4	79.2	1.1
10	8/24/1999	100	98	88	54	35	24	18	13	9	5.4	5.4	2.349	2.440	3.7	14.7	74.8	1.1
11	8/24/1999	100	96	85	54	35	23	17	12	9	5.6	5.2	2.347	2.434	3.6	14.6	75.3	1.1
12	8/24/1999	100	98	88	55	35	23	17	12	9	5.7	5.5	2.330	2.428	4.0	15.5	74.2	1.1
13	8/24/1999	100	97	89	55	35	23	17	12	9	5.6	5.6	2.342	2.429	3.6	15.1	76.2	1.1
14	8/25/1999	100	96	85	52	34	24	17	13	9	6.6	5.1	2.318	2.441	5.0	15.5	67.8	1.4
15	8/25/1999	100	97	86	55	35	22	18	13	9	6.4	5.4	2.361	2.434	3.0	14.3	79.0	1.3
16	8/26/1999	100	98	87	53	34	23	18	11	9	5.7	5.2	2.321	2.439	4.8	15.5	69.0	1.2
17	8/26/1999	100	96	83	46	29	21	16	11	8	5.7	5.8	2.325	2.443	4.8	15.9	69.8	1.2
18	8/27/1999	100	97	85	54	36	24	18	13	9	5.9	5.1	2.339	2.441	4.2	14.9	71.8	1.3
19	8/27/1999	100	96	83	54	35	24	18	13	9	6.2	5.5	2.350	2.437	3.6	14.8	76.2	1.3
20	8/27/1999	100	95	84	53	33	22	16	11	8	5.5	5.6	2.339	2.434	3.9	15.2	74.3	1.1
21	8/27/1999	100	97	84	52	34	23	17	12	9	5.9	5.1	2.354	2.424	2.9	14.3	79.7	1.2
22	8/28/1999	100	97	83	52	30	24	17	13	9	5.8	5.2	2.333	2.441	4.4	15.1	70.9	1.2
23	8/28/1999	100	97	84	51	34	23	17	12	9	5.7	5.0	2.342	2.438	3.9	14.6	73.3	1.2
24	8/30/1999	100	96	81	50	33	22	16	12	9	5.9	5.5	2.348	2.441	3.8	14.9	74.5	1.2
25	8/30/1999	100	96	81	51	33	23	17	12	9	6.1	5.5	2.355	2.438	4.2	15.3	72.5	1.2
26	8/30/1999	100	96	84	50	32	22	16	12	8	5.7	5.3	2.345	2.439	3.9	14.9	73.8	1.2
27	8/30/1999	100	98	86	51	32	22	16	12	8	5.5	5.4	2.348	2.446	4.0	14.8	73.0	1.2
28	9/1/1999	100	97	86	52	34	23	17	12	9	5.9	5.5	2.329	2.441	4.6	15.5	70.3	1.2
29	9/1/1999	100	96	83	51	32	22	16	12	8	5.4	5.3	2.325	2.436	4.6	15.6	70.5	1.1
30	9/1/1999	100	97	82	47	30	21	15	11	8	5.1	5.0	2.330	2.431	4.2	15.1	72.2	1.1
31	9/1/1999	100	97	82	49	30	21	15	11	8	5.1	5.3	2.337	2.452	4.7	15.1	68.9	1.1
32	9/2/1999	100	97	84	50	32	21	15	12	8	5.3	5.5	2.336	2.450	4.7	15.3	69.3	1.2
33	9/2/1999	100	96	83	49	31	22	16	12	9	5.5	5.4	2.334	2.448	4.7	15.3	69.3	1.2
34	9/2/1999	100	97	82	48	32	22	15	12	8	5.7	5.6	2.337	2.445	4.4	15.3	71.2	1.2
35	9/7/1999	100	97	81	48	31	21	16	12	8	5.4	5.5	2.344	2.445	4.1	15.0	72.7	1.1
	Average Gradation	*100*	*96.8*	*84.4*	*51.7*	*33.2*	*22.6*	*16.6*	*12.2*	*8.7*	*5.8*	*5.3*	*2.358*	*2.420*	*4.2*	*15.1*	*72.5*	*1.2*
	Standard Deviation	*0.00*	*0.80*	*2.09*	*2.53*	*1.91*	*1.11*	*0.94*	*0.67*	*0.53*	*0.38*	*0.20*	*0.043*	*0.041*	*0.76*	*0.42*	*4.59*	*0.12*

Table A3. Contract 5497 Superpave ½-inch Mix Field Results

5497	**Sieve Size (mm)**	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.600**	**0.300**	**0.150**	**0.075**	**AC**	**Gmb**	**Gmm**	**Va**	**VMA**	**VFA**	**D/A Ratio**
	JMF	*100*	*98*	*84*	*51*	*33*	*24*	*14*	*11*	*8*	*5.3*	*5.7*	*2.406*	*2.518*	*4.4*	*16.9*	*74*	*1.0*
	Tolerance Limits	*99 - 100*	*92 - 100*	*78 - 90*	*46 - 56*	*29 - 37*					*3.3 - 7.0*	*5.2 - 6.2*			*3.0 - 5.0*	*14.0 Min*	*65 - 75*	*0.6 - 1.6*
Test #	**Date**																	
TS 1-1	4/26/1999	100	99	88	52	32	18	11	8	6	4.6	5.2	2.353	2.586	9.0	18.7	51.9	1.1
TS 1-2	4/26/1999	100	99	89	59	39	23	15	11	8	5.8	5.3	2.370	2.545	6.9	18.2	62.1	1.2
TS 1-3	4/26/1999	100	99	90	59	38	22	14	10	7	5.4	5.2	2.377	2.542	6.5	17.9	63.7	1.1
TS 1-4	4/26/1999	100	98	88	57	36	21	13	9	7	5.2	5.3	2.353	2.544	7.5	18.8	60.1	1.1
1	4/29/1999	100	99	87	53	33	20	14	10	8	5.5	5.4	2.399	2.553	6.0	17.2	65.1	1.1
2	4/29/1999	100	98	86	52	32	20	13	10	8	5.5	5.3	2.369	2.545	6.9	18.2	62.1	1.1
3	4/29/1999	100	97	87	54	34	21	14	10	8	5.7	5.5	2.382	2.537	6.1	17.9	65.9	1.1
TS 2-1	5/4/1999	100	99	90	57	35	21	14	10	7	5.2	5.5	2.412	2.564	5.9	16.9	65.1	1.1
TS 2-2	5/4/1999	100	98	87	52	33	20	14	10	7	5.4	5.3	2.404	2.556	5.9	17.0	65.3	1.1
TS 2-3	5/4/1999	100	98	88	54	34	21	14	10	8	5.5	5.6	2.376	2.530	6.1	18.2	66.5	1.0
1	5/4/1999	100	99	88	51	31	19	13	9	7	5.1	5.6	2.387	2.538	5.9	17.8	66.9	1.0
2	5/4/1999	100	99	89	53	32	19	13	10	7	5.5	5.7	2.390	2.516	5.0	17.8	71.9	1.0
3	5/4/1999	100	99	89	55	34	21	14	10	8	6.0	5.6	2.430	2.524	3.7	16.4	77.4	1.1
4	5/7/1999	100	99	89	57	36	22	15	10	8	5.8	5.6	2.425	2.516	3.6	16.5	78.2	1.1
5	5/7/1999	100	99	88	57	35	21	14	10	8	5.8	6.0	2.455	2.526	2.8	15.9	82.4	1.1
6	5/8/1999	100	98	85	51	31	19	12	9	7	5.0	5.5	2.403	2.539	5.4	17.3	68.8	1.0
7	5/8/1999	100	99	90	57	35	22	15	11	8	5.2	5.6	2.435	2.539	4.1	16.2	74.7	1.0
8	5/8/1999	100	98	85	50	32	20	13	10	8	5.5	5.4	2.403	2.530	5.0	17.1	70.8	1.1
9	5/8/1999	100	98	86	55	35	21	14	10	8	5.7	6.1	2.409	2.515	4.2	17.5	76.0	1.0
10	5/10/1999	100	99	86	51	33	21	14	10	8	5.7	5.4	2.431	2.521	3.6	16.2	77.8	1.1
11	5/10/1999	100	98	89	58	37	22	15	11	8	6.1	5.9	2.427	2.509	3.3	16.8	80.4	1.1
12	5/11/1999	100	99	90	58	37	23	16	12	9	6.6	5.7	2.444	2.516	2.9	16.0	81.9	1.2
13	5/11/1999	100	98	91	58	37	22	15	11	8	6.3	6.0	2.453	2.524	2.8	15.9	82.4	1.1
14	5/11/1999	100	99	88	53	33	21	15	11	8	5.9	5.3	2.434	2.529	3.8	16.0	76.3	1.1
15	5/11/1999	100	98	87	53	34	21	15	11	8	5.9	5.6	2.429	2.519	3.6	16.4	78.0	1.1
16	5/12/1999	100	98	86	53	34	21	14	10	8	5.5	5.8	2.431	2.516	3.4	16.5	79.4	1.0
17	5/12/1999	100	99	88	55	36	22	15	11	8	6.1	5.8	2.434	2.527	3.7	16.4	77.4	1.1
18	5/12/1999	100	97	84	50	32	21	14	11	8	5.9	5.8	2.451	2.503	4.0	15.8	74.7	1.2
19	5/13/1999	100	97	85	54	34	21	15	11	9	6.2	5.4	2.446	2.525	3.1	15.6	80.1	1.2
20	5/13/1999	100	97	84	50	32	20	13	10	7	5.5	5.6	2.422	2.533	4.4	16.7	73.7	1.1
21	5/14/1999	100	98	88	55	35	22	15	11	8	6.0	5.7	2.416	2.516	4.0	17.0	76.5	1.1
22	5/14/1999	100	98	87	54	35	22	15	11	8	6.0	5.7	2.430	2.522	3.6	16.4	78.0	1.1
23	5/14/1999	100	98	87	56	35	22	15	11	8	5.9	5.8	2.422	2.523	4.0	16.8	76.2	1.1
24	5/14/1999	100	98	87	54	35	22	15	11	8	6.1	5.9	2.451	2.522	2.8	15.9	82.4	1.1
25	5/18/1999	100	98	88	56	36	22	15	11	8	6.0	5.5	2.428	2.536	4.3	16.4	73.8	1.2
26	5/18/1999	100	98	87	55	35	22	15	11	8	5.9	5.5	2.445	2.545	3.9	15.7	75.2	1.2
27	5/18/1999	100	99	90	56	35	22	14	10	8	5.7	5.7	2.422	2.525	3.9	16.7	76.6	1.0
28	5/19/1999	100	98	88	55	35	21	14	10	8	5.8	5.9	2.443	2.508	2.6	16.2	84.0	1.0
29	5/19/1999	100	98	88	56	36	21	14	10	8	5.6	5.7	2.407	2.516	4.3	17.3	75.1	1.0
30	5/19/1999	100	98	88	56	36	22	14	10	7	5.5	5.6	2.456	2.513	2.3	15.6	85.3	1.0
31	5/19/1999	100	99	87	54	34	21	14	11	8	5.8	5.5	2.426	2.515	3.5	16.4	78.7	1.1
32	5/20/1999	100	99	85	52	32	20	14	10	8	5.3	5.4	2.426	2.520	3.7	16.3	77.3	1.1
33	5/20/1999	100	98	87	56	35	21	14	11	8	5.9	5.8	2.414	2.522	4.3	17.1	74.9	1.1
34	5/20/1999	100	98	88	55	35	22	15	10	8	5.8	5.8	2.414	2.517	4.1	17.1	76.0	1.0
35	5/21/1999	100	98	90	56	35	22	15	11	8	6.0	5.6						
36	5/21/1999	100	97	88	55	34	20	14	10	8	5.6	5.8						
37	5/21/1999	100	98	88	51	33	21	14	11	8	5.3	5.6						
	Average Gradation	*100*	*98.3*	*87.6*	*54.5*	*34.4*	*21.1*	*14.2*	*10.3*	*7.8*	*5.7*	*5.6*	*2.417*	*2.529*	*4.5*	*16.8*	*73.8*	*1.1*
	Standard Deviation	*0.00*	*0.65*	*1.65*	*2.44*	*1.80*	*1.06*	*0.92*	*0.73*	*0.54*	*0.37*	*0.22*	*0.027*	*0.016*	*1.46*	*0.84*	*7.29*	*0.06*

Table A4. Contract 5677 Superpave ½-inch Mix Field Results.

5677	Sieve Size (mm)	19.0	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075	AC	Gmb	Gmm	Va	VMA	VFA	D/A Ratio
	JMF	100	96	75	44	29	19	14	9	6	4.5	6.2	2.324	2.421	4.1	14.1	72	1.1
	Tolerance Limits	99 - 100	90 - 100	69 - 81	39 - 49	28 - 33					3.0 - 6.5	5.7 - 6.7			3.0 - 5.0	14.0 Min	65 - 75	0.6 - 1.6
Test #	Date																	
TS 1	7/26/2000	100	97	86	56	38	27	19	13	9	6.3	6.6	2.353	2.401	2.0	13.4	85.1	1.3
TS 2	7/26/2000	100	96	81	49	32	21	15	10	7	5.3	6.5	2.328	2.412	3.5	14.2	75.4	1.1
TS 3	7/26/2000	100	98	82	52	34	23	16	11	8	5.5	6.8	2.301	2.421	5.0	15.4	67.5	1.2
TS 4	7/26/2000	100	94	78	47	31	21	15	10	7	5.0	6.3	2.307	2.422	4.8	14.8	67.6	1.1
5	7/31/2000	100	96	77	44	29	19	13	9	6	4.4	5.7	2.283	2.424	5.8	15.1	61.6	1.0
6	7/31/2000	100	97	85	51	32	21	15	10	7	4.9	6.1	2.237	2.411	7.2	17.2	58.1	1.1
7	7/31/2000	100	97	80	48	31	21	14	10	7	4.7	5.7	2.258	2.424	6.8	16.0	57.5	1.1
8	7/31/2000	100	95	78	44	28	19	13	9	6	4.5	5.8	2.308	2.421	4.7	14.3	67.1	1.0
9	8/1/2000	100	95	83	51	34	23	16	11	8	5.2	6.5	2.304	2.399	4.0	15.1	73.5	1.0
10	8/1/2000	100	95	83	50	32	21	15	10	7	4.9	6.6	2.247	2.402	6.5	17.3	62.4	1.0
11	8/1/2000	100	97	80	47	30	20	14	9	6	4.4	6.3	2.307	2.408	4.2	14.8	71.6	0.9
12	8/1/2000	100	95	78	45	29	19	13	8	6	4.0	6.4	2.308	2.405	4.0	14.8	73.0	0.8
13	8/2/2000	100	94	78	44	28	19	14	9	6	4.5	6.0	2.298	2.419	5.0	14.9	66.4	1.0
14	8/2/2000	100	95	74	42	27	19	13	9	6	4.1	5.7	2.270	2.427	4.5	13.8	67.4	1.0
15	8/2/2000	100	94	78	45	29	20	13	9	6	4.2	5.9	2.293	2.427	5.5	14.9	63.1	1.0
16	8/2/2000	100	94	77	44	28	19	13	9	6	4.3	6.0	2.196	2.412	9.0	18.7	51.9	0.9
17	8/2/2000	100	97	81	50	31	20	14	9	6	4.5	6.6	2.301	2.389	3.7	15.3	75.8	0.9
18	8/3/2000	100	93	73	39	25	18	13	9	6	4.3	5.3	2.147	2.433	11.8	19.9	40.7	1.2
19	8/3/2000	100	97	81	47	31	22	15	11	8	5.5	6.4	2.212	2.408	8.1	18.4	56.0	1.2
20	8/3/2000	100	97	78	45	29	20	13	9	6	4.4	5.8	2.130	2.416	11.8	20.9	43.5	1.0
	REVISED JMF	100	96	77	46	29	19	14	9	6	4.5	6.4			4.1	14.4	71.1	0.8
	Tolerance Limits	99 - 100	90 - 100	71 - 83	41 - 51	28 - 33					3.0 - 6.5	5.9 - 6.9			3.0 - 5.0	14.0 Min	65 - 75	0.6 - 1.6
1	8/7/2000	100	95	80	45	28	19	13	9	7	4.5	6.4	2.309	2.393	3.5	14.8	76.4	0.9
2	8/7/2000	100	96	78	46	30	20	14	9	6	4.3	6.4	2.344	2.391	2.0	13.6	85.3	0.8
3	8/7/2000	100	96	82	49	31	21	14	10	7	4.4	6.7	2.337	2.376	1.6	14.0	88.6	0.8
4	8/7/2000	100	96	84	51	32	21	14	10	7	4.7	7.2	2.339	2.374	1.5	14.5	89.7	0.8
5	8/7/2000	100	95	79	44	27	18	12	8	6	3.8	6.4	2.304	2.392	3.7	15.0	75.3	0.7
6	8/8/2000	100	93	68	37	23	16	11	8	5	3.5	5.6	2.244	2.417	7.2	16.5	56.4	0.8
7	8/8/2000	100	94	79	46	29	19	13	9	6	4.3	6.3	2.302	2.401	4.1	15.0	72.7	0.9
8	8/8/2000	100	94	75	42	27	18	13	9	6	4.1	6.2	2.276	2.407	5.4	15.8	65.8	0.9
9	8/8/2000	100	96	81	48	31	21	15	10	7	4.5	6.4	2.331	2.401	2.9	14.0	79.3	0.9
10	8/8/2000	100	95	80	46	30	20	14	9	7	4.5	6.4	2.314	2.405	3.8	14.6	74.0	0.9
11	8/9/2000	100	94	74	41	26	17	12	8	6	5.8	6.0	2.266	2.413	6.1	16.0	61.9	0.8
12	8/9/2000	100	96	80	48	30	20	13	9	6	4.1	6.4	2.307	2.403	4.0	14.9	73.2	0.8
13	8/9/2000	100	96	80	45	28	19	13	9	6	4.3	6.4	2.293	2.400	4.5	15.4	70.8	0.9
14	8/9/2000	100	97	79	44	27	18	12	9	6	4.2	6.0	2.262	2.415	6.3	16.2	61.1	0.9
17	8/14/2000	100	98	80	45	29	20	14	9	7	4.6	6.6	2.312	2.401	3.7	14.9	75.2	0.9
18	8/14/2000	100	97	81	47	30	20	13	9	6	4.5	6.8	2.307	2.393	3.6	15.3	76.5	0.9
19	8/14/2000	100	97	81	49	30	19	13	9	6	4.2	7.0	2.302	2.393	3.8	15.6	75.6	0.8
20	8/14/2000	100	95	80	45	28	18	12	8	6	4.1	6.7	2.279	2.400	5.0	16.2	69.1	0.8
21	8/15/2000	100	93	79	45	28	19	13	9	6	4.3	6.4	2.293	2.407	4.7	15.4	69.5	0.9
22	8/15/2000	100	96	85	49	30	19	13	9	6	4.2	6.8	2.28	2.401	5.0	16.2	69.1	0.8
23	8/16/2000	100	97	83	50	32	21	14	10	7	4.7	6.8	2.317	2.394	3.2	14.9	78.5	0.9
24	8/16/2000	100	94	79	43	27	18	13	9	6	4.2	6.3	2.291	2.408	4.9	15.4	68.2	0.9
25	8/17/2000	100	96	83	51	32	21	15	10	7	4.8	6.9	2.335	2.392	2.4	14.3	83.2	0.9
26	8/17/2000	100	98	80	50	32	21	14	10	7	4.6	6.9	2.322	2.394	3.0	14.8	79.7	0.9
27	8/17/2000	100	96	79	45	28	18	12	8	6	4.1	6.3	2.286	2.414	5.3	15.6	66.0	0.9
28	8/22/2000	100	97	81	48	30	19	13	9	6	4.3	6.7	2.285	2.414	5.3	15.9	66.7	0.9
29	8/22/2000	100	97	84	47	30	19	13	9	6	4.4	6.6	2.213	2.398	7.7	18.5	58.4	0.9
	Average Gradation	100	95.7	79.7	46.5	29.6	19.8	13.6	9.3	6.5	4.5	6.4	2.286	2.406	4.9	15.6	69.2	0.9
	Standard Deviation	0.00	1.38	3.32	3.53	2.54	1.79	1.34	0.93	0.75	0.51	0.41	0.046	0.013	2.21	1.56	10.42	0.13

Table A5. Contract 5636 Superpave ¾-inch Mix Field Results

5636	**Sieve Size (mm)**	**25.0**	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.600**	**0.300**	**0.150**	**0.075**	**AC**	**Gmb**	**Gmm**	**Va**	**VMA**	**VFA**	**D/A Ratio**
G9261	**JMF**	*100*	*96*	*79*	*70*	*46*	*28*	*18*	*12*	*9*		*5.5*	*4.6*	*2.669*	*2.801*	*4.2*	*13.9*	*70*	*0.8*
	Tolerance Limits	*99 - 100*	*90 - 100*	*73 - 85*	*64 - 76*	*41 - 51*	*24 - 32*					*3.5 - 7.0*	*4.1 - 5.1*			*3.0 - 5.0*	*13.0 Min*	*65 - 78*	*0.6 - 1.6*
Test #	**Date**																		
TS 1-1	9/13/1999	100	98	90	85	53	29	17	12	9		5.9	5.0	2.546	2.791	8.8	18.7	52.9	1.5
TS 1-2	9/13/1999	100	97	86	78	45	25	15	11	8		5.0	4.4	2.556	2.810	9.0	17.8	49.4	1.5
TS 1-3	9/13/1999	100	97	86	80	48	27	16	11	8		5.4	4.7	2.546	2.779	8.4	18.4	54.3	1.3
TS 1-4	9/13/1999	100	97	83	73	42	27	15	10	8		5.1	4.3	2.557	2.754	7.2	17.8	59.6	1.2
TS 2-1	9/15/1999	99	94	82	73	47	27	16	11	8		5.6	4.7	2.667	2.787	4.3	14.5	70.3	1.4
TS 2-2	9/15/1999	100	98	82	75	47	27	16	11	8		5.1	4.6	2.575	2.797	7.9	17.4	54.6	1.4
TS 2-3	9/15/1999	100	93	82	74	45	26	16	11	8		5.2	4.6	2.573	2.783	7.5	17.4	56.9	1.3
TS 2-4	9/15/1999	100	96	83	74	45	26	16	11	8		5.1	4.7	2.584	2.781	7.1	17.2	58.7	1.3
3	9/17/1999	100	98	85	75	48	27	16	11	8		5.4	4.8	2.581	2.778	7.1	17.4	59.2	1.3
4	9/17/1999	100	99	83	76	46	25	16	10	7		4.9	5.0	2.526	2.778	9.1	20.1	54.7	1.2
5	9/17/1999	100	99	86	78	52	29	17	12	9		5.6	5.1	2.592	2.767	6.3	17.3	63.6	1.3
TS 3-1	9/20/1999	100	91	76	69	43	25	16	11	8		5.3	4.6	2.604	2.788	6.6	16.5	60.0	1.4
TS 3-2	9/20/1999	100	92	71	62	39	23	15	10	7		4.7	4.4	2.593	2.791	7.1	16.7	57.5	1.2
TS 3-3	9/20/1999	100	94	81	72	45	26	16	11	8		5.3	4.8	2.612	2.767	5.6	16.4	65.9	1.2
TS 3-4	9/20/1999	100	95	64	56	39	25	16	11	8		5.1	4.2	2.649	2.781	4.7	14.6	67.8	1.3
	REVISED JMF	*100*	*96*	*79*	*70*	*46*	*28*	*18*	*12*	*9*		*5.5*	*5.1*						
	Tolerance Limits	*99 - 100*	*90 - 100*	*73 - 85*	*64 - 76*	*41 - 51*	*24 - 32*					*3.5 - 7.0*	*4.6 - 5.6*						
7	9/22/1999	100	93	79	71	43	24	15	10	7		4.9	5.1	2.593	2.786	6.9	17.2	59.9	1.2
8	9/22/1999	100	95	81	73	46	26	16	11	8		5.1	5.1	2.569	2.754	6.7	18.0	62.8	1.1
9	9/23/1999	100	97	77	70	46	27	17	12	9		5.9	5.1	2.623	2.763	5.1	16.3	68.7	1.3
10	9/23/1999	100	100	85	76	54	32	20	14	10		6.7	5.7	2.633	2.745	4.1	16.5	75.2	1.4
11	9/23/1999	100	94	78	69	47	28	18	12	9		5.7	5.3	2.625	2.748	4.5	16.4	72.6	1.2
12	9/23/1999	100	97	84	69	56	33	20	14	10		6.3	5.7	2.647	2.739	3.4	16.1	78.9	1.3
	REVISED JMF	*100*	*96*	*79*	*70*	*46*	*28*	*18*	*12*	*9*		*5.5*	*6.1*						
	Tolerance Limits	*99 - 100*	*90 - 100*	*73 - 85*	*64 - 76*	*41 - 51*	*24 - 32*					*3.5 - 7.0*	*5.6 - 6.6*						
13	9/24/1999	100	97	82	73	51	30	19	13	9		6.0	6.1	2.720	2.640	2.9	16.6	82.5	1.1
14	9/24/1999	100	94	80	72	49	29	18	12	9		5.7	6.1	2.724	2.652	2.6	16.2	84.0	1.0
15	9/24/1999	100	98	76	68	50	31	19	13	10		6.2	6.1	2.704	2.676	1.0	15.5	93.5	1.1
16	9/24/1999	100	96	71	61	42	26	17	12	9		5.5	5.6	2.717	2.646	2.6	16.0	83.8	1.1
	REVISED JMF	*100*	*96*	*79*	*70*	*46*	*28*	*18*	*12*	*9*		*5.5*	*5.4*						
	Tolerance Limits	*99 - 100*	*90 - 100*	*73 - 85*	*64 - 76*	*41 - 51*	*24 - 32*					*3.5 - 7.0*	*4.9 - 5.9*						
17	9/27/1999	100	97	79	70	51	32	21	14	11		7.0	5.7	2.688	2.733	1.6	14.7	89.1	1.4
18	9/27/1999	100	97	80	73	54	33	21	14	10		6.5	5.8	2.674	2.752	2.8	15.3	81.7	1.4
19	9/27/1999	100	96	83	74	52	30	19	13	10		6.4	5.8	2.657	2.711	2.0	15.8	87.3	1.2
20	9/27/1999	100	98	86	78	55	32	20	14	10		6.6	6.0	2.650	2.738	3.2	16.2	80.2	1.3
21	9/28/1999	100	91	71	63	45	29	19	13	9		6.0	4.9	2.662	2.727	2.4	14.9	83.9	1.3
22	9/28/1999	100	96	86	77	54	32	20	14	10		6.5	5.6	2.658	2.764	3.8	15.6	84.7	1.4
23	9/29/1999	100	98	83	75	46	26	16	11	8		5.4	5.4	2.562	2.768	7.4	19.0	60.0	1.2
24	9/29/1999	100	94	71	61	38	23	15	10	7		4.8	4.9	2.629	2.742	4.2	16.0	73.8	1.0
25	9/29/1999	100	97	74	66	37	22	14	9	7		5.0	5.0	2.523	2.754	8.4	19.4	56.7	0.8
26	9/30/1999	100	97	86	76	43	24	15	10	8		5.0	5.3	2.570	2.757	6.8	18.2	62.6	1.0
27	9/30/1999	100	96	83	74	49	30	18	12	9		5.8	5.5	2.631	2.752	4.4	16.4	73.2	1.2
28	9/30/1999	100	96	79	72	47	27	17	12	9		5.6	5.2	2.628	2.748	4.6	16.4	72.0	1.2
29	9/30/1999	100	97	85	78	44	23	14	10	7		4.7	5.5	2.533	2.753	8.0	19.5	59.0	1.0

Table A6. Contract 5779 Superpave ¾-inch Mix Field Results

5779	Sieve Size (mm)	25.0	19.0	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075	AC	Gmb	Gmm	Va	VMA	VFA	D/A Ratio
	JMF	100	96	88	79	52	34	23	14	10	7	5.1	5.1	2.502	2.604	4	15.8	75.1	1.1
	Tolerance Limits	99 - 100	90 - 100	82 - 90	73 - 85	47 - 57	30 - 38					3.1 - 7.0	4.6 - 5.6			3.0 - 5.0	13.0 Min	65 - 75	0.6 - 1.6
Test #	Date																		
TS 1	4/11/2000	100	98	92	85	60	41	27	18	15	13	6.2	5.1	2.496	2.591	3.7	15.9	76.7	1.2
TS 2	4/11/2000	100	98	92	84	58	40	27	18	15	13	6.3	5.1	2.512	2.595	3.2	15.4	79.0	1.3
TS 3	4/11/2000	100	99	90	82	58	40	28	19	15	13	6.3	4.9	2.498	2.600	3.9	15.8	75.0	1.3
TS 4	4/11/2000	100	97	93	86	62	42	29	19	14	10	6.7	5.3	2.519	2.601	3.2	15.4	79.0	1.4
	REVISED JMF	100	98	88	82	59	40	27	19	15	12	5.5	5.1						
	Tolerance Limits	99 - 100	92 - 100	82 - 90	76 - 88	54 - 64	36- 44					3.5 - 7.0	4.6 - 5.6						
1	4/14/2000	100	99	91	85	57	38	26	17	12	8	5.8	5.7	2.508	2.595	3.4	16.1	78.9	1.1
Info	4/14/2000	100	96	83	75	48	32	22	15	11	8	5.0	4.9	2.509	2.611	3.9	15.3	74.5	1.1
2	4/14/2000	100	96	86	79	53	36	25	17	12	8	5.5	5.4	2.503	2.590	3.4	16.0	78.8	1.1
3	4/17/2000	100	99	91	82	56	37	25	17	12	8	5.7	5.6	2.504	2.609	4.0	16.1	75.2	1.2
4	4/17/2000	100	99	93	86	60	41	27	18	13	9	6.0	6.0	2.520	2.603	3.2	15.9	79.9	1.2
5	4/17/2000	100	99	95	88	63	43	29	19	13	9	6.2	5.7	2.493	2.608	4.4	16.5	73.3	1.2
6	4/18/2000	100	97	87	80	55	38	26	17	12	8	5.8	5.5	2.502	2.622	4.6	16.1	71.4	1.2
7	4/18/2000	100	98	84	76	52	36	24	16	13	8	5.7	5.2	2.515	2.610	3.6	15.3	76.5	1.2
8	4/18/2000	100	97	87	79	55	37	25	17	12	8	5.7	5.2		2.603	3.9	15.8	75.3	1.2
9	4/19/2000	100	98	92	86	60	40	26	17	12	9	6.1	5.3	2.490	2.608	4.5	16.2	72.2	1.3
10	4/19/2000	100	96	84	77	53	36	25	17	12	8	5.5	4.8	2.494	2.626	5.0	15.7	68.2	1.3
11	4/19/2000	100	99	90	83	58	39	26	18	12	9	6.0	5.3	2.499	2.616	4.5	16.0	71.9	1.3
12	4/19/2000	100	98	90	81	56	38	26	17	12	9	5.7	5.1	2.499	2.633	5.1	15.8	67.7	1.3
13	4/20/2000	100	98	88	81	57	38	26	17	12	8	5.7	5.3	2.480	2.626	5.6	16.7	66.5	1.2
14	4/20/2000	100	96	84	74	47	32	24	15	11	8	5.2	4.7	2.499	2.632	5.1	15.5	67.1	1.2
15	4/20/2000	100	92	84	77	53	35	24	16	11	8	5.5	5.0	2.508	2.624	4.4	15.4	71.4	1.2
16	4/21/2000	100	97	88	80	55	37	25	17	12	8	5.7	5.2	2.508	2.603	3.6	15.6	76.9	1.2
17	4/21/2000	100	98	86	77	50	33	22	15	10	8	5.2	4.9	2.495	2.649	5.8	15.8	63.3	1.3
18	4/24/2000	100	95	87	79	54	36	25	17	12	8	5.5	5.1	2.500	2.624	4.7	15.8	70.3	1.2
19	4/24/2000	100	97	87	77	51	34	26	16	11	8	5.2	5.0						
20	4/24/2000	100	92	85	76	53	36	24	16	11	8	5.3	5.2	2.494	2.631	5.2	16.1	67.7	1.2
21	4/25/2000	100	96	88	81	53	36	25	16	11	8	5.5	5.2						
22	4/25/2000	100	97	91	84	60	41	28	18	13	9	6.2	5.5	2.504	2.597	3.6	15.8	77.2	1.2
23	4/25/2000	100	96	86	78	54	37	25	17	11	8	5.4	5.1						
24	4/25/2000	100	99	93	85	59	40	27	18	13	9	6.0	5.1	2.508	2.595	3.4	15.6	78.2	1.2
25	4/26/2000	100	96	88	79	52	35	24	16	11	8	5.7	4.9						
26	4/26/2000	100	95	88	78	52	35	24	16	11	8	5.4	4.9						
27	4/27/2000	100	100	94	87	61	42	28	18	12	9	6.0	5.4						
28	4/27/2000	100	98	92	84	58	39	26	17	12	8	5.8	5.2						
29	4/27/2000	100	96	89	80	54	37	25	17	12	9	6.0	4.8						
30	4/27/2000	100	95	89	82	57	38	26	17	12	8	5.8	4.8	2.473	2.605	5.1	16.5	69.1	1.2
31	4/28/2000	100	95	86	78	52	36	25	16	11	8	5.6	4.8						
32	4/28/2000	100	99	91	82	55	38	27	18	13	9	6.4	5.0	2.498	2.607	4.2	15.8	73.4	1.3
33	5/1/2000	100	95	86	77	53	36	25	16	11	8	5.6	4.8						
34	5/1/2000	100	98	94	89	63	43	29	19	13	9	6.3	5.3	2.505	2.589	3.2	15.7	79.6	1.2
35	5/1/2000	100	98	90	82	55	37	26	17	12	8	5.9	5.0						
36	5/2/2000	100	94	86	77	53	36	25	17	12	8	5.9	4.7	2.513	2.603	3.5	15.0	76.7	1.2
37	5/2/2000	100	99	92	85	58	40	27	17	13	9	6.1	5.1						
38	5/2/2000													2.519	2.605	3.3	15.1	78.1	1.2
40	5/4/2000													2.527	2.607	3.1	14.7	78.9	1.3
41	5/4/2000	100	97	87	76	48	33	23	15	11	8	5.5	5.0						
42	5/5/2000	100	99	91	82	57	39	26	17	12	9	6.2	5.1	2.514	2.599	3.3	15.3	78.4	1.3
43	5/5/2000	100	98	88	82	59	41	27	18	13	9	6.5	5.0						
44	5/8/2000	100	100	93	86	59	40	27	18	13		6.6	5.2	2.531	2.579	1.9	14.9	87.2	1.3
45	5/8/2000	100	97	86	78	52	35	24	16	11	8	5.9	4.8						
46	5/8/2000	100	93	87	79	51	35	24	17	12	9	6.1	4.7	2.529	2.608	3.0	14.4	79.2	1.3
47	5/9/2000	100	99	91	83	55	37	26	17	12	9	6.3	5.0						
48	5/9/2000	100	95	86	78	54	37	25	16	11	8	5.9	5.0	2.537	2.600	2.4	14.4	83.3	1.2
49	5/9/2000	100	96	90	81	56	38	26	17	12	9	6.2	5.1	2.548	2.606	2.3	13.8	83.3	1.3
50	5/9/2000	100	94	86	79	57	40	27	17	12	9	6.2	4.9	2.524	2.588	2.5	14.8	83.1	1.2
51	5/10/2000	100	99	92	85	60	41	27	18	12	9	6.5	5.3						
52	5/10/2000	100	95	83	76	51	34	24	16	11	8	5.8	4.6	2.522	2.600	3.0	14.6	79.5	1.2
53	5/11/2000	100	97	88	79	53	36	25	17	12	9	6.3	5.0						
54	5/11/2000	100	97	83	72	45	32	23	15	11	8	5.6	4.3	2.525	2.637	4.2	14.2	70.4	1.4
55	5/12/2000	100	100	91	83	56	38	26	17	12	8	5.8	5.0						
56	5/12/2000	100	97	89	80	55	37	25	17	12	9	6.1	4.8	2.516	2.595	3.0	14.9	79.9	1.3
57	5/15/2000	100	96	85	78	53	36	25	16	11	8	5.6	4.7						
58	5/15/2000	100	98	92	86	62	42	28	18	13	9	6.1	5.0	2.461	2.571	4.3	17.0	74.7	1.1
59	5/15/2000	100	95	88	82	58	40	27	18	12	8	5.7	4.7						
60	5/15/2000	100	99	90	83	57	40	27	18	12	8	5.6	4.7	2.476	2.575	3.8	16.2	76.5	1.1
	Average Gradation	100	97.0	88.7	80.8	55.3	37.6	25.7	17.0	12.0	8.6	5.9	5.1	2.507	2.606	3.8	15.6	75.4	1.2
	Standard Deviation	0.00	1.89	3.12	3.74	3.90	2.75	1.57	1.02	1.02	1.13	0.37	0.30	0.017	0.017	0.90	0.69	5.19	0.07

Table A7. Contract 5848 Superpave ¾-inch Mix Field Results

5848	**Sieve Size (mm)**	**25.0**	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.600**	**0.300**	**0.150**	**0.075**	**AC**	**G_{mb}**	**G_{mm}**	**Va**	**VMA**	**VFA**	**D/A Ratio**
G9478	**JMF**	*100*	*97*	*84*	*75*	*46*	*32*	*21*	*15*	*11*	*8*	*5.5*	*4.5*	*2.485*	*2.583*				
	Tolerance Limits	*99 - 100*	*91 - 100*	*78 - 89*	*69 - 81*	*41 - 51*	*28 - 36*					*3.5 - 7.0*	*3.8 - 5.2*			*3 - 5*	*13 min.*	*65 - 75*	*0.6 - 1.6*
Test #	**Date**																		
TS 1	6/20/2000	100	93	82	72	49	34	23	17	13	10	6.4	5.0	2.517	2.580	2.4	12.8	81.3	1.5
TS 2	6/20/2000	100	96	84	75	54	38	25	19	14	10	7.2	4.9	2.501	2.560	2.3	13.3	82.7	1.6
TS 3	6/20/2000	100	96	87	80	56	38	25	18	13	9	6.2	4.7	2.478	2.508	1.2	13.9	91.4	1.2
TS 4	6/20/2000	100	98	90	82	57	38	25	19	14	10	7.1	4.8	2.502	2.566	2.5	13.2	81.1	1.6
1	6/20/2000	100	93	82	72	49	34	23	17	13	10	6.4	5.0	2.517	2.580	2.4	12.8	81.3	1.5
2	6/22/2000	100	96	86	76	53	36	24	17	13	9	6.3	4.8	2.454	2.557	4.0	14.8	73.3	1.4
3	6/22/2000	100	99	87	79	56	37	25	18	13	9	6.6	4.6	2.541	2.591	5.4	14.8	63.5	1.9
4	6/22/2000	100	93	84	73	50	34	23	16	12	9	5.9	4.4	2.483	2.584	3.9	13.5	71.1	1.5
5	6/22/2000	100	97	90	82	58	39	26	18	13	10	6.6	4.8	2.446	2.563	4.6	15.2	69.7	1.5
6	6/23/2000	100	97	85	74	52	35	23	17	13	9	6.0	5.1	2.462	2.578	4.5	14.5	69.0	1.4
7	6/23/2000	100	97	87	77	51	34	23	16	12	9	5.8	4.7	2.440	2.561	4.7	15.2	69.1	1.3
8	6/23/2000	100	99	91	80	54	36	23	16	12	8	4.8	4.9	2.406	2.585	6.9	16.6	58.4	1.2
9	6/23/2000	100	96	88	76	54	37	24	17	13	9	6.4	4.8	2.478	2.575	3.8	14.1	73.0	1.5
G9478A	**REVISED JMF**	*100*	*97*	*84*	*75*	*48*	*33*	*21*	*15*	*11*	*8*	*5.5*	*4.5*						
	Tolerance Limits	*99 - 100*	*91 - 100*	*78 - 89*	*69 - 81*	*43 - 53*	*29 - 37*					*3.5 - 7.0*	*3.8 - 5.2*			*3 - 5*	*13 min.*	*65 - 75*	*0.6 - 1.6*
10	6/26/2000	100	98	84	74	51	35	22	16	12	8	5.5	4.7	2.478	2.584	4.1	13.9	70.5	1.4
11	6/26/2000	100	97	84	76	52	36	23	16	12	8	5.4	4.5	2.464	2.586	4.7	14.2	66.9	1.4
12	6/26/2000	100	97	87	74	50	34	22	16	12	8	5.4	4.5	2.435	2.578	5.5	15.2	63.8	1.2
13	6/27/2000	100	98	88	77	52	35	23	16	12	9	5.8	4.7	2.471	2.564	3.6	14.1	74.5	1.3
14*	6/27/2000	100	97	86	75	53	37	24	17	13	9	5.9	4.6	2.471	2.582	4.3	14.3	69.9	1.4
15	6/27/2000	100	98	87	77	52	35	23	16	12	9	5.7	4.7	2.467	2.594	4.9	14.3	65.7	1.5
16*	6/27/2000	100	96	82	73	48	33	22	15	11	8	5.4	4.3	2.462	2.569	4.1	14.1	70.9	1.2
17	6/27/2000	100	96	86	74	52	35	24	17	13	9	5.9	4.7	2.482	2.584	3.9	13.7	71.5	1.5
18	6/28/2000	100	98	86	75	50	34	23	17	12	9	5.9	4.3	2.475	2.570	3.7	13.7	73.0	1.4
19*	6/28/2000	100	95	84	74	51	35	23	16	12	8	5.6	4.5	2.483	2.570	3.4	13.2	74.2	1.5
20	6/28/2000	100	98	87	77	51	34	23	16	12	9	5.9	4.8	2.425	2.573	5.8	15.9	63.5	1.4
21	6/29/2000	100	94	85	74	49	33	22	16	12	8	5.6	4.6	2.475	2.574	3.8	13.9	72.7	1.3
22	6/29/2000	100	95	81	71	47	31	21	15	11	8	5.4	4.3	2.482	2.579	3.8	13.4	71.6	1.4
23	6/29/2000	100	99	88	78	53	36	24	17	13	9	6.1	5.1	2.474	2.579	4.1	14.4	71.5	1.4
24	6/29/2000	100	97	84	74	51	34	23	16	12	9	5.9	4.5	2.494	2.568	2.9	13.2	78.0	1.4
25	6/30/2000	100	96	88	79	53	36	23	17	13	9	6.0	4.7	2.485	2.574	3.5	13.7	74.5	1.4
26	6/30/2000	100	96	86	74	50	34	23	17	13	9	6.1	4.5	2.489	2.575	3.3	13.3	75.2	1.5
27	6/30/2000	100	97	87	77	52	35	23	16	12	9	6.1	4.7	2.512	2.574	2.4	12.7	88.1	1.5
28	7/5/2000	100	96	85	74	50	33	22	15	11	8	5.6	4.6	2.483	2.596	4.4	13.7	67.9	1.5
29	7/5/2000	100	98	86	77	53	37	24	17	13	9	6.1	4.6	2.497	2.586	3.4	13.1	74.0	1.5
30	7/5/2000	100	95	86	76	52	35	23	16	12	8	5.7	4.7	2.488	2.580	3.6	13.6	73.5	1.4
31	7/5/2000	100	99	85	75	50	34	22	16	12	8	5.8	4.6	2.485	2.583	3.8	13.6	72.1	1.8
32	7/7/2000	100	98	88	79	53	36	23	17	12	9	6.0	5.0	2.479	2.577	3.8	14.1	73.0	1.4
33	7/7/2000	100	97	87	78	53	35	23	17	12	9	6.1	4.7	2.485	2.577	3.6	13.7	73.7	1.5
34	7/7/2000	100	98	87	76	53	36	24	17	13	9	6.2	5.1	2.502	2.572	2.7	13.4	79.9	1.4
35	7/7/2000	100	96	84	74	51	34	23	16	12	9	6.0	4.5	2.503	2.588	3.3	12.9	74.4	1.5
36	7/7/2000	100	96	86	75	50	33	22	16	12	8	5.7	4.5	2.483	2.580	3.8	13.6	72.1	1.4
37	7/10/2000	100	97	86	74	50	33	21	15	13	8	5.8	4.4	2.484	2.563	3.1	13.4	76.9	1.4
38	7/10/2000	100	96	85	75	49	32	22	15	12	8	5.7	4.5	2.481	2.577	3.7	13.6	72.8	1.4
Average Revised Gradation		*100*	*96.8*	*85.7*	*75.4*	*51.1*	*34.5*	*22.8*	*16.2*	*12.2*	*8.6*	*5.8*	*4.6*	*2.479*	*2.578*	*3.8*	*13.8*	*72.6*	*1.4*
	Standard Deviation	*0.00*	*1.26*	*1.73*	*1.88*	*1.62*	*1.43*	*0.83*	*0.71*	*0.60*	*0.51*	*0.24*	*0.20*	*0.018*	*0.008*	*0.74*	*0.65*	*4.80*	*0.11*

Table A8. Contract 5882 Superpave ½-inch SMA Mix Field Results

5882	**Sieve Size (mm)**	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**0.300**	**0.075**	**AC**	**Gmb**	**Gmm**	**Va**	**VMA**	**VFA**	**D/A Ratio**
	JMF	*100*	*96*	*70*	*27*	*20*	*14*	*11.1*	*6.4*	*2.484*	*2.594*	*4.3*	*17.8*		
	Tolerance Limits	*99 - 100*	*90 - 100*	*64 - 75*	*23 - 28*	*16 - 24*	*10 - 18*	*9.1 - 12.0*	*5.9 - 6.9*			*3.5 - 4.5*	*17.0 - 18.0*		
Test #	**Date**														
TS 1-1	8/16/2000	100	98	78	33	24	14	9.6	6.5	2.555	2.605	1.9	15.4	87.7	1.8
TS 1-2	8/16/2000	100	98	74	30	21	13	8.9	6.3	2.562	2.589	1.0	15.0	93.3	1.6
TS 1-3	8/16/2000	100	99	77	31	22	13	8.9	6.8	2.528	2.570	1.6	16.6	90.4	1.5
TS 1-4	8/16/2000	100	97	76	31	22	14	9.9	6.5	2.581	2.579	0.0	14.7	100.0	1.7
TS 2-1	8/19/2000	100	96	75	28	20	13	10.0	6.1	2.491	2.603	4.3	17.2	75.0	1.9
TS 2-2	8/19/2000	100	97	73	26	18	12	8.9	6.2	2.489	2.609	4.6	17.4	73.7	1.7
TS 2-3	8/19/2000	100	98	76	28	20	13	10.3	6.1	2.516	2.608	3.5	16.4	78.7	2.0
TS 2-4	8/19/2000	100	97	74	27	19	12	8.7	6.4	2.493	2.617	4.7	17.4	73.0	1.7
1	8/21/2000	100	98	72	26	19	12	9.8	6.3	2.514	2.587	2.8	16.6	83.1	1.8
2	8/21/2000	100	96	72	26	19	13	10.0	6.3	2.509	2.584	2.9	16.8	82.7	1.8
3	8/22/2000	100	95	69	26	19	12	9.8	6.5	2.528	2.590	2.4	16.4	85.4	1.7
	REVISED JMF	*100*	*96*	*70*	*27*	*20*	*14*	*11.1*	*6.1*						
	Tolerance Limits	*99 - 100*	*90 - 100*	*64 - 75*	*23 - 28*	*16 - 24*	*10 - 18*	*9.1 - 12.0*	*5.6 - 6.6*						
1	8/22/2000	100	96	72	24	16	10	8.2	6.1	2.447	2.606	6.1	18.7	67.4	1.5
2	8/22/2000	100	97	70	25	18	13	9.2	6.2	2.485	2.588	4.0	17.5	77.1	1.6
3	8/23/2000	100	95	70	26	19	13	10.2	6.1	2.528	2.609	3.1	16.0	80.6	2.0
4	8/23/2000	100	94	60	21	15	10	7.4	6.1	2.470	2.591	4.7	18.0	73.9	1.3
5	8/24/2000	100	97	68	25	18	12	9.9	5.9	2.509	2.584	2.9	16.5	82.4	1.8
6	8/24/2000	100	95	66	25	18	13	10.3	6.0	2.537	2.593	2.2	15.6	85.9	1.9
7	8/25/2000	100	93	65	27	19	12	9.5	6.2	2.553	2.591	1.5	15.2	90.1	1.7
	Average Gradation	100	96.4	71.5	26.9	19.2	12.4	9.4	6.3	2.516	2.595	3.0	16.5	82.2	1.7
	Standard Deviation	0.00	1.58	4.66	2.88	2.13	1.10	0.79	0.22	0.034	0.013	1.54	1.08	8.27	0.18

Table A9. Contract 6020 Superpave ½-inch Mix Field Results

6020	Sieve Size (mm)	19.0	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075	AC	Gmb	Gmm	Va	VMA	VFA	D/A Ratio
	JMF	*100*	*93*	*84*	*59*	*39*	*24*	*16*	*11*	*8*	*6.0*	*7.4*	*2.216*	*2.318*	*4.4*	*15.9*	*73*	*1.1*
	Tolerance Limits	*99 - 100*	*90 - 100*	*78 - 90*	*54 - 64*	*34 - 43*					*4.0 - 7.0*	*6.9 - 7.9*			*3.0 - 6.0*	*14.9 Min*	*65 - 75*	*0.6 - 1.6*
Test #	**Date**																	
TS 1	8/7/2001	100	95	89	65	38	24	16	12	9	5.9	7.1	2.215	2.321	4.5	15.7	71	1.1
TS 2	8/7/2001	100	96	90	66	39	24	16	12	8	5.6	7.1	2.225	2.312	3.8	15.4	75	1.0
TS 3	8/7/2001	100	93	85	60	35	22	15	11	8	5.3	6.9	2.223	2.300	3.3	15.2	78	1.0
TS 4	8/7/2001	100	96	90	64	38	33	16	12	8	5.8	7.0	2.215	2.317	4.4	15.6	72	1.1
5	8/14/2001	100	96	89	65	39	24	17	12	9	5.8	7.0	2.217	2.294	3.4	15.6	78	1.0
6	8/14/2001	100	96	89	65	39	25	17	13	10	7.0	6.8	2.226	2.319	4.0	15.0	73	1.4
	REVISED JMF	*100*	*93*	*87*	*62*	*39*	*24*	*16*	*11*	*8*	*6.0*	*7.4*						
	Tolerance Limits	*99 - 100*	*90 - 100*	*81 - 90*	*57 - 67*	*34 - 43*					*4.0 - 7.0*	*6.9 - 7.9*						
7	8/15/2001	100	95	87	63	38	24	17	12	9	6.7	6.9	2.220	2.310	3.9	15.4	75	1.2
8	8/15/2001	100	95	90	68	41	25	18	12	9	6.1	7.0	2.211	2.319	4.7	15.8	70	1.2
9	8/15/2001	100	96	90	67	39	24	17	12	9	6.5	6.9	2.203	2.307	4.5	16.0	72	1.2
10	8/17/2001	100	96	91	68	40	26	18	13	10	7.4	7.1	2.229	2.322	3.5	14.7	76	1.4
11	8/17/2001	100	96	90	66	39	25	18	13	10	7.2	6.9	2.221	2.310	4.3	15.7	73	1.4
	REVISED JMF	*100*	*93*	*87*	*62*	*39*	*24*	*16*	*11*	*8*	*6.0*	*7.2*						
	Tolerance Limits	*99 - 100*	*90 - 100*	*81 - 90*	*57 - 67*	*34 - 43*					*4.0 - 7.0*	*6.7 - 7.7*						
12	8/20/2001	100	95	84	59	35	23	16	12	9	6.5	6.4	2.208	2.332	5.5	15.5	65	1.4
13	8/20/2001	100	97	89	64	39	24	17	12	9	6.5	6.9	2.202	2.313	4.8	16.0	70	1.2
14	8/20/2001	100	94	86	61	37	23	16	12	9	6.5	6.8	2.231	2.317	3.7	14.8	75	1.3
15	8/21/2001	100	97	89	64	38	25	17	12	9	6.8	6.9	2.229	2.339	4.7	14.9	69	1.4
16	8/27/2001	100	96	87	60	37	23	16	12	9	6.3	7.0	2.252	2.314	2.7	14.2	81	1.2
17	8/27/2001	100	93	85	60	37	23	16	11	8	5.6	7.1	2.234	2.308	3.2	14.9	79	1.0
18	8/28/2001	100	93	85	62	37	23	16	11	8	6.0	7.0	2.231	2.311	3.5	14.9	77	1.1
19	8/28/2001	100	95	84	58	35	23	16	12	9	6.3	6.7	2.223	2.325	4.4	15.0	71	1.3
20	8/29/2001	100	95	89	63	38	23	16	11	8	6.0	6.9	2.205	2.334	5.5	15.9	65	1.2
21	8/29/2001	100	94	87	62	37	23	16	11	8	5.7	7.1	2.233	2.314	3.5	15.0	77	1.1
22	8/29/2001	100	96	89	63	36	22	16	11	9	6.3	6.8	2.195	2.328	5.7	16.2	65	1.3
23	8/30/2001	100	95	87	61	36	23	16	11	8	5.7	6.9	2.246	2.319	3.1	14.3	78	1.1
24	9/4/2001	100	95	87	59	36	23	16	12	8	5.8	6.9	2.224	2.316	4.0	15.2	74	1.1
25	9/4/2001	100	94	85	62	38	24	17	12	9	6.1	6.9	2.224	2.314	3.9	15.2	74	1.2
26	9/5/2001	100	96	87	62	39	25	17	13	9	6.7	7.1	2.196	2.293	4.2	16.4	74	1.2
27	9/5/2001	100	95	86	61	37	24	17	12	9	6.5	6.8	2.206	2.319	4.9	15.8	69	1.3
28	9/5/2001	100	97	88	63	38	24	16	12	9	6.2	6.8	2.223	2.312	3.9	15.2	75	1.2
29	9/6/2001	100	95	86	61	37	24	17	12	9	6.3	6.7	2.219	2.320	4.3	15.2	72	1.2
30	9/6/2001	100	98	91	64	39	24	17	12	9	6.5	7.0	2.216	2.313	4.2	15.6	73	1.2
31	9/6/2001	100	97	87	62	38	23	16	12	8	5.8	7.0	2.195	2.303	4.7	16.3	71	1.1
32	9/7/2001	100	98	87	61	36	23	16	12	9	6.1	6.7	2.189	2.321	5.7	16.3	65	1.2
33	9/7/2001	100	96	88	64	38	24	16	12	8	5.7	7.0	2.217	2.315	4.2	15.5	73	1.1
34	9/10/2001	100	96	89	62	36	22	15	11	8	5.2	6.9	2.182	2.303	5.2	16.7	69	0.9
35	9/10/2001	100	96	89	62	38	24	16	11	8	5.6	6.9	2.188	2.307	5.2	16.5	69	1.0
36	9/10/2001										6.0	7.1	2.186	2.295	4.8	16.8	72	1.0
37	9/12/2001	100	95	89	64	40	25	17	12	9	5.8	7.1	2.217	2.308	4.0	15.7	75	1.1
38	9/12/2001	100	96	89	65	40	25	17	12	8	5.6	7.3	2.207	2.299	4.0	16.2	75	1.0
39	9/12/2001	100	95	88	61	37	23	16	11	8	5.6	6.8	2.201	2.317	5.0	16.0	69	1.1
40	9/13/2001	100	95	89	63	38	24	16	12	8	5.9	7.0	2.192	2.311	5.1	16.5	69	1.1
41	9/13/2001	100	97	89	65	40	25	17	12	9	5.7	7.0	2.206	2.306	4.3	16.0	73	1.0
42	9/13/2001	100	96	89	63	39	24	17	12	9	6.0	7.2	2.218	2.303	3.7	15.6	77	1.1
43	9/13/2001	100	94	84	57	36	24	18	13	10	6.8	6.9	2.279	2.319	1.7	13.1	70	1.3
44	9/18/2001	100	93	84	61	38	24	16	12	9	5.9	6.9	2.225	2.311	3.7	15.1	76	1.1
45	9/18/2001	100	95	86	62	39	25	17	12	9	6.0	7.1	2.203	2.312	4.6	16.1	71	1.1
46	9/18/2001	100	92	84	63	40	25	17	12	8	5.7	7.2	2.218	2.300	3.6	15.7	77	1.0
47	9/19/2001	100	96	90	67	42	26	18	12	9	6.1	7.1	2.200	2.300	4.3	16.3	73	1.1
48	9/19/2001	100	94	86	64	40	25	17	12	9	6.1	6.9	2.212	2.304	4.0	15.6	75	1.1
49	9/19/2001	100	94	88	65	40	25	17	12	9	5.9	7.2	2.206	2.300	4.1	16.1	75	1.0
50	9/20/2001	100	97	91	66	41	26	17	12	9	6.5	7.2	2.206	2.307	4.4	16.2	73	1.2
51	9/20/2001	100	95	88	59	36	23	16	11	8	5.4	6.9	2.212	2.316	4.5	15.6	71	1.0
52	9/21/2001	100	96	86	65	42	26	18	13	9	6.4	7.0	2.227	2.309	3.5	15.2	77	1.2
53	9/21/2001	100	95	87	63	39	25	17	12	9	6.1	6.9	2.219	2.312	4.0	15.4	74	1.1
54	9/22/2001	100	92	84	63	40	25	17	12	9	6.3	7.0	2.239	2.311	3.1	14.7	79	1.2
55	9/22/2001	100	96	85	62	38	24	17	12	9	5.9	6.9	2.225	2.310	3.7	15.2	76	1.1
56	9/24/2001	100	93	83	62	39	25	17	12	8	5.6	6.9	2.258	2.306	2.1	13.9	85	1.0
57	9/24/2001	100	96	86	65	42	27	18	13	10	6.5	7.2	2.258	2.304	2.0	14.2	86	1.2
	Average Gradation	100	95.3	87.4	62.9	38.3	24.3	16.6	11.9	8.7	6.1	7.0	2.217	2.312	4.1	15.5	73.5	1.1
	Standard Deviation	*0.00*	*1.36*	*2.13*	*2.42*	*1.75*	*1.61*	*0.75*	*0.57*	*0.60*	*0.46*	*0.16*	*0.019*	*0.009*	*0.84*	*0.72*	*4.35*	*0.12*

Table A10. Contract 6104 Superpave ¾-inch Mix Field Results

6104	**Sieve Size (mm)**	**25.0**	**19.0**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.600**	**0.300**	**0.150**	**0.075**	**AC**	**Gmb**	**Gmm**	**Va**	**VMA**	**VFA**	**D/A Ratio**
	JMF	*100*	*98*	*81*	*63*	*39*	*27*	*19*	*14*	*9*	*6*	*4.5*	*4.8*	*2.422*	*2.533*	*4.4*	*13.5*	*68*	*1.1*
	Tolerance Limits	*99 - 100*	*92 - 100*	*75 - 87*	*57 - 69*	*34 - 44*	*23 - 31*					*3.0 - 6.5*	*4.3 - 5.3*			*3.0 - 6.0*	*12.5 Min*	*65 - 75*	*0.6 - 1.6*
Test #	**Date**																		
NWR																			
TS 1-1	8/2/2001	100	98	83	67	45	32	23	17	12	9	6.2	4.9	2.478	2.519	1.6	11.6	85	1.5
TS 1-2	8/2/2001	100	99	83	66	45	32	23	17	12	9	6.2	5.0	2.479	2.534	2.2	11.7	81	1.6
TS 1-3	8/3/2001	100	96	81	62	40	28	20	15	11	8	5.6	4.6	2.478	2.527	1.9	11.3	83	1.4
TS 1-4	8/3/2001	100	98	81	65	42	29	21	16	11	8	5.9	4.8	2.467	2.534	2.6	11.9	78	1.5
TS 2-1	8/7/2001	100	98	83	63	39	27	20	14	10	7	4.9	4.9	2.452	2.523	2.8	12.6	78	1.2
TS 2-2	8/7/2001	100	99	84	69	45	30	21	16	11	8	5.4	5.0	2.453	2.525	2.9	12.6	77	1.3
TS 2-3	8/7/2001	100	96	82	63	39	27	20	15	11	8	5.6	4.6	2.459	2.527	2.7	12.0	78	1.4
TS 2-4	8/7/2001	100	100	83	64	40	27	19	14	10	8	5.2	4.7	2.421	2.538	4.6	13.5	66	1.4
TS 3-1	8/9/2001	100	99	84	67	43	29	20	15	11	8	5.3	4.8	2.428	2.523	3.8	13.3	72	1.3
TS 3-2	8/9/2001	100	99	84	71	47	32	22	16	12	8	5.8	5.1	2.450	2.523	2.9	12.8	77	1.4
TS 3-3	8/10/2001	100	100	90	75	49	32	23	16	12	8	5.6	5.1	2.441	2.518	3.0	13.1	77	1.3
TS 3-4	8/10/2001	100	98	78	60	38	26	19	14	10	7	4.9	4.6	2.418	2.518	4.0	13.5	70	1.2
Lakeside																			
TS 3-1	8/9/2001	100	99	84	65	42	28	20	14	10	7	4.9	4.8	2.399	2.518	4.7	14.4	67	1.2
TS 3-2	8/9/2001	100	97	80	61	38	27	19	14	10	7	5.3	4.5	2.410	2.533	4.9	13.8	65	1.4
TS 3-3	8/10/2001	100	100	84	66	42	29	20	15	10	7	4.9	4.8	2.409	2.528	4.7	14.0	66	1.2
TS 3-4	8/10/2001	100	97	85	68	44	29	20	15	10	7	4.9	4.9	2.396	2.504	4.3	14.6	71	1.1
Mats Lab																			
TS 3-1	8/9/2001	100	97	82	67	42	29	20	14	10	7	5.0	4.8	2.409	2.533	4.9	14.2	66	1.1
TS 3-2	8/9/2001	100	99	75	56	35	25	19	14	10	7	4.8	4.4	2.432	2.535	4.1	13.0	69	1.1
TS 3-3	8/10/2001	100	100	82	64	42	28	20	15	11	8	5.1	4.9	2.413	2.523	4.4	14.2	69	1.1
TS 3-4	8/10/2001	100	98	79	63	40	27	19	14	10	7	4.6	4.6	2.410	2.526	4.6	14.0	67	1.0
NWR																			
1	8/13/2001	100	100	88	72	45	30	21	15	10	7	5.2	5.1	2.438	2.537	3.9	13.2	71	1.3
2	8/13/2001	99	98	85	68	42	29	20	15	10	7	5.0	4.9	2.413	2.527	4.5	14.0	68	1.2
Lakeside																			
1	8/13/2001	100	99	84	65	42	28	20	14	10	7	4.9	4.8	2.399	2.517	4.7	14.4	67	1.2
2	8/13/2001	100	99	84	67	43	29	20	15	11	8	5.3	4.8	2.396	2.510	4.5	14.5	69	1.1
Mats Lab																			
1	8/13/2001	100	100	88	69	43	29	20	14	10		4.9	5.0	2.418	2.528	4.3	13.8	69	
2	8/13/2001	100	97	78	59	38	27	19	14	10		4.7	4.4	2.396	2.528	5.2	14.1	63	
NWR																			
3	8/14/2001	100	98	79	62	41	28	20	14	10	7	4.8	4.6	2.426	2.525	3.9	13.2	70	1.2
Lakeside																			
3	8/14/2001	100	97	80	61	38	27	19	14	10	7	5.3	4.9	2.405	2.524	4.7	14.2	67	1.1
Mats Lab																			
3	8/14/2001	100	99	87	71	45	31	21	15	11		4.9	5.1	2.409	2.531	5.1	14.5	65	
NWR																			
4	8/15/2001	100	98	80	60	38	26	18	13	9	7	4.7	4.5	2.406	2.539	5.2	13.8	62	1.3
5	8/15/2001	100	97	80	66	40	28	19	14	10	7	4.8	4.6	2.419	2.525	4.2	13.5	69	1.2
Lakeside																			
4	8/15/2001	100	96	80	61	39	27	19	14	9	7	4.7	4.6	2.401	2.523	4.9	14.2	66	1.2
5	8/15/2001	100	98	85	65	41	28	19	14	10	7	4.6	4.7	2.392	2.522	5.2	14.6	64	1.1
Mats Lab																			
4	8/15/2001	100	97	82	64	40	27	19	14	10	7	4.9	4.8	2.413	2.531	4.7	13.9	66	
5	8/15/2001	100	97	82	64	43	30	20	15	10	7	5.0	4.7	2.384	2.528	5.7	14.8	62	
NWR																			
6	8/16/2001	100	98	87	69	44	30	20	14	10	7	5.2	4.7	2.424	2.527	4.1	13.7	70	1.3
7	8/16/2001	100	97	80	61	38	26	17	12	9	6	4.3	4.7	2.403	2.529	5.0	14.2	65	1.1
Lakeside																			
6	8/16/2001	100	96	81	62	41	28	19	13	9	7	4.7	4.8	2.396	2.511	4.6	14.5	68	1.1
7	8/16/2001	100	99	82	63	40	27	18	13	9	6	4.5	4.7	2.389	2.515	5.0	14.6	66	1.1
Mats Lab																			
6	8/16/2001	100	98	87	71	44	30	20	15	11	8	5.5	5.2	2.392	2.525	5.3	15.0	65	1.3
7	8/16/2001	100	97	83	64	40	27	18	13	9	7	4.9	5.0	2.386	2.528	5.6	15.0	63	1.2
NWR																			
8	8/20/2001	100	97	78	58	36	25	18	13	9	6	3.9	4.5	2.410	2.512	4.1	13.7	70	1.0
Mats Lab																			
8	8/20/2001	100	99	86	72	47	32	21	15	10	7	5.0	5.2	2.400	2.532	5.2	14.7	65	1.2
Average Gradation (NWR)		*100*	*98.2*	*82.7*	*65.4*	*41.8*	*28.7*	*20.2*	*14.8*	*10.5*	*7.5*	*5.2*	*4.8*	*2.438*	*2.527*	*3.5*	*13.0*	*73.3*	*1.3*
Standard Deviation (NWR)		*0.21*	*1.17*	*3.35*	*4.75*	*3.72*	*2.38*	*1.68*	*1.37*	*1.05*	*0.90*	*0.68*	*0.21*	*0.025*	*0.008*	*0.99*	*0.85*	*6.04*	*0.18*

Table A11. Contract 6151 Superpave ¾-inch Mix Field Results

6151	Sieve Size (mm)	19.0	12.5	9.5	4.75	2.36	1.18	0.600	0.300	0.150	0.075	AC	Gmb	Gmm	Va	VMA	VFA	D/A Ratio
	JMF	*100*	*96*	*82*	*51*	*32*	*19*	*13*	*9*	*7*	*5.2*	*5.6*	*2.465*	*2.577*	*4.4*	*14.5*	*70*	*1.2*
	Tolerance Limits	*99 - 100*	*90 - 100*	*76 - 88*	*46 - 56*	*28 - 36*					*3.2 - 7.0*	*5.1 - 6.1*			*3.0 - 6.0*	*14.0 Min*	*65 - 75*	*0.6 - 1.6*
Test #	Date																	
TS 1	9/12/2001	100	98	87	53	33	21	15	10	8	5.7	5.6	2.453	2.554	4.0	15.0	73.3	1.2
TS 2	9/12/2001	100	98	83	53	34	23	16	11	8	5.8	5.4	2.456	2.566	4.3	14.7	70.7	1.3
TS 3	9/12/2001	100	96	83	51	32	21	15	10	8	5.8	5.4	2.458	2.565	4.2	14.6	71.2	1.3
TS 4	9/12/2001	100	98	86	51	35	23	16	11	8	5.9	5.8	2.459	2.579	4.6	14.9	69.1	1.4
1	9/14/2001	100	98	87	53	34	22	15	11	8	5.9	5.7	2.462	2.574	4.4	14.8	70.0	1.4
2	9/14/2001	100	96	84	54	33	21	14	10	7	5.1	5.6	2.450	2.524	3.0	15.0	80.0	1.0
3	9/14/2001	100	98	85	55	36	23	16	11	8	5.7	5.6	2.468	2.554	3.4	14.5	77.0	1.2
4	9/14/2001	100	97	86	57	36	23	16	11	8	5.8	5.9	2.473	2.560	3.4	14.5	77.0	1.2
5	9/15/2001	100	98	86	56	34	21	14	10	7	5.5	5.7	2.445	2.540	3.7	15.3	76.0	1.1
6	9/15/2001	100	98	83	55	35	23	16	11	8	5.8	5.7	2.470	2.566	3.7	14.4	74.0	1.3
7	9/15/2001	100	96	80	51	31	20	14	10	7	5.2	5.5	2.444	2.562	4.6	15.2	70.0	1.2
8	9/17/2001	100	94	83	53	32	20	13	9	6	4.4	5.5	2.410	2.566	6.1	16.0	62.0	1.0
9	9/17/2001	100	98	87	55	35	23	16	11	8	6.1	5.6	2.485	2.575	3.5	14.0	75.0	1.4
10	9/18/2001	100	96	82	51	32	21	14	10	7	5.4	5.6	2.435	2.578	5.5	15.5	65.0	1.3
11	9/18/2001	100	98	82	52	33	22	15	10	8	5.7	5.8	2.461	2.563	4.0	14.9	73.0	1.2
12	9/18/2001	100	99	87	53	31	20	14	10	7	5.2	6.0	2.436	2.567	5.1	15.9	68.0	1.1
13	9/18/2001	100	97	85	54	34	22	15	10	7	5.5	6.0	2.466	2.534	2.7	14.9	82.0	1.1
14	9/19/2001	100	98	86	57	36	23	16	11	8	6.1	5.8	2.472	2.579	4.1	14.4	72.0	1.4
15	9/19/2001	100	96	83	52	33	21	15	10	7	5.5	5.7	2.452	2.573	4.7	15.1	69.0	1.3
16	9/19/2001	100	97	83	51	31	2	14	9	7	5.0	5.6	2.437	2.579	5.5	15.5	65.0	1.2
17	9/19/2001	100	98	85	53	33	21	14	10	7	5.4	5.8	2.451	2.574	4.8	15.2	68.0	1.2
18	9/20/2001	100	98	88	58	36	24	16	11	8	5.7	5.9	2.459	2.583	4.8	15.0	68.0	1.3
19	9/20/2001	100	97	85	53	33	22	15	10	8	5.6	5.7	2.461	2.555	3.7	14.8	75.0	1.2
20	9/20/2001	100	96	86	56	35	23	15	11	8	5.7	5.9	2.458	2.579	4.7	15.1	69.0	1.3
21	9/20/2001	100	96	82	53	33	22	15	10	7	5.4	5.6	2.455	2.575	4.7	14.9	69.0	1.3
22	9/21/2001	100	98	86	50	31	20	14	10	7	5.5	5.7	2.440	2.572	5.1	15.5	67.0	1.3
23	9/21/2001	100	96	83	52	33	21	14	10	7	5.4	5.7	2.437	2.566	5.0	15.6	68.0	1.2
24	9/21/2001	100	98	82	50	31	20	14	10	7	5.5	5.6	2.433	2.587	6.0	15.7	62.0	1.3
25	9/21/2001	100	97	87	56	33	22	15	10	7	5.4	5.7	2.482	2.575	5.7	15.9	64.0	1.2
26	9/22/2001	100	97	87	55	35	23	16	11	8	5.9	5.9	2.456	2.566	4.3	15.1	72.0	1.3
27	9/22/2001	100	98	86	52	32	21	14	10	7	5.3	5.7	2.445	2.570	4.9	15.4	68.0	1.2
28	9/22/2001	100	98	84	51	32	21	14	10	7	5.4	5.7	2.446	2.567	4.7	15.3	69.0	1.2
29	9/24/2001	100	98	83	57	36	24	16	11	8	6.0	5.7	2.474	2.577	4.0	14.3	72.0	1.4
30	9/24/2001	100	95	81	52	33	21	14	10	7	5.3	5.6	2.443	2.576	5.2	15.3	66.0	1.2
31	9/24/2001	100	97	80	45	28	19	13	9	7	4.9	5.3	2.432	2.599	6.4	15.4	58.0	1.3
32	9/24/2001	100	98	87	54	34	21	14	10	7	5.3	5.7	2.445	2.567	4.8	15.3	69.0	1.2
33	9/25/2001	100	98	84	52	34	22	15	10	8	5.7	5.6	2.468	2.576	4.2	14.4	71.0	1.3
34	9/25/2001	100	98	85	54	34	22	15	11	8	5.9	5.6	2.483	2.550	2.6	13.9	81.0	1.3
35	9/25/2001	100	97	85	53	32	21	14	10	7	5.4	5.8	2.448	2.568	4.7	15.3	69.0	1.2
36	9/25/2001	100	96	77	51	31	20	14	10	7	5.3	5.6	2.445	2.575	5.0	15.2	67.0	1.4
37	9/25/2001	100	97	86	53	32	20	14	9	7	5.1	5.9	2.429	2.572	5.6	16.7	65.0	1.1
38	9/26/2001	100	97	86	56	35	22	14	10	7	5.0	5.8	2.449	2.579	5.0	15.2	67.0	1.2
39	9/26/2001	100	96	81	48	31	20	14	9	7	5.2	5.6	2.452	2.527	4.7	15.0	69.0	1.2
40	9/26/2001	100	97	83	51	32	20	13	9	7	5.2	5.5	2.444	2.576	5.1	15.2	66.0	1.3
41	9/26/2001	100	98	80	52	34	20	14	10	7	5.4	5.4	2.456	2.552	3.7	14.6	75.0	1.2
42	9/27/2001	100	95	84	53	32	20	13	9	7	5.1	5.9	2.422	2.556	5.2	16.3	68.0	1.1
43	9/27/2001	100	96	83	53	34	22	16	11	8	6.1	5.5	2.447	2.592	5.6	15.0	63.0	1.5
44	10/27/2001	100	97	87	57	35	23	15	11	8	5.6	6.2	2.418	2.541	4.8	16.1	70.2	1.2
Average Gradation		*100*	*97.1*	*84.2*	*53.1*	*33.2*	*21.1*	*14.6*	*10.2*	*7.4*	*5.5*	*5.7*	*2.451*	*2.567*	*4.6*	*15.1*	*69.9*	*1.2*
Standard Deviation		*0.00*	*1.06*	*2.39*	*2.49*	*1.74*	*3.07*	*0.93*	*0.66*	*0.54*	*0.35*	*0.17*	*0.016*	*0.015*	*0.85*	*0.57*	*4.94*	*0.10*

APPENDIX B
Specific Gravities Used for Chapter 5 Calculations

Table B1. Superpave Specific Gravity Values.

Blended G_{sb}	G_{mb} @ design	G_{mm} @ design	G_b
2.695	2.456	2.531	1.020
2.615	2.501	2.431	1.020
2.789	2.480	2.548	1.020
2.639	2.453	2.476	1.020
2.646	2.414	2.486	1.038
2.654	2.510	2.581	1.020
2.652	2.428	2.502	1.020
2.677	2.477	2.543	1.023
2.663	2.490	2.551	1.021
2.662	2.474	2.492	1.027
2.673	2.453	2.523	1.030
2.743	2.406	2.518	1.034
2.606	2.361	2.457	1.025
2.783	2.511	2.616	1.028
2.974	2.669	2.801	1.030
2.651	2.358	2.460	1.044
2.663	2.391	2.491	1.022
2.771	2.491	2.597	1.023
2.728	2.458	2.559	1.021
2.644	2.370	2.474	1.028
2.537	2.324	2.421	1.031
2.817	2.502	2.604	1.035
2.725	2.499	2.600	1.032
2.861	2.405	2.508	1.026
2.743	2.485	2.583	1.035
2.757	2.484	2.588	1.023
2.766	2.483	2.599	1.035
2.739	2.476	2.576	1.035
2.672	2.438	2.542	1.035
2.672	2.320	2.505	1.025
2.642	2.395	2.496	1.033
2.688	2.404	2.509	1.026
2.699	2.412	2.513	1.026
2.677	2.425	2.528	1.030
2.790	2.479	2.582	1.031
2.753	2.451	2.558	1.026
2.441	2.216	2.318	1.040
2.446	2.244	2.345	1.031
Averages			
2.694	2.437	2.527	1.028