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INTER LABORATORY VARIABILITY OF THE MARSHALL TEST METHOD FOR ASPHALT CONCRETE

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Thesis submitted to the College of Engineering and Mineral Resources at West Virginia University in partial fulfillment of the requirements for the degree of

Masters of Science
In
Civil and Environmental Engineering

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Abstract

Inter Laboratory Variability of the Marshall Test Method for Asphalt Concrete

Master's Theses

Michael S. Hughes

Statistical quality control measures, such as used by the West Virginia Division of Highways (WVDOH), require quantification of the variability of the test methods to set meaningful material acceptance parameters. The Division currently uses the Marshall method for asphalt concrete mix design and quality control. Although the Marshall method will be replaced as the Division transitions to the Superpave method, in the interim, the Division will continue to use the Marshall method. The objective of this project was to determine multi-laboratory precision statements for the Marshall method that the WVDOH can use in developing statistically based quality acceptance specifications.

The Marshall method has been in use for more than 50 years. However, an examination of the literature did not reveal a data source that could be used for developing the precision statements. Thus, an experiment was designed to generate the data needed for the development of precision statements for the Marshall method. Data from the literature were compared to the results of the experiment performed during this research. The literature data demonstrated that the data collected during this research are in reasonable agreement with the experience of other asphalt technologists.

An inter-laboratory study was performed in accordance with ASTM standards to evaluate the multi-laboratory variability of test methods. All WVDOH laboratories, two contractor laboratories and the Asphalt Technology Laboratory at West Virginia University (WVU) participated in the study. The experiment included three WVDOH asphalt concrete types. All samples were mixed at the WVU laboratory and shipped to the laboratories for compaction and testing using the Marshall method. From the results of these tests, within-laboratory and between laboratory precision statements were developed for 102mm and 152mm Marshall test specimens.

A side issue evaluated during this project was mixing of large quantities of material needed for the 152mm Marshall samples and for Superpave. Traditional laboratory mixers lack the capacity to conveniently prepare these larger mix quantities. A five gallon bucket style mixer was evaluated, and operating procedures were established. This mixer was an efficient tool for preparing large size samples for laboratory testing.

Acknowledgments

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In the late 1860’s the first bituminous pavements were placed in Washington D.C. These pavements were a significant improvement over the common earth road surfaces of the day. However, with continuous growth in traffic, particularly during World War II, the need to improve pavement quality became an important issue to highway agencies and the Department of Defense. As a result, mix design methods were developed for improving the quality of asphalt concrete. One of these methods, developed by Bruce Marshall, has been widely adopted by state highway agencies, including West Virginia.

The West Virginia Division of Highways, WVDOH, uses statistical quality control methods. Under these methods, the precision of all test procedures must be known in order to ensure equitable evaluation of contractors’ products. Although the Marshall method has been in use for approximately 50 years, the precision of the method is not quantified in the ASTM standard test method. Hence, the WVDOH needs to quantify the precision of the Marshall method as it is implemented in the state. This need defined the primary objective of this research. In essence, this requires performing a test method precision experiment as described in ASTM Standard C 802 “Standard Practice for Conducting and Inter-laboratory Test Program to Determine the Precision of Test Methods for Construction Materials.” The standard requires preparing and distributing at least 3 replicate samples of 3 material types to a minimum of 10 laboratories. Obviously, sample preparation is a significant effort during this type of experiment.

1.2 PROBLEM STATEMENT

Even though the Superpave procedures will eventually replace the Marshall procedure for mix design and quality control, in the interim, WVDOH will continue to use the Marshall method. For quality control, the inter-laboratory precision and variance in the Marshall method must be quantified for statistical based quality control methods. In a previous project, single laboratory precision of the Marshall method was evaluated (Head, 93). The current project expands on the work of Head to include inter-laboratory precision.

1.3 OBJECTIVES

The objective of this research was to develop precision statements for Marshall parameters. The Marshall parameters evaluated during this project were stability, flow, air void, maximum theoretical specific gravity, and bulk specific gravity.

The precision statements must apply to all laboratories working for and with WVDOH, therefore, all WVDOH district laboratories and the central laboratory participated in the study. In addition, since contractors have a direct responsibility for quality control, contractors laboratories were included in the study. The precision statements must be valid for all asphalt concrete types, so three mix types were included in the research. To ensure the experiment design and analysis fulfilled these objectives, ASTM standard practices for performing precision statements were used during the research.

The Marshall method was developed to accommodate mixes with relatively small maximum size aggregates. This permitted the use of a 102 mm diameter mold, which can accommodate a 25 mm maximum aggregate size. Recently, in response to heavier traffic loads, highway agencies have introduced mixes with larger maximum aggregate sizes to improve mix durability. Consequently, there is a need to increase the Marshall sample size to accommodate the larger size aggregates. The use of larger sample molds is also accommodated in more modern mix design methods, such as the Superpave system developed during the Strategic Highway Research Program. Both the large Marshall mold and the mold used for the Superpave system require approximately 4,000 g of aggregate as opposed to the 1,200 g sample needed for the standard Marshall mold.

Increasing the sample size significantly affects laboratory sample preparation. Due to the mass of material required, it is difficult to prepare samples using traditional methods. In response to this need, industry has introduced a large capacity mixer for asphalt concrete. Since the objective of this project required preparation of many samples, the large capacity mixer was evaluated.

1.4 THESIS SUMMARY

This thesis is organized into six chapters and seven appendices. Following the introduction chapter is a summary of the literature. Given the fact that the Marshall method was developed 50 years ago and was the standard method for approximately seventy-five percent of the stated highway agencies, the lack of information on the test method precision seems unusual. The literature survey found two studies covering single-laboratory precision and two reports on inter-laboratory precision. The studies indicate the variability of the Marshall method is relatively high. Others have recognized this fact and studies of methods for reducing the variability have been conducted. One such study was reviewed to highlight the difficulty in reducing the variability of the seemingly simple Marshall mix design method.

One aspect of the standard Marshall test method is the small mold size which limits the maximum aggregate size that can be considered for mix design. To overcome this limitation, an ASTM test method for using a 152 mm diameter mold was developed. In addition, the Superpave method uses large sample sizes. Chapter 3 outlines a method for mixing large samples.

Chapter 4 presents the process used to select the specific aggregate gradations and asphalt contents for the mixture types used during this research. The types of mixtures were selected in concert with the project sponsor. Once the mixture types were selected, samples of aggregate were obtained from Greer Industries. A Marshall mix design was preformed to determine the optimum asphalt content. However, mixes with the Greer aggregates failed to meet all the WVDOH Marshal criteria. Therefore the mix designs used by the Greer plant for DOH projects were used for the research.

The samples were prepared in the WVU Asphalt Technology Laboratory and distributed to the 10 WVDOH district laboratories, the WVDOH central laboratory, two contractor laboratories, and the WVU Asphalt Technology Laboratory. The samples were tested using standard Marshall methods adopted by WVDOH. The test results were returned to the researchers and analyzed as reported in Chapter 5.

Chapter 6 presents the conclusions and recommendations for the research project. The objective of the project was achieved with the presentation of precision statements, which the WVDOH can implement. However, the research discovered two issues which should be evaluated further. First, data from one of the laboratories was discarded as being too variable. The reasons for this variability should be investigated and the equipment and testing technique should be modified as needed. Second, when the research project was designed, three material types were selected as specified by the ASTM standard for developing precision statements. However, two of the material types are compacted in 102 mm molds and the other in 152 mm molds. There were significant differences in the variability of test results obtained with standard and large molds. In essence, the precision statements developed during this research treated the standard and large molds as separate test methods.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The Marshall mix design method was developed approximately 50 years ago and was adopted as the standard mix design for the majority of state highway agencies. Standard Marshall test methods were published by both the American Society for Testing and Materials (ASTM), and by the American Association of State Highway and Transportation Officials (AASHTO). However, these standards lack quantified precision statements.

ASTM published standards for developing precision statements which were extensively used for this project. These standards are summarized in Appendix A.

ASTM precision statements recognize the difference in precision that can be achieved within a single laboratory and between multiple laboratories. Two studies were found which examined the within, or single-laboratory variability. One examined the repeatability of the Marshall stability test using a single technician but two “identical” Marshall hammers (Kovac, 62). The other study examined the single laboratory variability for four asphalt concrete types used by WVDOH (Head, 93). Two studies were found which evaluated the inter-laboratory variability. One study was performed specifically to develop precision statements for Marshall stability tests performed on 152 mm samples (Kandhal, 96). The other study presents a compilation of inter-laboratory Marshall variability data that were collected, but not published, by several agencies (Siddiqui, 95).

Each of these studies demonstrated considerable variability in the Marshall test method. Therefore, although it is not directly related to the current project, information on ways to reduce variability in the Marshall method was sought. The Federal Highway Administration (FHWA) sponsored a study for calibrating the compaction effort of the Marshall hammer (Sherton, 94).

2.2 SINGLE LABORATORY VARIABILITY

In 1962, Kovac expressed concern that publications in the proceedings of the Association of Asphalt Paving Technologists, AAPT, indicated the standard deviation of the Marshall Stability test was in the range of 1980 and 5930 N (Kovac, 62). Kovac preformed an experiment to quantify the single operator standard deviation. Factors and levels in the experiment were:

1. Compaction hammers – two “identical hammers,
2. Sample position – the hammers were capable of compacting two samples simultaneously.
3. Molds – four molds were used in the experiment

A single mix design with a 9.5 mm maximum aggregate size and 85/100 penetration grade binder was used for all samples. A total of 64 samples were prepared over a 4 week period. The standard deviation for all samples was 304 N, which was considerably less than the previously unpublished values. Kovac found significant differences in the compactive effort produced by the two “identical” hammers. Also, the first sample made each day had the highest variability. After the variability associated with experimental factors was removed from the analysis, the resulting error standard deviation for the Marshall stability was 272 N.

The WVDOH sponsored a project at WVU to quantify the single laboratory precision for Marshall mix design tests for 102 mm and 152 mm samples (Head, 93). Four mix types were evaluated:

1. Patching and Leveling 2, 12.5 mm max aggregate size, 102 mm mold,
2. Wearing 3, 4.75 mm maximum aggregate size, 102 mm mold,
3. Base 1, 37.5 mm maximum aggregate size, 152 mm mold, and
4. Modified Base 1, 19 mm maximum aggregate size, 152 mm mold.

The gradation for each mix type was established by using the midpoint of the allowable range for percent passing for each sieve size. The optimum asphalt content was determined in accordance with provisions contained in the Asphalt Institute Manual MS-2, Pennsylvania Department of Transportation (PennDOT) Marshall criteria for compacted specimens, and WVDOH specifications. Ten samples were prepared for each mix type. A sample consisted of the average of three results. The Marshall parameters evaluated in the study were stability, flow, unit weight, and percent air voids.

The WVU research found the variability of the Marshall parameters was greater for the 152 mm samples than for the 102 mm samples. The mean value for stability, flow, and unit weight were greater for the 152 mm samples than for the 102 mm samples (Head, 93). The material types and sample size were confounded in the experiment, i.e., no material type was tested at both sample sizes. Hence, the difference in the means and variability may be attributed to either material type or sample size.

2.3 INTER-LABORATORY VARIABILITY

The precision of the Marshall procedure for 152 mm samples was evaluated when ASTM published a standard test method for preparing and testing this size sample (Kandhal, 96). The AASHTO Material Reference Laboratory (AMRL) distributed replicate samples to twelve laboratories. The laboratories were instructed to follow ASTM D5581, “Test Method for Resistance to Flow of Bituminous Mixtures Using Marshall Apparatus (6 inch Diameter Specimen)”. The laboratories mixed and compacted samples, at temperatures specified by the researchers, and then tested for Marshall stability and flow, air voids, and bulk specific gravity. The laboratories were provided with a sufficient amount of 25 mm maximum size aggregates and AC-20 to prepare 3 Marshall sampled, “butter” the mixer, and make samples for determining the maximum theoretical specific gravity.

The data received from the laboratories were analyzed using ASTM Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials (C 670), the ASTM practice for Conducting an Inter-laboratory Test Program to Determine the Precision of Test Methods for Construction Materials (C 802), and ASTM Practice for Use of the Terms Precision and Bias in ASTM Test Methods (E 177) (Kandhal, 96). The parameters of precision from this study are presented in Table B.1.

Siddiqui, Trethewey, and Anderson studied variables affecting Marshall test results (Siddiqui, 95). The primary objectives of the study were to identify the key equipment-related factors associated with inconsistencies in test results obtained by using different compaction equipment and to recommend calibration equipment and techniques for Marshall compaction equipment.

Inter-laboratory variability results from differences in equipment characteristics, and the skill of the technician. The variability of the Marshall procedures has been a concern since at least 1984 (Lee, 84). However, there are relatively few published studies which quantify the precision of these procedures.

Siddiqui reported on experts' and users' opinions on the sources of variability in the Marshall procedure. A questionnaire was used to capture the opinion of eleven experts concerning the variables that significantly affect Marshall compaction. Analysis of the questionnaire identified the rank order of the five most influential variables as:

1. Hammer alignment,
2. Pedestal support,
3. Height of free fall,
4. Hammer weight, and
5. Pedestal construction.

Users were then interviewed relative to the differences in brands of equipment and operator technique. These users reported significant differences in pedestal construction, shape of the hammer foot, hammer weight and dimensions of the breaking head used in the stability and flow tests. In addition, the users identified concerns that experienced technicians were not following the ASTM standard test procedure (Siddiqui, 95).

The experts' and users' opinions provide an expectation of high inter-laboratory variability. This expectation was verified with data collected by highway agencies in Georgia, Utah, and Canada. These agencies conducted inter-laboratory studies to examine Marshall variability within their agency. These were unpublished studies prior to being reported by Siddiqui. The data from these studies are presented in Appendix B. An analysis of these data for the ASTM precision parameters is presented in Chapter 5.

Qualitative findings from these studies include (Siddiqui, 95):

1. Results from the Georgia Department of Transportation (GDOT) showed samples prepared with mechanical hammers were consistently different from samples prepared with manual hammers with respect to density.
2. The GDOT data showed most laboratories could operate within the desired levels of precision, but some data indicated potential problems with either the equipment or technician technique.
3. The Utah Department of Transportation (UDOT) data demonstrated that the precision of the Marshall method was influenced by operator technique.
4. The Canadian data demonstrated the variability of mechanically compacted samples was higher than the variability associated with manually compacted samples.

2.4 CALIBRATION OF MARSHALL HAMMER

After research demonstrated the large variability in the Marshall procedure, especially for the mechanical compaction hammers, the Federal Highway Administration (FHWA) sponsored research on methods to calibrate these hammers (Sherton, 94). Since the WVDOH uses mechanical Marshall hammers, the FHWA research was reviewed to determine if it was applicable to the division's procedures.

Sherton developed equipment to measure the compaction force applied to Marshall samples. The equipment consisted of a power supply, data acquisition system and an elastic spring-mass device with an integral force transducer. The basic premise behind the equipment was that the compaction effort of the hammer could be measured with an elastic spring-mass device positioned inside a standard Marshall mold. As the hammer impacts the device, the spring is compressed. The rate of compression and maximum deformation is sent to the data acquisition system. The force, impulse, and energy are then calculated for each individual blow.

After the prototype device was developed, tests were performed to evaluate the potential of reducing variability by calibrating each hammer. This laboratory evaluation program evaluated conditions that produced scatter in Marshall test results. The topic of comparing different hammers and standardization was indirectly examined. The main focus was on Marshall equipment related variables such as variation in drop weight, friction, wear, and foundation compliance.

Five different machine setups were evaluated:

1. New Pine Instruments Marshall compaction hammer,
2. Twenty year old Reinhart Testing Equipment Marshall compaction hammer,
3. The Pine Instruments hammer with the mass increased by 277 g,
4. The Reinhart Testing Equipment hammer with a rubber pad between the mold and base plate, and
5. Manual Marshall compaction hammer.

Three samples were compacted in each of the five device setups. The samples were compacted with fifty blows on each side of the sample. The bulk specific gravity, stability, stability, flow, air voids and height of each sample were determined. The standard deviation of each parameter was computed from three replicate specimens prepared with each machine setup.

The machines were then calibrated using the calibration device. A standard cumulative impulse value and cumulative energy value were computed. Calibration consisted of computing the number of times each machine would have to drop the hammer to achieve energy and impulse values theoretically computed for 50 blows per side. The “calibrated” number of blows are shown in Table 2.1.

Three samples were then compacted in each machine with the impulse and energy modified blow counts. The mean and standard deviation for the three samples were computed for each of the Marshall parameters. In almost all cases, the standard deviation of the samples prepared with the calibrated number of blows was less than the standard deviation for samples prepared using the standard number of blows. Samples prepared using the number of blows computed from the impulse calibration procedure had less variable than samples prepared using the number of blows computed the energy calibration procedure (Sherton, 96).

Sherton claimed that since the standard deviations were reduced, the calibration method was effective. However, this comparison was not made between hammers. The efficacy of the

Table 2.1. Calibrated Machine Blow Count

	Standard Pine	Standard Reinhart	Modified Pine	Modified Reinhart	Manual Hammer
Energy Calibration	38	66	41	103	53
Impulse Calibration	53	56	50	60	43

calibration method to produce consistent results with different compaction machines was not determined during the research. One test compared the bulk specific gravity, stability, flow, air voids, and height of the specimens compacted to the same impulse and energy levels. However, these samples were compacted with a rubber pad between the pedestal and the sample, so the conclusions cannot be applied to standard practices.

The finding that the modified Pine (with extra weight) requires more blows than the standard Pine to achieve the same total energy is highly questionable. Clearly, increasing the mass of the falling hammer while maintaining a constant the drop height should increase the compaction energy and reduce the number of blows required to produce a fixed amount of compaction energy.

2.5 SUMMARY

Although the Marshall procedure was developed over 50 years ago, there is relatively little information in the literature to quantify the variability of the test method. Studies have demonstrated that differences in equipment and operator technique affect variability. The literature demonstrates that different manufactures' equipment produce different results and may or may not comply with ASTM standards. In addition, experienced technicians may become complacent and not follow prescribed test methods. Therefore, data on Marshall variability from the literature while interesting and only provides a benchmark for comparison to the other studies. However, the available literature is not sufficient for determining Marshall precision statements for the WVDOH.

CHAPTER 3

BUCKET MIXER TESTING

3.1 INTRODUCTION

In the past, the size and capacity of a laboratory asphalt concrete mixer has been of little concern due to the small quantities needed. Samples were mixed in a tabletop mechanical mixer or by hand. These two methods sufficed because the Marshall and the Hveem mix design method were the two predominant mix design methods. Both procedures use 102 mm diameter by 63 mm high samples requiring approximately 1200 g of aggregate.

In recent years, new testing procedures have been accepted in the asphalt industry. In 1996, ASTM introduced a testing procedure for 152 mm diameter Marshall apparatus. The Strategic Highway Research Program (SHRP) developed a new system for asphalt concrete mix design using the Superpave Gyratory Compactor. This machine, over the next several years, will replace the Hveem and Marshall methods. The Superpave Gyratory Compactor uses a 150 mm diameter sample. The samples weigh more than 4500 g. This quantity of material is difficult to mix with traditional methods. Since AASHTO and ASTM mix design test standards for Marshall and Superpave only specify that the mixture have a uniform distribution of asphalt binder, a different style mixer may be introduced.

A few laboratories across the country have started using five-gallon bucket mixers, depicted in Figure 3.1. The effectiveness of this style mixer was investigated to in this study to determine if quantities of material needed for 152 mm Marshall and Superpave samples can be mixed successfully.

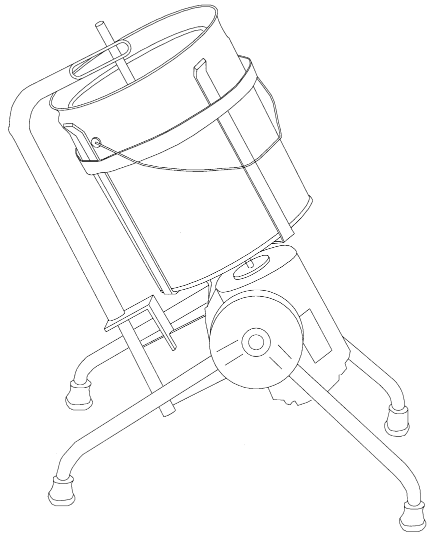

Figure 3.1. Diagram of Bucket Mixer

3.2 MIXER DESCRIPTION

A Kol Brand five-gallon bucket mixer was purchased from QC Resource, the asphalt equipment division of Virginia Laboratories Inc. The mixer has a ½ horsepower motor, which rotates the bucket at a constant rate of 60 RPM. The mixer can be tilted about a plane perpendicular to the floor, and can be locked at six different positions in 15° increments from upright to 15° from horizontal. Virginia Laboratories Inc. developed the paddle, Figure 3.2, included with the mixer, specifically for mixing asphalt concrete.

3.3 MIXER EVALUATION

The first objective in evaluating the mixer was to determine the most effective setup and procedure for using the mixer. No instructions were included with the mixer. Virginia Laboratories Inc. was contacted for instructions. The contact explained that the mixer should be locked at the lowest angle possible without allowing any of the mixture to spill out. The orientation of the paddle inside the bucket was not described.

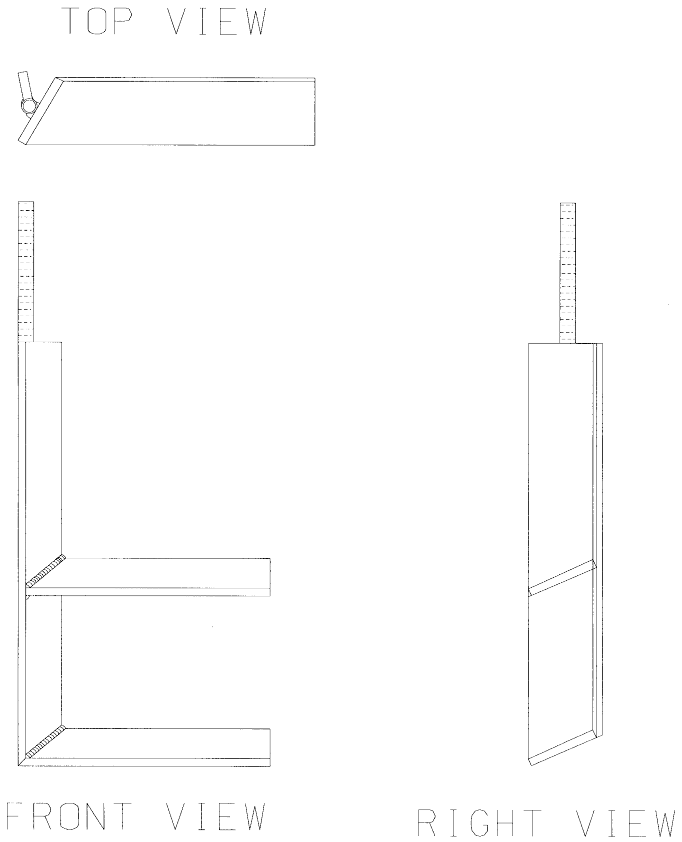

Figure 3.2. Isometric Drawing of Paddle

Several configurations were tested to determine the paddle orientation that mixed asphalt concrete most effectively. The first position was to set the along the diameter of the bucket mixer as shown in Figure 3.3. Heated aggregates for a Base 1 mixture were placed in the heated metal bucket and asphalt cement was poured into a crater formed in the center of the rocks. The bucket was placed in the mixer and the hot paddle was bolted onto the paddle arm. The mixer was turned on and tilted down to a 15° angle as Virginia Laboratories Inc. had specified. Initially, the mixture turned over, but after a few seconds the mix clumped up against the paddle while the bucket was spinning freely. Eventually, the torque of the mix against the end of the paddle caused the paddle to rotate out of position. Different tilt angles were tried but the asphalt concrete would not mix. It became apparent that there was not enough friction between the paddle bolt and the paddle arm to hold it in place.

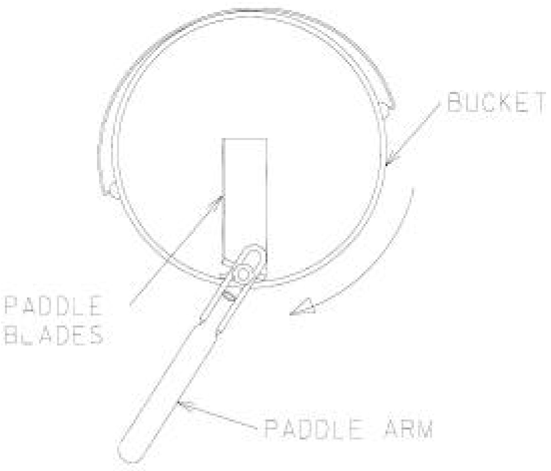

Figure 3.3. First Bucket Mixer Configuration

Virginia Laboratories Inc. was contacted about this problem. The company shipped a speed nut to the laboratory to see if it would hold the paddle in place. The speed nut was easier to use but the paddle would still rotate. In addition, securing the paddle took too much time, allowing the mixture to cool.

The decision was made to secure the paddle with the conventional nut to the paddle arm before heating. The two items could be heated together. The paddle arm could be placed onto its holding rod, slid down in place and secured. This resolved the problems with the paddle rotating while mixing and the excessive time required for setting up the mixer.

Several mixes were run with the paddle properly secured. Although the paddle did not move, the mix clumped up against the paddle rather than mixing freely. A new paddle orientation was needed. For the next configuration the paddle arm, was oriented parallel to the bucket's tilting plane as shown in Figure 3.4. When the material was placed in the mixer and run, the same problem occurred. The material would mix briefly then become lodged against the paddle. Mixes were attempted at every tilting angle with no success. Next, the bucket mixer was tilted in the opposite direction, away from the lock stops. The material circulated around the bucket until the mix encountered the paddle blades. The blades scraped the material from the side and bottom of the bucket and caused the mixture to free-fall. The mixture would fall on itself

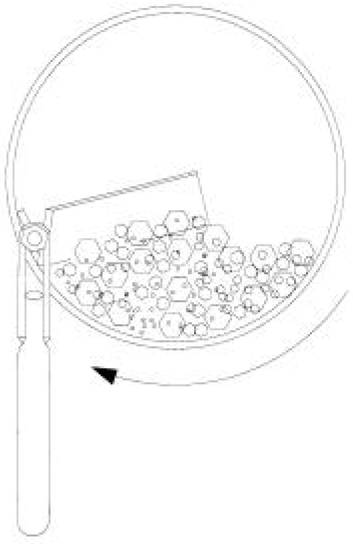

Figure 3.4. Aggregates Lodged Against Paddle in the Second Configuration

and coat the aggregates with asphalt. The aggregates would continuously spin around in an elliptical / D-shaped cycle coating aggregates.

Although this seemed to be the most effective way to run the mixer there were other problems. It was observed that the finer aggregates circulate near the edge of the bucket while the larger aggregates migrated to the center and never contacted to the paddle blade. This caused two problems; the large aggregates were not getting completely coated with asphalt and the aggregates were segregated. Changing the angle at which the bucket was tilted alleviated most of the segregation. The closer the tilt angle was to vertical the wider the ellipse became. The closer to the angle came to horizontal the narrower the ellipse became. By rocking the bucket back and forth, the large aggregates were reintroduced into the mixture. This procedure improved coating of the large aggregates, but did not completely relieve the problem.

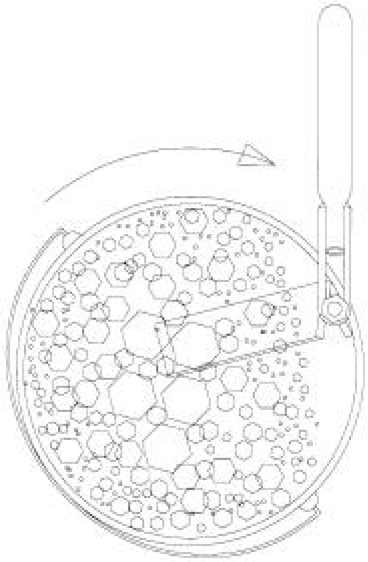

Figure 3.5. Segregation of Aggregates with Mixer Tilted Away from Lock Stops

Different attempts were made to improve coating of the large aggregates. Specifications for the gyratory compactor require heating that the mixture in a shallow pan for a period of two hours after mixing. This allowed the large aggregates to become completely coated as the heated asphalt cement flowed to the uncoated surfaces. However, heating after mixing is not part of the Marshall specifications, so a better mixing method was still needed.

It was observed that upon initial mixing, there was thorough coating of the fine aggregates but inadequate coating of the largest aggregate. Hence, it was decided to try a two step mixing process. In the first step, the coarse aggregate and asphalt were placed in the bucket and mixed for about 10 seconds. Then the fine aggregates were introduced while the mixer was running and the bucket was locked in the vertical position. The fine aggregates were poured into the center of the mix, avoiding the bucket side and paddle. It was observed that after another 20 seconds of mixing, all aggregates were thoroughly coated.

Different separations between large and small aggregates were attempted to see which separations allowed for the fastest mixing time while still completely coating all aggregates. It was discovered that for mixtures with a nominal maximum aggregate size of 9.5 mm or smaller, aggregates retained on 2.36 mm sieves should be mixed first. Aggregates passing the 2.36 mm sieve are then introduced and mixed until all aggregates are uniformly coated. For mixtures with a nominal maximum aggregate size of 12.5 mm or greater, aggregates retained on a 4.75 mm sieve are mixed first, followed by the smaller aggregates.

An additional problem with the mixer was its inability to scrape the entire bucket. In the center of the bucket, a 25 mm to 75 mm circle of asphalt cement and fines was never scraped from the bottom of the bucket. The paddle was long enough but the bottom edge of the paddle blade did not contact the bottom of the bucket at the center. As the bucket spun, the area of the bucket not reached by the blade had a thin coating of asphalt and fine material. These materials had to be scraped with a spoon and reintroduced with the rest of the material after the mechanical mixing was complete. At the seam where the side of the bucket and the bottom met there was a three millimeter wide two millimeter deep indent. While the mixer was running, the end of a metal spatula was placed in this indent to dig out the fines and allow them to be mixed.

3.4 MIXER CAPACITY

The next phase of the evaluation was to the bucket mixer's capacity. In the previous phase of the testing it was observed that the mixer could provide a homogeneous mixture for 4000 g samples. It now needed to be seen if the mixer could handle mixes significantly smaller and larger.

It was decided that the smallest size mixture that would be needed for asphalt concrete mix design would be for a single Marshall sample, 1200 g. The mixing procedures developed for the 4000 g samples were used for all of the samples. Both WVDOH Base 2 and Wearing 1 mix designs were evaluated at optimum asphalt content. 1200 g samples the paddle was hardly touched by the material when the bucket was tilted to a steep angle. The material mixed through centripetal acceleration and gravity, providing a uniform coating of the aggregates. In mixing the smaller samples, segregation was not a problem.

Next, the ability of the bucket mixer to prepare large batch sizes was evaluated. An 18,000 g batch was selected this would enable asphalt samples to be quartered into Superpave Gyratory Compactor specimens of approximately 4500 g.

The first samples were run at the optimum asphalt content. The bucket was unable to be tilted over very far because the mixture was approximately 70 mm from the top of the bucket. The aggregates turned over very well and the mixer had no problem handling such a large batch. Through visible inspection it was determined that all of the aggregates were evenly coated. However, severe segregation was observed. The fine aggregates migrated to the bottom of the bucket while the larger aggregates remained on top. No method could be seen to alleviate this. Careful quartering of the batch into the required sample size should mitigate this segregation problem.

Mixes were evaluated with low asphalt contents. For this particular aggregate gradation no problems occurred in mixing at one percent below optimum asphalt content. When a mixture was attempted at 1.5 percent below optimum asphalt content it was observed that not all of the aggregates were evenly coated with asphalt. The fine aggregates that were introduced into the mixture after the large aggregates were not being completely coated. The aggregates were migrating to the bottom of the bucket forcing the coarse aggregates to surface. The large aggregates that were thoroughly coated with asphalt were not coming in contact with the fine aggregates at the bottom. Agitating the mixture with a hot spoon did not improve coating.

18000 g batches were run at high asphalt contents. The asphalt cement on the bucket and aggregates acted as a lubricant. There was not enough friction between the aggregate and the bucket to cause the mix to turn over. The mix would stop moving. When this occurred the bucket was rocked back-and-forth vigorously and a hot spoon was used to agitate the stopped mixture. This reactivated the mixing and good aggregate coating was achieved.

3.5 TEMPERATURE TESTS

Tests were run to see if different bucket setups would affect the temperature retained in a sample after mixing. Three different five-gallon bucket configurations were evaluated, the standard bucket, a 16 gauge steel bucket, and the standard bucket with a fiberglass insulated wrap. Mixtures were run at optimum asphalt content on batch of sizes 18000 g, 4000 g and 1200 g.

Table 3.1. Temperature at Completion of Mixing for Different Bucket Configurations in Celsius

Sample size (g)	Standard Steel Bucket	Standard Steel Bucket Insulated	16 Gauge Steel Bucket
1200	151.7-154.4	151.7-154.4	155.6-156.7
4000	154.4-155.6	160-162.8	157.2-160
18000	162.2-162.8	167.2-168.3	162.8-163.3

WVDOH Base 1 gradation was used for the 18000 g and 4000 g samples while WVDOH Base 2 gradation was used for the 1200 g samples. The buckets and the aggregates were heated to 170°C. The asphalt cement was heated to 158°C. The samples were mixed using the procedure developed previously. After the asphalt was thoroughly mixed the asphalt was formed into a cone in the bucket and a dial thermometer was placed in the center of the cone. The range of results for the three specimens under each condition is presented in Table 3.1.

It can be seen in Table 3.1 that the 1200 g samples in the 16 gauge steel bucket retained the heat better than the standard steel bucket, even with the insulation in place. It was hypothesized that the insulation did not improve temperature retention because the wrap only went around the sides of the bucket and not the bottom. With a small sample, little asphalt concrete touched bucket side. Heat was lost through the bottom of the bucket. The 16 gauge bucket was best for small batches. For medium and large batches there was a significant difference between the three configurations. The insulated bucket performing the best with the larger batches. There was a significant amount of contact between the sample and the side of the bucket. The insulation effectively reduced heat loss.

It should be noted that sample removal from 16 gauge steel bucket was significantly easier than the other bucket. The bottom of this bucket was welded to the sides as opposed to the standard bucket, which was crimped together. The crimped seam created a crevice that retained material. Also, because the sides and bottom of the bucket remained hot, the asphalt slid out of the bucket without sticking. With the standard bucket, even when insulated, the asphalt stuck to the bottom and sides of the bucket. This was especially true with the 1200 g samples. This is significant when preparing samples for the Marshall test method where the sample goes directly from the mixer to the compaction mold.

3.6 CONCLUSION

Overall, the five-gallon bucket mixer performed extremely well at mixing asphalt. An effective mixer configuration and procedure was developed for creating a well coated homogeneous mixture. Sample sizes ranging from 1200 g to 18,000 g can be effectively mixed. Large samples at low asphalt contents pose a problem in mixing and should be avoided. If heat loss is critical either fiberglass insulating blanket or a high gauge steel bucket is recommended. If individual Marshall specimens are going to be made a 16 gauge steel bucket is beneficial for consistent sample preparation. A recommended bucket mixer operating procedure is presented in Appendix C.

CHAPTER 4

MIX DESIGN PROCEDURE AND SAMPLE PREPARATION

4.1 INTRODUCTION

Three different WVDOH mixes were used in assessing the precision and repeatability of the Marshall mix design method. The three mixes selected for the testing were WVDOT Wearing 1, Base 2 and Base 1. These mixes were selected because of their frequent use by the WVDOH. The statistical evaluation is most meaningful when performed at the optimum asphalt content. This chapter describes the procedures used to determine the optimum asphalt content for each mix type.

4.2 AGGREGATE PREPARATION

All aggregates used for testing in this project were crushed limestone donated by Greer Limestone in Sabraton, WV. The aggregates were sieved into the following sizes: 37.5 mm, 25 mm, 19 mm, 12.5 mm, 9.5 mm, 4.75 mm, 2.35 mm, 1.18 mm, 0.60 mm, 0.15 mm, and 0.075 mm. Once the aggregates were separated, the specific gravity of each sieve size was determined in accordance with ASTM C128 and ASTM 127 for fine and coarse aggregates, respectively (Table 4.1).

The Federal Highway Administration recommends using a 0.45 power gradation chart to find the best gradation for a mix. Three methods are currently recognized in practice (Roberts, 96):

> Method A: Draw a straight line from the origin to the maximum aggregate size.
>
> Method B: Draw a straight line from the origin to the nominal maximum aggregate size.
>
> Method C: Draw a straight line from the origin to the percentage point for the largest sieve that retains material.

Table 4.1. Specific Gravity of Individual Aggregate Sizes

Type aggregate	Sieve size (mm)	Bulk Specific Gravity	Apparent Specific Gravity
Coarse aggregate	37.5	2.696	2.721
	25	2.695	2.722
	19	2.701	2.730
	12.5	2.691	2.729
	9.5	2.695	2.724
	4.75	2.691	2.718
Fine aggregate	2.36	2.658	2.825
	1.18	2.664	2.882
	0.300	2.504	2.818
	0.075	2.327	2.619
	Pan		2.568

Each of the three methods is demonstrated in Figure 4.1 for the Wearing 1 gradation. Method A was chosen for each gradation. This line nearly fit the center of the WVDOH specifications.

The first attempt at finding an acceptable gradation for each mix type followed the method A line as closely as possible, while still staying within Superpave (Tables 4.2 to 4.4) and WVDOH (Table 4.5) specifications. The gradation deviates from the maximum density line near 1.18 mm to avoid the restricted zone set forth by Superpave specifications (Figures 4.2 to 4.4).

Once the gradation for each mix design was chosen the specific gravity for the aggregate blend was computed using the equation:

$$G = \frac{P_1 + P_2 + ... + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + ... + \frac{P_n}{G_n}} \qquad (4.1)$$

Where,

G = average specific gravity

G_1, G_2, …, G_n = specific gravity values for fraction 1, 2, …n; and

P_1, P_2, …P_n = weight percentages of fraction 1, 2, …n

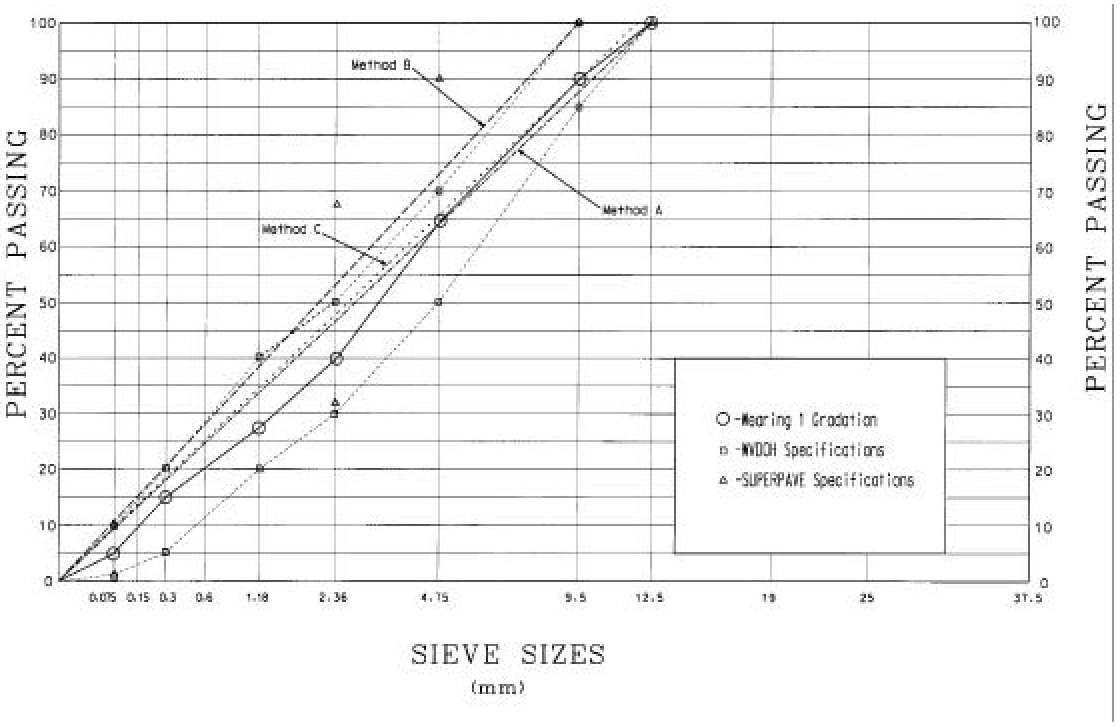

Figure 4.1. Three Methods for Determining Dense Gradation Line

Table 4.2. Superpave Specifications for 37.5 mm Nominal Aggregate Size Mix (Wearing 1) (Roberts, 96)

Sieve Size (mm)	Control Points		Restricted Zone Boundary	
	Lower	Upper	Lower	Upper
12.5	100.0	100.0	-	-
9.5	90.0	100.0	-	-
4.75	-	90.0	-	-
2.36	32.0	67.0	47.2	47.2
1.18	-	-	31.6	37.6
0.6	-	-	23.5	27.5
0.3	-	-	18.7	18.7
0.15	-	-	-	-
0.075	2.0	10.0	-	-

Table 4.3. Superpave Specifications for 19 mm Nominal Aggregate Size Mix (Base 2) (Roberts, 96)

Sieve Size (mm)	Control Points		Restricted Zone Boundary	
	Lower	Upper	Lower	Upper
25	100.0	100.0	-	-
19	90.0	100.0	-	-
12.5	-	90.0	-	-
9.5	-	-	-	-
4.75	-	-	-	-
2.36	23.0	49.0	34.6	34.6
1.18	-	-	22.3	28.3
0.6	-	-	16.7	20.7
0.3	-	-	13.7	13.7
0.15	-	-	-	-
0.075	2.0	8.0	-	-

Table 4.4. Superpave Specifications for 37.5 mm Nominal Aggregate Size Mix (Base 1) (Roberts, 96)

Sieve Size (mm)	Control Points		Restricted Zone Boundary	
	Lower	Upper	Lower	Upper
50	100.0	100.0	-	-
37.5	90.0	100.0	-	-
25	-	90.0	-	-
9.5	-	-	-	-
4.75	-	-	34.7	34.7
2.36	15.0	41.0	23.3	27.3
1.18	-	-	15.5	21.5
0.6	-	-	11.7	15.7
0.3	-	-	10.0	10.0
0.15	-	-	-	-
0.075	0.0	6.0	-	-

Table 4.5. WVDOH Master Ranges for Base 1, Base 2, and Wearing 1

Sieve Size (mm)	Base 1		Base 2		Wearing 1	
	Lower	Upper	Lower	Upper	Lower	Upper
50	100	-	-	-	-	-
37.5	80	100	-	-	-	-
25	-	-	100	-	-	-
19	50	80	85	100	-	-
12.5	-	-	-	-	100	-
9.5	35	65	60	80	85	100
4.75	25	55	35	65	50	70
2.36	-	-	20	50	30	50
1.18	10	35	-	-	20	40
0.6	-	-	-	-	-	-
0.3	4.0	20.0	4	20	5	20
0.15	-	-	-	-	-	-
0.075	0	8	1	8	1	8

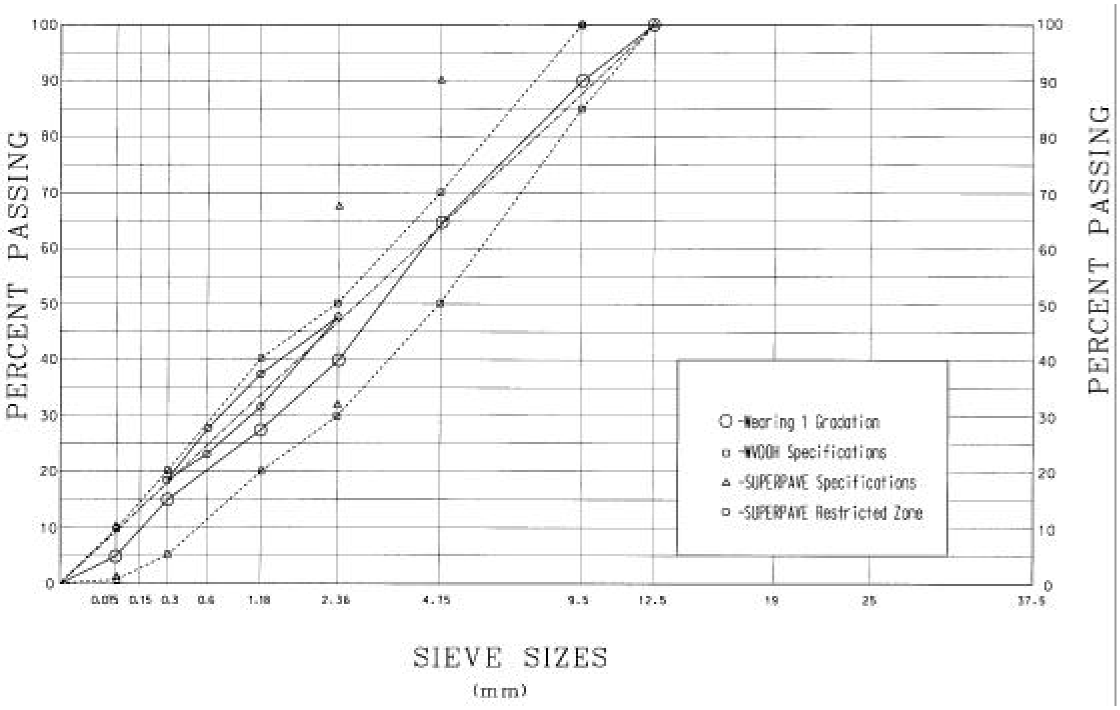

Figure 4.2. Gradation of First Wearing 1 Sample

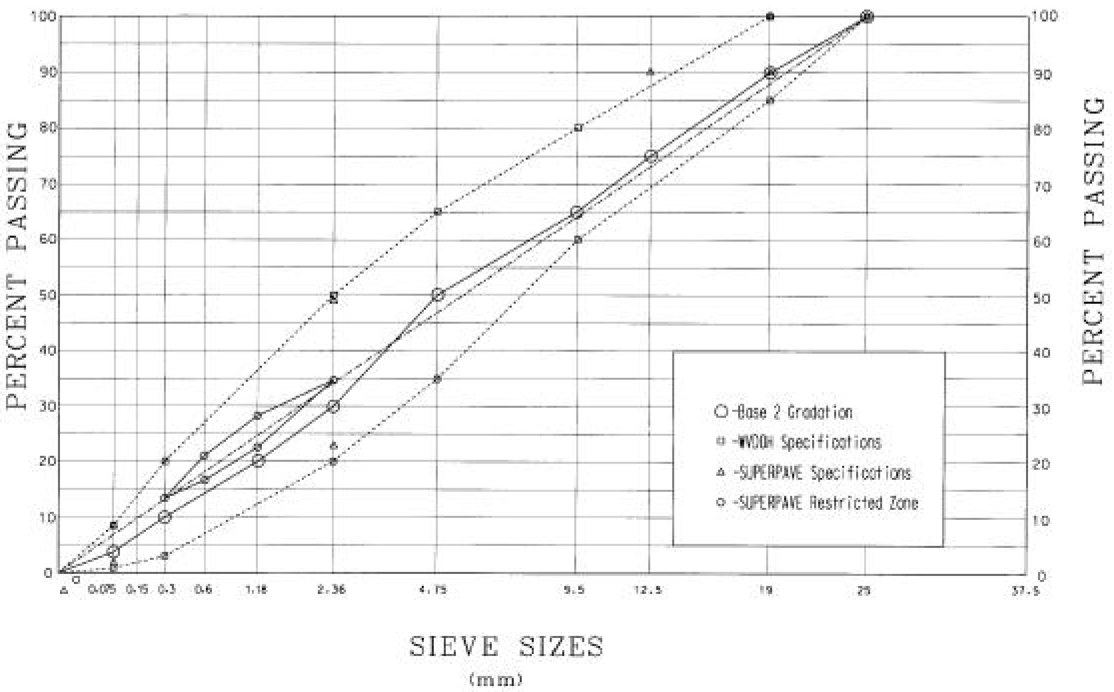

Figure 4.3. Gradation for First Base 2 Sample

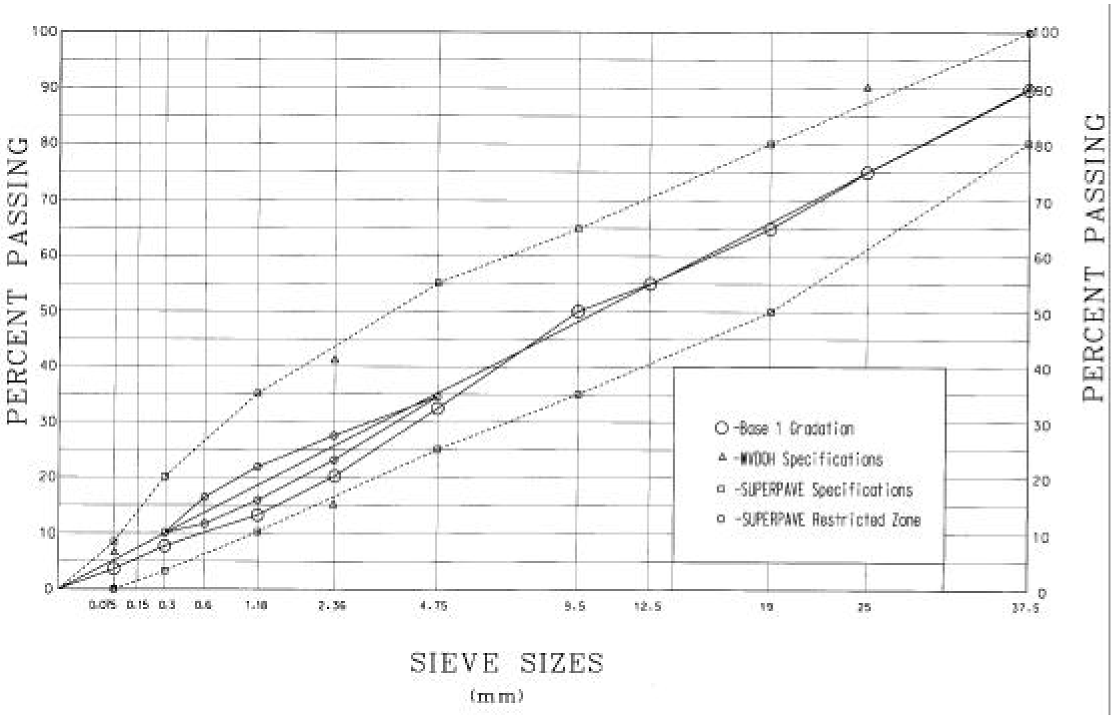

Figure 4.4. Base 1 Gradation

4.3 SPECIMEN FABRICATION

Once each aggregate gradation was selected, the optimum asphalt content for each mix type was determined using the Marshall method and the Asphalt Institute criteria (Roberts, 96). The Asphalt Institute criteria requires averaging the asphalt content at maximum stability, maximum density, and mid point of specified air void range (typically 4 percent) from plots of stability, flow, air voids, and VMA versus asphalt content. The properties of the mix at this asphalt content are then compared to mixture acceptance criteria.

Marshall testing for this project conformed to ASTM D 1559, for 102 mm samples and ASTM D 5581 for 152 mm samples. ASTM D 1559 was followed for the Base 2 and Wearing 1 mixes and ASTM D 5581 was followed for the Base 1 mix.

For the 102 mm diameter Marshall samples personnel, of WVDOH recommended that approximately 1200 g of hot mix asphalt be used to achieve the desired 63.5 mm high samples. It was determined through trial and error that 1150 g of aggregates produced 63.5 mm sample heights. Samples heights changed slightly from the varying asphalt cement content but not enough to require changing the aggregate quantity. For the 152 mm samples, 3950 g of aggregate were used in the mix to achieve the target 95.25 mm sample height.

The asphalt cement used in all testing was performance grade PG64-22 produced by Ashland Petroleum Company. Greer Limestone, Sabraton, WV, donated the asphalt cement. The proper mixing temperature and compaction temperatures were determined from a temperature viscosity chart obtained from Ashland Petroleum Company. ASTM D 1559 specifies a viscosity during mixing of 170 ± 20 cSt. and a viscosity of 280 ± 30 cSt. for compaction. This corresponds to 153°C to 159°C and 142°C to147°C for asphalt cement used in this project (Figure 4.5). The asphalt cement was heated to 158°C for mixing.

The aggregates were heated in an oven to 170°C as were the mixing tools, bucket, and mixing paddle. When items were heated to their proper temperatures, the asphalt cement and aggregate were mixed in accordance with the methods stated in the previous chapter. Each day the first batch in the bucket mixer was used to “butter” the bucket and paddle and was

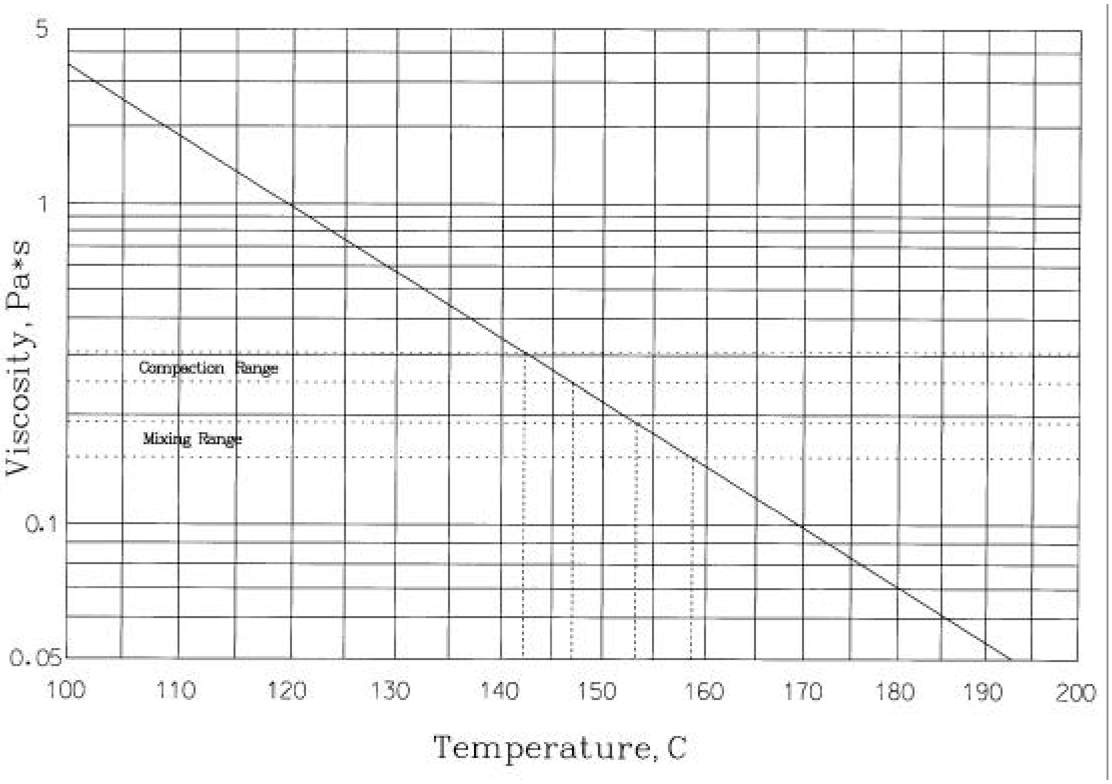

Figure 4.5. Temperature-viscosity Curve for Asphalt Cement Used in the Research

discarded. Once the aggregates were thoroughly coated, the mixture was re-heated in the oven an hour. The molds and tools were heated to 170°C. The material was placed in the proper size mold, and spade along the inner edge of the mold 15 times and 10 times in the middle of the sample. For the 152 mm mold, the material was added in two lifts and the spading was applied to each lift.

The specimen was then compacted. For the 102 mm molds, the samples were compacted with a standard hammer. The hammer was mechanically lifted and dropped 75 times. The specimen was turned over and another 75 blows were applied. For the 152 mm samples, 112 blows were applied to each side with the 10.2 kg hammer. Once the samples were compacted they were set in front of a fan to cool. When cool to the touch, the sample was extracted from the mold and allowed to cool to room temperature.

Mixes were made at five asphalt contents for each mix type; one at the estimated optimum asphalt content, at 0.5 percent above and 0.5 percent below the estimated optimum asphalt content, and at 1.0 percent above and 1.0 percent below the estimated optimum asphalt content. The Greer Asphalt plant was contacted to obtain an estimate of the optimum asphalt content. For Base 1, Base 2 and Wearing 1 the recommended asphalt contents were 3.9, 4.6, and 5.5 percent, respectively. For the trial mix design the, for Base 1, Base, 2 and Wearing 1 the estimated optimum asphalt contents were 3.5, 4.5, and 5.5 percent, respectively.

4.4 SPECIMEN TESTING

4.4.1 Specific Gravity

The bulk specific gravity of the specimen was determined in accordance with ASTM D 2726. The specimen was cooled to room temperature and weighed. The specimen was hung from a scale and immersed in a water bath at 25±1°C for three to five minutes. The weight of the specimen in water was then recorded. The sample was removed from the water bath, surface dried with a towel and weighed again. The bulk specific gravity, G_{mb}, was determined as:

$$G_{mb} = \frac{A}{B - C} \tag{4.2}$$

Where:

A = Dry weight of specimen, grams

B = Surface Dried weight of specimen, grams

C = Weight of specimen in water, grams

The unit weight of the specimen was calculated by multiplying the bulk specific gravity by the unit weight of water. The averages of the three specimens were the values recorded for unit weight and bulk specific gravity.

4.4.2 Stability and Flow

Once the bulk specific gravity was determined, the heights of the samples were measured. Following the height measurement the 102 mm specimens were immersed in a water bath at 60°C for 35±5 minutes while the 152 mm specimens were immersed for 45±5 minutes. A specimen was removed from the water bath and quickly placed in the Marshall loading head and then into a Pine Instrument Company brand Marshall stability apparatus. The Marshall apparatus deformed the specimen at a constant rate of 50.8 mm per minute. The apparatus automatically plotted load versus specimen deformation. Stability was identified as the maximum load sustained by the sample. Flow was the deformation at maximum load. The stability values were then adjusted with respect to sample height using the equations:

$$A = \frac{B}{0.252C - 0.6016} \tag{4.3}$$

$$D = \frac{E}{0.0174 * F - 0.6594} \tag{4.4}$$

Where :

A= Adjusted 102 mm Sample Stability

B= 102 mm Sample Stability

C= Sample Height

D= Adjusted 152 mm Sample Stability

E= 152 mm Sample Stability

F= Sample Height

These functions were developed by regression analysis of the correction factors given in ASTM D 1559 and ASTM D 5581.

4.4.3 Maximum Theoretical Specific Gravity

The maximum theoretical specific gravity of each mixture was determined in accordance with ASTM D 2041. After the sample was properly mixed, it was spread on a table and allowed to cool. The clumps of fine aggregate materials were then broken into particles ¼ inch in diameter or smaller. Following separation of the coated fine and coarse aggregate particles, the sample was weighed and then placed into a pycnometer and submerged in water at a temperature of 25±1°C. The sample was subjected to a vacuum of 30 mmHg for 15 minutes while the pycnometer was adgetated on a vibrating table. The pycnometer was then filled completely with water and the pycnometer and contents were weighed. The maximum theoretical specific gravity, G_{mm}, was calculated as:

$$G_{mm} = \frac{A}{A+B+C} \tag{4.5}$$

Where:

A = Weight of Dry Sample, grams

B = Weight of pycnometer completely filled with water, grams

C = Weight of pycnometer filled with water and sample, grams

4.4.4 Voids Analysis

The percent air voids, or voids in the total mix (VTM), in the compacted mixtures was found in accordance ASTM D 2041. Percent air voids is the air voids in the compacted sample expressed as a percentage of the total volume of the sample. Percent air voids was computed as:

$$VTM = \left(\frac{A-B}{A}\right)100 \tag{4.6}$$

Where:

A = Average bulk specific gravity of three specimens

B = Maximum theoretical specific gravity of the mixture

The percent voids in the mineral aggregate (VMA) is the volume of space between the aggregate particles (air voids of the compacted mixture) plus the volume of the asphalt not absorbed into the aggregates. Percent voids in the mineral aggregate was computed as:

$$VMA = 100 - \left(\frac{A*B}{C}\right) \tag{4.7}$$

Where:

A = Average bulk specific gravity of compacted mixture

B = Percent by weight of aggregate mixture

C = Bulk specific gravity of combined aggregate

The percent voids filled with asphalt (VFA) is the percentage of the VMA that is made up of asphalt. The percent voids filled with asphalt was calculated using the following relationship:

$$VFA = \left(\frac{VMA - VTM}{VMA} \right) * 100 \tag{4.8}$$

4.5 MIX DESIGN RESULTS

Once the optimum asphalt contents for the three mix designs were determined the percent air voids, bulk specific gravity, stability, flow, and VMA were compared to the values required by WVDOH. The properties of the Wearing 1 mixture were acceptable except for the VMA. For a mix with a maximum aggregate size of 9.5 mm, the minimum VMA is 15 percent. Depending on the analytical method used, the VMA was low by 2.1 to 2.75 percent. The Base 2 mix met all criteria except for VMA. The VMA for the mix was low by 1.4 percent. The Base 1 mix met all WVDOH specifications. The VMA specification for a mixture with a maximum aggregate size of 37.5 mm was 11 percent and the mix had a VMA of 11.0 to 11.1 percent. In proportioning a mixture for constructed, the Base 1 mix might be redesigned however, because the scope of this study was focused on the test variability the Base 1 mix design was accepted. Since the Wearing 1 and Base 2 did not meet the VMA criteria, they were redesigned.

Alterations were first made to the Wearing 1 mixture. The gradation originally used was altered slightly (Figure 4.6). A greater amount of the large aggregates was used assuming this would increase the VMA. However, samples made with the new gradation showed only a slight change in VMA; not enough to meet the specifications. Greer Limestone was contacted to determine the gradation they used for each of the mixes. The Greer Limestone gradation was more uniformly graded than the mixes previously attempted at the WVU laboratory (Figure 4.7). The Wearing 1 gradation used by Greer Limestone had 5 percent of the aggregate retained on the 9.5 mm sieve. The Greer Limestone gradation was evaluated. The VMA was under specification but very close to the minimum limit. One last attempt was made to find a gradation that would provide a suitable VMA. A more exaggerated uniformly graded blend was used while staying within WVDOH and SUPERPAVE specifications (Figure 4.8). At four percent air voids the VMA was greater than the required 15 percent but the percent air voids versus percent asphalt showed that the asphalt content was close to 10

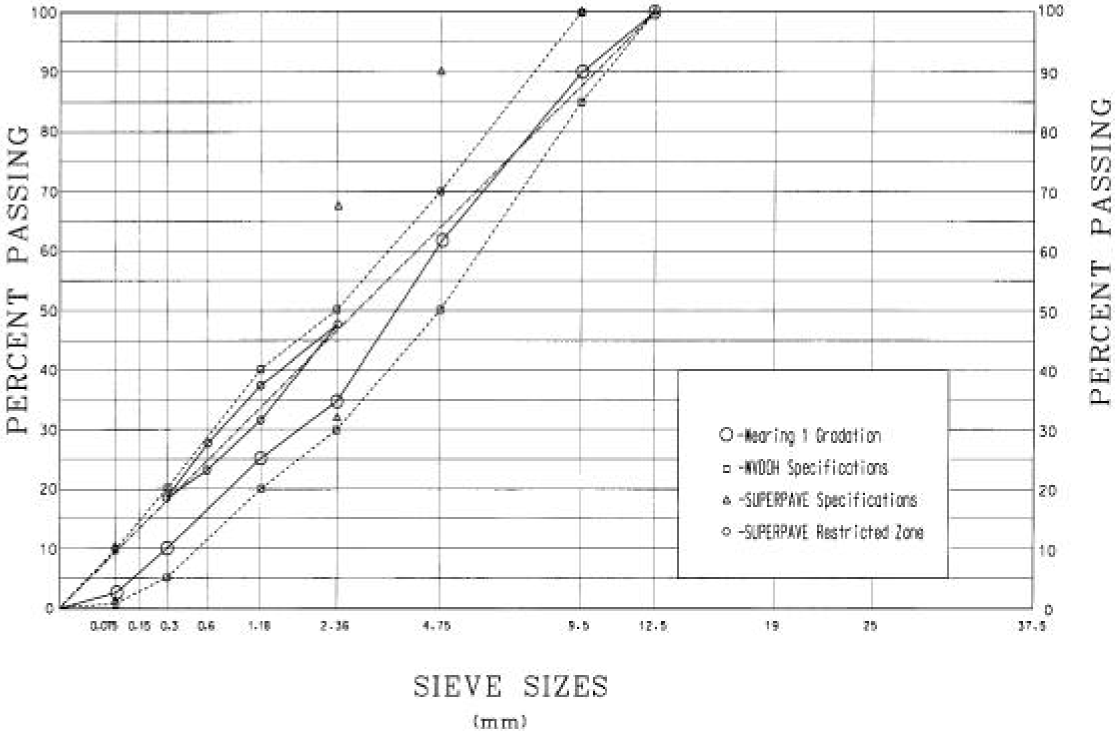

Figure 4.6. Second Gradation Attempt for Wearing 1

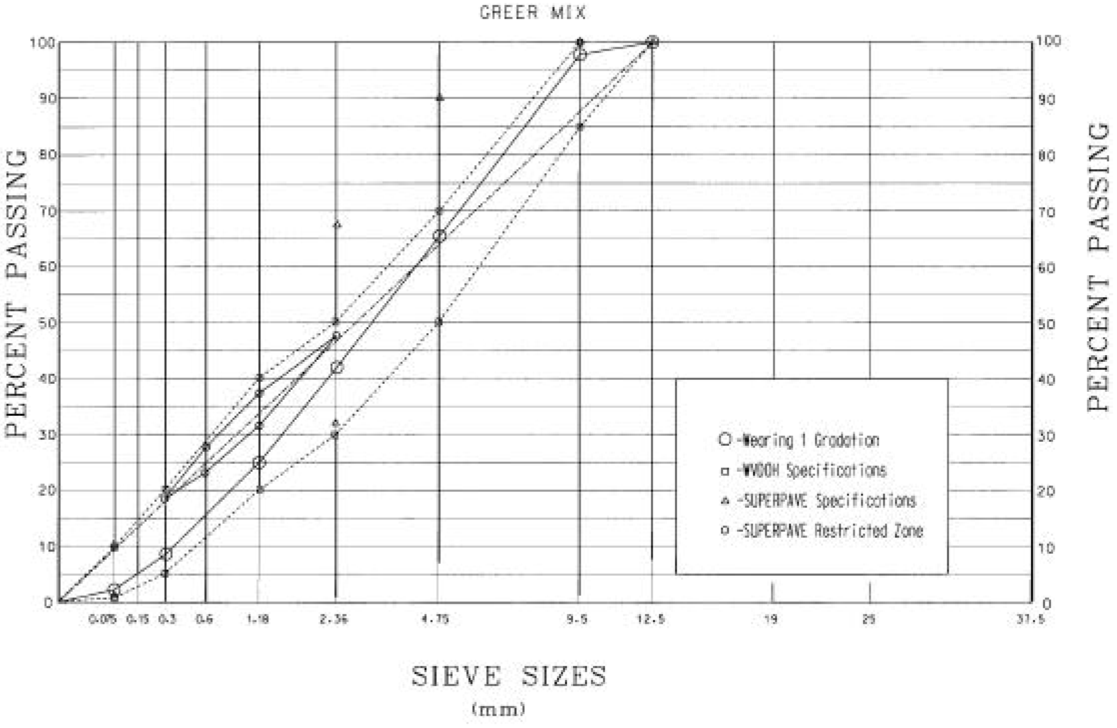

Figure 4.7. Third Gradation Attempt for Wearing 1 (Greer Gradation)

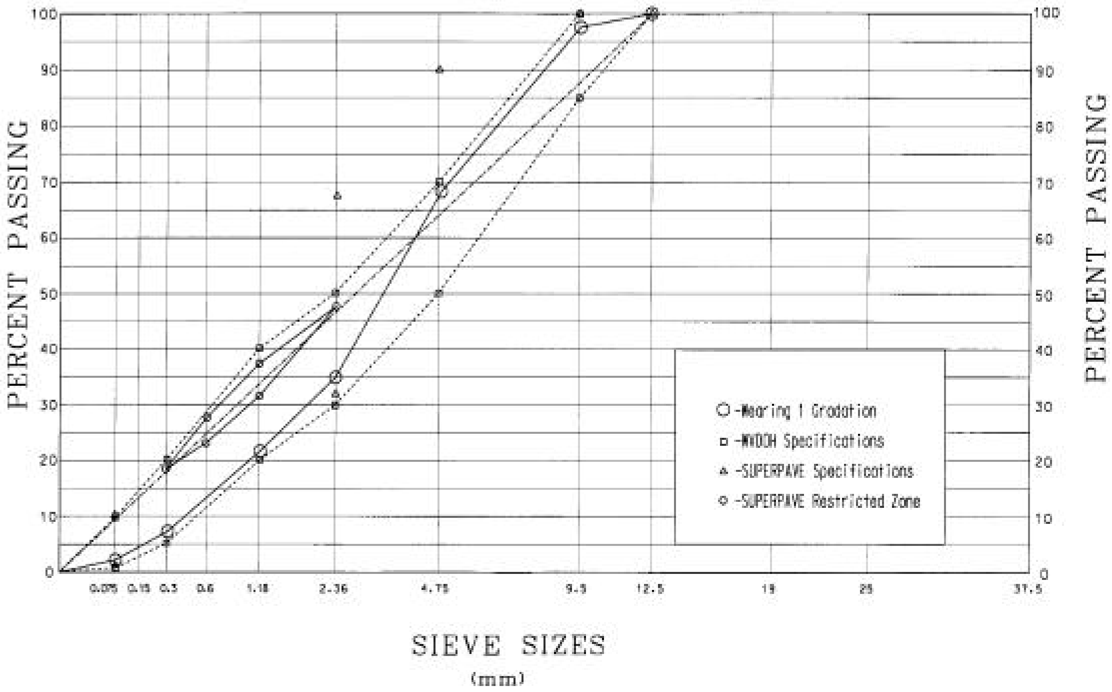

Figure 4.8. Forth Gradation Attempt for Wearing 1

percent. The WVDOH specification allows up to 10 percent asphalt content, but this would not be an economical mix and would probably fail the stability requirements.

After reviewing all four of the Wearing 1 mixes, the gradation used by Greer Limestone was selected even though it did not passed all WVDOH requirements.

The Base 2 gradation used by Greer Limestone was evaluated (Figure 4.9), even though this gradation passes through the restricted zone. However, meeting Superpave criteria was not a constraint on this project. Unfortunately, a low VMA resulted in this mixture as well. Since the Greer mixture was used for WVDOH projects, it was chosen over the initial mix design. The selected gradations are presented in Table 4.6.

The Marshall mix design charts for each of the mixes used in the balance of the research are presented in Appendix D. Even though the Wearing 1 and Base 2 failed the VMA criteria, they passed all of the other WVDOH criteria. Since the objective of this project is to evaluate the precision of the Marshall method, the failure of the selected mixes to satisfy the VMA criteria should not appreciably affect the research results.

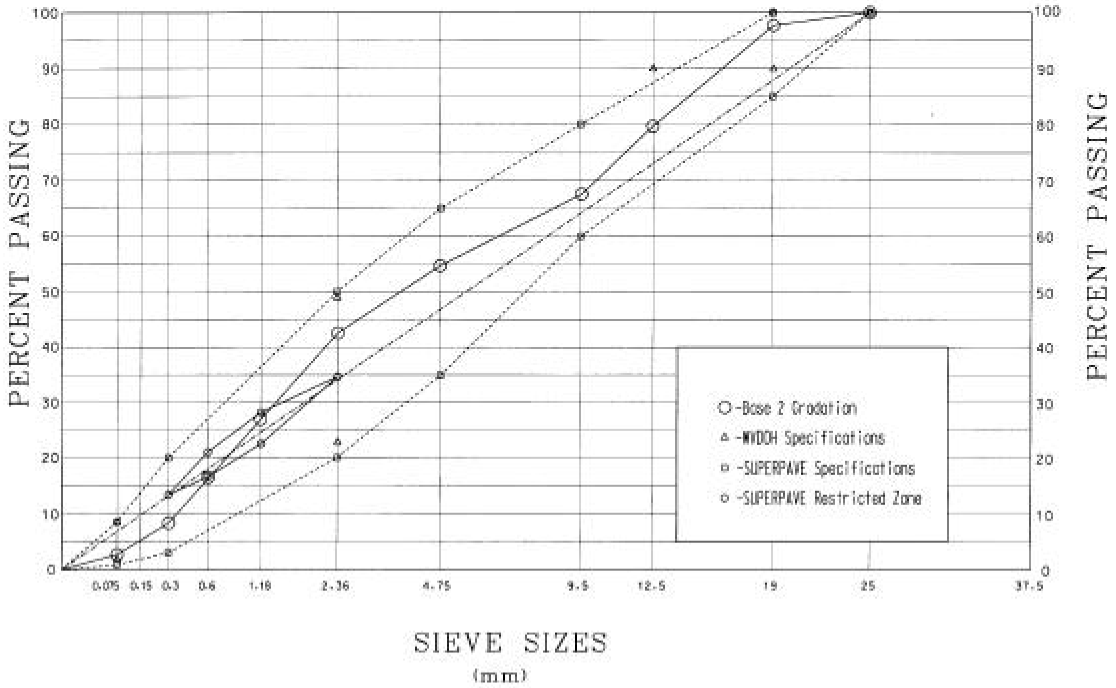

Figure 4.9. Gradation for Second Base 2 Mixture (Greer Gradation)

Table 4.6. Gradations Used in Study

Sieve Size (mm)	Percent Passing			Sieve Size (mm)	Percent Retained		
	Base 1	Base 2	Wearing 1		Base 1	Base 2	Wearing 1
50	100	-	-	50	0	-	-
37.5	90	-	-	37.5	10	-	-
25	75	100	-	25	15	0	-
19	65	97.8	-	19	10	2.2	-
12.5	55	80	100	12.5	10	17.8	-
9.5	50	67	98	9.5	5	13	2
4.75	33	54.8	66	4.75	17	12.2	32
2.36	20	40.3	43	2.36	13	14.5	23
1.18	13	27	25	1.18	7	13.3	18
0.6	-	-	-	0.6	-	-	-
0.3	8.0	8.8	9	0.3	5	18.2	16
0.15	-	-	-	0.15	-	-	-
0.075	4	3.5	2.2	0.075	4	5.3	6.8
-	-	-	-	Pan	4	3.5	2.2

4.6 SAMPLE FABRICATION

Once the mix designs for each of the mixes were completed, the samples were fabricated and distributed to laboratories. Fourteen laboratories, including the Asphalt Technology Laboratory at West Virginia University, all ten WVDOH District material laboratories, the central materials laboratory, and the Greer Limestone, and West Virginia Paving laboratories, participated in the study.

All asphalt cement and aggregates for this research were obtained from Greer Limestone in Clarksburg, WV. Samples were mixed in a bucket mixer at the Asphalt Technology Laboratory ant West Virginia University. Aggregates were heated to the mix temperature. The asphalt cement was kept at a constant temperature of 158°C in a pour pot.

Aggregates were weighed out in each sieve size to the proper amount specified for that aggregate gradation. All aggregates passing the 19 mm sieve were weighed to ±0.1 g. All aggregates passing the 37.5 mm sieve but retained on the 19 mm sieve or higher were weighed to ±1 g. Any aggregate retained on the 37.5 mm sieve was weighed to ±2 g. The scale used for weighing the asphalt cement would not allow for measurements more accurate than ±0.1 g because of the weight of the bucket and aggregate also being weighed.

Base 1 mixes were fabricated first followed by Wearing 1 and then Base 2 mixes. The order in which the mixtures were made was deemed insignificant since comparisons of the variability between different mixture types were not the focus of this project. Only variability between the same type mixes was evaluated.

Originally, four specimens were to be sent to each laboratory for each of mix type. Three of the samples were to be compacted and tested for voids, stability, and flow for each mixture type. The fourth sample was to be used to determine maximum theoretical specific gravity. After the Base 1 mixing was started, it was decided that two maximum theoretical specific gravity tests should be performed to provide data on the within laboratory variability. This created a problem because additional containers had to be ordered and would not arrive in time to finish all of the Base 1 mixes at one time. For this reason 60 of the Base 1 samples were prepared initially. The remaining Base 1 samples were prepared after the Base 2 and Wearing 1 samples were mixed. .

The samples were placed in shipment containers and labeled. The samples were randomly selected for each laboratory except for those used by the Asphalt Technology Laboratory at WVU. The samples sent to each laboratory are identified in Appendix E. The samples tested at WVU were prepared after the samples were shipped to the other laboratories. If significant differences occurred in the results then all of the results for the WVU laboratory would be disregarded since there was the potential for a bias in the sample preparation due to these samples not being randomly selected.

4.7 SPECIMEN DISTRIBUTION

Two days after all of the samples were mixed the samples were mailed to the laboratories. Instructions were also included with a cover letter, giving the compaction temperature range and explanation of the code on each can. The package also included a survey form with brief questions concerning the equipment and technician. A copy of the letter, survey form, and data sheets are included in Appendix F.

After all of the samples were sent to the laboratories, each laboratory was contacted to review the project requirements. The laboratories were also asked to return the results of the tests within two weeks of receiving the samples. In response to questions from the technicians at the laboratories, it was necessary to provide additional testing information requiring (1) compacting the samples for a heavy traffic design, (2) use of the dryback method for the maximum theoretical specific gravity test and (3) compaction of the samples at the middle temperature of the allowable range..

CHAPTER 5

DATA ANALYSIS AND RESULTS

5.1 INTRODUCTION

The 14 laboratories returned the data within one month. The raw data were consolidated into six tables presented in Appendix E. From this raw data the stability, flow, unit weight and percent air voids were calculated and tabulated in Appendix G. These data were analyzed in accordance with ASTM Standard C 802, “Conducting an Inter-laboratory Test Program to Determine the Precision of Test Methods for Construction Materials.”

Once all of the data from this experiment were analyzed, select data from the literature review were analyzed and compared to the data from this study. Finally, the data were evaluated for correlation between different characteristics of the participating laboratories and technicians. These characteristics were obtained through the survey form distributed with the samples. The survey form is included in Appendix F.

5.2 TEST FOR OUTLIERS

ASTM C 802 specifies that no data may be ruled as an outlier in an inter-laboratory study unless an assignable cause is identified. For this reason, in the first stage of the data analysis only two results were discarded. The two discarded values came from the District 1 maximum theoretical specific gravity tests. When analyzed, these data indicated specific gravity for two samples of asphalt concrete were 0.997 and 1.013. The laboratory technician was contacted to see if he could locate the source of the error but a cause could not be identified. Since these two values obviously resulted from a gross blunder, they were discarded. Since the calculation of percent air voids is dependent on the maximum theoretical specific gravity, the Wearing 1 percent air voids results from the District 1 laboratory were discarded as well.

5.3 PRELIMINARY DATA ANALYSIS

The next stage in the research was to calculate the within-laboratory average and variance for each characteristic of the three replicates. These results are presented in Tables 5.1, 5.2, and 5.3.

The variability of the three mix types was calculated and investigated for agreement of variances. To find out if the range of variability was too great, the ratio of the highest variance to the average variance was compared to a standard value in ASTM C 802. The standard value represents a 95 percent confidence interval of how large this ratio should be for 14 laboratories and three replicate samples.

It can be seen in Table 5.4 that several samples did not meet the ASTM C 802 criteria. The Wearing 1 and Base 2 samples did not fit the criteria in 4 out of the 5 characteristics. In fact, the maximum theoretical specific gravity was the only parameter where the fluctuation in the variability between laboratories was within the expected range for the Base 2 and Wearing 1 mixes.

ASTM C 802 also recommends testing to determine if the range of variability is extraordinarily low by comparing the ratio of the highest variance to the lowest variance. This ratio is compared to a standard value that represents a 95 percent confidence interval of how large this ratio should be. The low variability test determines if a laboratory has constrained the natural variability that is expected to occur. The Base 1 and Base 2 mixes failed this check for the maximum theoretical specific gravity. The Wearing 1 mix failed the criteria for the bulk specific gravity and percent air voids.

It is interesting to note that the Wearing 1 material failed both the low and high variability tests for the bulk specific gravity and the percent air voids. This is possible since the statistical tests are performed on different variability parameters. However, it does indicate that there are very unusual variability occurrences in the data set.

Multiple failures of the high variance test is a major concern. Large fluctuations in the variability indicate the test procedure is not stable. Looking at Figures 5.1 to 5.15 the nature of the variability can be more closely investigated. These charts demonstrate that of the nine

Table 5.1. Base 1 Within-laboratory Averages and Standard Deviations

Laboratory		Rice Specific Gravity		Stability (N)		Flow (0.25 mm)		Bulk Specific Gravity		Percent Air Voids	
		$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
District	1	*	*	15382	2745	9.33	0.722	2.427	0.0053	*	*
District	2	2.490	0.0001	13607	1464	9.60	0.347	2.408	0.0054	3.3181	0.210
District	3	2.485	0.0021	7495	2528	13.27	1.182	2.278	0.0054	8.3395	0.209
District	4	2.481	0.0004	14353	2123	10.83	0.389	2.407	0.0039	3.0052	0.153
District	5	2.494	0.0254	11503	144	11.25	0.292	2.374	0.0062	4.7992	0.241
District	6	2.484	0.0022	12961	3074	11.33	2.056	2.377	0.0055	4.2960	0.215
District	7	2.472	0.0091	12424	1391	13.00	15.167	2.399	0.0083	2.9512	0.327
District	8	2.486	0.0022	11249	511	10.00	0.500	2.386	0.0070	4.0209	0.272
District	9	2.484	0.0003	14419	1922	9.83	0.222	2.385	0.0153	3.9862	0.597
District	10	2.480	0.0005	15889	3915	9.58	0.347	2.362	0.0176	4.7421	0.244
Central		2.490	0.0021	12677	1264	10.33	0.056	2.403	0.0106	3.4924	0.224
Greer		2.481	0.0016	11883	1390	9.33	0.389	2.392	0.0177	3.6169	0.074
WV Paving		2.484	0.0010	10120	663	13.37	0.202	2.354	0.0163	5.2111	0.372
WVU		2.490	0.0014	14243	509	9.67	0.056	2.403	0.0078	3.5145	0.106

$\bar{x}$ = mean
s = standard deviation

Table 5.2. Base 2 Within-laboratory Averages and Standard Deviations

Laboratory		Rice Specific Gravity		Stability (N)		Flow (0.25 mm)		Bulk Specific Gravity		Percent Air Voids	
		$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
District	1	*	*	15382	903	9.33	0.722	2.427	0.0061	*	*
District	2	2.490	0.0001	13607	625	9.60	0.347	2.408	0.0052	3.3181	0.206
District	3	2.485	0.0006	7495	2285	13.27	1.182	2.278	0.0301	8.3395	1.193
District	4	2.481	0.0007	14353	378	10.83	0.389	2.407	0.0074	3.0052	0.293
District	5	2.494	0.0003	11503	1340	11.25	0.292	2.374	0.0018	4.7992	0.071
District	6	2.484	0.0007	12961	965	11.33	2.056	2.377	0.0045	4.2960	0.178
District	7	2.472	0.0000	12424	1591	13.00	15.167	2.399	0.0078	2.9512	0.308
District	8	2.486	0.0003	11249	466	10.00	0.500	2.386	0.0042	4.0209	0.165
District	9	2.484	0.0020	14419	518	9.83	0.222	2.385	0.0041	3.9862	0.161
District	10	2.480	0.0002	15889	1123	9.58	0.347	2.362	0.0051	4.7421	0.571
Central		2.490	0.0012	12677	548	10.33	0.056	2.403	0.0047	3.4924	0.343
Greer		2.481	0.0005	11883	590	9.33	0.389	2.392	0.0015	3.6169	0.572
WV Paving		2.484	0.0018	10120	1046	13.37	0.202	2.354	0.0078	5.2111	0.527
WVU		2.490	0.0015	14243	821	9.67	0.056	2.403	0.0022	3.5145	0.254

$\bar{x}$ = mean
s = standard deviation

Table 5.3. Wearing 1 Within-laboratory Averages and Standard Deviations

Laboratory	Rice Specific Gravity		Stability (N)		Flow (0.25 mm)		Bulk Specific Gravity		Percent Air Voids	
	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
District 1	*	*	15382	270	9.33	0.722	2.427	0.0518	*	*
District 2	2.490	0.0006	13607	344	9.60	0.347	2.408	0.0083	3.3181	0.334
District 3	2.485	0.0003	7495	3425	13.27	1.182	2.278	0.0699	8.3395	2.775
District 4	2.481	0.0027	14353	619	10.83	0.389	2.407	0.0020	3.0052	0.081
District 5	2.494	0.0001	11503	162	11.25	0.292	2.374	0.0077	4.7992	0.310
District 6	2.484	0.0006	12961	352	11.33	2.056	2.377	0.0030	4.2960	0.120
District 7	2.472	0.0028	12424	149	13.00	15.167	2.399	0.0044	2.9512	0.176
District 8	2.486	0.0003	11249	260	10.00	0.500	2.386	0.0043	4.0209	0.174
District 9	2.484	0.0006	14419	643	9.83	0.222	2.385	0.0069	3.9862	0.280
District 10	2.480	0.0021	15889	797	9.58	0.347	2.362	0.0030	4.7421	0.122
Central	2.490	0.0026	12677	299	10.33	0.056	2.403	0.0053	3.4924	0.212
Greer	2.481	0.0005	11883	250	9.33	0.389	2.392	0.0066	3.6169	0.267
WV Paving	2.484	0.0030	10120	342	13.37	0.202	2.354	0.0093	5.2111	0.374
WVU	2.490	0.0019	14243	580	9.67	0.056	2.403	0.0066	3.5145	0.265

$\bar{x}$ = mean
s = standard deviation

Table 5.4. Test for High and Low Variability

Parameter	Material	Test for High Variance Upper 5% Level (High/Sum) Must be < 0.345	Test for Low Variance Upper 5% Level (High/Low) Must be < 885
Max. Theoretical Specific Gravity	Base 1	0.298	**37195**
	Base 2	0.313	**14915**
	Wearing 1	0.220	696
Stability	Base 1	0.276	741
	Base 2	**0.783**	37
	Wearing 1	**0.826**	526
Flow	Base 1	0.266	77
	Base 2	**0.488**	*****
	Wearing 1	**0.692**	273
Bulk Specific Gravity	Base 1	0.197	20
	Base 2	**0.720**	378
	Wearing 1	**0.610**	**1201**
Percent Air Voids	Base 1	**0.336**	65
	Base 2	**0.489**	283
	Wearing 1	**0.916**	**1167**

***** Zero Variability

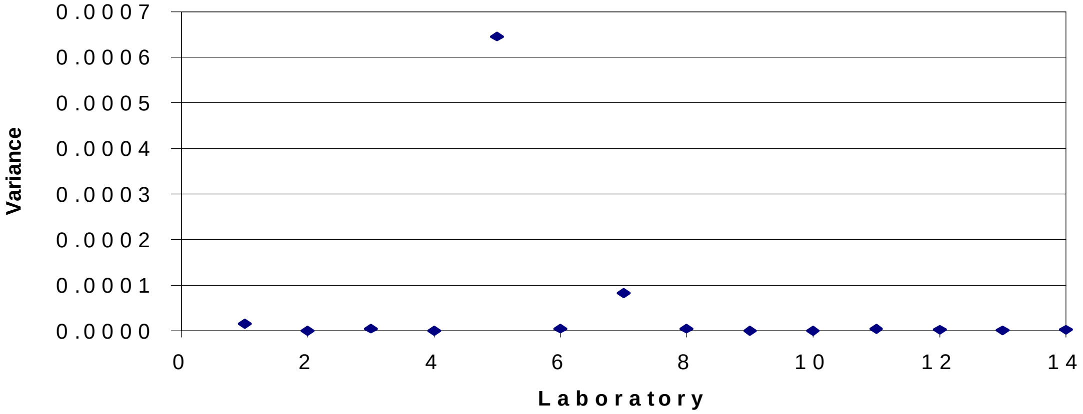

Figure 5.1. Base 1 Rice Specific Gravity Variance versus Laboratory.

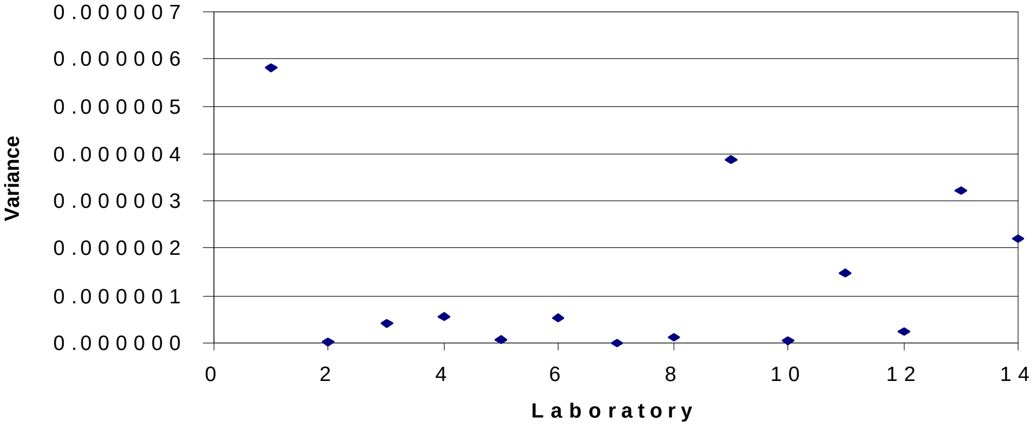

Figure 5.2. Base 2 Rice Specific Gravity Variance versus Laboratory

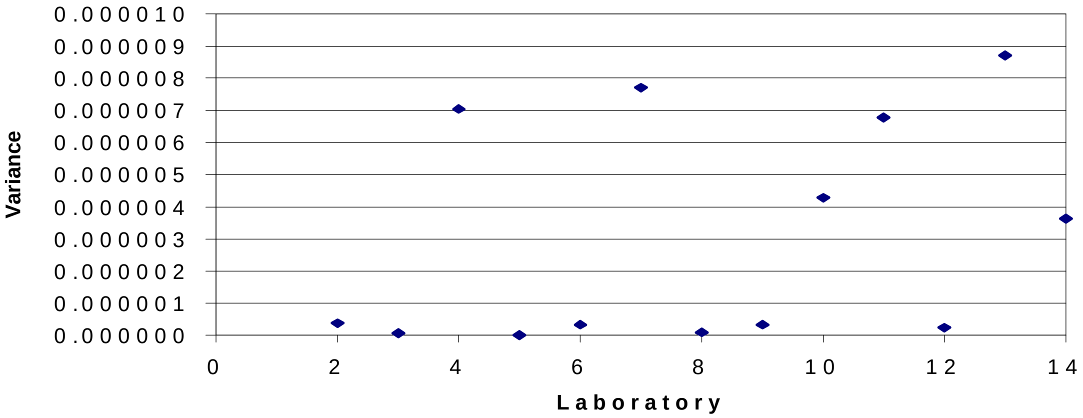

Figure 5.3. Wearing 1 Rice Specific Gravity Variance versus Laboratory

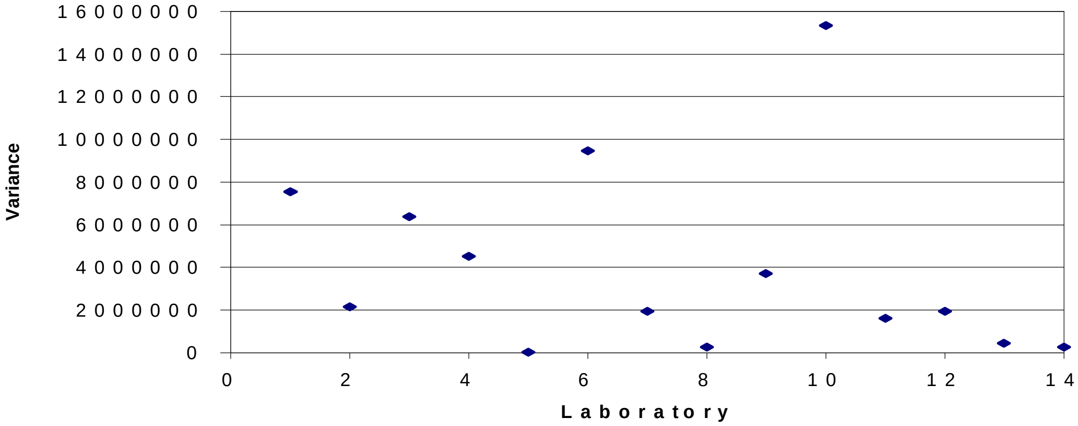

Figure 5.4. Base 1 Marshall Stability Variance versus Laboratory

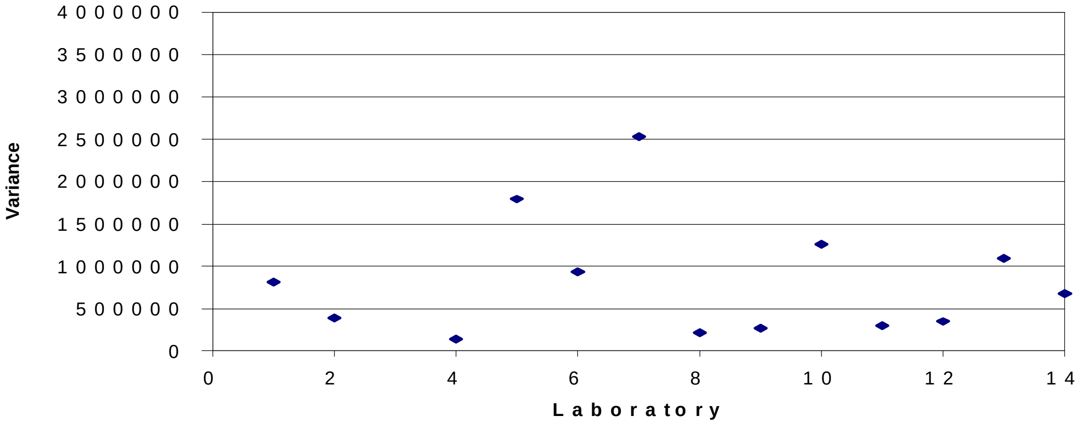

Figure 5.5. Base 2 Marshall Stability Variance versus Laboratory

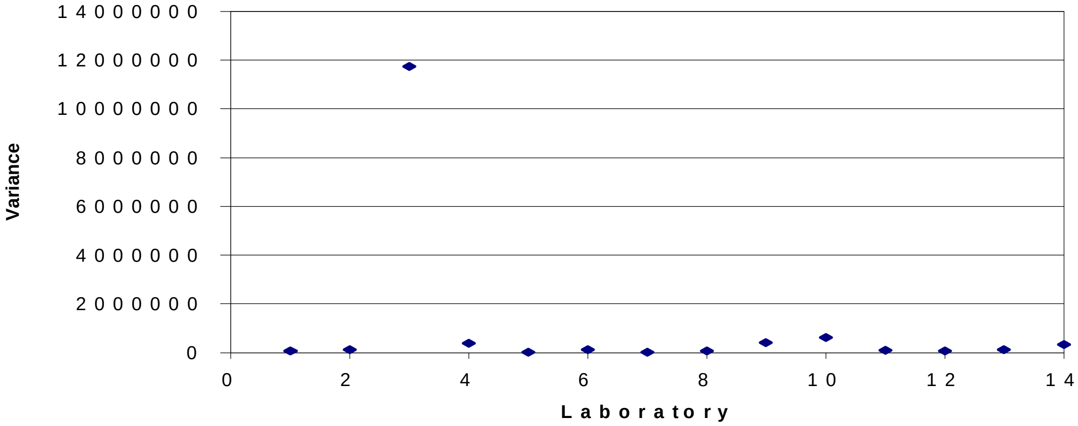

Figure 5.6. Wearing 1 Marshall Stability Variance versus Laboratory

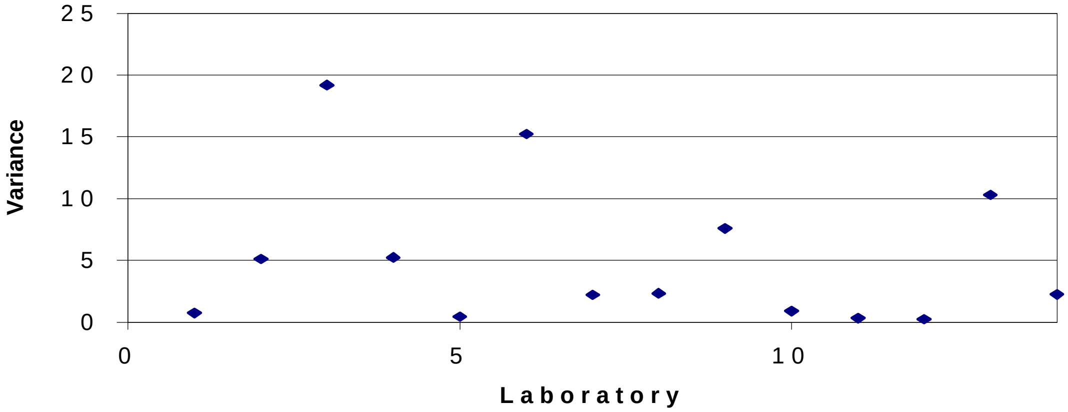

Figure 5.7. Base 1 Marshall Flow Variance versus Laboratory

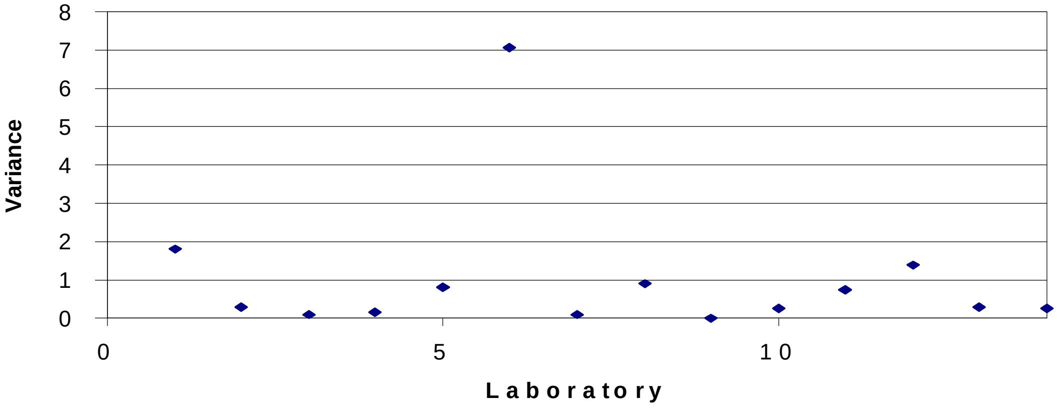

Figure 5.8. Base 2 Marshall Flow Variance versus Laboratory

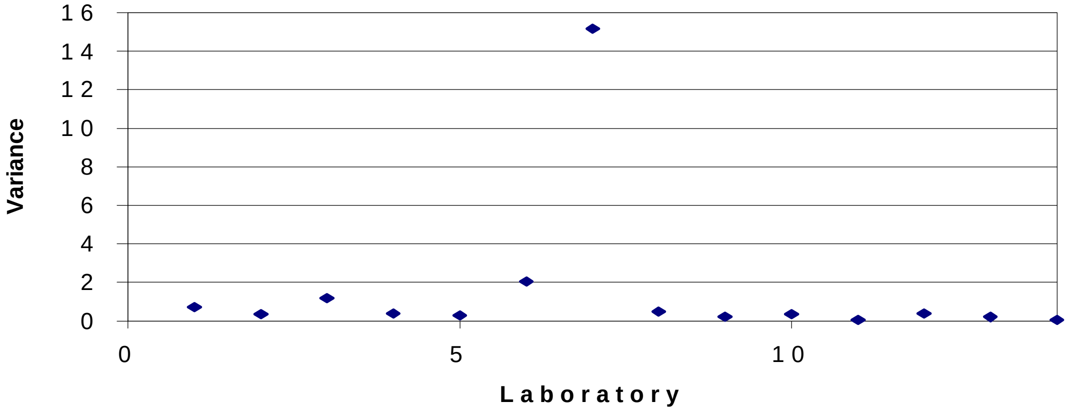

Figure 5.9. Wearing 1 Marshall Flow Variance versus Laboratory

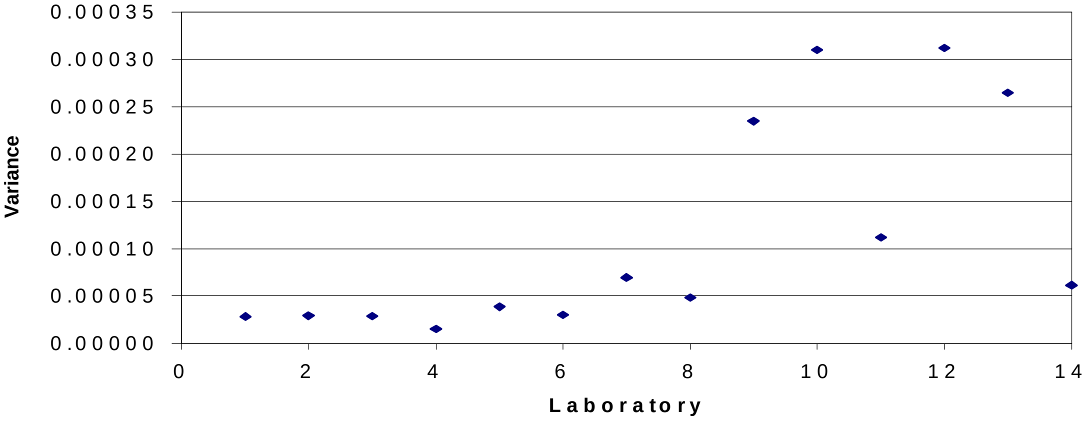

Figure 5.10. Base 1 Bulk Specific Gravity Variance versus Laboratory

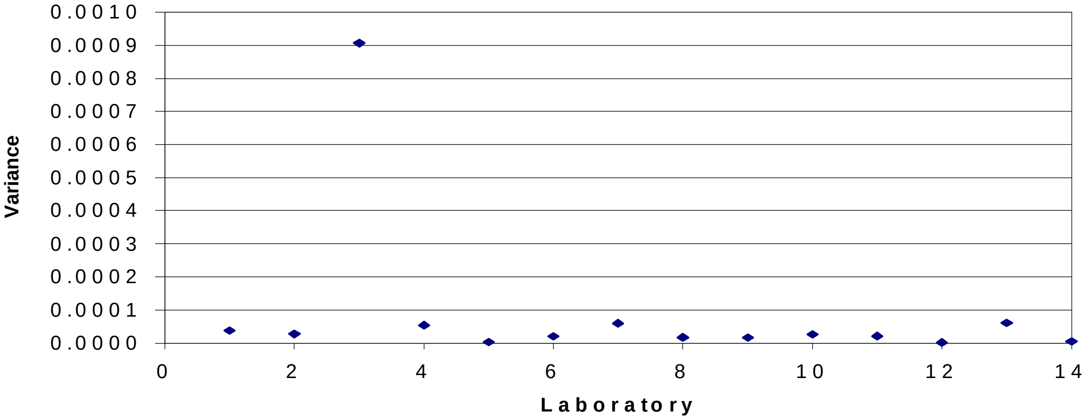

Figure 5.11. Base 2 Bulk Specific Gravity Variance versus Laboratory

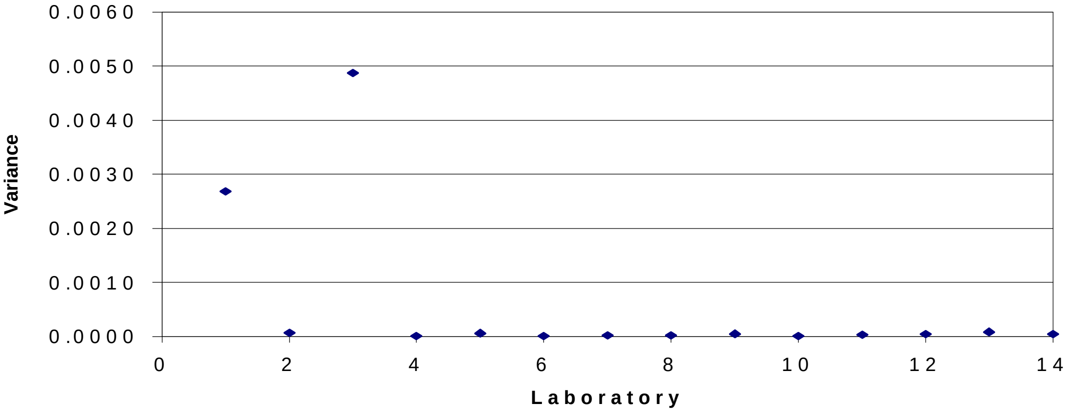

Figure 5.12. Wearing 1 Bulk Specific Gravity Variance versus Laboratory

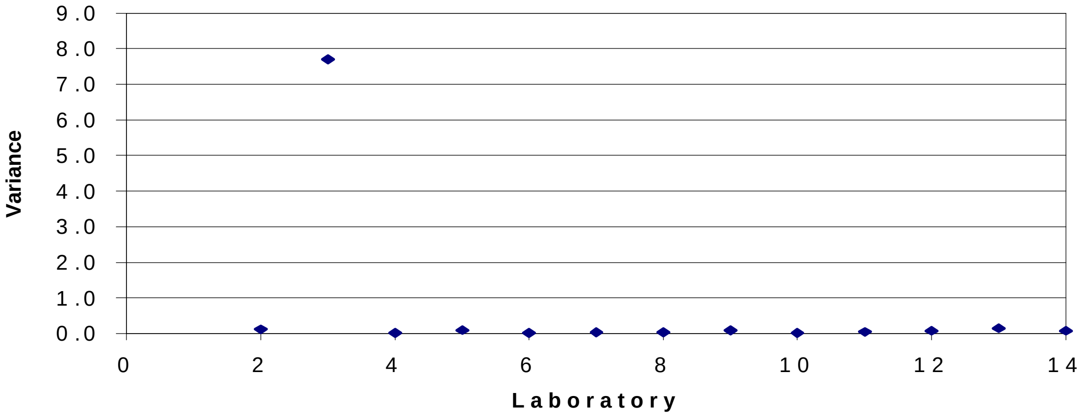

Figure 5.13. Wearing 1 Percent Air Voids Variance versus Laboratory

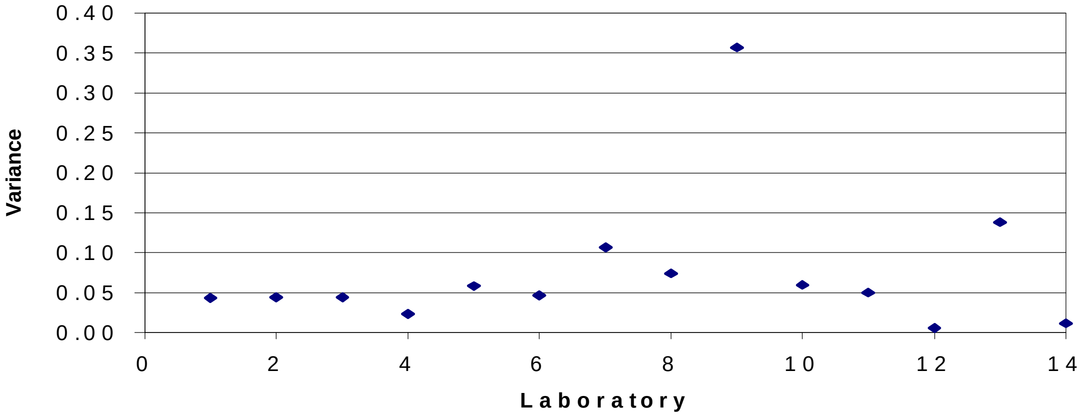

Figure 5.14. Base 1 Percent Air Voids Variance versus Laboratory

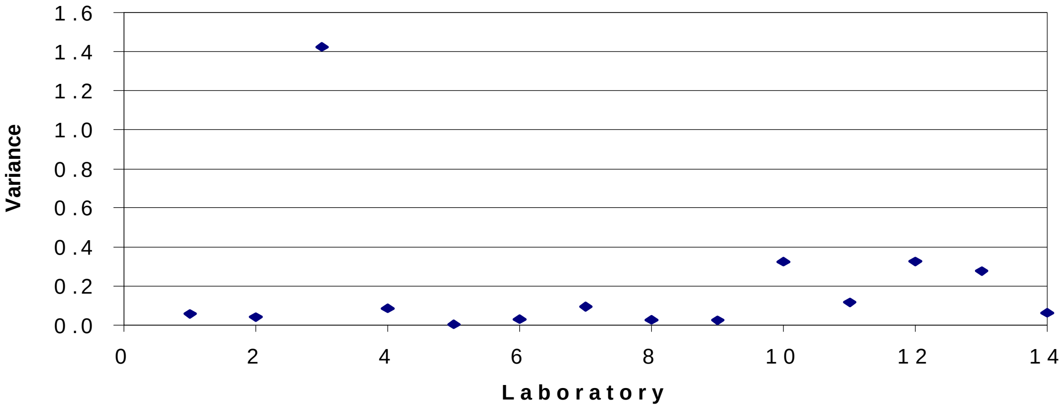

Figure 5.15. Base 2 Percent Air Voids Variance versus Laboratory

failing tests, all variance are relatively low except for one or two laboratories: six of the failures are caused by the District 3 data.

A common problem with test results from an inter-laboratory study is the presence of interactions between the laboratories and materials. This means that the pattern of change of the results obtained on a given group of materials in one laboratory differs from the pattern obtained from other laboratories (ASTM C 802). Differences in the patterns between several laboratories indicate the test method should be reevaluated. To test for interactions, five charts were made. Each chart consists of a plot of the sample property against the material type. Lines are drawn between each material for each laboratory and the slope and location of the lines are compared to the other laboratories (Figures 5.16 to 5.20). The trend lines on each of these figures should have similar slopes and magnitudes. If a line for one laboratory differs from the pattern of the other laboratories the data from that laboratory may be an outliers.

Figure 5.16 shows the maximum theoretical specific gravity from District 5 is higher than the other laboratories for all three material types. For the stability data, Figure 5.17, there seem to be two laboratories that deviate from the trend set by the other laboratories. The District 3 laboratory has a high Base 1 value but low Base 2 and Wearing 1 values. District 5 values seem to stay constant over the range of materials, with the Base 1 stability is lower than the other two mixes. Figure 5.18 shows no distinguishing trend across the flow values of the mixes. This is a strong indication that this test method does not evaluate the characteristic of the material very well. It has been known that flow tests have a significant amount of variation so this is not new information. WVDOH specifications of flow allow a wide range of flow values for this reason.

Figures 5.19 and 5.20 show reasonable agreement and similar trends for bulk specific gravity and percent air voids for all laboratories with the exception of District 3. The low bulk specific gravity and high air void content of the Base 2 and Wearing 1 samples from District 3 indicate inadequate compaction. This could be a reason the Marshall stability of these samples was relatively low, especially for the Wearing 1 samples.

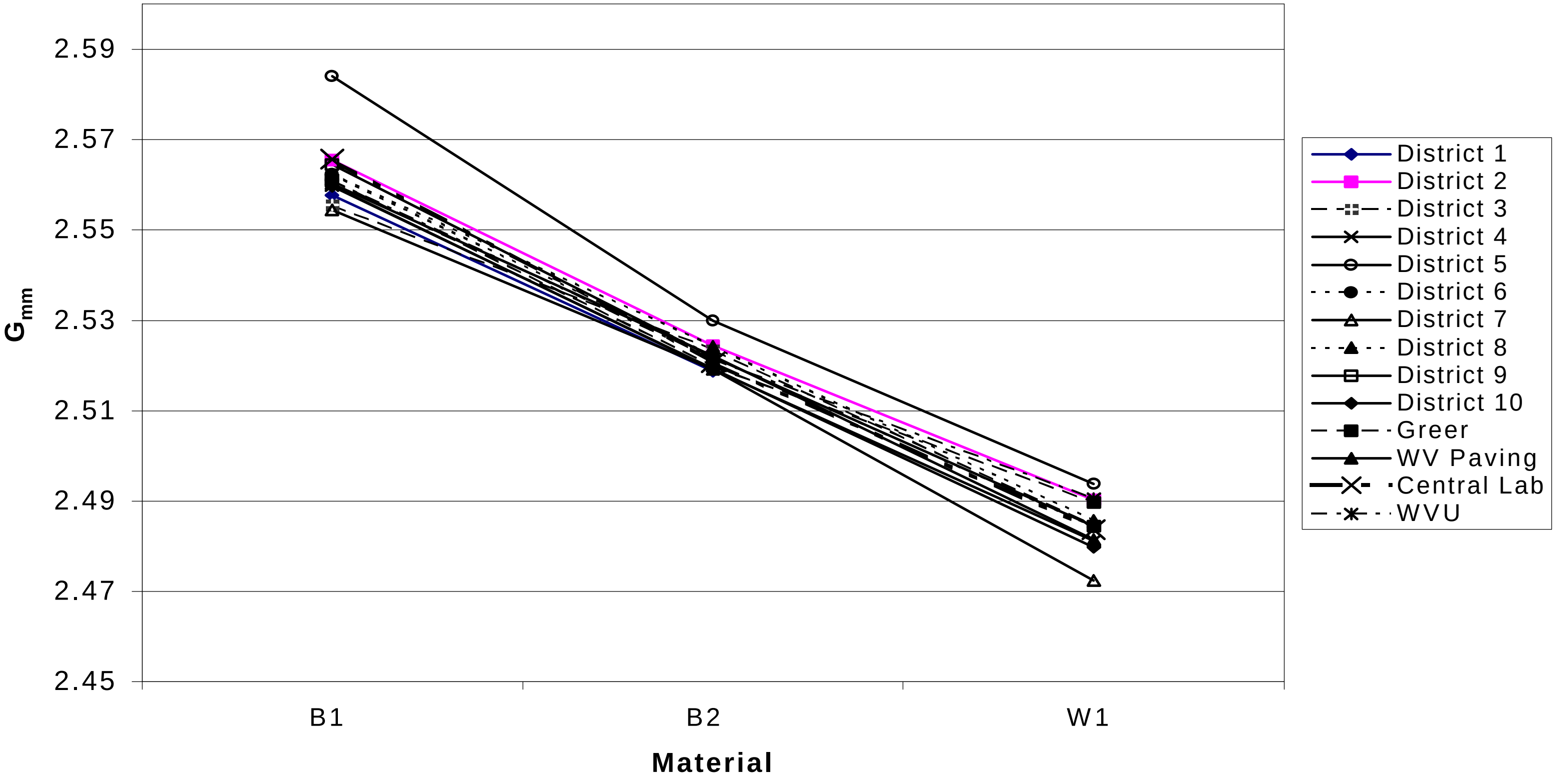

Figure 5.16. Chart of Interactions in Maximum Theoretical Specific Gravity

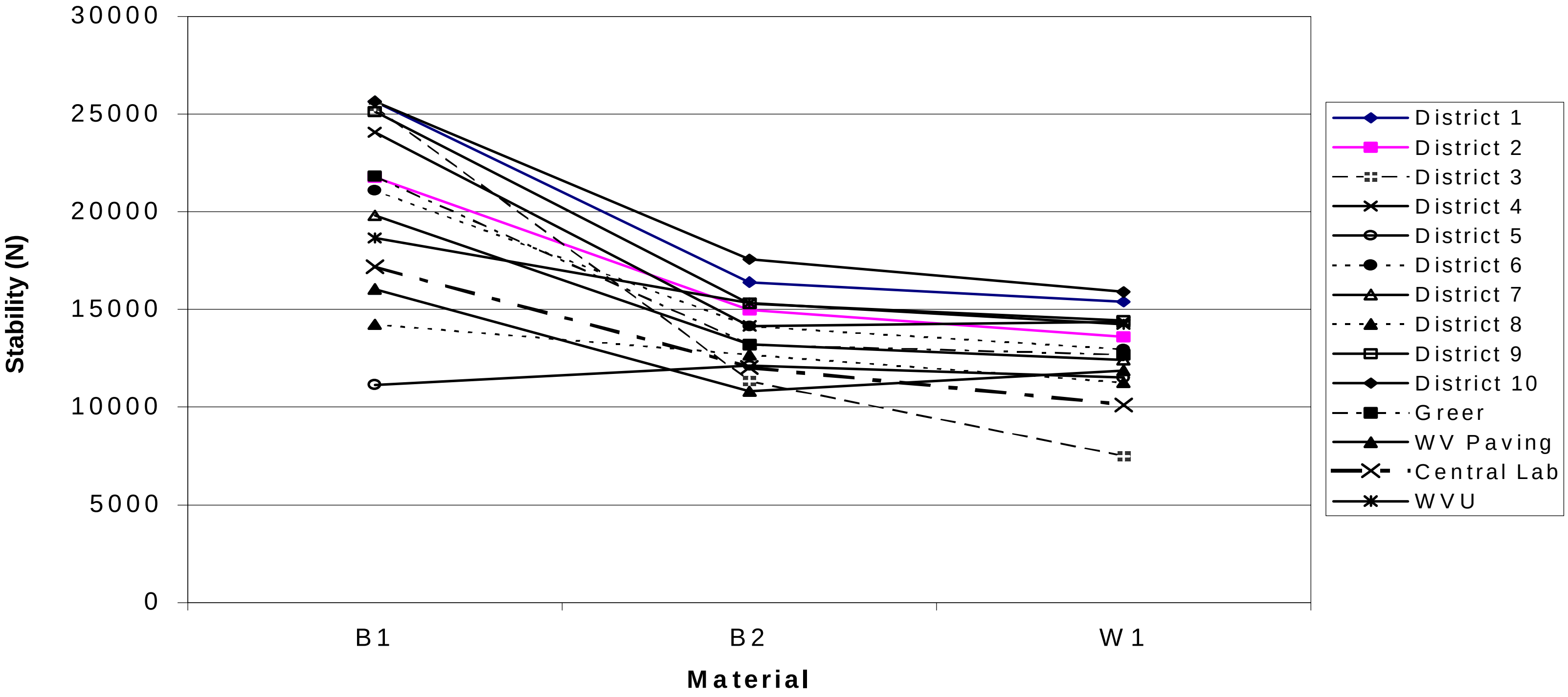

Figure 5.17. Chart of Interactions in Marshall Stability

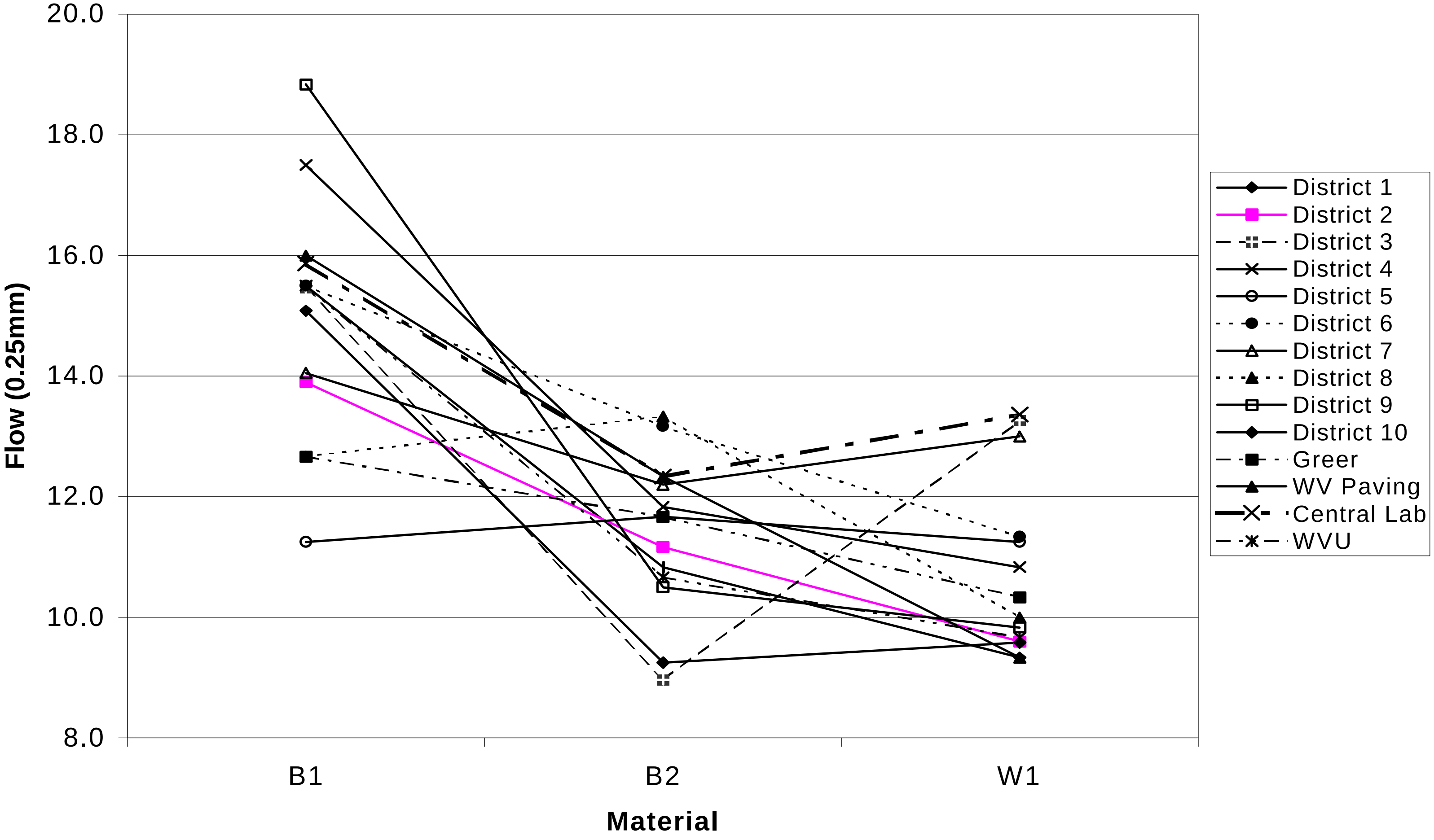

Figure 5.18. Chart of Interactions in Marshall Flow

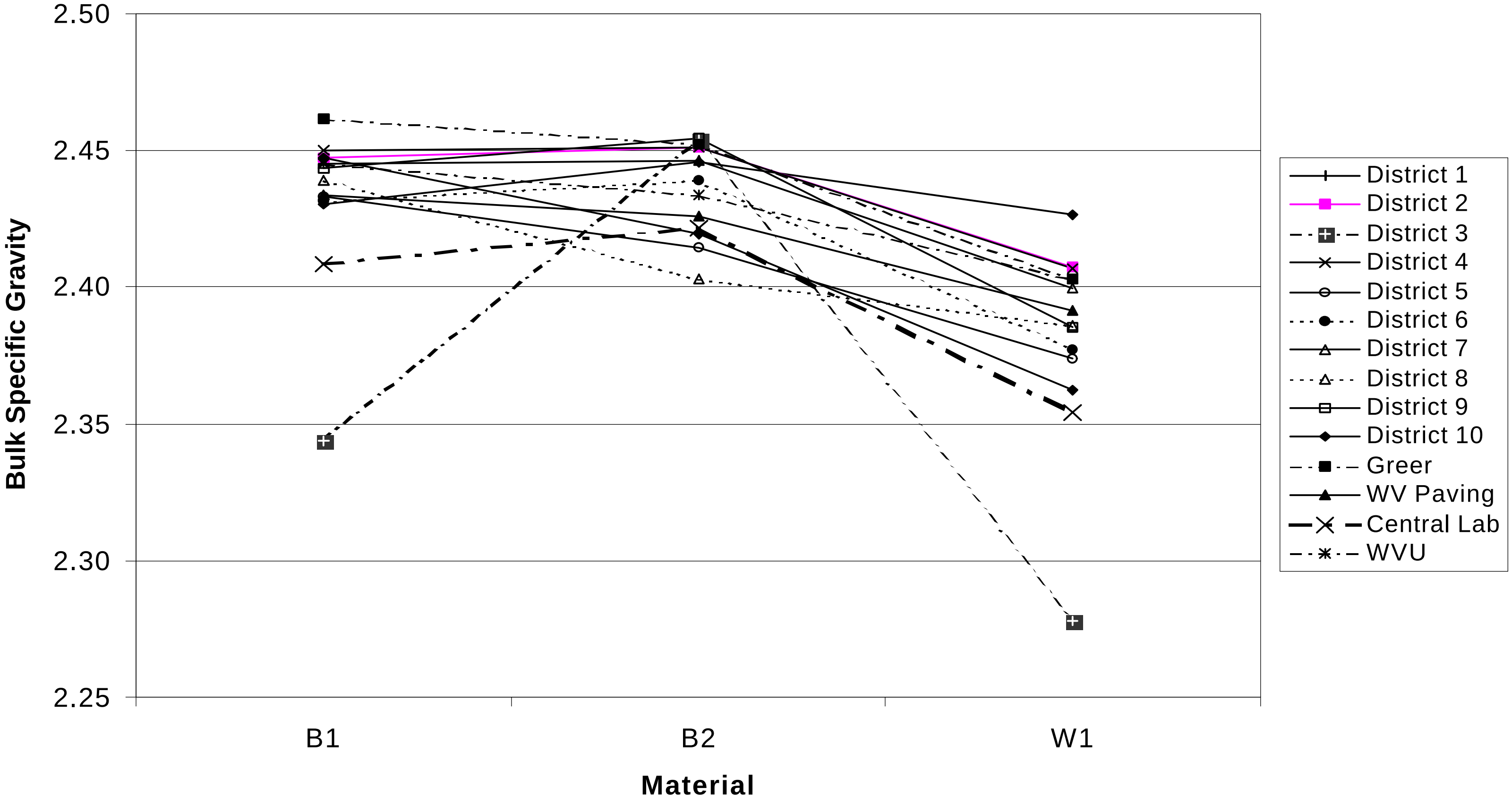

Figure 5.19. Chart of Interactions in Bulk Specific Gravity

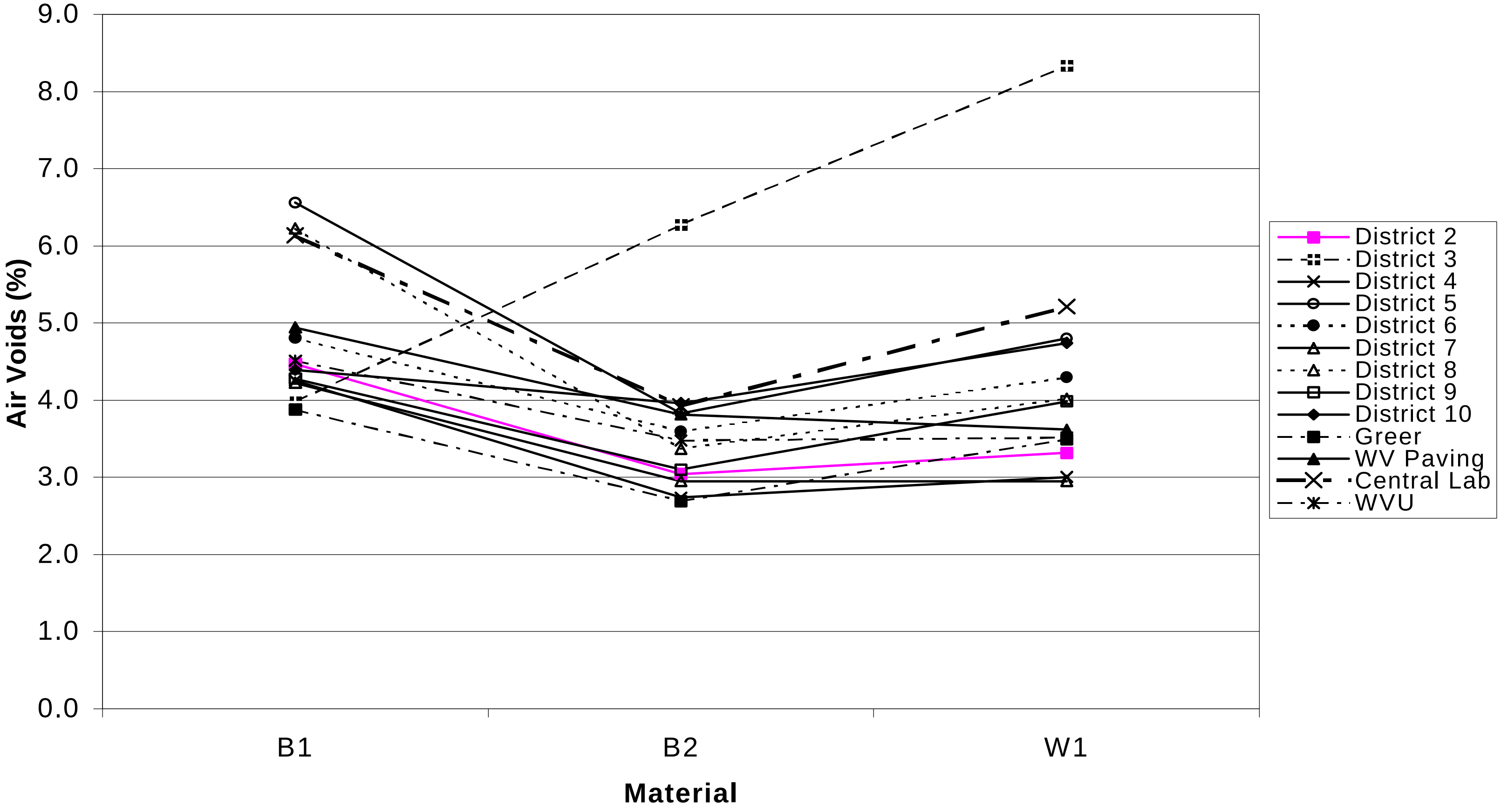

Figure 5.20. Chart of Interactions in Percent Air Voids

5.4 PRECISION PARAMETERS FOR ALL DATA

The data from all 14 laboratories were used to compute the precision parameters in Tables 5.5 to 5.9. These tables present the 1s and d2s values for the single operator and multi-laboratory analysis. The 1s values are the standard deviations associated with each analysis situation. The d2s values represent maximum range expected in the difference between two tests. There is a one in twenty chance of the difference between two properly conducted tests being greater than the d2s value. The precision parameters were computed for four situations:

1. Analysis of the individual material types,
2. Analysis pooling the variability of all data, and
3. Analysis pooling the variability of the 102 mm samples independent from the 152 mm samples, and
4. Analysis of the 152 mm samples independent from the 102 mm samples.

The first type of analysis is used for exploring the data, not for the development of precision statements. The second type of analysis represents the ideal situation where the variability in the test method is independent of material type and sample size. However, the analysis of the data demonstrated that there are significant differences in the variability of the test results based on the sample size. Therefore, the third and fourth types of analyses are needed to identify the precision of the test methods using the 102 mm and 152 mm sample sizes.

For analysis methods 2 to 4, Tables 5.5 to 5.9 show the precision parameters for the assumptions of constant standard deviation and constant coefficient of variation. The constant standard deviation assumption applies when the magnitude of the standard deviation is independent of the magnitude of the dependent variable. The constant coefficient of variation assumption is used when the magnitude of the variation is correlated with the magnitude of the dependent variable. The analysis of the data collected during this research demonstrates the constant standard deviation assumption is acceptable for both the 102 mm and 152 mm sample sizes.

Table 5.5 Precision of Rice Specific Gravity (all data)

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Material				
Base 1	0.0074	0.0209	0.0100	0.0284
Base 2	0.0012	0.0033	0.0032	0.0090
Wearing 1	0.0017	0.0049	0.0058	0.0164
All Materials				
Constant Standard Deviation	0.0044	0.0126	0.0069	0.0196
Constant Coefficient of Variation (percent)	0.1350	0.3818	0.2504	0.7083
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	0.0015	0.0042	0.0047	0.0132
Constant Coefficient of Variation (percent)	0.0580	0.1639	0.1799	0.5090
152 mm Sample (Base 1)				
Constant Standard Deviation	0.0074	0.0209	0.0100	0.0284
Constant Coefficient of Variation (percent)	0.2890	0.8174	0.3914	1.1071

Table 5.6 Precision of Stability (all data)

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1 (N)	1991	5631	4993	14121
Base 2 (N)	1069	3023	2213	6259
Wearing 1 (N)	1007	2849	2427	6865
All Materials				
Constant Standard Deviation (N)	1428	4040	3450	9759
Constant Coefficient of Variation (percent)	8.45	23.89	19.80	56.00
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation (N)	1038	2937	2322	6569
Constant Coefficient of Variation (percent)	7.83	22.14	17.55	49.64
152 mm Sample (Base 1)				
Constant Standard Deviation (N)	1991	5631	4993	14121
Constant Coefficient of Variation (percent)	9.69	27.40	24.30	68.73

Table 5.7. Precision of Flow (all data)

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1 (0.25 mm)	2.270	6.422	2.948	8.337
Base 2 (0.25 mm)	1.016	2.875	1.624	4.594
Wearing 1 (0.25 mm)	1.251	3.540	1.905	5.389
All Materials				
Constant Standard Deviation (0.25 mm)	1.608	4.547	2.233	6.316
Constant Coefficient of Variation (percent)	11.89	33.63	17.20	48.64
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation (0.25 mm)	1.140	3.224	1.770	5.007
Constant Coefficient of Variation (percent)	10.26	29.02	15.96	45.14
152 mm Sample (Base 1)				
Constant Standard Deviation (0.25 mm)	2.270	6.422	2.948	8.337
Constant Coefficient of Variation (percent)	15.15	42.86	19.67	55.64

Table 5.8. Precision of Bulk Specific Gravity (all data)

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1	0.0106	0.0301	0.0198	0.0560
Base 2	0.0095	0.0268	0.0252	0.0714
Wearing 1	0.0239	0.0676	0.0425	0.1203
All Materials				
Constant Standard Deviation	0.0161	0.0455	0.0308	0.0870
Constant Coefficient of Variation (percent)	0.610	1.725	1.211	3.426
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	0.0182	0.0514	0.0350	0.0989
Constant Coefficient of Variation (percent)	0.696	1.970	1.411	3.990
152 mm Sample (Base 1)				
Constant Standard Deviation	0.0106	0.0301	0.0198	0.0560
Constant Coefficient of Variation (percent)	0.437	1.235	0.812	2.298

Table 5.9. Precision of Percent Air Voids (all data)

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1	0.275	0.779	0.913	2.581
Base 2	0.804	2.275	1.611	4.557
Wearing 1	0.456	1.289	0.985	2.786
All Materials				
Constant Standard Deviation	0.557	1.575	1.211	3.425
Constant Coefficient of Variation (percent)	12.45	35.219	28.124	79.53
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	0.654	1.849	1.335	3.777
Constant Coefficient of Variation (percent)	15.80	44.69	32.65	92.36
152 mm Sample (Base 1)				
Constant Standard Deviation	0.275	0.779	0.9127	2.581
Constant Coefficient of Variation (percent)	5.75	16.26	19.06	53.92

5.5 DATA ANALYSIS AND PRECISION PARAMETERS WITHOUT DISTRICT 3

There was no assignable cause to remove the data from any of the laboratories. However, the District 3 data have high variability in many parameters compared to the other laboratories, as demonstrated on Figures 5.16 to 5.20. An analysis of variance showed District 3 has several results that are outside the 95 percentile for the data (Appendix G, Tables G.16 to G.20). Thus, an analysis was performed without the District 3 data. Removing a suspect data set from the analysis is described in the ASTM specification for developing precision statements.

The agreements of variance results, without District 3, are presented in Table 5.10. The comparative number for extreme high and low variances changed from 0.345 and 855 to 0.363 and 790, respectively. This was because of the reduction in the number of laboratories used in the analysis. It can be seen that by removing District 3, five sample characteristics were identified as having a high variance as opposed to the original nine. The test for low variance showed the number of questionable data points was reduced from four to two. District 9 reported three flow values of 10.5 (0.25 mm) giving a variance of zero. This is possible, so these data were kept in the data set.

Table 5.10. Test for High and Low Variability without District 3

Parameter	Material	Test for High Variance Upper 5% Level (High/Sum) Must be < 0.363	Test for Low Variance Upper 5% Level (High/Low) Must be < 790
Max. Theoretical Specific Gravity	Base 1	**0.845**	**37195**
	Base 2	0.319	**14915**
	Wearing 1	0.220	696
Stability	Base 1	0.312	741
	Base 2	0.235	18
	Wearing 1	0.257	28
Flow	Base 1	0.288	61
	Base 2	**0.493**	*
	Wearing 1	**0.731**	273
Bulk Specific Gravity	Base 1	0.201	20
	Base 2	0.172	25
	Wearing 1	**0.860**	660
Percent Air Voids	Base 1	**0.351**	65
	Base 2	0.220	65
	Wearing 1	0.198	21

***** Zero Variability

The parameters of precision without District 3 are reported in Tables 5.11 to 5.15. Comparing these results to those with the entire data set shows little change for most parameters. However, the 1s and d2s single operator limits changes from 1038 and 2937 to 714 and 2018 for the 102 mm samples by the elimination of District 3. The multi-laboratory 1s and d2s limits for this sample size changed from 2322 and 6569 to 1931 and 5460 by eliminating District 3 from the data set. The changes for the 152 mm samples were relatively small.

5.6 ANALYSIS OF OTHER STUDIES

Next, the results from this research were compared to the results from similar studies. Table B.1 in Appendix B is a summary of the precision found from a round-robin study between AMRL laboratories, conducted for ASTM (Kandhal, 96). This study used 152 mm samples and a 25.4 mm maximum aggregate sized, so the results are compared to the Base 1 data from the current study. The Kandhal results are similar to the Base 1 standard deviations for bulk specific gravity, flow, and percent air voids to the current study. The Kandhal single operator standard deviation for stability was 65 percent greater than the Base 1 results, while the multi-

Table 5.11 Precision of Rice Specific Gravity without District 3

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1	0.0077	0.0217	0.0102	0.0288
Base 2	0.0012	0.0033	0.0033	0.0092
Wearing 1	0.0018	0.0051	0.0061	0.0172
All Materials				
Constant Standard Deviation	0.0046	0.0130	0.0071	0.0201
Constant Coefficient of Variation	0.1396	0.3949	0.2572	0.7276
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	0.0015	0.0043	0.0049	0.0138
Constant Coefficient of Variation	0.0600	0.1696	0.1869	0.5285
152 mm Sample (Base 1)				
Constant Standard Deviation	0.0077	0.0217	0.0102	0.0288
Constant Coefficient of Variation	0.2990	0.8456	0.3980	1.1256

Table 5.12 Precision of Stability without District 3

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1 (N)	1943	5497	4940	13972
Base 2 (N)	910	2574	2092	5916
Wearing 1 (N)	436	1233	1755	4963
All Materials				
Constant Standard Deviation	1264	3576	3259	9217
Constant Coefficient of Variation	6.49	18.34	17.60	49.78
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	714	2018	1931	5460
Constant Coefficient of Variation	4.91	13.89	14.15	40.04
152 mm Sample (Base 1)				
Constant Standard Deviation	1943	5497	4940	13972
Constant Coefficient of Variation	9.63	27.25	24.49	69.26

Table 5.13 Precision of Flow without District 3

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1 (0.25 mm)	2.018	5.709	2.827	7.995
Base 2 (0.25 mm)	1.049	2.968	1.517	4.290
Wearing 1 (0.25 mm)	1.263	3.573	1.810	5.121
All Materials				
Constant Standard Deviation	1.502	4.249	2.127	6.015
Constant Coefficient of Variation	11.50	32.51	16.36	46.29
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	1.161	3.284	1.670	4.724
Constant Coefficient of Variation	10.49	29.67	15.09	42.68
152 mm Sample (Base 1)				
Constant Standard Deviation	2.018	5.709	2.827	7.995
Constant Coefficient of Variation	13.50	38.19	18.91	53.49

Table 5.14 Precision of Bulk Specific Gravity without District 3

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1	0.0109	0.0309	0.0199	0.0562
Base 2	0.0052	0.0147	0.0139	0.0394
Wearing 1	0.0155	0.0438	0.0250	0.0708
All Materials				
Constant Standard Deviation	0.0114	0.0321	0.0201	0.0570
Constant Coefficient of Variation	0.437	1.236	0.812	2.296
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	0.0116	0.0327	0.0203	0.0573
Constant Coefficient of Variation	0.431	1.218	0.809	2.289
152 mm Sample (Base 1)				
Constant Standard Deviation	0.0109	0.0309	0.0199	0.0562
Constant Coefficient of Variation	0.449	1.271	0.816	2.309

Table 5.15 Precision of Percent Air Voids without District 3

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
Single Materials				
Base 1	0.2798	0.7914	0.9163	2.5917
Base 2	0.2431	0.6877	0.7659	2.1662
Wearing 1	0.3380	0.9559	0.5497	1.5549
All Materials				
Constant Standard Deviation	0.2896	0.8191	0.7590	2.1469
Constant Coefficient of Variation	7.323	20.713	18.237	51.581
102 mm Samples (Wearing 1 and Base 2)				
Constant Standard Deviation	0.2944	0.8327	0.6666	1.8855
Constant Coefficient of Variation	8.101	22.912	17.909	50.655
152 mm Sample (Base 1)				
Constant Standard Deviation	0.2798	0.7914	0.9163	2.5917
Constant Coefficient of Variation	5.769	16.316	18.892	53.434

laboratory standard deviation was 23 percent lower. Given the magnitude of the variability in the stability testing, this amount of difference in two studies conducted at different times, with different materials and laboratories, is not unreasonable.

The Georgia DOH study (Siddiqui, 95) provides results comparable to the Base 2 and Wearing 1 materials (Table B.2). The within laboratory and between-laboratory standard deviation of stability for the Georgia Study were 968 N and 1232 N, respectively. These compare to values of 714 N and 1931 N, respectively, for the current study.

Siddiqui also provided data from Canadian and Utah studies, but only the average test values from each of the laboratories were reported. Thus, the precision statements cannot be calculated. To compare the results of these studies to the current study, the standard deviation of the average results from each laboratory were calculated (Table 5.16). The magnitude of the standard deviation between laboratories is similar to the data in the literature. The WVU Base 1 results correspond to the ASTM study. The Base 2 and Wearing 1 results correspond to the Utah, Georgia, and Canadian studies.

Table 5.16. Comparison of Standard Deviations From Average Laboratory Results From Different Inter-laboratory Studies

		Bulk Specific Gravity	Air Voids (Percent)	Stability (N)	Flow (0.25 mm)
WVU Study	Base 1	0.017	0.88	4571	2.05
	Base 2	0.013	0.44	1899	1.13
	Wearing 1	0.020	0.73	1704	1.13
Utah Study	5.5% Asphalt	0.013	0.05	2304	3.49
	6.0% Asphalt	0.012	0.35	1739	2.91
	6.5% Asphalt	0.090	2.00	1263	2.95
Canadian Study		0.031	-	2500	2.00
Georgia Study		0.015	0.58	3673	1.64
ASTM Study	152 mm sample	0.022	0.74	3034	3.59

5.7 EVALUATION OF QUESTIONNAIRE INFORMATION

Regression analyses was performed to determine if a correlation existed between information on the questionnaire and the results from each laboratory. All Marshall hammers and stability and flow machines where manufactured by Pine Instruments, which eliminates the possibility of variability between brands of equipment. The technicians' experience was evaluated but there was no correlation with the averages and variances of the test results. A regression analysis was performed on the stability of Base 1 samples and the re-heating oven temperature showed a positive trend but statistical tests showed the correlation was not significant, as shown on Figure 5.21. This trend was less evident for the Base 2 and Wearing 1 materials, as shown on Figures 5.22 and 5.23.

It is commonly know in the industry that the maximum aggregate size should not exceed one-fourth the mold diameter. It was hypothesized that variability in stability is related to the ratio of the maximum aggregate size to mold diameter. With a small ratio there is little room for the aggregates to move into a dense configuration. With only a vertical force on the sample from the hammer, little lateral movement can occur. A regression analysis was performed on the ratios of the maximum aggregate size to mold diameter for Base 1, Base 2 and Wearing 1 samples. For single operator variability an inverse trend could be seen. However, the significance of this trend cannot be evaluated since only three points were available to develop the model.

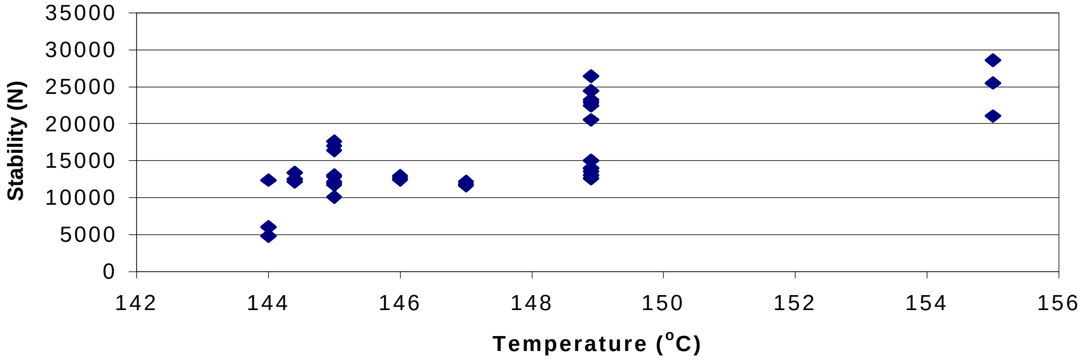

Figure 5.21. Re-heat Temperature versus Base 1 Stability

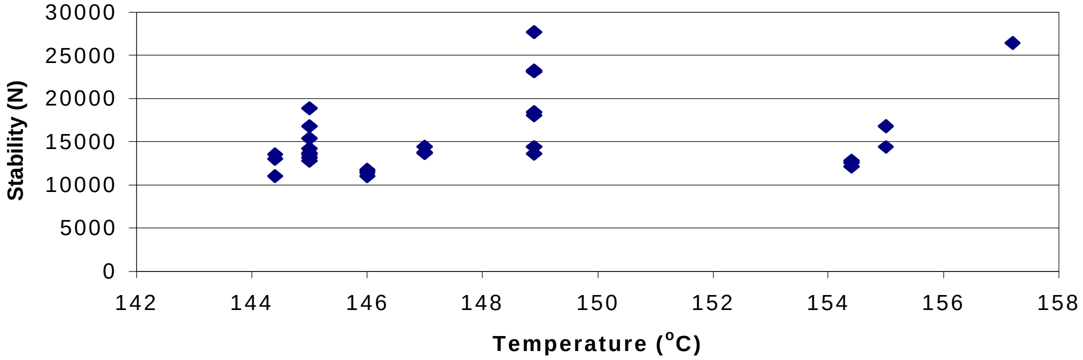

Figure 5.22. Re-heat Temperature versus Wearing 1 Stability

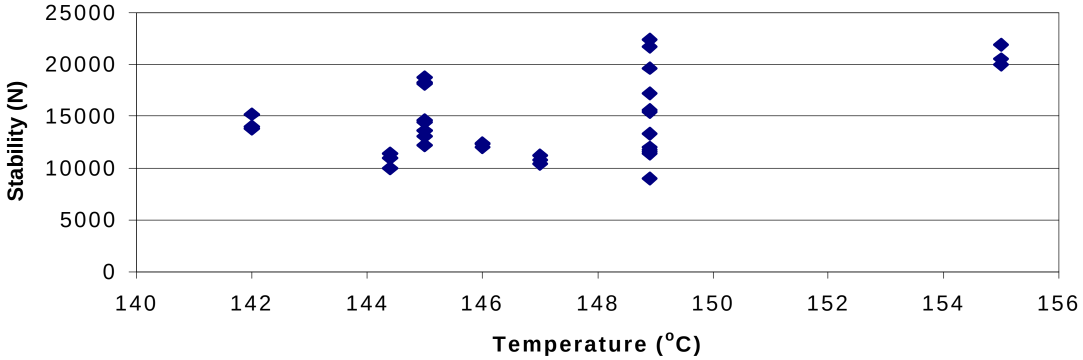

Figure 5.23. Plot of Re-heat Temperature versus Base 2 Stability

5.8 PRECISION STATEMENTS

The data collected for this project compare favorably with information in the literature. Thus, precision statements based on these data are defensible. Since there are differences in the variances for the 102 mm and 152 mm samples, separate precision statements are needed. The statements for the 152 mm samples are from the Base 1 data and were developed with the assumption that the standard deviation is constant. The statements for the 102 mm samples combine the data from the Wearing 1 and Base 2 mixes and the standard deviation was assumed to be constant.

The treatment of the data from District 3 is a concern. A rigorous statistical analysis would include these data since there was not an assignable cause to support their exclusion. However, the fact that five of the nine stability values reported by District 3 were more than two standard deviations from the mean for all the data indicates there is a problem with the data and the cause was undiscovered. There is a one in twenty chance for one value to be more than two standard deviations from the mean. When one laboratory has five values that exceed this limit there is a strong indication that an undetected factor was affecting the results produced at that lab. Using this reasoning, it is prudent to exclude the District 3 data when developing the precision statements. Therefore, the following precision statements are recommended based on the data in Tables 5.11 to 5.15.

Maximum Theoretical Specific Gravity (152 mm samples):

> *The single-operator standard deviation is 0.0077 for calculated maximum theoretical specific gravities ranging from 2.554 to 2.584. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 0.0217.*
>
> *The multi-laboratory standard deviation is 0.0102. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 0.0288.*

Maximum Theoretical Specific Gravity (102 mm samples):

> *The single-operator standard deviation is 0.0015 calculated maximum theoretical specific gravities ranging from 2.472 to 2.530. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 0.0043.*

The multi-laboratory standard deviation is 0.0049. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 0.0138.

Marshall Stability (152 mm samples):

The single-operator standard deviation is 1943 N for measured Marshall stability ranging from 11138 to 25644 N. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 5497 N.

The multi-laboratory standard deviation is 4940 N. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 13972 N.

Marshall Stability (102 mm samples):

The single-operator standard deviation is 714 N for Marshall stability ranging from 10120 to 17558 N. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 2018.

The multi-laboratory standard deviation is 1931 N. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 5460 N.

Marshall Flow (152 mm samples):

The single-operator standard deviation is 2.018 (0.25 mm) for measured Marshall flow ranging from 11.25 to 18.83 (0.25 mm). Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 5.709 (0.25 mm).

The multi-laboratory standard deviation is 2.827 (0.25 mm). Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 7.995 (0.25 mm).

Marshall Flow (152 mm samples):

The single-operator standard deviation is 1.161 (0.25 mm) for measured Marshall flow ranging from 9.25 to 13.37 (0.25 mm). Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 3.284 (0.25 mm).

The multi-laboratory standard deviation is 1.670 (0.25 mm). Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 4.724 (0.25 mm).

Bulk Specific Gravity (152 mm samples):

The single-operator standard deviation is 0.0109 for calculated bulk specific gravities ranging from 2.405 to 2.455. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 0.0309.

The multi-laboratory standard deviation is 0.0199. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 0.0562.

Bulk Specific Gravity (102 mm samples):

The single-operator standard deviation is 0.0116 calculated bulk specific gravities ranging from 2.362 to 2.462. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 0.0327.

The multi-laboratory standard deviation is 0.0203. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 0.0573.

Percent Air Voids (152 mm samples):

The single-operator standard deviation is 0.280 for percent air voids ranging from 3.88 to 6.56. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 0.791.

The multi-laboratory standard deviation is 0.916. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 2.591.

Percent Air Voids (102 mm samples):

The single-operator standard deviation is 0.294 for percent air voids ranging 2.69 to 5.21. Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference two-sigma limit of 0.833.

The multi-laboratory standard deviation is 0.667. Therefore, the results of properly conducted tests from two different laboratories on the same mix should not differ by more than 1.886.

5.9 SUMMARY OF ANALYSIS

After performing analysis on the asphalt samples tested by the fourteen laboratories across the state, precision parameters were computed. Comparing the results to those of similar studies from the literature validated these results. Precision statements were developed for maximum theoretical specific gravity, Marshall stability, Marshall flow, bulk specific gravity and percent air voids. Due to the nature of the data provided by the District 3 laboratory, these data were excluded from the recommended precision statements. Separate precision statements were prepared for 102 mm and 152 mm samples. In all cases, the standard deviation was assumed constant for each Marshall parameter.

C H A P T E R 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The objective of this research, the development of precision statements for the Marshall method, was accomplished. Of the 14 laboratories participating in the study, the data from 13 laboratories were of sufficient quality to include in the analysis to develop the precision statements. Three WVDOH mixes were included in the study, Wearing 1, Base 1, and Base 2. Due to the maximum aggregate size of these mixes, the Wearing 1 and Base 2 mixes were evaluated in the standard 102 mm Marshall mold. The maximum aggregate size of the Base 2 mix requires use of the 152 mm mold. Evaluation of the variability of the data from these two mold sizes demonstrated that separate precision statements are needed for each. Based on these data, precision statements for each sample size, were prepared for:

Marshall stability,
Marshall flow,
Bulk specific gravity,
Percent air voids, and
Maximum theoretical specific gravity.

The results from this study were compared to data from the literature. Similar results were found, indicating that the data used to develop the precision statements are reasonable when compared to the results of other asphalt technologists. Thus, the WVDOH can implement the results of this research with some assurance that all laboratories in the state should be capable of achieving these levels of testing precision.

In a side issue, the 152 mm Marshall and the Superpave molds require sample sizes that are difficult to prepare with conventional mixers. A bucket mixer was evaluated and operating procedures were developed. The mixer and operating procedures were found to prepare the larger sample size mixes efficiently.

6.2 RECOMMENDATIONS

It is recommended that precision statements based on the results found in this study be used in the WVDOH specifications for asphalt concrete. These statements identify the variability of the different parameters of the Marshall method. These precision statements will also aid in the quality assurance process for reviewing the work performed by contractors on WVDOH projects.

Further research could improve the precision statements for WVDOH. The results of this project are based on single sources for the aggregates and asphalt cement. The study should be expanded to include more aggregate and asphalt cement types. This will return more representative precision statements of the mixes used the state.

The study was limited to three of the standard WVDOH mix types. To make precision statements that better represent the variability of Marshall testing, an inter-laboratory study could be conducted using all of the WVDOH mix types. Also, only one mix design was used to develop precision statements for all 152 mm samples and only two samples were used to develop 102 mm sample precision statements. ASTM C802 recommends a minimum of three material types for developing precision statements. Since the magnitude of the variability between the 102 mm and 152 mm samples required separate precision statements, the ASTM recommendation of a minimum of three materials for each type of precision statement was not followed. Data should be collected from at least one additional material using the 102 mm mold and two additional materials using the 152 mm mold.

As the WVDOH implements the Superpave gyratory compactor, an experiment should be performed to determine precision statements for the test parameters for this method.

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Appendix A

PROCEDURE FOR DEVELOPING PRECISION STATEMENTS

PROCEDURE FOR DEVELOPING PRECISION STATEMENTS

The objective of this research is to determine precision statements for Marshall testing. A similar study was performed for 152 mm size Marshall stability and flow parameters (Kandhal, 96). The resulting precision statement was used as a model for this study. The precision statement was:

> The single-operator standard deviation is 722 lbs (3212 N) for measured Marshall stabilities ranging from 4657 lbs (20,715 N) to 6852 lbs (30,524 N). Therefore, the results of two properly conducted tests by the same operator on the same mix should not differ by more than the difference of two-sigma limit of 2042 lbs (9083 N),
>
> The multilaboratory standard deviation is 901 lbs (408 N). Therefore, the results of the properly conducted tests from two different laboratories on the same mix should not differ by more than 2548 lbs (11,334 N).

Developing this type of precision statement requires determining the single-operator and multilaboratory standard deviations. In ASTM terminology, these are the 1s values. The two sigma limit equals the standard deviation times $2\sqrt{2}$. In ASTM termonology, this is the d2s values. This limit is used to represent 95 percent of the data. Thus, to develop the precision statements requires collecting and analysing stat to quantify the single operator and multilaboreatory standard deviations. The procedures for setting up the experiments and performing the analysis are defined in several ASTM standards.

ASTM standard C 802 – "Standard Practice for Conduting an Inter-laboratory Test Program to Determine the Precision of Test Methods of Construction Materials," gives procedures for designing the experiment and analysing the data for preparing precision statements. This practice was closely followed during research. The experimental design requirement and analytical procedures are summarized below. In addition, ASTM C 670 – "Practice for

Preparing Precison and Bias Statements for Test Methods for Construction Materials," provides detailed instrucions for preparing precision statements as needed for this research.

ASTM C 802 requires a minimum of ten laboratories participate in the study. Each laboratory needs personnel with practiced knowledge of the test method being analysed. A minimum of three materials with at least three replicates each are required for developing multi-laoreatory precision statements. A replicate is defined as a materal samples which are faricated to have "identical" characteristics and properties. Laboratories participatng in the study are instructed to follow "normal" operating procedures when testing the samples. All materials should be the "same" and no special instructions should be given on how to test them. The idea is to compare how the tests are normally run.

Once the laboratories submit the test data, ASTM C 802 gives analytical methods for evaluating the data quality prior to the calculation of the precision statement parameters. The data are analysed for outliers, agreement of variance and interactions. To evaluate outliers ASTM C 802 refers to ASTM E 178 "Dealing With Outlying Observations." ASTM E 178 recommeds the Student's t test for evaluating the sample population for outliers. InSudent's t test, the normalied difference between an observation and the mean for all observations in the sample are the selected confidence level. The normalized difference is compted as:

$$t_i = \frac{(x_i - \bar{x})}{s}$$

Where:

t_i = computed t value for observation i

x_i = single observation from population

$\bar{x}$ = arithmetic average of all n values

s = estimate of population standard deviation based on the sample data

If the computed t value is greater than the corresponding table value, at that confidence level, the data point is a potential outlier. The standard deviation emphasizes that values should not be eliminated from the analysis simply because they fall outside of the selected confidence range. Some samples will be outside this range through natural variability. For example, if a confidence level of 95 percent was selected, one observation out of twenty will fall outside of this range. However, the test is helpful in identifying obervations that can be investigated to determine if there is an assignable cause for the abnormal observation.

Variance is a measure of the spread in the data. Variances are tested for being either too high, indicating flawed testing methods, or too low, indicating a constraint on the actual material variability. The test for high variance consists of comparing the ratio of the highest variance within a laboratory to the sum of the variances from all of the laboratories. The ratio is then compared to a value based on the number or replicates for each sample, the number of laboratories, and a confidence limit (Table A.1). The test for low variance consists of comparing the ratio of the highest variance within a laboratory to the lowest variance withn a laboratory to a standard table (Table A.2). If the ratios from either test are greater than their respective table values then the variance of the material parameter must be investigated more closly by examinimg plots of the variance for each laboratory. If the plot shows one high or low variance then that laboratory may be removed from the analysis. If the data points are scattered then the test method may need to be re-evaluated.

Once the data has been evaluated for agreement of variance, the data must be checked for interactions. Interactions are when "…the pattern of change of results obtained on a given group of materials in one laboratory differs from the pattern obtained in another laboratory. In extreme cases, different laboratories may even fail to rate materials in the same order." (ASTM C 802). Agreement of variance can be checked either by performing an analysis of variance or by observing a plot of the material versus the parameter value. Looking at this plot, the relationship between the materials may be compared to that of the other laboratories. Similar slopes from one material to the next should be observed. If the relationship between materials form one laboratory differ greatly from the other observations there may have been some testing error ato that laboratory. The difference in interactions for this laboratory may be cause to omit the results from the analysis.

Once outliers, agreement of variance and interactions have been checked within-laboratory and between laboratory variances, standard deviations, and coefficient of variations should be

Table A.1 Approximate Values (Upper 5 percent Level) for the Ratio of the Largest Variance to the Sum of the Variances

No. of Labs	No. of replicates				
	2	3	4	5	6
5	0.8412	0.6838	0.5981	0.5441	0.5065
6	0.7808	0.6161	0.5321	0.4803	0.4447
7	0.7271	0.5612	0.48	0.4307	0.3974
8	0.6798	0.5157	0.4377	0.391	0.3595
9	0.9385	0.4775	0.4027	0.3584	0.3286
10	0.602	0.445	0.3733	0.3311	0.3029
11	0.57	0.414	0.348	0.307	0.281
12	0.541	0.3924	0.3264	0.288	0.2624
13	0.514	0.363	0.308	0.269	0.247
14	0.492	0.345	0.291	253	0.232
15	0.4709	0.3346	0.2758	2419	0.2195
20	0.3894	0.2705	0.2205	1921	0.1735
30	0.2929	0.198	0.1593	1377	0.1237

Table A.2 Approximate Values (Upper 5 percent Level) for the Ratio of the Highest to Lowest Variance

No. of Labs	No. of replicates			
	3	4	5	6
5	202	51	25	16
6	266	62	30	19
7	333	73	34	21
8	403	84	38	23
9	475	94	41	25
10	550	104	45	26
11	626	114	48	28
12	704	124	51	30
13	790	135	54	31
14	885	145	57	32
15	995	155	59	33

calculated. The within-laboratory and between-laboratory components of variation are calculated, as:

$$Within - Laboratory\ Component\ of\ Variance = average(A)$$

$$Between - Laboratory\ Component\ of\ Variance = \mathrm{var}\,iance(B) - \frac{average(A)}{n}$$

Where:

A = Variance of the replicates tested by each laboratory for each mix (within laboratory variance)

B = Average value of three replicates tested by each laboratory for each mix.

n = the number of laboratories

Table A.3 is an example of the calculation of the component of variance. In this example, there are three materials with three replicate each, and 10 laboratories. For material A, the within-laboratory component of variance is 6.1. The between laboratory component of variance is 1.1-(6.1/10)=0.49.

Table A.3. Example Calculation of Components of Variance

	Material														
	A					B					C				
	Replicate			Mean	Variance	Replicate			Mean	Variance	Replicate			Mean	Variance
lab	1	2	3			1	2	3			1	2	3		
1	5.0	4.0	3.8	4.27	0.41	5.0	2.6	9.0	5.53	10.45	5.5	9.0	6.0	6.83	3.58
2	8.2	2.2	4.0	4.80	9.48	9.0	5.0	7.2	7.07	4.01	3.2	6.5	1.7	3.80	6.03
3	5.9	2.8	1.3	3.33	5.50	9.8	2.1	5.2	5.70	15.01	4.1	4.0	0.4	2.83	4.44
4	3.6	8.3	6.7	6.20	5.71	5.4	7.6	9.6	7.53	4.41	0.6	8.4	9.2	6.07	22.57
5	5.6	0.9	4.1	3.53	5.76	5.9	5.9	9.2	7.00	3.63	3.9	3.7	3.8	3.80	0.01
6	5.2	6.2	1.1	4.17	7.30	3.8	8.0	3.2	5.00	6.84	1.8	7.7	7.6	5.70	11.41
7	6.6	1.4	3.6	3.87	6.81	8.1	5.3	4.8	6.07	3.16	7.8	9.4	5.3	7.50	4.27
8	5.0	5.9	8.9	6.60	4.17	8.3	4.6	1.0	4.63	13.32	3.8	3.6	7.5	4.97	4.82
9	4.5	2.4	7.0	4.63	5.30	5.8	9.7	3.5	6.33	9.82	8.0	8.6	8.5	8.37	0.10
10	3.6	1.4	7.8	4.27	10.57	1.7	5.6	8.0	5.10	10.11	5.0	4.7	4.0	4.57	0.26
Overall average				4.57					5.8					5.44	
Pooled within-lab var					6.10					8.26					5.80
Var of lab avg.				1.1					0.9					3.2	
Btw lab comp. of var					0.49					0.07					2.62

Knowing the within and between-laboratory variance, the standard deviation and coefficient of variation can be calculated. The within and between-laboratory standard deviations are the square roots of their respective variances. The coefficient of variation can be calculated using the following relationship:

$$COV = 100\frac{s}{x}$$

Where:

s = standard deviation

$\bar{x}$ = average of all observations

From these values the parameters of precision can be calculated.

Appendix B

DATA FROM PREVIOUS STUDIES

Table B.1. Precision Summary of Study by ASTM (Kanhdal, 96)

	Single Operator		Multi-laboratory	
	1s	d2s	1s	d2s
ASTM Study Data Analysis				
Stability	3206	4534	4006.1	11331
Stability COV (percent)	12.26	17.34	15.32	43
Flow	3.11	4.40	4.40	12.44
Flow COV (percent)	16.79	23.74	23.71	67.07
Bulk Specific Gravity	0.0084	0.012	0.0921	0.260
Bulk Specific Gravity COV (percent)	0.32	0.45	3.46	9.77
Percent Air Voids	0.30	0.43	0.78	2.22
Percent Air Voids COV (percent)	7.80	11.03	20.14	56.97

Table B.2. Georgia Laboratory Comparison Study (Siddiqui, 95)

Laboratory	Location	Height (in.)	Density (lb/ft^3)	Voids (percent)	Stability (lb)	Flow (0.01 in.)
District 2	Tennille, Ga.	2.55	154.4	4.3	2500	12
		2.6	**150.3**	6.8	2240	12
		2.51	**155.6**	3.6	**3020**	**15**
District 4	Tifton, Ga.	2.5	154.8	4.1	**2880**	13.1
		2.5	152.9	5.3	2350	13.3
District 5	Jesup, Ga.	2.5	154.6	4.2	2200	**15**
		2.5	154.3	4.4	2175	14.8
		2.5	154.6	4.2	2275	13.6
District 7	Forest Park Ga.	2.562	153	5.2	2100	12
		2.555	154.1	4.5	2460	13
		2.54	154.3	4.4	2520	11
Producer 1	Macon Ga.	2.567	153.1	5.1	2150	10
		2.574	153.6	4.8	2190	**9**
		2.562	153.6	4.8	2340	10
Producer 2	Atlanta Ga.	2.56	152.6	5.4	2320	11
		2.56	153.2	5.1	2470	13
		2.56	152.8	5.3	2330	13
Producer 3	Doraville, Ga.	2.44	154.4	4.3	2200	**9**
		2.5	153.6	4.8	2050	10
		2.5	152.5	5.5	**1950**	10
Producer 4	Birmingham, Ala.	2.51	153	4.9	2400	13.5
		2.5	157	2.9	2650	13.5
		2.5	155	3.8	2250	12
Producer 5	Chattanooga, Tenn.	2.615	152.9	5.3	2550	11
		2.615	**151.6**	6	2550	10
		2.615	**150.8**	6.5	2525	12
Average (of all laboratories)			153.6	4.8	2371	12
Acceptable range for a given Laboratory			152.1 to 155.1		1971 to 2771	10 to 14

Note: Values in bold are outside acceptable (95 percent) confidence range

Table B.3. Utah-Marshall Study, Same Operator, Different Equipment at Various Laboratories (Siddiqui, 95)

	Bulk Specific Gravity at Asphalt Content			Voids (%) at Asphalt Content			VMA Filled (%) at Asphalt Content			Stability (lb) Asphalt Content			Flow (0.01 in.) at Asphalt Content		
Laboratory	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%
District 1	2.29	2.29	2.30	3.3	2.4	1.5	78.7	84.7	90.6	2256	2064	1871	10	11	14
District 2	2.29	2.30	2.30	2.8	2.0	1.5	81.4	87.0	90.6	2477	2559	2216	9	9	12
District 3	2.29	2.30	2.30	3.3	2.0	1.5	78.7	87.0	90.8	2538	2642	2380	8	9	11
District 4	2.29	2.30	2.29	3.3	2.0	1.9	78.7	87.0	88.4	2663	2678	1825	10	11	14
District 5	2.30	2.31	2.30	2.8	2.6	1.5	81.9	89.4	90.6	2729	2620	2045	10	11	14
District 6	2.29	2.29	2.30	3.3	2.4	1.5	78.7	84.8	90.6	2367	2178	2023	8	11	12
Main lab	2.29	2.29	2.29	3.3	2.4	1.9	78.7	84.7	88.4	2767	1945	1826	9	11	12
Average	2.29	2.30	2.30	3.16	2.26	1.61	79.5	86.4	90.0	2542	2384	2027	9	10	13
Std. Dev.	0.004	0.008	0.005	0.24	0.25	0.20	1.4	1.8	1.1	190	310	211	1	1	1
Range	0.01	0.02	0.01	0.5	0.6	0.4	3.2	4.7	2.4	511	733	555	2	2	3

Table B.4. Utah-Marshall Study, Different Operator and Equipment at Various Laboratories (Siddiqui, 95)

	Bulk Specific Gravity at Asphalt Content			Voids (%) at Asphalt Content			VMA Filled (%) at Asphalt Content			Stability (lb) Asphalt Content			Flow (0.01 in.) at Asphalt Content		
Laboratory	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%	5.50%	6.00%	6.50%
District 1	2.28	2.29	2.29	3.3	2.1	1.5	78.3	86.2	90.6	2776	2691	2237	10	10	14
District 2	2.31	2.31	2.31	2.2	1.5	0.9	84.9	90.0	94.2	3528	3194	2494	16	17	19
District 3	2.28	2.28	2.28	3.5	2.7	1.9	77.6	83.0	88.2	3012	3000	2664	10	11	13
District 4	2.29	2.30	2.29	3.3	2.0	1.9	78.8	87.0	88.5	2450	2762	2109	7	10	12
District 5	2.29	2.30	2.30	3.4	2.1	1.7	78.6	86.6	89.5	2790	2455	2065	10	10	13
District 6	2.29	2.30	2.29	3.4	2.1	1.7	78.4	86.3	89.4	3561	3224	2572	7	8	11
Main lab	2.28	2.30	2.30	3.6	2.0	1.4	77.2	87.0	91.4	2166	2158	1921	14	14	17
Average	2.29	2.30	2.29	3.24	2.07	1.57	79.1	86.6	90.3	2898	2783	2295	11	11	14
Std. Dev.	0.011	0.010	0.010	0.472	0.350	0.350	2.6	2.0	2.1	518	391	284	3	3	3
Range	0.03	0.03	0.03	1.4	1.2	1	7.7	7.0	6.0	1395	1066	743	9	9	8

Table B.5. Canadian Mix Exchange,

Statistical Summary for All Data

	Bulk Specific Gravity			Stability (kN)			Flow (0.25 mm.)		
No. of Labs – 31	Manual	Mechanical	Manual*	Manual	Mechanical	Manual*	Manual	Mechanical	Manual*
Mean	2.382	2.357	2.377	11.3	10.2	12.4	12	12	10
Standard Deviation	0.017	0.031	0.019	1.8	2.5	1.9	3	2	1
95% confidence Interval	2.348-2.416	2.295-2.419	2.339-2.415	7.7 14.9	5.2-15.2	8.6-16.2	6-18	8-18	8-12
Data Range	2.322-2.412	2.273-2.405	2.321-2.322	5.7-14.5	4.3-14.6	8.2-15.1	7-19	8-16	8-12

Statistical Summary for Selected Data (excludes data that were outside 95% confidence interval)

	Bulk Specific Gravity			Stability (kN)			Flow (0.25 mm.)		
No. of Labs – 31	Manual	Mechanical	Manual*	Manual	Mechanical	Manual*	Manual	Mechanical	Manual*
Mean	2.384	2.361	2.379	11.5	10.4	12.5	12	12	10
Standard Deviation	0.014	0.026	0.016	1.4	2.2	1.7	3	2	1
95% confidence Interval	2.358-2.41	2.309-2.413	2.547-2.411	8.7-14.3	6-14.8	9.1-13.9	8-16	8-16	8-12
Data Range	2.359-2.412	2.299-2.405	2.346-2.399	8.6-14.5	6-14.6	9.2-15.1	7-18	8-16	8-12

* specimens were manually compacted at participating laboratories but tested at a central laboratory

Appendix C

BUCKET MIXER INSTRUCTIONS

BUCKET MIXER INSTRUCTIONS

SETTING UP THE MIXER.

Install paddle arm so arm sits parallel to the plane to which the bucket can rotate

Secure paddle to paddle are so both back edges sit flush to the side of the bucket and blade touches bottom of bucket

MIXING PROCEDURE

Weigh out aggregates and separate into two containers: course and fine

- Nominal maximum aggregate size ≤ 9.5 mm
  - Fine aggregate ≤ 2.36 mm
  - Coarse aggregate > 2.36 mm
- Nominal maximum aggregate size > 9.5 mm
  - Fine aggregate ≤ 4.75 mm
  - Coarse aggregate > 4.75 mm

Heat 5-gallon bucket and paddle attached to paddle arm.
Allow enough time for bucket and paddle to achieve proper temperature
Remove bucket from oven and add coarse aggregate and asphalt to bucket
Place bucket in mixer basket and turn mixer on
Remove paddle and arm from oven and slide over rod
With aggregates moving the paddle should slide down until touching the bucket bottom.
Unlock mixer and tilt mixer away from paddle arm side.
Hold on to paddle arm and tilt bucket as far as possible without spilling contents
After 10 seconds lock bucket in upright position.
Remove fine aggregate from oven and introduce into the mix.
Pour fine aggregates into bucket with allowing aggregate to touch paddle or side of bucket
Unlock bucket and tilt
Rock bucket up-and-down to reduce segregation
After about 20 seconds when the aggregate looks thoroughly coated take a hot spatula, and as the bucket is spinning, scrape all of the material out of the seam between the bottom and side of the bucket.
Shut off mixer.
Slide paddle off of the rod and with a hot spoon scrape the asphalt off the paddle into the bucket.
Remove bucket from mixer and tilt bucket onto its side and scrape circle of asphalt and fines stuck to the center of the bucket bottom.
Scrape material out of seem again.
Dump bucket contents
Scrape entire side and bottom of bucket.

Appendix D

MIX DESIGN CHARTS

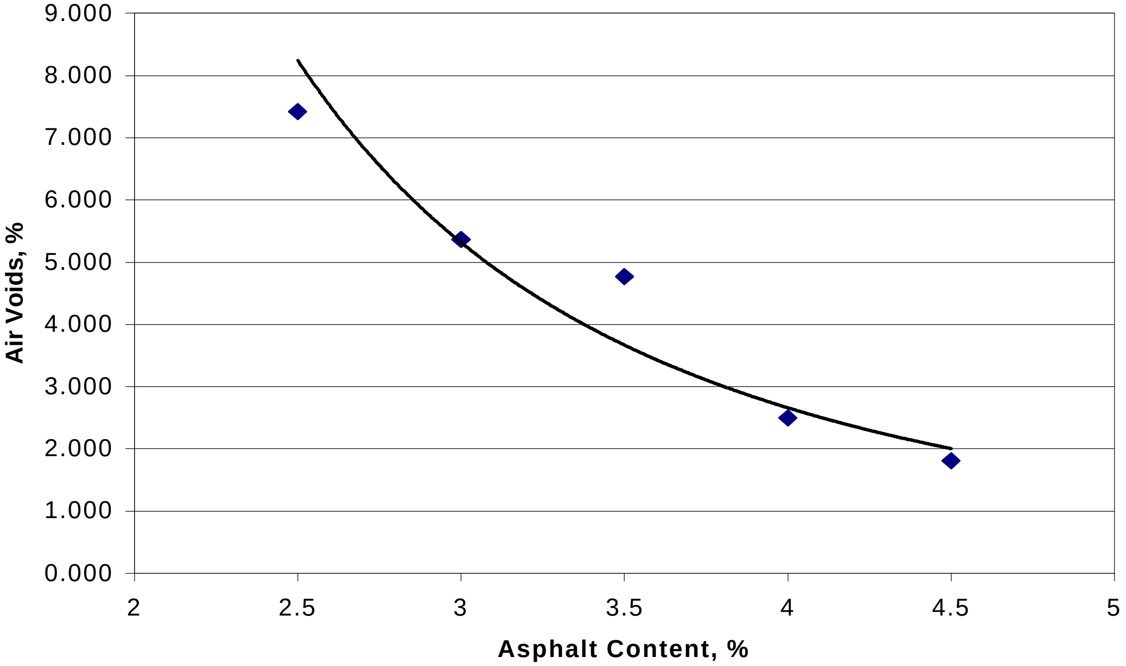

Figure D.1. Percent Air Voids Versus Asphalt Content for Base 1

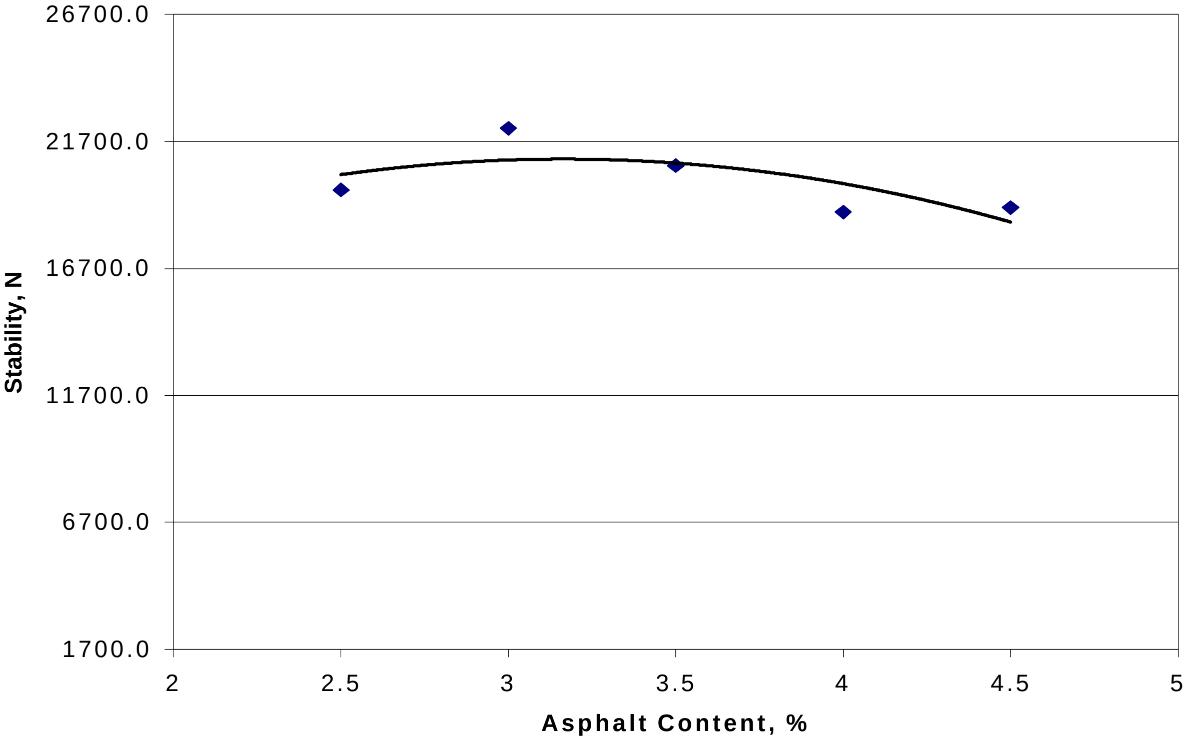

Figure D.2. Stability Versus Asphalt Content for Base 1

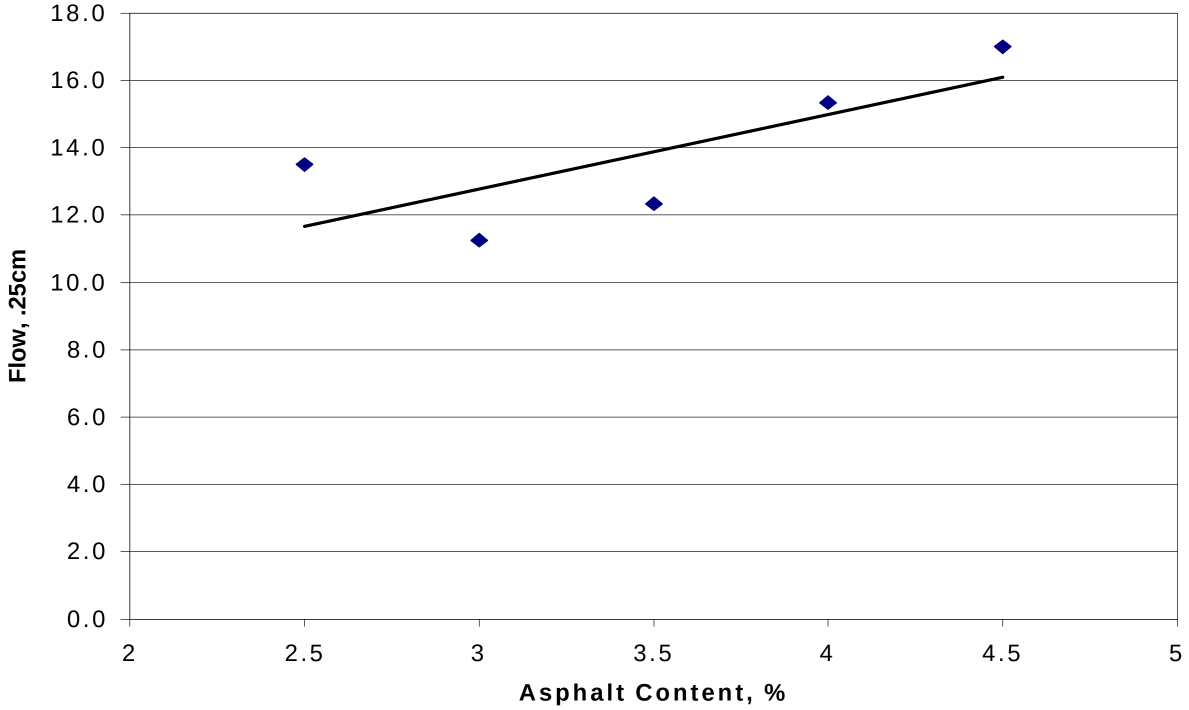

Figure D.3. Flow Versus Asphalt Content for Base 1

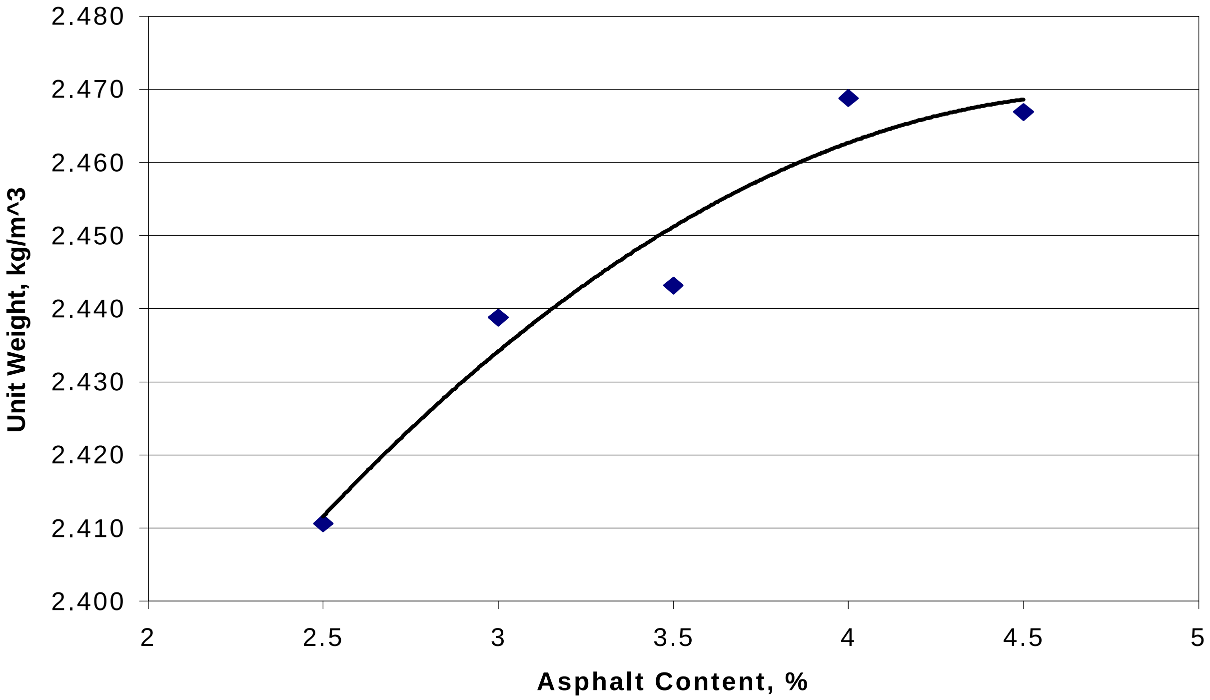

Figure D.4. Unit Weight Versus Asphalt Content for Base 1

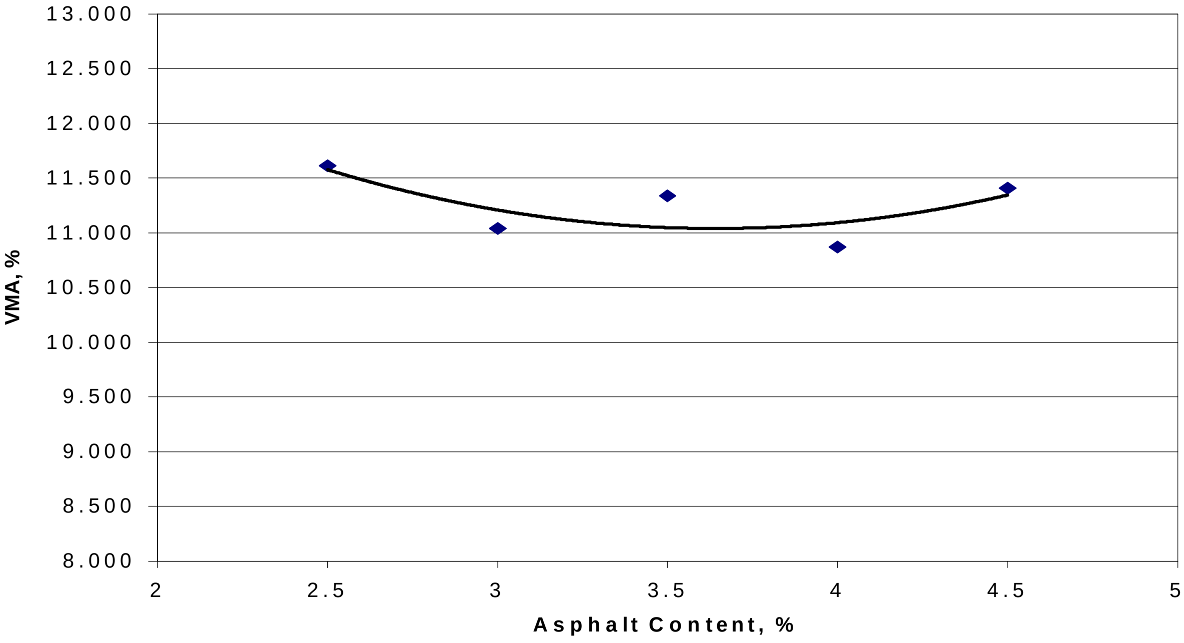

Figure D.5. Percent VMA Versus Asphalt Content for Base 1

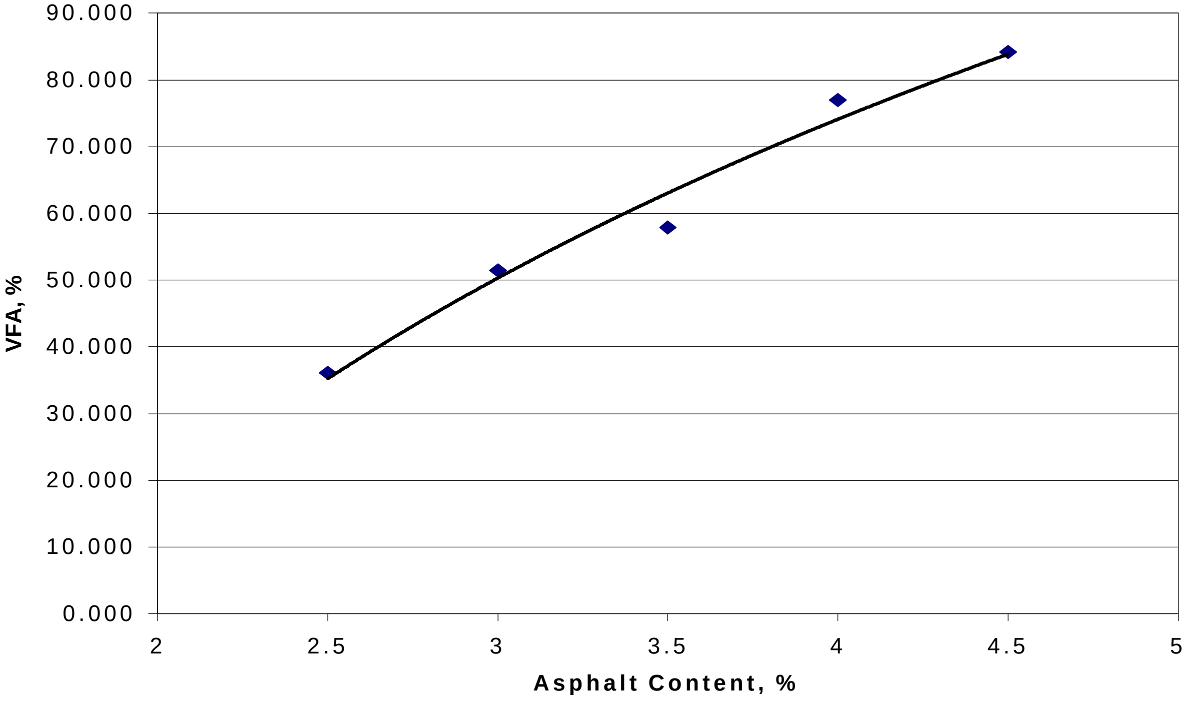

Figure D.6 Percent VMA Versus Asphalt Content for Base 1

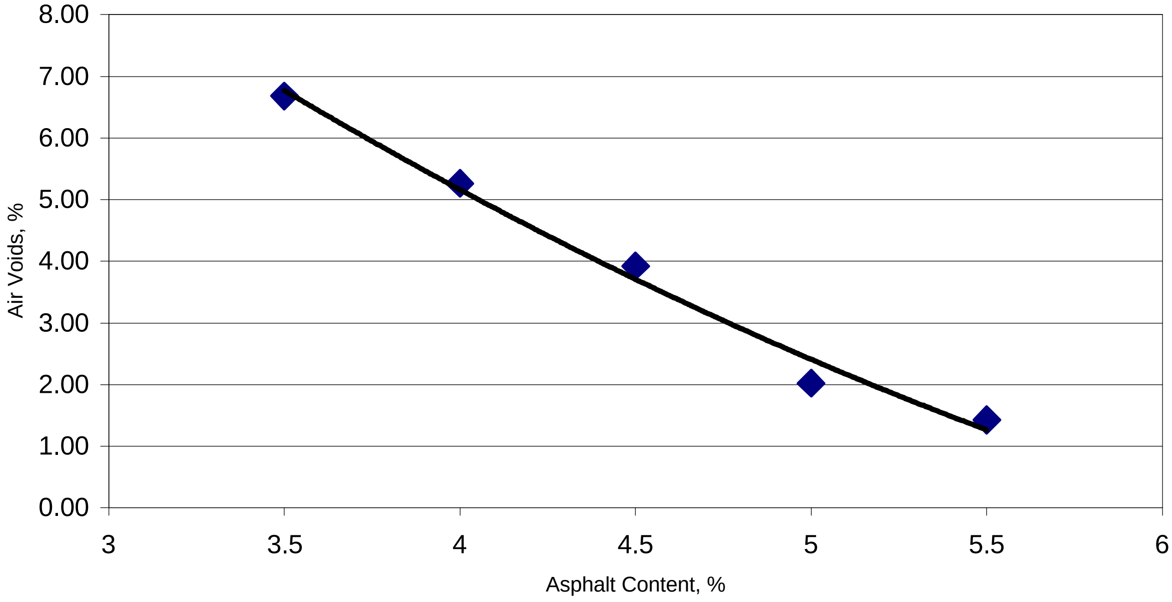

Figure D.7. Percent Air Voids Versus Asphalt Content for Base 2

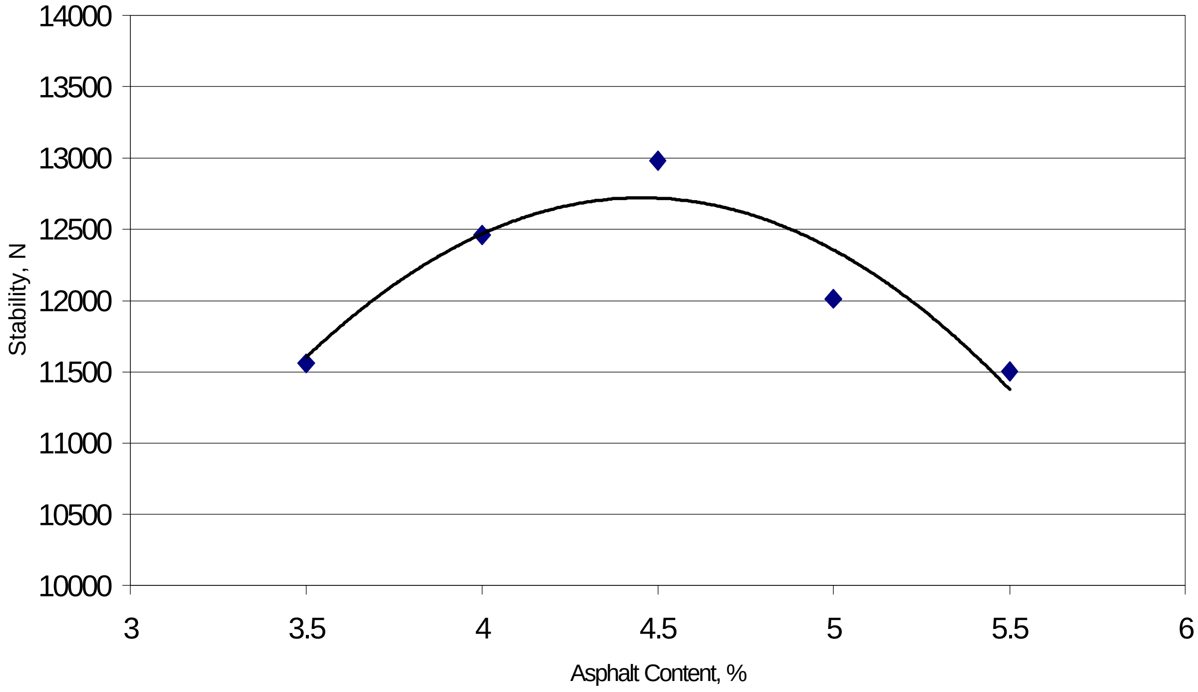

Figure D.8. Stability Versus Asphalt Content for Base 2

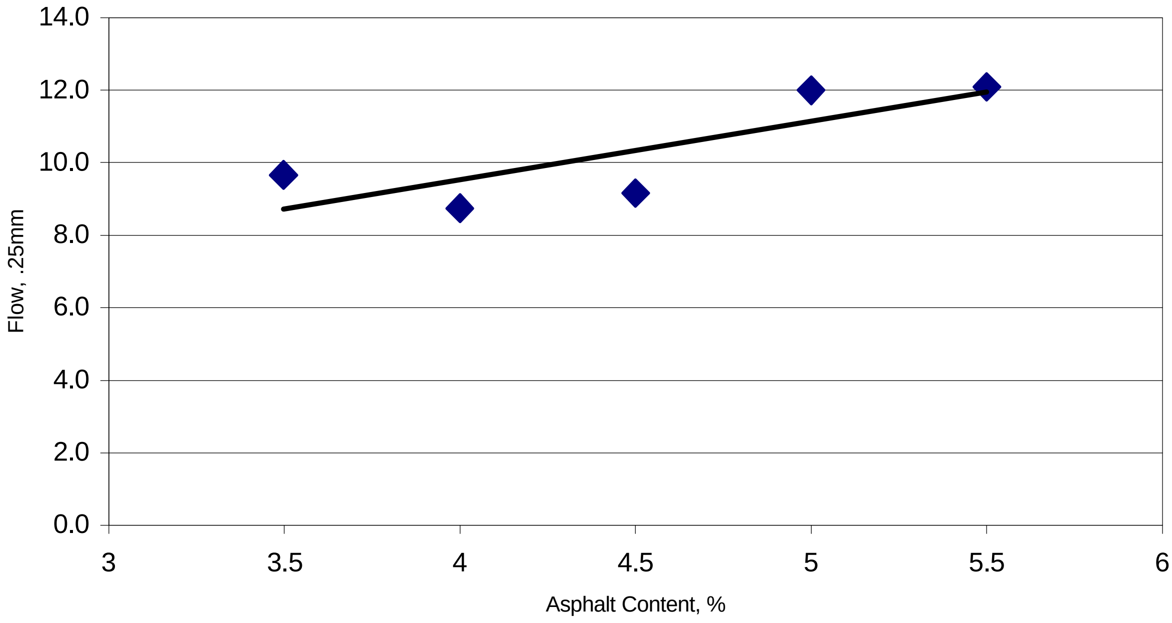

Figure D.9. Flow Versus Asphalt Content for Base 2

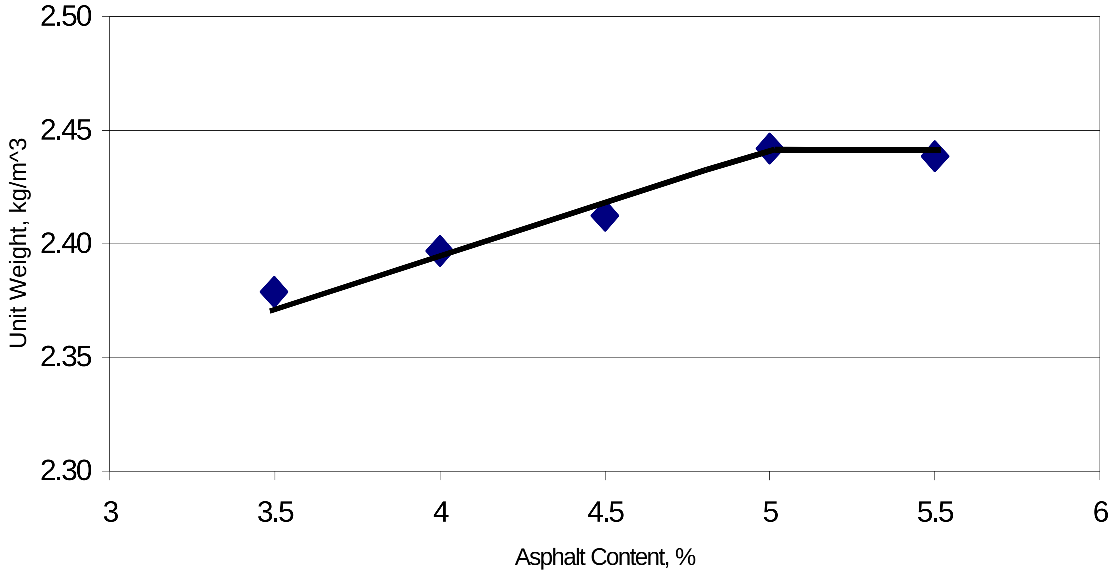

Figure D.10. Unit Weight Versus Asphalt Content for Base 2

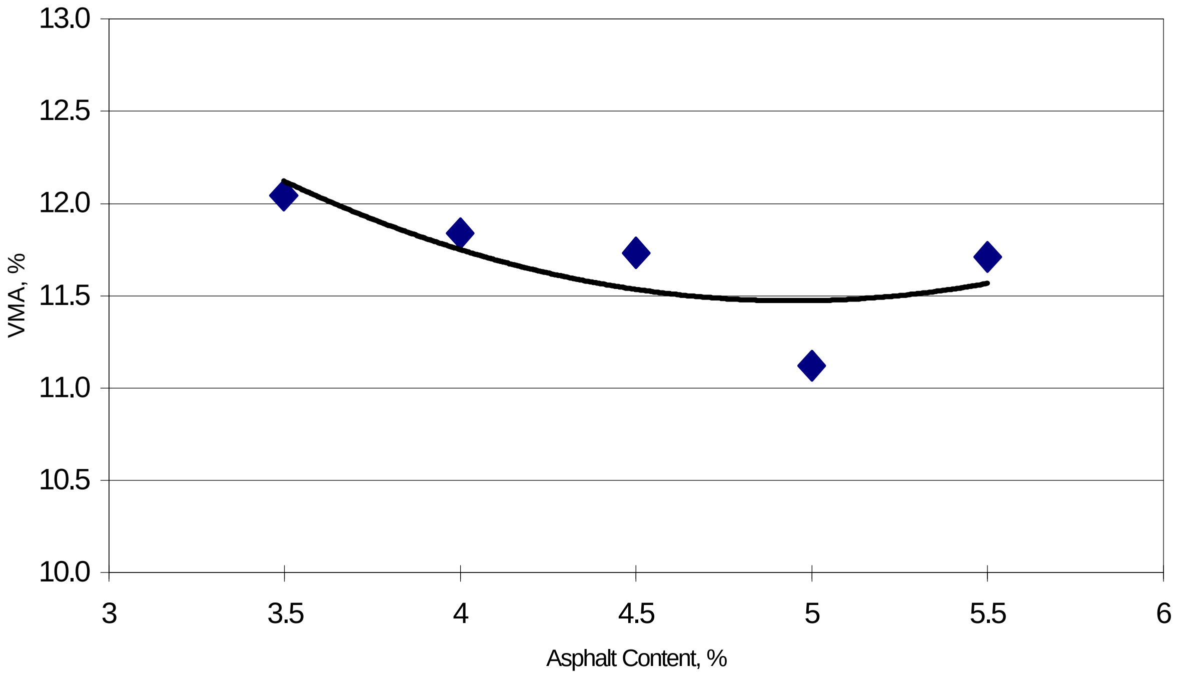

Figure D.11. Percent VMA Versus Asphalt Content for Base 2

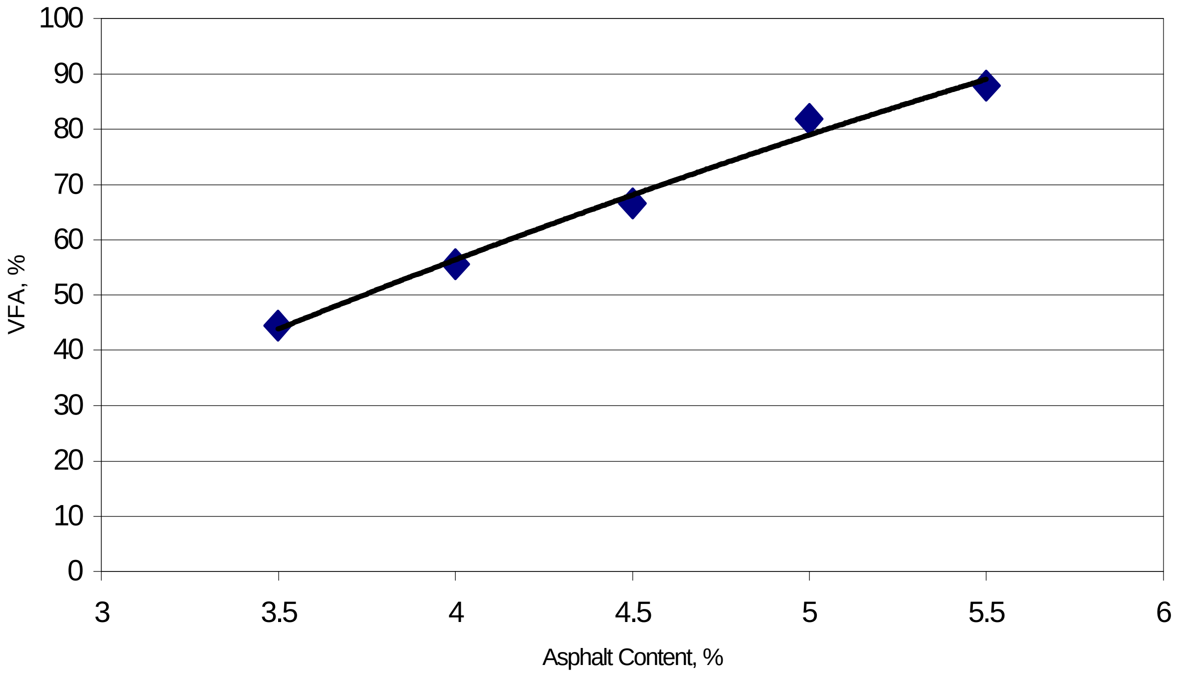

Figure D.12. Percent VFA Versus Asphalt Content for Base 2

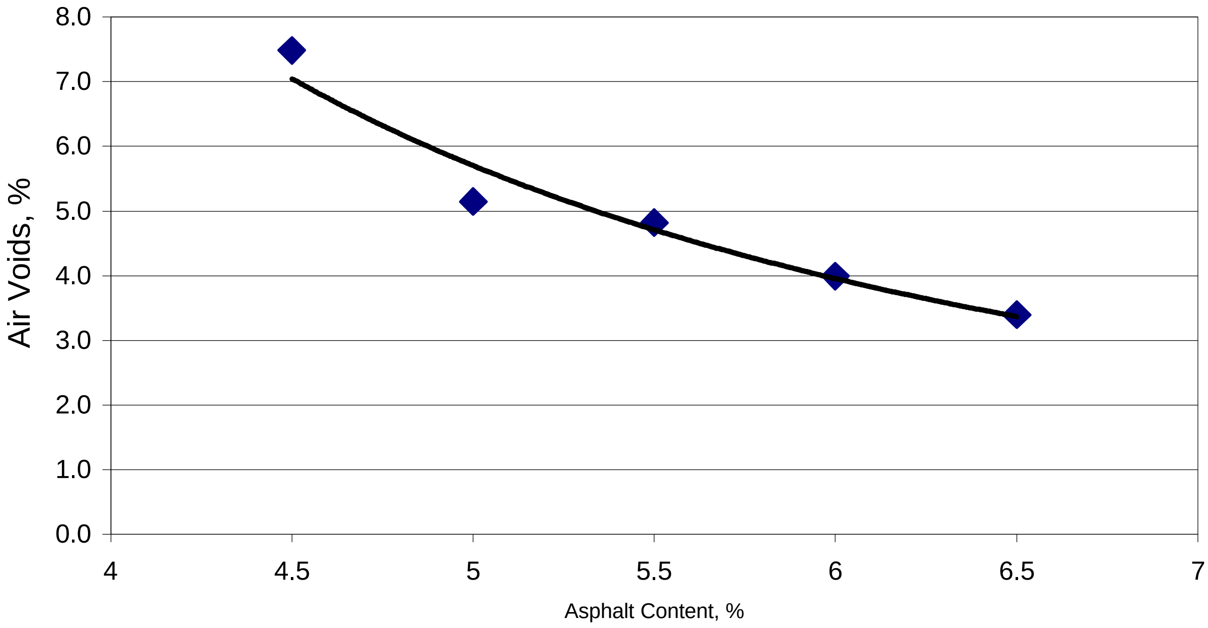

Figure D.13. Percent Air Voids Versus Asphalt Content for Wearing 1

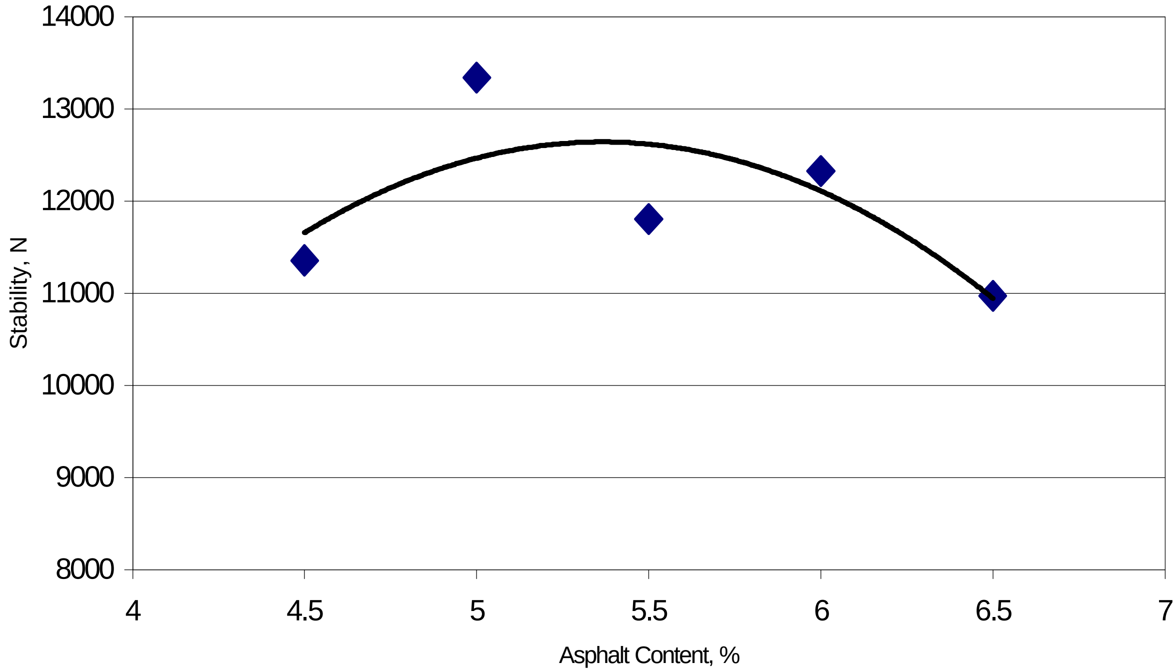

Figure D.14. Stability Versus Asphalt Content for Wearing 1

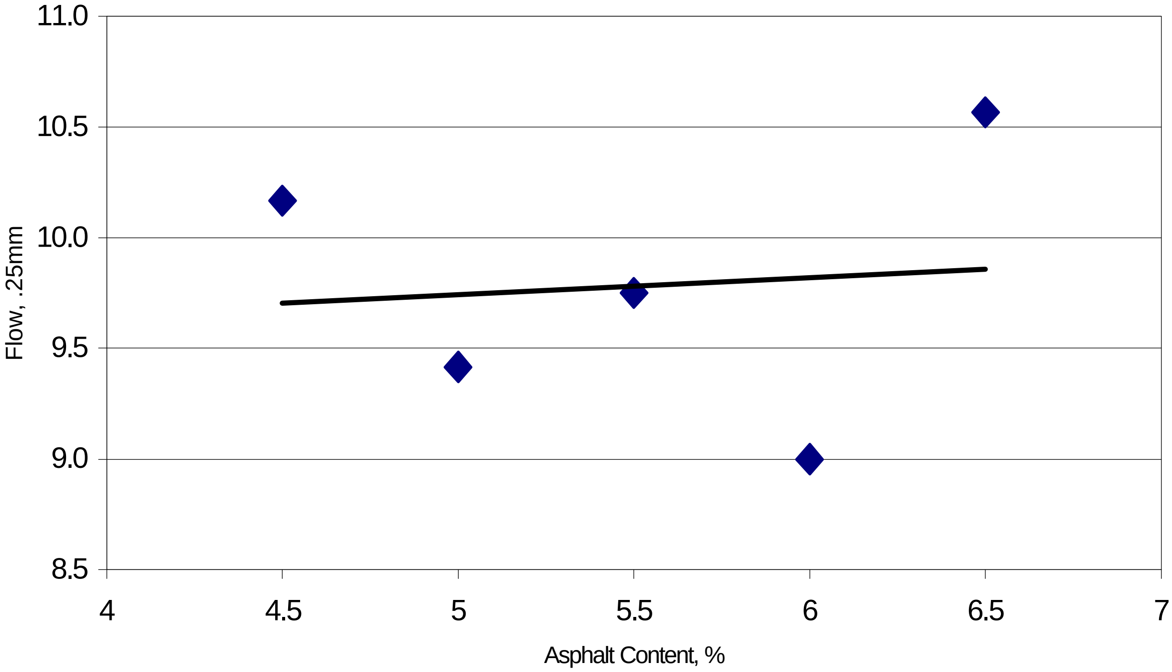

Figure D.15. Flow Versus Asphalt Content for Wearing 1

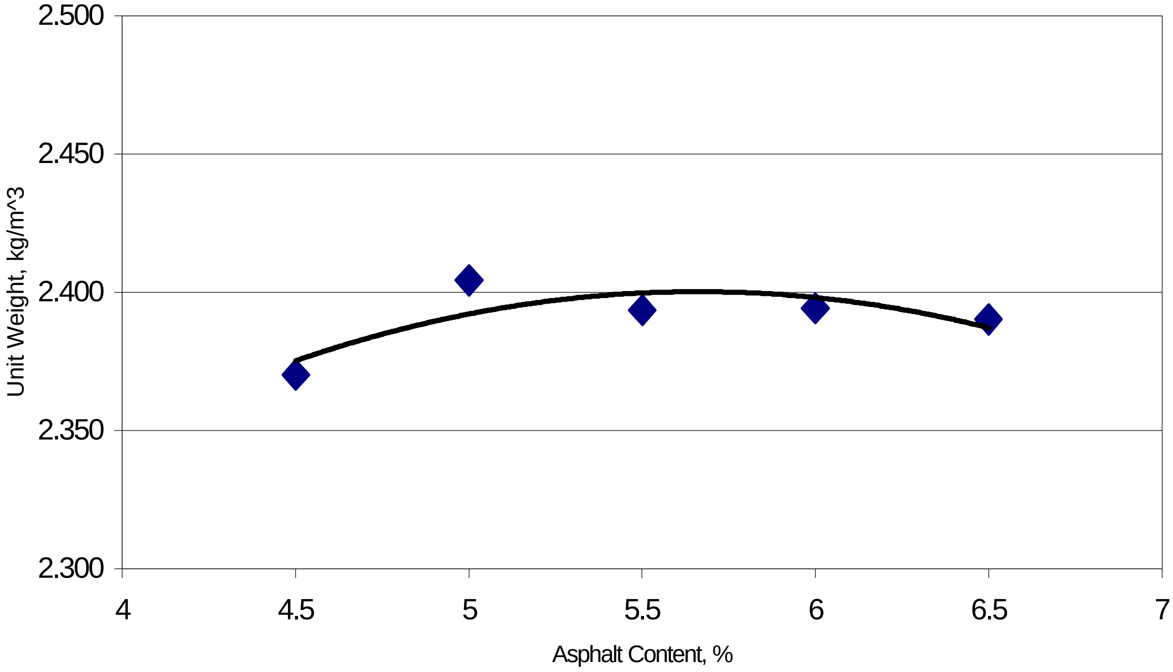

Figure D.16. Unit Weight Versus Asphalt Content for Wearing 1

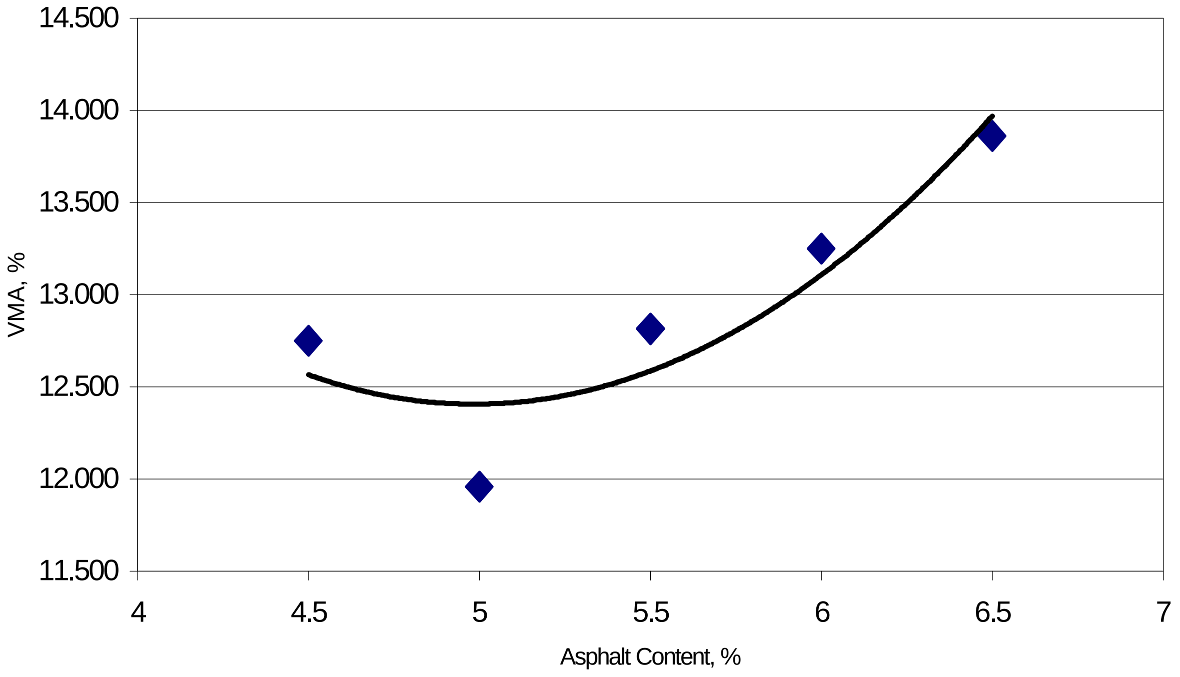

Figure D.17. Percent VMA Versus Asphalt Content for Wearing 1

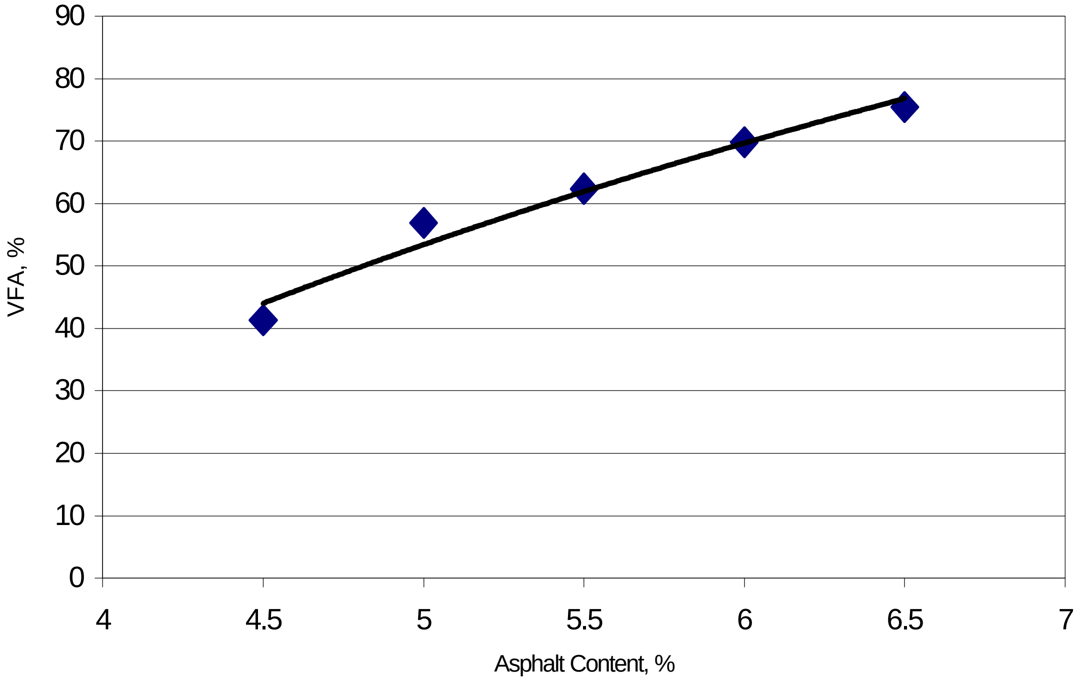

Figure D.18. Percent VFA Versus Asphalt Content for Wearing 1

APPENDIX E

LABORATORY DATA

Table E.1. Compacted Base 1 Samples Raw Data

Lab	#	Sample	Dry Weight (g)	SSD (g)	Wt. in Water (g)	Stability (N)	Thickness (mm)	Flow (0.25 mm)
District	1	B1 8 37 1	4055.6	4071.8	2417.1	22900	88.00	15.00
		B1 3 14 2	4054.4	4072.0	2410.6	24400	88.00	15.00
		B1 1 8 3	4040.0	4066.3	2414.9	20500	90.00	16.50
District	2	B1 3 10 1	4048.8	4065.1	2411.7	19650	94.00	16.00
		B1 3 5 2	4057.7	4067.6	2416.2	21700	94.00	14.20
		B1 3 1 3	4062.3	4079.2	2419.1	22400	94.00	11.50
District	3	B1 3 19 1	4062.8	4075.5	2424.0	27650	94.00	13.40
		B1 1 10 2	4066.4	4083.4	2424.4	23230	94.00	12.50
		B1 1 4 3	4069.8	4086.2	2425.4	23120	93.00	20.50
District	4	B1 1 14 1	4064.2	4080.6	2424.0	22400	95.20	15.50
		B1 8 32 2	4060.8	4077.4	2417.5	23200	95.20	17.00
		B1 2 13 3	4057.1	4073.4	2419.5	26400	95.20	20.00
District	5	B1 1 9 1	4062.7	4089.9	2407.4	11600	97.00	10.50
		B1 2 10 2	4077.7	4113.3	2420.0	11750	98.50	11.50
		B1 8 36 3	4057.9	4087.1	2410.7	11400	97.50	11.75
District	6	B1 3 4 1	4063.7	4075.1	2413.1	18400	92.00	13.00
		B1 2 3 2	4056.5	4074.6	2411.1	18000	92.00	13.50
		B1 2 18 3	4070.8	4086.1	2413.7	23200	92.00	20.00
District	7	B1 3 8 1	4056.0	4075.9	2412.8	17900	94.00	13.40
		B1 3 24 2	4066.7	4083.7	2420.6	19500	94.00	15.75
		B1 3 18 3	4068.8	4085.2	2428.1	20600	94.00	13.00
District	8	B1 1 15 1	4063.4	4096.0	2407.7	14400	98.00	13.00
		B1 2 6 2	4073.6	4113.0	2412.0	14800	98.00	14.00
		B1 3 17 3	4075.7	4105.9	2412.6	13400	90.00	11.00
District	9	B1 2 15 1	4062.1	4075.8	2422.2	22000	93.00	19.00
		B1 2 2 2	4063.7	4081.4	2415.0	24800	93.00	16.00
		B1 3 12 3	4051.3	4066.3	2425.5	26400	95.00	21.50
District	10	B1 1 12 1	4060.1	4072.6	2415.8	21000	94.00	15.50
		B1 3 16 2	4069.8	4081.2	2413.3	25500	94.00	14.00
		B1 3 21 3	4069.5	4079.8	2419.6	28600	94.00	15.75
Central	11	B1 1 2 1	4075.6	4089.2	2429.2	20000	93.00	12.00
		B1 2 14 2	4076.2	4085.9	2432.2	20500	93.00	13.00
		B1 8 38 3	4054.9	4063.8	2419.0	21900	92.00	13.00
Greer	12	B1 3 13 1	4068.4	4088.6	2415.5	14400	95.20	15.50
		B1 2 12 2	4037.1	4054.1	2395.5	16800	95.20	16.00
		B1 8 34 3	4060.3	4077.5	2410.3	16800	95.20	16.50
WV Paving	13	B1 2 4 1	3997.1	4024.6	2362.4	16400	95.25	15.60
		B1 1 11 2	3998.3	4018.5	2365.6	17000	93.66	12.80
		B1 2 11 3	3991.4	4018.5	2356.0	17600	95.25	19.20
WVU	14	B1 9 15 1	4072.2	4084.9	2421.7	18772	94.00	17.00
		B1 9 12 2	4071.9	4082.3	2416.8	18238	94.50	15.50
		B1 9 14 3	4068.2	4083.0	2417.8	18127	95.00	14.00

Table E.2. Compacted Base 2 Samples Raw Data

Lab	#	Sample	Dry Weight (g)	SSD (g)	Wt. in Water (g)	Stability (N)	Thickness (mm)	Flow (0.25 mm)
District	1	B2 8 1 1	1192.4	1195.1	702.7	13200	56.00	9.00
		B2 7 2 2	1203.0	1205.3	711.2	12800	57.00	11.50
		B2 7 22 3	1201.4	1203.4	709.9	14200	56.00	12.00
District	2	B2 7 15 1	1191.4	1192.7	707.3	14990	61.50	10.50
		B2 7 18 2	1193.9	1196.5	708.5	13990	61.50	12.00
		B2 7 6 3	1197.0	1198.7	708.5	13580	61.50	11.00
District	3	B2 7 25 1	1195.4	1201.3	691.3	9000	65.00	8.60
		B2 7 9 2	1199.8	1204.3	706.0	12000	67.00	8.80
		B2 7 1 3	1187.2	1209.9	699.5	13340	61.00	9.50
District	4	B2 7 17 1	1202.9	1204	714.8	13600	63.50	11.50
		B2 6 24 2	1199.7	1201.1	709.6	14400	63.50	11.50
		B2 6 16 3	1194.8	1196.5	709.0	14400	63.50	12.50
District	5	B2 7 16 1	1195.2	1197.7	706.3	10050	62.50	12.00
		B2 7 4 2	1201.5	1203.3	710.0	12200	62.50	12.50
		B2 7 14 3	1198.5	1200.0	707.1	13000	62.00	10.50
District	6	B2 7 12 1	1195.9	1198.5	705.6	13100	61.00	10.00
		B2 8 4 2	1202.5	1204.0	710.6	12200	61.00	13.00
		B2 8 3 3	1194.0	1195.4	704.2	14400	61.00	16.50
District	7	B2 6 20 1	1199.6	1201.2	712.4	13650	61.00	12.50
		B2 7 10 2	1198.6	1200.1	707.9	13175	61.00	12.50
		B2 6 19 3	1200.3	1202.0	711.2	13500	72.62	11.60
District	8	B2 6 17 1	1198.5	1200.8	709.3	12000	62.00	14.00
		B2 6 23 2	1197.2	1199.1	709.4	11750	62.00	12.00
		B2 7 20 3	1202.0	1203.3	709.6	12800	62.00	14.00
District	9	B2 7 7 1	1196.9	1198.6	707.7	13600	60.00	10.50
		B2 7 24 2	1198.2	1200.0	710.5	14600	60.00	10.50
		B2 6 25 3	1199.1	1201.7	711.3	13600	60.00	10.50
District	10	B2 7 11 1	1195.0	1196.2	701.3	15400	62.00	10.00
		B2 7 21 2	1181.3	1185.0	693.8	18900	64.00	8.75
		B2 6 18 3	1193.7	1194.8	705.4	16800	61.00	9.00
Central	11	B2 7 8 1	1201.1	1202.7	712.4	12500	62.00	12.50
		B2 7 19 2	1197.0	1198.9	708.9	12150	62.00	12.00
		B2 8 2 3	1208.9	1209.5	718.8	13400	62.00	10.50
Greer	12	B2 7 23 1	1194.0	1194.9	706.0	11000	63.50	11.50
		B2 8 5 2	1190.1	1193.0	698.6	10000	63.50	11.50
		B2 7 3 3	1196.3	1198.8	706.2	11400	63.50	14.00
WV Paving	13	B2 6 21 1	1199.8	1201.3	702.1	11000	65.10	12.00
		B2 7 5 2	1199.0	1201.2	707.3	13500	66.70	11.80
		B2 7 13 3	1197.0	1198.4	706.7	13000	63.50	13.20
WVU	14	B2 9 8 1	1195.7	1197.9	705.6	14012	62.50	11.50
		B2 9 6 2	1195.6	1197.6	705.5	15747	62.00	10.25
		B2 9 7 3	1195.0	1197.2	708.0	14568	62.00	10.25

Table E.3. Compacted Wearing 1 Samples Raw Data

Lab	#	Sample	Dry Weight (g)	SSD (g)	Wt. in Water (g)	Stability (N)	Thickness (mm)	Flow (0.25 mm)
District	1	W1 6 6 1	1191.6	1193.3	694.8	13000	57.00	10.50
		W1 4 31 2	1202.1	1203.4	700.4	12900	58.00	8.50
		W1 5 1 3	1203.5	1204.8	723.4	13000	57.00	9.00
District	2	W1 4 10 1	1202.5	1203.1	704.1	13200	62.00	9.40
		W1 5 9 2	1203.9	1204.8	706.6	13400	62.00	10.40
		W1 6 2 3	1210.0	1210.9	706.0	12620	62.00	9.00
District	3	W1 6 7 1	1211.6	1211.7	701.7	12380	64.00	12.40
		W1 4 7 2	1207.6	1224.2	685.6	6020	64.00	14.80
		W1 6 13 3	1209.2	1233.3	687.7	4770	68.00	12.60
District	4	W1 5 3 1	1208.7	1209.5	707.7	15200	63.50	10.00
		W1 3 28 2	1206.1	1206.7	705.7	14000	63.50	11.00
		W1 5 2 3	1207.5	1208.4	706.1	13800	63.50	11.50
District	5	W1 6 10 1	1197.0	1198.0	692.1	11600	63.50	10.50
		W1 4 15 2	1208.9	1209.8	700.1	11750	64.00	11.50
		W1 5 7 3	1210.4	1211.3	703.7	11400	64.00	11.75
District	6	W1 4 6 1	1210.3	1211.4	702.7	12700	63.00	9.50
		W1 4 4 2	1206.8	1208.0	699.5	12400	63.00	11.50
		W1 4 12 3	1205.2	1206.1	699.7	12900	62.00	13.00
District	7	W1 4 5 1	1210.7	1211.7	707.2	12400	63.00	18.50
		W1 4 19 2	1208.0	1209.0	704.4	12300	63.00	10.50
		W1 4 25 3	1206.4	1207.2	705.5	12050	63.00	10.00
District	8	W1 3 27 1	1208.9	1210.5	704.4	11050	63.50	9.50
		W1 4 32 2	1209.6	1210.9	702.6	11050	63.50	9.50
		W1 6 8 3	1212.7	1214.0	706.4	11600	63.50	11.00
District	9	W1 4 28 1	1207.3	1208.1	699.9	13000	60.20	9.50
		W1 6 5 2	1208.3	1209.2	703.7	12600	60.20	9.50
		W1 4 33 3	1209.8	1210.5	704.4	14000	60.20	10.50
District	10	W1 6 15 1	1202.1	1203.3	694.4	15600	64.00	8.75
		W1 4 14 2	1202.6	1203.9	695.6	15400	64.00	10.00
		W1 4 23 3	1210.4	1211.6	698.4	17200	64.00	10.00
Central	11	W1 4 2 1	1212.5	1213.3	707.3	12800	63.00	10.50
		W1 4 17 2	1208.1	1208.7	705.9	12100	63.00	10.00
		W1 5 12 3	1209.4	1209.9	707.9	12600	63.00	10.50
Greer	12	W1 4 8 1	1201.9	1202.4	698.3	12200	63.50	10.00
		W1 4 13 2	1204.3	1205.1	701.3	11800	63.50	9.50
		W1 4 30 3	1205.7	1206.7	704.4	11600	63.50	8.50
WV Paving	13	W1 5 13 1	1206.9	1208.8	695.1	10400	66.70	13.90
		W1 4 21 2	1208.5	1209.7	699.2	10750	65.10	12.80
		W1 5 4 3	1205.2	1207.0	693.3	11200	66.70	13.40
WVU	14	W1 9 3 1	1200.0	1200.4	702.5	14457	62.00	10.00
		W1 9 2 2	1203.8	1204.9	702.1	13678	63.50	9.50
		W1 9 5 3	1208.3	1209.0	706.5	13789	63.00	9.50

Table E.4. Base 1 Rice Samples Raw Data

Lab	#	Sample				Dry Weight (g)	Asphalt+Pycnometer +Water (g)	Pycnometer+Water (g)
District	1	B1R	2	20	1	4090.4	3926.7	1433.8
		B1R	3	25	2	4067.2	3909.1	1433.8
District	2	B1R	1	1	2	4064.1	3839.7	1359.8
		B1R	2	5	1	4068.5	3842.5	1359.8
District	3	B1R	1	6	1	2013.3	2654.9	1429.3
						2067.7	2690.4	1429.3
		B1R	3	11	2	2209.7	2773.1	1429.3
						1870.7	2574.1	1429.3
District	4	B1R	3	6	2	4014.4	3842.6	1396.6
		B1R	8	33	1	4006.6	3838.2	1396.6
District	5	B1R	1	7	1	2251.6	2760.1	1386.1
						1821.2	2497.7	1386.1
		B1R	8	35	2	2347.5	22821.4	1386.1
						1734.2	2494.6	1386.1
District	6	B1R	2	8	1	4064.1	3864.2	1387.2
		B1R	2	19	2	4070.9	3870.3	1387.2
District	7	B1R	2	7	2	4063.3	3865.2	1388.6
		B1R	3	7	1	4004.7	3821.6	1388.6
District	8	B1R	2	9	1	4089.5	5229.5	2735.0
		B1R	3	22	2	4094.1	5230.4	2735.0
District	9	B1R	2	17	2	4061.0	5289.7	2812.4
		B1R	3	15	1	4075.1	5298.6	2812.4
District	10	B1R	3	2	1	4066.4	3880.6	1402.6
		B1R	3	3	2	4074.8	3885.3	1402.6
Central	11	B1R	1	3	1	4083.6	3809.7	1321.5
		B1R	2	1	2	4074.4	3805.9	1321.5
Greer	12	B1R	1	5	1	4058.7	3828.4	1355.7
		B1R	3	9	2	4081.8	3843.9	1355.7
WV Paving	13	B1R	1	13	2	4039.7	5454.4	2988.8
		B1R	3	23	1	4061.6	5466.9	2988.8
WVU	14	B1R	9	11	1	4061.1	9956.2	7480.2
		B1R	9	13	2	4087.1	9970.8	7480.2

Table E.5. Base 2 Rice Samples Raw Data

Lab	#	Sample	Dry Weight (g)	Asphalt+Pycnometer +Water (g)	Pycnometer+Water (g)
District	1	B2R 8 26 1	2091.6	2694.2	1433.8
		B2R 8 8 2	2088.8	2694.1	1433.8
District	2	B2R 8 28 2	2087.3	2620.3	1359.8
		B2R 8 21 1	2088.6	2621.0	1359.8
District	3	B2R 8 25 2	2089.7	2690.7	1429.3
		B2R 8 15 1	2090.5	2691.6	1429.3
District	4	B2R 8 16 1	2083.5	2653.3	1396.6
		B2R 8 31 2	2085.8	2654.2	1396.6
District	5	B2R 8 22 1	2086.6	2648.0	1386.1
		B2R 8 29 2	2087.7	2648.5	1386.1
District	6	B2R 8 6 1	2091.4	2649.6	1387.2
		B2R 8 14 2	2091.7	2649.3	1387.2
District	7	B2R 8 12 2	2087.7	2647.6	1388.6
		B2R 8 27 1	2085.4	2646.2	1388.6
District	8	B2R 8 13 1	2093.9	2631.8	1367.5
		B2R 8 19 2	2088.9	2629.0	1367.5
District	9	B2R 8 7 1	2088.5	2665.9	1406.2
		B2R 8 17 2	2090.0	2668.1	1406.2
District	10	B2R 8 23 2	2089.1	2662.4	1402.6
		B2R 8 30 1	2091.5	2664.0	1402.6
Central	11	B2R 8 9 1	2086.2	2580.2	1321.5
		B2R 8 10 2	2093.0	2583.5	1321.5
Greer	12	B2R 8 20 1	2077.6	2609.7	1355.7
		B2R 8 24 2	2077.3	2609.2	1355.7
WV Paving	13	B2R 8 18 2	2089.1	2755.3	1494.4
		B2R 8 11 1	2089.9	2754.6	1494.4
WVU	14	B2R 9 9 1	2083.0	8736.6	7480.2
		B2R 9 10 2	2084.7	8738.6	7480.2

Table E.6. Compacted Wearing 1 Rice Samples Raw Data

Lab	#	Sample				Dry Weight (g)	Asphalt+Pycnometer +Water (g)	Pycnometer+Water (g)
District	1	W1R	5	11	1	1200.5	1430.1	1433.8
		W1R	4	29	2	1218.0	1449.1	1433.8
District	2	W1R	5	15	2	1211.3	2084.8	1359.8
		W1R	6	9	1	1212.2	2085.1	1359.8
District	3	W1R	4	3	1	1211.6	2153.3	1429.3
		W1R	4	18	2	1219.8	2158.1	1429.3
District	4	W1R	6	4	2	1211.4	2120.3	1396.6
		W1R	6	12	1	1216.0	2122.0	1396.6
District	5	W1R	4	26	1	1213.3	2112.9	1386.1
		W1R	5	8	1	1209.7	2110.7	1386.1
District	6	W1R	4	24	1	1212.0	2111.2	1387.2
		W1R	5	5	2	1214.8	2113.1	1387.2
District	7	W1R	6	11	2	1213.1	2111.6	1388.6
		W1R	3	26	1	1216.8	2112.7	1388.6
District	8	W1R	6	14	2	1213.2	2092.7	1367.5
		W1R	4	20	1	1213.9	2093.0	1367.5
District	9	W1R	4	11	2	1212.4	2130.5	1406.2
		W1R	4	9	1	1215.7	2132.7	1406.2
District	10	W1R	6	3	2	1211.4	2125.9	1402.6
		W1R	5	14	1	1212.6	2125.8	1402.6
Central	11	W1R	6	1	2	1211.2	2045.7	1321.5
		W1R	5	6	1	1209.0	2045.4	1321.5
Greer	12	W1R	4	22	1	1204.5	2074.7	1355.7
		W1R	4	1	2	1207.7	2076.8	1355.7
WV Paving	13	W1R	4	16	1	1201.8	2212.9	1494.4
		W1R	5	10	2	1211.6	2217.6	1494.4
WVU	14	W1R	9	1	1	1212.8	8206.4	7480.2
		W1R	9	4	2	1210.2	8204.1	7480.2

Table E.7. Questionnaire Results

		Experience (Yrs)	Oven Temp. (^{o}C)	Hammer Calibrated	Calibration Verified	Marshall Hammer Brand	Marshall Stability Brand	Hammer Calibrated to Manual Hammer
District 1		1	148.9	Jun-90	May-98	Pine Inst.	Pine Inst.	No
District 2		0.25	148.9	Apr-98	May-98	Pine Inst.	Pine Inst.	No
District 3		20	157.2	Apr-98	Apr-98	Pine Inst.	Pine Inst.	No
District 4		8	155.0	-	-	Pine Inst.	Pine Inst.	No
District 5		3	145.0	Jun-91	Jun-98	Pine Inst.	Pine Inst.	No
District 6		12	148.9	Jun-90	Jun-98	Pine Inst.	Pine Inst.	No
District 7		7	145.0	-	Jul-98	Pine Inst.	Pine Inst.	No
District 8		10	145.0	Apr-98	Apr-98	Pine Inst.	Pine Inst.	No
District 9		0.667	144.4	Aug-90	Nov-97	Pine Inst.	Pine Inst.	No
District 10		-	-	-	-	-	-	No
Central	Base 1	8	144.0	-	Mar-98	Pine Inst.	Pine Inst.	Yes - 75 Blows
	Base 2	8	142.0					
	Wearing 1	8	146.0					
Greer		20	146.0	Mar-98	Mar-98	Pine Inst.	Pine Inst.	No
WV Paving		5	154.4	Jul-95	Mar-98	Pine Inst.	Pine Inst.	No
WVU		1	147	Jun-91	May-98	Pine Inst.	Pine Inst.	No

APPENDIX F

LABORATORY INSTRUCTIONS, QUESTIONNAIRE AND DATA SHEETS

JOHN P. ZANIEWSKI

West Virginia University
P.O. Box 6103
Morgantown, WV. 26506
(304) 293-3031 ext. 648

District ______

Even though the SUPERPAVE procedures will eventually replace the Marshall procedure for mix design and quality control the West Virginia DOH will continue to use the Marshall method in the interim. For quality control, the inter-laboratory precision and variance in the Marshall method need to be quantified for statistical based quality control methods. WVU has a DOH contract to assist with measuring variability in the Marshall method. This requires several labs to test identical samples.

All ten West Virginia DOH district laboratories will participate in the study to provide the most reliable results possible. In addition, the headquarters, the WVU laboratory, and two contractors will participate in the study. Each laboratory will test samples of Wearing 1, Base 1 and Base 2. The Wearing 1 and Base 2 will be compacted in 4-inch molds and Base 1 will be compacted in 6-inch molds. One test will be run at each laboratory consisting of three samples each for the stability, flow, and bulk specific gravity procedures. For maximum theoretical specific gravity two samples will be used.

One person with practiced knowledge of Marshall testing procedures must be designated to do all testing at each lab. All tests for each asphalt concrete type should be performed in a single day. All tests should be performed according to standard West Virginia DOH/AASHTO testing procedures. If testing procedures are properly followed but unusual results are found the test is not to be re-run. Record the actual data.

The compaction temperature for all of the samples is 142-157°C (287.6-296.6°F). Each sample is coded with a number. The first two digits signifies which mix type the container holds: Base 1 = B1, Base 2 = B2, and Wearing 1 = W1. The following digit signifies which day the mix was fabricated and the next two digits signify the order at which the mix was made that day. For Base 2 mixes, two of the containers have an “R” written on them. The maximum theoretical specific gravity test should be performed on these specimens and the other three should be compacted. For Wearing 1 and Base 1 the two samples chosen for the maximum theoretical specific gravity test and three samples chosen for compaction should be randomly selected.

Please fill out the questionnaire attached to this sheet and record all data on the attached form. We will do all calculations. Once all testing has been completed and data has been recorded, photocopy each worksheet, graph and questionnaire, then fax them to John Zaniewski at (304) 293-7109 and send the original to the above address.

Your participation in this study is greatly appreciated. If there are any questions or comments about the study please feel free to call me or the inter-laboratory study coordinator, Mike Hughes at (304) 293-3031 ext. 383.

Thank you again for your participation.

Sincerely,

John P. Zaniewski

West Virginia University

QUESTIONNAIRE

Please supply an answer for each question.

Name of technician performing tests:______________________

Job Title:_____________________

Years of Marshall test experience?______________

When was the last time the Marshall Stability and Flow apparatus was calibrated?___________________________

When was the last time the Marshall Stability and Flow apparatus calibration was verified? ______________________________

What is the brand name of the Marshall Stability and Flow apparatus? _____________________________

What is the brand name of the Marshall Hammer?_____________________________

Has the Marshall Hammer ever been correlated to the manual compaction hammer?_____

If yes, when, and how many blows is the automatic hammer set at?___________ _________________________________

At what temperature was the oven set to reheat the samples?_____________________

How long were the samples heated in the oven?

Base 1 Compacted: _________________ Base 1 Rice: _________________

Base 2 compacted: __________________ Base 2 Rice: _________________

Wearing 1 Compacted: ______________ Wearing 1 Rice: ______________

West Virginia University Marshall Variability Study

Lab ______________________________

Technician: ______________________ Date Completed: ______________________

Base 1

Maximum Theoretical Specific Gravity (AASHTO T-209)

Sample No:		Sample No:	
Sample Weight		Sample Weight	
Pycnometer+Sample+Water		Pycnometer+Sample+Water	
Pycnometer+Water		Pycnometer+Water	

Bulk Specific Gravity (AASHTO T-166)

Specimen No.:			
Weight in Air			
Saturated Surface Dry Weight			
Weight in Water			

Marshall Stability and Flow (AASHTO T-245)

Specimen Thickness (mm)			
Measured Stability (N)			
Flow (0.25 mm)			

West Virginia University Marshall Variability Study

Lab ______________________________

Technician: Date Completed:

Base 2

Maximum Theoretical Specific Gravity (AASHTO T-209)

Sample No:		Sample No:	
Sample Weight		Sample Weight	
Pycnometer+Sample+Water		Pycnometer+Sample+Water	
Pycnometer+Water		Pycnometer+Water	

Bulk Specific Gravity (AASHTO T-166)

Specimen No.:			
Weight in Air			
Saturated Surface Dry Weight			
Weight in Water			

Marshall Stability and Flow (AASHTO T-245)

Specimen Thickness (mm)			
Measured Stability (N)			
Flow (0.25 mm)			

West Virginia University
Marshall Variability Study

Lab ____________________

Technician: Date Completed: ____________________

Wearing 1

Maximum Theoretical Specific Gravity (AASHTO T-209)

Sample No:		Sample No:	
Sample Weight		Sample Weight	
Pycnometer+Sample+Water		Pycnometer+Sample+Water	
Pycnometer+Water		Pycnometer+Water	

Bulk Specific Gravity (AASHTO T-166)

Specimen No.:			
Weight in Air			
Saturated Surface Dry Weight			
Weight in Water			

Marshall Stability and Flow (AASHTO T-245)

Specimen Thickness (mm)			
Measured Stability (N)			
Flow (0.25 mm)			

APPENDIX G

VARIABILITY ANALYSIS TABLES

Table G.1. Base 1, Rice, Within-Laboratory Average and Variance

Laboratory	#	Sample 1	Sample 2	Average	Within-Laboratory Variance
District	1	2.561	2.555	2.558	0.0000155
District	2	2.565	2.566	2.565	0.0000000
District	3	2.557	2.554	2.556	0.0000045
District	4	2.560	2.560	2.560	0.0000002
District	5	2.566	2.602	2.584	0.0006452
District	6	2.561	2.564	2.562	0.0000050
District	7	2.561	2.548	2.554	0.0000825
District	8	2.564	2.561	2.562	0.0000047
District	9	2.564	2.565	2.564	0.0000001
District	10	2.560	2.559	2.560	0.0000002
Central	11	2.560	2.563	2.561	0.0000042
Greer	12	2.559	2.561	2.560	0.0000026
WV Paving	13	2.566	2.565	2.566	0.0000010
WVU	14	2.562	2.560	2.561	0.0000020

Table G.2. Base 2, Rice, Within-Laboratory Average and Variance

Laboratory		Sample 1	Sample 2	Average	Within-Laboratory Variance
District	1	2.516	2.521	2.519	0.0000058
	2	2.525	2.524	2.524	0.0000000
	3	2.523	2.524	2.524	0.0000004
	4	2.520	2.518	2.519	0.0000005
	5	2.530	2.530	2.530	0.0000001
	6	2.523	2.521	2.522	0.0000005
	7	2.519	2.519	2.519	0.0000000
	8	2.524	2.525	2.524	0.0000001
	9	2.520	2.524	2.522	0.0000039
	10	2.519	2.520	2.519	0.0000001
Central	11	2.521	2.519	2.520	0.0000015
Greer	12	2.523	2.522	2.522	0.0000002
WV Paving	13	2.522	2.519	2.521	0.0000032
WVU	14	2.520	2.523	2.521	0.0000022

Table G.3. Wearing 1, Rice, Within-Laboratory Average and Variance

Laboratory		Sample 1	Sample 2	Average	Within-Laboratory Variance
District	2	2.491	2.490	2.490	0.0000004
District	3	2.485	2.484	2.485	0.0000001
District	4	2.484	2.479	2.481	0.0000070
District	5	2.494	2.494	2.494	0.0000000
District	6	2.484	2.485	2.484	0.0000003
District	7	2.475	2.470	2.472	0.0000077
District	8	2.486	2.485	2.486	0.0000001
District	9	2.484	2.485	2.484	0.0000003
District	10	2.482	2.478	2.480	0.0000043
Central	11	2.487	2.492	2.490	0.0000068
Greer	12	2.481	2.482	2.481	0.0000002
WV Paving	13	2.487	2.481	2.484	0.0000087
WVU	14	2.492	2.489	2.490	0.0000036

Table G.4. Base 1, Stability, Within-Laboratory Average and Variance

Laboratory		Sample 1 (N)	Sample 2 (N)	Sample 3 (N)	Average (N)	Within-Laboratory Variance
District	1	26267	27988	22612	25623	7537655
District	2	20129	22229	22946	21768	2143307
District	3	28324	23796	24113	25411	6388444
District	4	22466	23268	26477	24070	4506278
District	5	11280	11143	10992	11138	20675
District	6	19545	19120	24644	21103	9448220
District	7	18336	19975	21102	19805	1934311
District	8	13769	14152	14780	14234	260649
District	9	22945	25866	26570	25127	3693809
District	10	21512	26122	29297	25644	15324079
Central	11	20859	21381	23263	21835	1598910
Greer	12	14442	16849	16849	16047	1931262
WV Paving	13	16434	17521	17636	17197	440122
WVU	14	19230	18518	18244	18664	259004

Table G.5. Base 2, Stability, Within-Laboratory Average and Variance

Laboratory		Sample 1 (N)	Sample 2 (N)	Sample 3 (N)	Average (N)	Within-Laboratory Variance
District	1	16304	15333	17540	16392	815316
District	2	15809	14754	14322	14962	390052
District	3	8684	11042	14258	11328	5219838
District	4	13619	14420	14420	14153	142621
District	5	10325	12533	13530	12129	1794386
District	6	14002	13040	15391	14144	931694
District	7	14590	14082	10989	13220	2532198
District	8	12490	12229	13322	12680	217254
District	9	14938	16037	14938	15305	268116
District	10	16028	18691	17956	17558	1260532
Central	11	13010	12646	13947	13201	300305
Greer	12	11015	10014	11416	10815	347639
WV Paving	13	10588	12509	13018	12038	1095078
WVU	14	14395	16389	15162	15316	674795

Table G.6. Wearing 1 Stability, Within-Laboratory Average and Variance

Laboratory		Sample 1 (N)	Sample 2 (N)	Sample 3 (N)	Average (N)	Within-Laboratory Variance
District	1	15573	15000	15573	15382	72858
District	2	13739	13947	13135	13607	118533
District	3	12243	5953	4290	7495	11731308
District	4	15221	14020	13819	14353	383295
District	5	11616	11620	11274	11503	26349
District	6	12880	12576	13426	12961	123733
District	7	12576	12475	12221	12424	22286
District	8	11065	11065	11616	11249	67411
District	9	14201	13764	15293	14419	413668
District	10	15427	15229	17009	15889	634594
Central	11	12982	12272	12779	12677	89145
Greer	12	12217	11817	11616	11883	62397
WV Paving	13	9636	10347	10378	10120	117304
WVU	14	15047	13697	13985	14243	336917

Table G.7. Base 1, Flow, Within-Laboratory Average and Variance

Laboratory		Sample 1 (0.25 mm)	Sample 2 (0.25 mm)	Sample 3 (0.25 mm)	Average (0.25 mm)	Within-Laboratory Variance
District	1	15.00	15.00	16.50	15.50	0.750
District	2	16.00	14.20	11.50	13.90	5.130
District	3	13.40	12.50	20.50	15.47	19.203
District	4	15.50	17.00	20.00	17.50	5.250
District	5	10.50	11.50	11.75	11.25	0.438
District	6	13.00	13.50	20.00	15.50	15.250
District	7	13.40	15.75	13.00	14.05	2.207
District	8	13.00	14.00	11.00	12.67	2.333
District	9	19.00	16.00	21.50	18.83	7.583
District	10	15.50	14.00	15.75	15.08	0.896
Central	11	12.00	13.00	13.00	12.67	0.333
Greer	12	15.50	16.00	16.50	16.00	0.250
WV Paving	13	15.60	12.80	19.20	15.87	10.293
WVU	14	17.00	15.50	14.00	15.50	2.250

Table G.8. Base 2, Flow, Within-Laboratory Average and Variance

Laboratory		Sample 1 (0.25 mm)	Sample 2 (0.25 mm)	Sample 3 (0.25 mm)	Average (0.25 mm)	Within-Laboratory Variance
District	1	9.00	11.50	12.00	10.83	1.722
District	2	10.50	12.00	11.00	11.17	0.389
District	3	8.60	8.80	9.50	8.97	0.149
District	4	11.50	11.50	12.50	11.83	0.222
District	5	12.00	12.50	10.50	11.67	0.722
District	6	10.00	13.00	16.50	13.17	7.056
District	7	12.50	12.50	11.60	12.20	0.180
District	8	14.00	12.00	14.00	13.33	0.889
District	9	10.50	10.50	10.50	10.50	0.000
District	10	10.00	8.75	9.00	9.25	0.292
Central	11	12.50	12.00	10.50	11.67	0.722
Greer	12	11.50	11.50	14.00	12.33	1.389
WV Paving	13	12.00	11.80	13.20	12.33	0.382
WVU	14	11.50	10.25	10.25	10.67	0.347

Table G.9. Wearing 1, Flow, Within-Laboratory Average and Variance

Laboratory		Sample 1 (0.25 mm)	Sample 2 (0.25 mm)	Sample 3 (0.25 mm)	Average (0.25 mm)	Within-Laboratory Variance
District	1	10.50	8.50	9.00	9.33	0.722
District	2	9.40	10.40	9.00	9.60	0.347
District	3	12.40	14.80	12.60	13.27	1.182
District	4	10.00	11.00	11.50	10.83	0.389
District	5	10.50	11.50	11.75	11.25	0.292
District	6	9.50	11.50	13.00	11.33	2.056
District	7	18.50	10.50	10.00	13.00	15.167
District	8	9.50	9.50	11.00	10.00	0.500
District	9	9.50	9.50	10.50	9.83	0.222
District	10	8.75	10.00	10.00	9.58	0.347
Central	11	10.50	10.00	10.50	10.33	0.056
Greer	12	10.00	9.50	8.50	9.33	0.389
WV Paving	13	13.90	12.80	13.40	13.37	0.202
WVU	14	10.00	9.50	9.50	9.67	0.056

Table G.10. Base 1, Bulk Specific Gravity, Within-Laboratory Average and Variance

Laboratory		Sample 1	Sample 2	Sample 3	Average	Within-Laboratory Variance
District	1	2.451	2.440	2.446	2.446	0.000028
District	2	2.449	2.457	2.447	2.451	0.000029
District	3	2.460	2.451	2.451	2.454	0.000029
District	4	2.453	2.446	2.453	2.451	0.000015
District	5	2.415	2.408	2.421	2.414	0.000039
District	6	2.445	2.439	2.434	2.439	0.000030
District	7	2.439	2.445	2.455	2.446	0.000070
District	8	2.407	2.395	2.407	2.403	0.000048
District	9	2.457	2.439	2.469	2.455	0.000235
District	10	2.415	2.405	2.439	2.420	0.000310
Central	11	2.450	2.443	2.464	2.452	0.000112
Greer	12	2.442	2.407	2.429	2.426	0.000312
WV Paving	13	2.403	2.428	2.434	2.422	0.000265
WVU	14	2.429	2.430	2.443	2.434	0.000062

Table G.11. Base 2, Bulk Specific Gravity, Within-Laboratory Average and Variance

Laboratory		Sample 1	Sample 2	Sample 3	Average	Within-Laboratory Variance
District	1	2.422	2.435	2.434	2.430	0.000037
District	2	2.454	2.447	2.442	2.448	0.000027
District	3	2.344	2.408	2.344	2.365	0.000906
District	4	2.459	2.441	2.451	2.450	0.000054
District	5	2.432	2.436	2.432	2.433	0.000003
District	6	2.426	2.437	2.431	2.431	0.000020
District	7	2.454	2.435	2.446	2.445	0.000060
District	8	2.438	2.445	2.435	2.439	0.000017
District	9	2.438	2.448	2.445	2.444	0.000016
District	10	2.451	2.440	2.451	2.447	0.000026
Central	11	2.455	2.465	2.465	2.462	0.000022
Greer	12	2.432	2.434	2.435	2.434	0.000002
WV Paving	13	2.405	2.419	2.401	2.408	0.000061
WVU	14	2.448	2.445	2.443	2.445	0.000005

Table G.12. Wearing 1, Bulk Specific Gravity, Within-Laboratory Average and Variance

Laboratory		Sample 1	Sample 2	Sample 3	Average	Within-Laboratory Variance
District	1	2.390	2.390	2.500	2.427	0.002683
District	2	2.410	2.416	2.397	2.408	0.000069
District	3	2.376	2.242	2.216	2.278	0.004880
District	4	2.409	2.407	2.404	2.407	0.000004
District	5	2.366	2.372	2.385	2.374	0.000060
District	6	2.379	2.373	2.380	2.377	0.000009
District	7	2.400	2.394	2.405	2.399	0.000019
District	8	2.389	2.380	2.389	2.386	0.000019
District	9	2.376	2.390	2.390	2.385	0.000048
District	10	2.362	2.366	2.359	2.362	0.000009
Central	11	2.396	2.403	2.409	2.403	0.000028
Greer	12	2.384	2.390	2.400	2.392	0.000044
WV Paving	13	2.349	2.367	2.346	2.354	0.000086
WVU	14	2.410	2.394	2.405	2.403	0.000044

Table G.13. Base 1, Percent Air Voids, Within-Laboratory Average and Variance

Laboratory		Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Average (%)	Within-Laboratory Variance
District	1	4.17	4.59	4.35	4.37	0.043
District	2	4.56	4.23	4.63	4.47	0.044
District	3	3.73	4.08	4.11	3.98	0.044
District	4	4.16	4.43	4.17	4.25	0.023
District	5	6.55	6.81	6.32	6.56	0.058
District	6	4.57	4.83	5.00	4.80	0.046
District	7	4.53	4.27	3.88	4.23	0.107
District	8	6.07	6.54	6.07	6.23	0.074
District	9	4.21	4.91	3.72	4.28	0.357
District	10	4.26	4.67	4.24	4.39	0.060
Central	11	4.13	3.75	3.74	3.88	0.050
Greer	12	5.02	4.93	4.88	4.94	0.005
WV Paving	13	6.27	5.72	6.42	6.14	0.138
WVU	14	4.40	4.54	4.61	4.51	0.011

Table G.14. Base 2, Percent Air Voids, Within-Laboratory Average and Variance

Laboratory		Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Average (%)	Within-Laboratory Variance
District	1	3.86	3.34	3.35	3.51	0.059
District	2	2.77	3.09	3.27	3.04	0.043
District	3	7.12	4.59	7.12	6.27	1.423
District	4	2.39	3.11	2.71	2.74	0.086
District	5	3.86	3.73	3.89	3.82	0.005
District	6	3.80	3.37	3.62	3.59	0.032
District	7	2.58	3.34	2.92	2.95	0.095
District	8	3.40	3.15	3.55	3.37	0.027
District	9	3.32	2.94	3.04	3.10	0.026
District	10	4.16	4.54	3.18	3.96	0.326
Central	11	2.78	3.06	2.23	2.69	0.118
Greer	12	3.17	4.56	3.71	3.81	0.327
WV Paving	13	4.65	3.69	3.42	3.92	0.278
WVU	14	3.67	3.64	3.12	3.48	0.065

Table G.15. Wearing 1, Percent Air Voids, Within-Laboratory Average and Variance

Laboratory		Sample 1 (%)	Sample 2 (%)	Sample 3 (%)	Average (%)	Within-Laboratory Variance
District	2	3.2294	2.9611	3.7637	3.3181	0.111279
District	3	4.4613	9.7587	10.7984	8.3395	7.700207
District	4	2.9228	2.9770	3.1157	3.0052	0.006601
District	5	5.1224	4.8936	4.3816	4.7992	0.095920
District	6	4.2260	4.4654	4.1964	4.2960	0.014505
District	7	2.9376	3.1733	2.7426	2.9512	0.031009
District	8	3.9065	4.2670	3.8893	4.0209	0.030325
District	9	4.3815	3.7911	3.7859	3.9862	0.078139
District	10	4.7441	4.5920	4.8901	4.7421	0.014807
Central	11	3.7524	3.4913	3.2335	3.4924	0.044873
Greer	12	3.9164	3.6672	3.2672	3.6169	0.071505
WV Paving	13	5.4064	4.6872	5.5396	5.2111	0.140162
WVU	14	3.2270	3.8667	3.4497	3.5145	0.070286

Table G.16. Outlying Percentile for Rice Specific Gravity

Laboratory	Replicate	Rice Specific Gravity			Percentile		
		Base 1	Base 2	Wearing 1	Base 1	Base 2	Wearing 1
District 1	1	2.561	2.516	-	59	**96**	-
	2	2.555	2.521	-	80	59	-
District 2	1	2.565	2.525	2.491	63	80	86
	2	2.566	2.524	2.490	64	78	80
District 3	1	2.557	2.523	2.485	73	62	50
	2	2.554	2.524	2.484	83	76	53
District 4	1	2.560	2.520	2.484	63	73	56
	2	2.560	2.518	2.479	60	86	86
District 5	1	2.566	2.530	2.494	66	**100**	**95**
	2	2.602	2.530	2.494	**100**	**99**	94
District 6	1	2.561	2.523	2.484	58	61	58
	2	2.564	2.521	2.485	57	57	50
District 7	1	2.561	2.519	2.475	57	80	**95**
	2	2.548	2.519	2.470	**95**	80	**100**
District 8	1	2.564	2.524	2.486	57	75	59
	2	2.561	2.525	2.485	57	81	55
District 9	1	2.564	2.520	2.484	58	74	56
	2	2.565	2.524	2.485	60	73	52
District 10	1	2.560	2.519	2.482	61	81	69
	2	2.559	2.520	2.478	64	77	89
Central	1	2.560	2.521	2.487	63	60	66
	2	2.563	2.519	2.492	50	85	90
Greer	1	2.559	2.523	2.481	65	58	75
	2	2.561	2.522	2.482	55	54	69
WV Paving	1	2.566	2.522	2.487	67	57	63
	2	2.565	2.519	2.481	61	83	76
WVU	1	2.562	2.520	2.492	52	73	91
	2	2.560	2.523	2.489	61	63	75

Table G.17. Outlying Percentile for Marshall Stability

Laboratory	Replicate	Stability			Percentile		
		Base 1	Base 2	Wearing 1	Base 1	Base 2	Wearing 1
District 1	1	26267	16304	15573	88	87	88
	2	27988	15333	15000	94	76	83
	3	22612	17540	15573	67	**96**	88
District 2	1	20129	15809	13739	53	82	66
	2	22229	14754	13947	64	67	69
	3	22946	14322	13135	69	59	57
District 3	1	28324	8684	12243	**95**	**99**	58
	2	23796	11042	5953	75	90	**100**
	3	24113	14258	4290	77	58	**100**
District 4	1	22466	13619	15221	66	53	85
	2	23268	14420	14020	72	61	70
	3	26477	14420	13819	89	61	68
District 5	1	11280	10325	11616	**97**	94	68
	2	11143	12533	11620	**98**	72	68
	3	10992	13530	11274	**98**	55	73
District 6	1	19545	14002	12880	58	54	53
	2	19120	13040	12576	62	64	53
	3	24644	15391	13426	80	77	61
District 7	1	18336	14590	12576	68	64	53
	2	19975	14082	12475	55	55	54
	3	21102	10989	12221	55	90	58
District 8	1	13769	12490	11065	92	73	76
	2	14152	12229	11065	91	76	76
	3	14780	13322	11616	89	59	68
District 9	1	22945	14938	14201	69	70	73
	2	25866	16037	13764	87	85	67
	3	26570	14938	15293	90	70	86
District 10	1	21512	16028	15427	58	84	87
	2	26122	18691	15229	88	**99**	85
	3	29297	17956	17009	**97**	**97**	**96**
Central	1	20859	13010	12982	53	64	54
	2	21381	12646	12272	57	70	58
	3	23263	13947	12779	71	53	51
Greer	1	14442	11015	12217	90	90	58
	2	16849	10014	11817	78	**96**	65
	3	16849	11416	11616	78	86	68
WV Paving	1	16434	10588	9636	80	93	90
	2	17521	12509	10347	74	72	84
	3	17636	13018	10378	73	64	84
WVU	1	19230	14395	15047	61	61	83
	2	18518	16389	13697	66	88	66
	3	18244	15162	13985	68	73	70

Table G.18. Outlying Percentile for Marshall Flow

Laboratory	Replicate	Flow			Percentile		
		Base 1	Base 2	Wearing 1	Base 1	Base 2	Wearing 1
District 1	1	15.00	9.00	10.50	50	93	56
	2	15.00	11.50	8.50	50	52	88
	3	16.50	12.00	9.00	71	64	82
District 2	1	16.00	10.50	9.40	65	71	76
	2	14.20	12.00	10.40	61	64	58
	3	11.50	11.00	9.00	90	60	82
District 3	1	13.40	8.60	12.40	72	**96**	80
	2	12.50	8.80	14.80	82	**95**	**98**
	3	20.50	9.50	12.60	98	88	83
District 4	1	15.50	11.50	10.00	58	52	66
	2	17.00	11.50	11.00	77	52	55
	3	20.00	12.50	11.50	**97**	75	65
District 5	1	10.50	12.00	10.50	**95**	64	56
	2	11.50	12.50	11.50	90	75	65
	3	11.75	10.50	11.75	89	71	70
District 6	1	13.00	10.00	9.50	77	81	75
	2	13.50	13.00	11.50	71	83	65
	3	20.00	16.50	13.00	**97**	**100**	88
District 7	1	13.40	12.50	18.50	72	75	**100**
	2	15.75	12.50	10.50	61	75	56
	3	13.00	11.60	10.00	77	54	66
District 8	1	13.00	14.00	9.50	77	94	75
	2	14.00	12.00	9.50	64	64	75
	3	11.00	14.00	11.00	93	94	55
District 9	1	19.00	10.50	9.50	93	71	75
	2	16.00	10.50	9.50	65	71	75
	3	21.50	10.50	10.50	**99**	71	56
District 10	1	15.50	10.00	8.75	58	81	85
	2	14.00	8.75	10.00	64	95	66
	3	15.75	9.00	10.00	61	93	66
Central	1	12.00	12.50	10.50	87	75	56
	2	13.00	12.00	10.00	77	64	66
	3	13.00	10.50	10.50	77	71	56
Greer	1	15.50	11.50	10.00	58	52	66
	2	16.00	11.50	9.50	65	52	75
	3	16.50	14.00	8.50	71	94	88
WV Paving	1	15.60	12.00	13.90	59	64	**95**
	2	12.80	11.80	12.80	79	59	86
	3	19.20	13.20	13.40	94	86	92
WVU	1	17.00	11.50	10.00	77	52	66
	2	15.50	10.25	9.50	58	76	75
	3	14.00	10.25	9.50	64	76	75

Table G.19. Outlying Percentile for Bulk Specific Gravity

Laboratory	Replicate	Bulk Specific Gravity			Percentile		
		Base 1	Base 2	Wearing 1	Base 1	Base 2	Wearing 1
District 1	1	2.451	2.422	2.390	78	68	57
	2	2.440	2.435	2.390	58	51	57
	3	2.446	2.434	2.500	70	51	**100**
District 2	1	2.449	2.454	2.410	74	78	74
	2	2.457	2.447	2.416	86	68	79
	3	2.447	2.442	2.397	71	62	63
District 3	1	2.460	2.344	2.376	89	**100**	56
	2	2.451	2.408	2.242	78	84	**100**
	3	2.451	2.326	2.216	77	**100**	**100**
District 4	1	2.453	2.459	2.409	81	83	73
	2	2.446	2.441	2.407	70	60	72
	3	2.453	2.451	2.404	81	74	69
District 5	1	2.415	2.432	2.366	88	53	65
	2	2.408	2.436	2.372	94	52	60
	3	2.421	2.432	2.385	80	54	52
District 6	1	2.445	2.426	2.379	67	62	53
	2	2.439	2.437	2.373	54	55	59
	3	2.434	2.431	2.380	55	55	52
District 7	1	2.439	2.454	2.400	55	78	66
	2	2.445	2.435	2.394	68	52	61
	3	2.455	2.446	2.405	84	67	70
District 8	1	2.407	2.438	2.389	94	57	56
	2	2.395	2.445	2.380	**99**	66	53
	3	2.407	2.435	2.389	94	51	56
District 9	1	2.457	2.438	2.376	86	56	56
	2	2.439	2.448	2.390	54	70	57
	3	2.469	2.445	2.390	**96**	66	57
District 10	1	2.415	2.451	2.362	88	73	68
	2	2.405	2.440	2.366	**95**	59	65
	3	2.439	2.451	2.359	55	74	71
Central	1	2.450	2.455	2.396	76	79	63
	2	2.443	2.465	2.403	63	88	68
	3	2.464	2.465	2.409	93	88	73
Greer	1	2.442	2.432	2.384	62	54	52
	2	2.407	2.434	2.390	94	50	57
	3	2.429	2.435	2.400	67	52	66
WV Paving	1	2.403	2.405	2.349	**96**	87	78
	2	2.428	2.419	2.367	68	71	64
	3	2.434	2.401	2.346	55	89	80
WVU	1	2.429	2.448	2.410	66	71	74
	2	2.430	2.445	2.394	65	66	61
	3	2.443	2.443	2.405	63	63	70

Table G.20. Outlying Percentile for Percent Air Voids

Laboratory	Replicate	Percent Air Voids			Percentile		
		Base 1	Base 2	Wearing 1	Base 1	Base 2	Wearing 1
District 1	1	4.174	3.858	-	76	59	-
	2	4.589	3.337	-	59	60	-
	3	4.352	3.348	-	69	60	-
District 2	1	4.557	2.771	3.229	60	79	74
	2	4.232	3.086	2.961	74	69	79
	3	4.626	3.271	3.764	57	63	62
District 3	1	3.734	7.117	4.461	88	**100**	55
	2	4.085	4.586	9.759	79	83	**100**
	3	4.109	7.826	10.798	78	**100**	**100**
District 4	1	4.160	2.394	2.923	76	88	80
	2	4.431	3.109	2.977	66	68	79
	3	4.172	2.713	3.116	76	80	76
District 5	1	6.552	3.860	5.122	**98**	60	71
	2	6.805	3.725	4.894	**99**	55	66
	3	6.323	3.888	4.382	**96**	61	53
District 6	1	4.575	3.799	4.226	60	57	51
	2	4.830	3.366	4.465	52	59	55
	3	5.003	3.619	4.196	60	50	51
District 7	1	4.526	2.582	2.938	62	84	79
	2	4.274	3.336	3.173	72	60	75
	3	3.878	2.923	2.743	85	74	83
District 8	1	6.073	3.402	3.906	93	58	59
	2	6.540	3.152	4.267	**98**	67	50
	3	6.067	3.551	3.889	93	52	59
District 9	1	4.210	3.319	4.381	74	61	53
	2	4.909	2.937	3.791	55	74	61
	3	3.720	3.043	3.786	89	71	62
District 10	1	4.264	4.156	4.744	72	70	62
	2	4.674	4.542	4.592	55	81	58
	3	4.239	3.185	4.890	73	66	65
Central	1	4.134	2.784	3.752	77	79	62
	2	3.755	3.056	3.491	88	70	68
	3	3.740	2.232	3.233	88	91	74
Greer	1	5.022	3.167	3.916	60	66	58
	2	4.929	4.557	3.667	56	82	64
	3	4.876	3.709	3.267	54	54	73
WV Paving	1	6.273	4.650	5.406	**95**	84	76
	2	5.718	3.691	4.687	85	53	61
	3	6.424	3.422	5.540	**97**	57	79
WVU	1	4.398	3.674	3.227	67	53	74
	2	4.537	3.643	3.867	61	51	60
	3	4.606	3.121	3.450	58	68	69

V I T A

Michael S. Hughes was born in Bristol, Pennsylvania on June 10, 1975. He later graduated from Council Rock High School in Newtown, Pennsylvania in June, 1993. In May, 1997, Michael received his Bachelor's degree in civil engineering from West Virginia University in Morgantown, where he currently resides. He has since completed graduate level course work in the areas of paving materials, geotechnical engineering, and transportation engineering. Michael is currently a candidate for the Masters of Science degree in Civil Engineering at West Virginia University, and plans to graduate in December, 1998.