# COMPARISON OF 9.5 MM SUPERPAVE AND MARSHALL WEARING I MIXES IN WEST VIRGINIA

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**16. Abstract**

The West Virginia Division of Highways is currently using the Superpave mix design method for high traffic volume roads and the Marshall method for other highways. The objective of this research was to evaluate the differences between the mix designs from these two design methods for

asphalt concrete wearing courses typically used in the state. These are the WVDOH wearing I mix for the Marshall method and the 9.5 mm design for the Superpave method. Mixes were developed for light, medium and heavy traffic. In addition, mixes were developed for 100 percent limestone and a blend of limestone and natural sand aggregates.

Evaluation of the mixes with the Asphalt Pavement Analyzer demonstrated that the mixes developed under either the Marshall or Superpave mix design method have similar rutting potential. The optimum asphalt content of the mixes varied between the Marshall and Superpave methods. However, there was not a consistent trend that would favor one method.

The total relaxation of the Fine Aggregate Angularity requirement in Superpave for mixes designed for low traffic volume roads allows the use of a high percent of sand in the mix. It was demonstrated that this would produce a mix with high rutting potential if a high percent of sand is used in a mix.

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# CHAPTER 1 INTRODUCTION

Bituminous pavements were first constructed in the United States during the late 1800's. Since this time several mixture design methods have been developed to improve the quality of asphalt concrete mixtures. These include methods such as Hveem, Marshall and Superpave (Roberts, 1996). The Marshall method was developed during the 1930's and has undergone several refinements over the years. The Superpave method was developed during the Strategic Highway Research Program in the late 1980's. The West Virginia Division of Highways, WVDOH, uses the Marshall mix design procedure for the majority of its pavement designs. However, the Superpave method is used in West Virginia for the high traffic volume roads. The WVDOH is currently evaluating the impact of phasing in the Superpave method for all asphalt concrete mix designs.

One of the primary differences between the Marshall and Superpave methods is the aggregate specifications. The stability of asphalt concrete is strongly dependent on friction between the aggregate particles. The Marshall method controls the stability of the asphalt concrete by testing the asphalt concrete. The Superpave method uses tests and specifications on the aggregates to assure interparticle friction.

In West Virginia, aggregate properties vary greatly across the state. Mix designs in the eastern and north central part of the state tend to be composed almost entirely of crushed limestone aggregate due to abundant limestone deposits and quarries. Other parts of the state use a blend of crushed limestone and natural gravel and sand. Crushed limestone particles are strong and possess a level of angularity that is very resistant to rutting. Gravel and sand aggregates are dredged from large rivers such as the Ohio. They are inexpensive compared limestone. However, the polished and rounded nature of this material can result in pavements that rut.

The WVDOH has successfully implemented the Superpave method for the high traffic volume roads in the state. The Superpave aggregate specifications for high traffic volume roads effectively eliminate the use of natural gravel and sands. However, for lower volume roads, natural gravel and sand may meet the specifications. There is a need to evaluate the quality of asphalt concrete that can be developed with the natural gravel and sand available to state contractors. This study will allow both the WVDOH and its contractors to better design projects using the Superpave design method.

## 1.1 PROBLEM STATEMENT

Although the West Virginia has successfully implemented Superpave on high volume roads, there are concerns in both the industry and the Division of Highways regarding the impacts of implementing Superpave on all paving projects. Some are concerned that implementing Superpave will impact the economy of asphalt paving and others are concerned with potential impacts on pavement performance.

The research performed during this project is part of a broader research program. The scope of the research presented herein focuses on a comparison of the Marshall Wearing I mix to the Superpave 9.5mm mix. Both the Marshall Wearing I and Superpave 9.5mm mixes have a nominal maximum aggregate size of 3/8in (9.5mm).

**1.2 OBJECTIVES**

The objective of this research was to evaluate the consequences of full implementation of the Superpave mix design method by the WVDOH. In particular, the use of natural gravel and sand in surface course asphalt concrete was examined during this research to determine if there are differences between the mixes produced under the Marshall and Superpave mix design methods. These effects were measured by testing the rutting potential for each mix and analyzing the difference between the rutting of all limestone mixes with that of mixes that contain various percentages of natural sand. In addition, a few smaller side studies were also performed including:

1. the effects of fine aggregate angularity and voids in the mineral aggregates on mix design and performance,
2. "hidden" restrictions brought about by the interaction between voids in the mineral aggregate and voids filled with asphalt specifications, and
3. the effect of the dust to binder ratio on the gradation requirements of #200 material.

**1.3 RESEARCH APPROACH, SCOPE, AND LIMITATIONS**

Evaluating Superpave implementation issues placed several limitations on the research. In general, a statistically designed experiment has fixed factors and levels, which allow for an efficient analysis of the data. However, when studying asphalt concrete, this approach limits practical implementation of the research results. This is the result of a correlation between the factors being studied and the appropriate levels of the variables for that factor. More specifically, the mix designs primarily are a function of the traffic levels, so it is not appropriate to study the same levels of aggregate gradation, asphalt content, etc for the different traffic levels. The approach used in this research was to develop mix designs for each traffic level and mix design method. This resulted in differences in aggregate blends and asphalt contents as dictated by the mix design process.

To make the research results as practical as possible, all mix designs were performed to WVDOH specifications, and in a manner compatible with industry practices. To comply with these practices, the gradations selected for the mix design had to meet two criteria:

1. Comply with the requirements for the mix design methods, and

2. The mix design gradations could be achieved by blending stockpile material.

The second criterion significantly limited the range of aggregate gradations considered in this study.

The Marshall and Superpave mix design methods have different criteria depending on the level of traffic anticipated on a project. For this project, the following designations and traffic levels were used for comparing mixes.

| Designation | Superpave (ESALs) | Marshall (ESALs) |
|---|---|---|
| Heavy | 10 to 3 | > 3 |
| Medium | 3 to 0.3 | < 3 |
| Light | < 0.3 | (use Medium) |

The asphalt cement used in this study was PG 64-22. This is the standard binder specified by WVDOH. On interstate projects WVDOH uses PG 70-22. However, since the primary interest of this study is for lower volume roads, it was decided to use PG 64-22 consistently for all mix designs.

The materials used in this study were donated by contractors and suppliers used by WVDOH. Limestone aggregates were donated by J.F. Allen Company of Elkins, WV. The natural sand aggregate was obtained from the WVDOH District 6 Materials Lab, Wheeling, WV. The PG 64-22 asphalt cement was donated by Citgo Asphalt Refining Co., Paulsboro, NJ.

This study used equipment available in the Asphalt Technology Laboratory at WVU. The only available equipment for evaluating asphalt concrete performance is the Asphalt Pavement Analyzer.

The research started with a literature review of the relevant mix design methods and criteria, with particular focus on practices in West Virginia. Literature comparing the Marshall and Superpave methods was evaluated to assist in framing the research. Two parameters that are a particular concern to asphalt technologists designing Superpave mixes in West Virginia are the voids in the mineral aggregate and the fine aggregate angularity. Hence, these parameters were examined during the literature review. Finally, the literature on applications of the Asphalt Pavement Analyzer was examined since this device was used during this research to assess mix performance.

Following the literature survey, a preliminary experimental design was completed to identify the specific factors and levels that should be included in the research. The preliminary experimental design was refined as practical issues concerning blending of aggregate to meet specifications that arose during the mix design process. The final experimental design used the mix design types shown in Table 1.1.

Table 1.1 Mix Design Types in Experimental Plan.

| Mix Design Method | Traffic Level | Fine Agg. Content | Designation |
|---|---|---|---|
| Superpave | Heavy | 100% limestone | SP HVY 100%LS |
| | | 87% limestone | SP HVY 13%NS |
| | Medium | 100% limestone | SP MED 100%LS |
| | | 87% limestone | SP MED 13%NS |
| | Light | 100% limestone | SP LGT 100%LS |
| | | 50% limestone | SP LGT 40%NS |
| | | 36% limestone | SP LGT 64%NS |
| | | 100% limestone | SP LGT 100%LS |
| Marshall | Heavy | 100% limestone | M HVY 100%LS |
| | | 87% limestone | M HVY 13%NS |
| | Medium | 100% limestone | M MED 100%LS |
| | | 87% limestone | M MED 13%NS |

The experimental design is somewhat convoluted due to the nature of the material being studied. The Superpave mix design method accommodates more traffic levels than the Marshall method. Three Superpave traffic levels were selected to cover the range of traffic in West Virginia from interstates to local roads. The Marshall method, as implemented in West Virginia, is limited to two traffic levels.

In compliance with the objective of the study, natural sand was incorporated into the experimental design. However, the quantity of sand used in the mixes was constrained to meet aggregate blend specifications and mix design requirements.

While developing the mix designs for the planned experiment, issues arose with determining the fine aggregate angularity, voids in the mineral aggregate and dust to binder ratio for the Superpave mixes. In addition, "hidden" restrictions were identified due to the interaction between the voids in mineral aggregate and voids filled with asphalt specifications. These issues were evaluated to identify and document their importance.

## 1.4 REPORT SUMMARY

This report is organized into six chapters and three appendices. Following this introductory chapter there is a summary of related literature, Chapter 2 that includes background into Marshall and Superpave methods, fine aggregate angularity tests, APA tests and pertinent information from related studies and projects. Chapter 3 presents information on the equipment and methods used during this study. Chapter 4 presents the method for testing and analyzing the fine aggregate angularity (FAA) values for each mix design developed. Chapter 5 describes the Marshall and Superpave mixes evaluated during the research and the results of the Asphalt Pavement Analyzer testing. The summary, conclusions, and recommendations are presented in Chapter 6.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 INTRODUCTION

A preliminary investigation into the topics of interest for this study identified four areas for evaluation during the literature review:

1. A comparison of the Marshall and Superpave procedures
2. The effect of fine aggregate angularity on asphalt concrete mixes
3. The effect of aggregate characteristics on the voids in the mineral aggregate
4. The utility of the Asphalt Pavement Analyzer, APA, for ranking the ruttine potential of asphalt concrete mixes.

Only one study was found that focused on a comparison of Superpave and Marshall mixtures for low-traffic volume roads. This research found that aggregate blends, which meet both Superpave and Marshall gradation requirements, require greatly varying asphalt contents between the two mix design methods (Habib, 1998).

Two studies were found that addressed fine aggregate angularity, FAA, issues. The first study looked into how FAA and particle shape contributes to Superpave mix performance (Huber, 1998). The second examined the use of the FAA value as an indicator of pavement quality (Casanova, 2000).

Three studies were found that evaluated the VMA criteria. The first looked at how highway agencies and designers can best meet the minimum VMA values with the gradations that exist in their areas (Aschenbrener, 1992). The second examines the past problems with meeting the minimum VMA requirements and failing mixes that do not meet the specifications, even though the field performance of the mixes were adequate (Coree, 1999). The third paper discusses the relationship between VMA values and placement of the gradation curve in relation to the Superpave restricted zone (Kandhal, 1998).

Three papers were found evaluating the effectiveness of the APA rut test results as an indication of pavement quality. One of these papers deals with the overall suitability of the APA to predict pavement rutting potential (Choubane, 2000). The other two papers address the rutting characteristics of different pavement types and aggregate blends (Mohammad, 2001 and Tarefder, 2001).

## 2.2 MIX DESIGN METHODS

The objective of an asphalt concrete mix design method is to determine the proper proportions of aggregates and asphalt to produce an economical mix that meets the performance requirements of the pavement. Over the years, several mix design methods have been

developed and implemented by state and federal agencies. This review focuses on the Marshall and Superpave methods since they are currently used by the WVDOH.

### *2.2.1 Overview of the Marshall Method*

Bruce Marshall developed the earliest version of the Marshall mix design method at the Mississippi Highway Department in 1939. The Marshall procedure uses a drop hammer to compact samples and the stability and flow are tested in a confined compression mold. In addition, the volumetric characteristics of the mix are evaluated. In 1943, the Corps of Engineers Waterways Experiment Station began a study to develop a portable apparatus for designing and testing asphalt mixtures for airfield pavements. The Corps began experimenting with Marshall's apparatus and developed a series of laboratory and field experiments. Mixtures were designed in the lab using a variety of compactive efforts to produce lab densities that were similar to those achieved in the field under construction and aircraft loads. Laboratory methods included different drop hammer weights, combinations of numbers of blows per side, compactor foot designs and mold base shapes and materials (Roberts, 1996).

The main goal of the Corps study was to adopt a sample preparation procedure that would involve minimum effort and time while providing a basis for selecting the "optimum" asphalt content. It was also desirable to develop a method that was portable and could be taken to the field for quality control tests. Based on the results of this study, a 10-pound hammer with a 3 7/8 inch diameter foot was selected and a compaction effort of 50 blows per side of the specimen was selected. It was also determined that two major variables stood out in the design and performance of HMA: asphalt content and density of the mix.

During the late 1940s and early 1950s, aircraft size, weight and tire pressure increased. This called for an increase in the required number of blows per side from 50 to 75. The initial stability requirement of 500 pounds minimum was raised to 1000 pounds and then to 1800 pounds to help limit rutting potential of the mixtures. This rutting was primarily seen in mixtures that contained high amounts of natural sand aggregates. These standards were adopted for the construction of high traffic volume highways, such as interstates.

Detailed procedures for Marshall mix design can be found in Roberts, et al, (1996) and the applicable test standard for the Marshall test is AASHTO T 245-97. West Virginia has published specifications for using the Marshall method for pavement design in the state (WVDOH, 2000), Guide to Designing Hot-Mix Asphalt Using the Marshall Design Method, MP 401.02.22.

The Marshall mix design procedure begins with acceptance tests performed on the aggregates and asphalt cement. After these tests, the procedure presented in ASTM D1559: Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus is performed on the mix. The major steps involved in performing a mixture are:

1. aggregate acceptance tests,

2. determine aggregate stockpile blend meeting specifications,
3. specimen preparation and evaluation of bulk specific gravity,
4. evaluation of theoretical maximum specific gravity,
5. stability and flow tests,
6. volumetric analysis, and
7. selection of optimum asphalt content.

The aggregate acceptance tests ensure the aggregates are suitable for asphalt concrete. The WVDOH specifications requirements are given in Table 2.1 (WVDOH, 1996).

Table 2.1 WVDOH Aggregate Requirements for the Marshall Mix Design Method

| **Coarse Aggregate** | |
|---|---|
| Gravel and Crushed Stone | clean hard durable rock free from adherent coatings. |
| Thin or elongated particles (4:1 ratio) | 5% max |
| Shale | 1% max |
| Coal and other lightweight materials | 1.5% max |
| Friable particles | 0.25% max |
| Percent wear (LA abrasion) | 40% max |
| Soundness | 12% max |
| Additional Gravel and Crushed Particle Requirements | |
| Bituminous Base I | min 80% one fractured face |
| All other asphalt concrete | min 80% two fractured faces |
| **Fine Aggregate** | |
| Must meet requirements of ASTM D 1073, except gradation. | |
| **Mineral Filler** | |
| Must meet requirements of ASTM D 242 except for gradation and must be free of harmful organic compounds. | |

The WVDOH Marshall gradation requirements for the mix studied in the research, Wearing I, are:

| Sieve | Allowable Percent Passing Sieve |
|---|---|
| 1/2” | 100 |
| 3/8” | 85 – 100 |
| #4 | 80 max |
| #8 | 30 - 55 |
| #200 | 2.0 – 9.0 |

The percent material passing a sieve when blending multiple stockpiles is computed as (Roberts et al, 1996):

$$P = aA + Bb + Cc \ldots \qquad [2.1]$$

Where,

P = percentage of material passing a given sieve for the combined aggregates A, B, C,…

A, B, C,… = the percent of material passing a given sieve for each aggregate

a, b, c,… = proportions of aggregates A, B, C,… to be used in the blend,
a + b + c… = 1.00.

The combined specific gravity of an aggregate blend is needed to correctly calculate each compacted sample of asphalt pavement. The equation used to determine the combined specific gravity is:

$$G = \frac{P_1 + P_2 + \cdots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \cdots + \frac{P_n}{G_3}} \qquad [2.2]$$

Where,

G = combined specific gravity

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

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

Once a suitable gradation is determined, Marshall samples are compacted. The WVDOH uses 75 and 50 blows per side for heavy and medium traffic volume designs, respectively. The Marshall

mix design was developed to design asphalt pavement mixtures consisting of aggregates with a nominal maximum size less than 19mm. Because of this, a relatively small mold was selected for the compaction of test samples. This mold was 102mm in diameter and accommodated a maximum aggregate size of 25mm. The weight of sample compacted in this mold is approximately 1200g.

Prior to compaction, the aggregates, asphalt cement and all equipment, which come in contact with the mix are heated to the mixing temperature. The asphalt cement supplier generally identifies the mixing temperature based on the viscosity temperature characteristics of the binder.

When the mix is at the correct temperature, it is placed in the mold and the compaction begins. Both the mold, including top and bottom plates, and the head of the drop hammer are heated to the compaction temperature prior to compacting the samples. Once compacted, the sample is allowed to cool and extracted from the mold. The sample is then cooled to room temperature prior to obtaining the weights required for determining the bulk specific gravity.

Bulk specific gravity is measured in accordance with AASHTO T 166-00 as soon as the compacted specimens have cooled to room temperature. Method A of the above standard is described since it is the procedure used in this research. First, the sample weight is measured and recorded. The sample is then submerged in water at 77°F for 4 $\pm$1 minutes and that weight is recorded. The sample was then removed from the water, quickly blotted dry with a damp towel and weighed as the saturated dry condition. Bulk specific gravity is computed as:

$$G_{mb} = \frac{A}{B - C} \qquad [2.3]$$

Where,

$G_{mb}$ = bulk specific gravity

A = mass of sample in air (g)

B = mass of surface-dry specimen in air (g)

C = mass of sample in water (g).

Once the bulk specific gravity of the specimen is determined, stability and flow tests are conducted in accordance with AASHTO T 245-97. The sample is brought to a temperature of 140°F by immersion in a water bath for 30 to 40 minutes. It is then removed from the bath, blotted dry and placed in the loading head of the Marshall testing machine. Load is then applied to the test specimen at a rate of 2 in/min. The load and deformation data are recorded on an x –y plotter.

Stability is recorded as the maximum load attained while testing the sample. Flow is the vertical deformation of the sample at the maximum load.

A separate sample is mixed for determination of the theoretical maximum specific gravity, $G_{mm}$, of the mix, as per AASHTO T 209-94. Procedures for heating and mixing are the same as stated above for the Marshall compaction specimens. The sample is prepared at the estimated optimum asphalt content. After mixing, the $G_{mm}$ sample is spread out on a level surface and allowed to cool. The sample is then broke down into approximately ¼-inch pieces and weighed. The sample was then placed into a vacuum container of known weight, covered with water and subjected to a vacuum for approximately 15 minutes. After this, the sample and container were submerged completely under water and weighed. The two values obtained by this test, dry weight and submerged weight, are used in the following equation to determine the maximum specific gravity that the mixture can possess.

$$G_{mm} = \frac{W_d}{(W_d - (W_w - W_c))} \qquad [2.4]$$

Where,

$G_{mm}$ = maximum specific gravity

$W_c$ = weight of vacuum container submerged in water

$W_d$ =dry weight of sample in air

$W_w$ = weight of sample and container submerged in water.

The volumetric analysis consists of a series of calculations to determine:

- voids in the total mix, VTM,
- voids in mineral aggregate, VMA,
- voids filled with asphalt, VFA, and
- dust to binder ratio, D/B.

The equations for computing these values are:

$$VTM = 100\left(1 - \frac{G_{mb}}{G_{mm}}\right) \qquad [2.5]$$

$$VMA = 100\left[1 - \frac{G_{mb}(-P_b)}{G_{sb}}\right] \qquad [2.6]$$

$$VFA = 100\left[\frac{VMA - VTM}{VMA}\right] \quad [2.7]$$

$$D/B = \frac{P_D}{P_b} \quad [2.8]$$

The maximum theoretical specific gravity varies with asphalt content. The Marshall method allows computation of $G_{mm}$ for asphalt contents other than the one tested using the equations:

$$G_{se} = \frac{1 - P_b}{\left(\frac{1}{G_{mm}} - \frac{P_b}{G_b}\right)} \quad [2.9]$$

$$G_{mm} = \frac{1}{\left(\frac{1 - P_b}{G_{se}} + \frac{P_b}{G_b}\right)} \quad [2.10]$$

Where,

$G_{se}$ = estimated effective specific gravity of aggregate

$G_{mm}$ = estimated theoretical maximum specific gravity

$G_b$ = specific gravity of binder

$P_b$ = percent binder in mix.

The final step is to determine the optimum asphalt content. Graphs are prepared of the asphalt content versus:

- Air voids
- Stability
- Flow
- VMA
- VFA
- Unit weight

The WVDOH procedure for determining optimum asphalt content is to use the air void graph to determine the asphalt content that has 4 percent air voids. This asphalt content is used with the other graphs to determine the corresponding values for each criterion. The values are compared to the criterion set forth by WVDOH. The optimum asphalt content for the aggregate blend is accepted if all design values meet the criteria. If any of the design values fail, the aggregate blend is altered and the mix design process is repeated. The Marshall criteria used by the WVDOH are in Table 2.2. Medium traffic designs are used if the projected 20 ESAL is less than 3 million.

Table 2.2 WVDOH Marshall Design Criteria

| Design Criteria | Medium Traffic | Heavy Traffic |
|---|---|---|
| Compaction (# blows) | 50 | 75 |
| Stability (N) | min. 5300 | min. 8000 |
| Flow (0.25 mm) | 8 - 16 | 8 - 14 |
| Air Voids (%) | 3 - 5 | 3 - 5 |
| VMA (%), 9.5 mm mix | min. 15 | min. 15 |
| VFA (%) | 65 - 78 | 65 - 75[1] |
| D/B | 0.6-1.2 | 0.6-1.2 |

[1] 65-76 for wearing I heavy.

### *2.2.2 Overview of the Superpave Method*

Starting in 1987, the Strategic Highway Research Program (SHRP) conducted research into developing new methods to specify, test and design asphalt materials and pavements. This research lasted until 1993 when the Federal Highway Administration, FHWA, began implementing the SHRP research program. The Superpave design method, that was a direct result of the SHRP research, is becoming the standard for bituminous pavement design (FHWA, 1995).

SHRP researchers recognized that the Marshall method of mix design had been used for many years and those pavements have performed well, however, with increased traffic and heavier axle loads it was decided that an improved method of design was needed. The Superpave mix design method was developed to fulfill this need. The SHRP researchers envisioned a Superpave

design system implemented at three levels. The level one methods relied totally on volumetric analysis to determine mix proportions. The other levels of Superpave analysis require complex equipment and have not been implemented. There is ongoing research to refine Superpave with respect to quantifying the effects of aggregate size, type and gradation on the mixture and correlating these data with pavement performance. In addition, research is being conducted to develop tests for quantifying the asphalt concrete mechanical properties.

The Superpave mix design process starts with aggregate evaluation. Aggregate characteristics are identified as either source properties or consensus properties. Source properties are defined by the purchasing agency. The WVDOH Marshall requirements in Table 2.1 are used as the Superpave source property specifications, with the exception that the flat and elongated property is treated as a consensus property. Consensus aggregate properties were defined by the Superpave researchers to ensure mixes made with the aggregates have good performance characteristics. The researcher envisioned that all agencies using Superpave would adopt these specifications without modification for local conditions. The consensus aggregate properties are given in Table 2.3. WVDOH has implemented these specifications, but has augmented them with requirements for skid-resistant aggregates. The consensus aggregate properties are:

- coarse aggregate angularity,

Table 2.3 Superpave Consensus Aggregate Properties.

| Design Level | Course Aggregate Angularity (% min) | Fine Aggregate Angularity (% min) | Sand Equi-valency (% min) | Flat and Elongated (% min) |
|---|---|---|---|---|
| Light Traffic | 55/- | - | 40 | - |
| Medium Traffic | 75/- | 40 | 40 | 10 |
| Heavy Traffic | 85/80 | 45 | 45 | 10 |

*85/80 denotes min percentages of one fractured face % / two fractured face

- coarse aggregate flat and elongated,
- fine aggregate angularity and,
- sand equivalency.

Coarse aggregate angularity is evaluated by the percent weight of aggregates with one and more than one fractured face. The test is performed on materials retained on the 4.75mm

sieve. This is somewhat different than the WVDOH Marshall requirement that specifies the minimum percent of material with two fractured faces.

Coarse aggregate flat and elongated is evaluated by the percent mass of aggregates whose ratio of longest dimension to smallest dimension is greater than 5. This test is performed on material retained on the 9.5mm sieve. Superpave limits the amount of flat and elongated particles to less than 10 percent. The WVDOH Marshall specification limits flat and elongated particles to 5 percent based on a 4:1 ratio.

Fine aggregate angularity, FAA, is evaluated using the Uncompacted Void Content procedure, AASHTO T304 - 96. The test is performed on material passing the 2.36mm sieve. This test method was available prior to the development of Superpave, but was not a requirement for asphalt concrete mix design. The purpose of the test is to ensure the fine aggregates have sufficient angularity and texture to produce a rut resistant mix. Inclusion of the FAA requirement is controversial, so further attention is focused on this test and specification later in the chapter.

The sand equivalency test is used to evaluate the clay content of materials passing the 4.75mm sieve. This test was implemented by some states prior to Superpave, but is a new requirement for the WVDOH.

Superpave requires that the blended aggregates also meet this specification. The tests can be performed on materials from the individual stockpile then mathematically combined as:

$$X = \frac{(x_1 P_1 p_1 + x_2 P_2 p_2 + \ldots + x_n P_n p_n)}{(P_1 p_1 + P_2 p_2 + \ldots + P_n p_n)} \qquad [2.11]$$

Where,

X = the consensus test value for the aggregate blend

$x_i$ = the consensus test result for stockpile *i*

Pi = the percent of stockpile *i* in the blend

$p_i$ = the percent of stockpile *i* that either passes or is retained on the dividing sieve.

The dividing sieves for the tests are:

| | |
|---|---|
| Course Aggregate Angularity | retained on 4.75mm |
| Flat and Elongated | retained on 9.5mm |
| Fine Aggregate Angularity | passing 2.36mm |
| Sand Equivalency | passing 4.75mm. |

The Superpave gradation specifications bans represent a minor revision to as compared to the Marshall requirements. However, the concept of a restricted zone in the aggregate gradation was added to the Superpave specification to control the amount of fine material of certain sizes used in pavement mixtures. The restricted zone was introduced to limit the potential for tender mixes. The restricted zone has been removed from the WVDOH Superpave specification, in accordance with national recommendations. The gradation requirements for the 9.5 mm mix studied in this research are:

| **Sieve** | **Allowable Percent Passing Sieve** |
|---|---|
| 1/2” | 100 |
| 3/8” | 90 – 100 |
| #4 | 90 max |
| #8 | 32 - 67 |
| #200 | 2.0 – 10.0 |

The Superpave process requires identifying a design aggregate structure using stockpile blends, which meet both the gradation and consensus aggregate properties. The recommended practice is to select three blends. The Federal Highway Administration has prepared a Superpave Mix design workshop that covers the details of the analysis process as presented in the following (Harmon et al, 2002). The required asphalt content for each blend is estimated based on either experience or the following equations:

Estimate effective specific gravity of aggregates,

$$G_{se} = G_{sb} + F\left(G_{sa} - G_{sb}\right) \qquad [2.12]$$

Where,

$G_{se}$ = estimated effective specific gravity of aggregate

$G_{sb}$ = bulk specific gravity of aggregate

$G_{sa}$ = apparent specific gravity of aggregate

F = absorption factor (approx. 0.8).

Estimate volume of absorbed binder,

$$V_{ba} = \left( \frac{P_s (1 - V_a)}{\frac{P_b}{G_b} + \frac{P_s}{G_{se}}} \right) \left( \frac{1}{G_{sb}} - \frac{1}{G_{se}} \right) \qquad [2.13]$$

Where,

$V_{ba}$ = volume of absorbed asphalt

$V_a$ = volume of air voids

$P_s$ = percent aggregate in decimal fractions

$P_b$ = percent binder in decimal fractions

$G_b$ = specific gravity of binder

$G_{se}$ = effective specific gravity of aggregate [from Equation 2.12]

$G_{sb}$ = bulk specific gravity of aggregate.

Volume of effective binder,

$$V_{be} = 0.176 - 0.0675 \log (S_n) \qquad [2.14]$$

Where,

$V_{be}$ = volume of effective binder

$S_n$ = nominal maximum aggregate size, mm.

Estimate aggregate weight,

$$W_s = \frac{P_s * (1 - V_a)}{\left( \frac{P_b}{G_b} + \frac{P_s}{G_{se}} \right)} \qquad [2.15]$$

Where,

$W_s$ = weight of aggregate

$P_b$ = estimated asphalt content,

$$P_{bi} = 100\left[\frac{G_b * (V_{be} + V_{ba})}{G_b * (V_{be} + V_{ba}) + W_s}\right] \qquad [2.16]$$

Where,

$P_{bi}$ =initial estimated percent binder.

For each aggregate blend, two samples are prepared for compaction and two samples are prepared for determining the maximum theoretical specific gravity.

Superpave samples are compacted using the gyratory compactor developed during the SHRP research. The number of revolutions of the gyratory compactor regulates the amount of compaction effort. Three levels of compaction effort are used in the Superpave procedure; initial, design and maximum, $N_i$, $N_d$, and $N_{max}$, respectively. The initial level is reflective of the ability of the mixture to consolidate under low forces and is used to identify "tender" mixes. The design level compaction simulates the density of the mix immediately after construction. The maximum density level simulates the density of the asphalt after 5 to 10 years of service. The number of gyration cycles depends on the design situation as presented in Table 2.4.

Table 2.4 Number of Gyrations at Specific Design Traffic Levels

| | Traffic Level (ESAL millions) | | | |
|---|---|---|---|---|
| | <0.3 | 0.3 to 3 | 3 to 30 | >30 |
| $N_i$ | 6 | 7 | 8 | 9 |
| $N_d$ | 50 | 75 | 115 | 125 |
| $N_{max}$ | 75 | 100 | 160 | 205 |

During mix design all samples are compacted to the design level with the exception that once the optimum asphalt content is determined, a pair of samples are compacted to the maximum level to verify compliance with the specification. Superpave has a requirement for the maximum compaction when the sample is compacted with the initial number of revolutions of the gyratory compactor. This requirement is expressed as the percent of the maximum

theoretical gravity at the initial number of revolutions. This value cannot be measured directly, but it is estimated as:

$$\% G_{mm,ini} = \frac{G_{mb}}{G_{mm}} \frac{h_{des}}{h_{ini}} 100 \qquad [2.17]$$

where,

% $G_{mm,ini}$ = percent of maximum theoretical gravity when the number of revolutions equals the specified initial value,

$G_{mb}$ = bulk specific gravity of the mix when compacted to the design number of revolutions,

$G_{mm}$ = maximum theoretical specific gravity,

$h_{des}$ = height of sample measured by the gyratory compactor at the design number of revolutions, mm,

$h_{ini}$ = height of sample measured by the gyratory compactor at the initial number of revolutions, mm.

The bulk specific gravity is measured for the compacted samples. This is used with the measured maximum specific gravity for the volumetric analysis. The Superpave method uses the same equations as the Marshall method for voids in the total mix, voids in the mineral aggregate and voids filled with asphalt. The Superpave method defines the dust to binder ratio as the percent aggregate passing the 0.075mm sieve divided by the percent effective binder. The percent effective binder content is the difference between the total binder content and the absorbed binder. The equations needed for these calculations are:

$$P_{ba} = 100\left(\frac{G_{se} - G_{sb}}{G_{sb}G_{se}}\right)G_b \qquad [2.18]$$

$$P_{be} = P_b - \left(\frac{P_{ba}}{100}\right)P_s \qquad [2.19]$$

$$D/B = \frac{P_D}{P_{be}} \qquad [2.20]$$

Where,

D/B = dust to binder ratio,

$P_{ba}$ = percent absorbed binder based on the mass of aggregates,

$P_D$ = percent dust, or % of aggregate passing the 0.075mm sieve.

$P_{be}$ = percent effective binder content,

Since the asphalt content of the samples is based on an estimate, the air content of the compacted samples is generally not at the required four percent. So the volumetric calculations are adjusted using the equations:

$$P_{b,est} = P_{bt} - 0.4(4 - VTM_t) \quad [2.21]$$

$$VMA_{est} = VMA_t + C(4 - VTM_t) \quad [2.22]$$

C = 0.1 for $VTM_t$ < 4.0%

C = 0.2 for $VTM_t$ >= 4.0%

$$VFA_{est} = 100\frac{VMA_t - VTM_t}{VMA_t} \quad [2.23]$$

$$P_{be,est} = P_{b,est} - \frac{P_s G_b (G_{se} - G_{sb})}{G_{se}} \quad [2.24]$$

$$D/B_{est} = \frac{P_D}{P_{be}, est} \quad [2.25]$$

Where,

$P_{b,est}$ = adjusted estimated binder content,

$VMA_{est}$ = adjusted VMA,

$VMA_t$ = VMA determined from volumetric analysis,

$VFA_{est}$ = adjusted VFA,

$VTM_t$ = VTM determined from the volumetric analysis,

$P_{be,est}$ = adjusted percent effective binder,

$D/B_{est}$ = adjusted dust to binder ratio,

$P_D$ = percent aggregate passing 0.075mm sieve.

The adjusted volumetric parameters are compared to the Superpave acceptance criteria Table 2.5. The aggregate blend that produces the best compliance with the criteria is selected as the design aggregate structure for determining the design binder content. If none of the aggregate blends produce a design aggregate structure with acceptable volumetric characteristics, a new aggregate blend and subsequent testing must be selected and evaluated.

Table 2.5 Superpave Mix Design Criteria

| | | | | | |
|---|---|---|---|---|---|
| Design Air Voids | | | | | 4% |
| Fines to Effective Asphalt[1] | | | | | 0.6 - 1.2 |
| Tensile strength ratio[2] | | | | | 80% min |
| Minimum Voids in the Mineral Aggregate | Nominal Maximum Size | | | | |
| | 37.5mm | 25mm | 19mm | 12.5mm | 9.5mm |
| | 11 | 12 | 13 | 14 | 15 |
| Design EASL millions | Percent Maximum Theoretical Specific Gravity | | | Voids Filled with Asphalt[3,4,5] | |
| | Ninitial | Ndesign | Nmax | | |
| <0.3 | ≤91.5 | 96 | ≤98.0 | 70-80 | |
| 0.3<3 | ≤90.5 | 96 | ≤98.0 | 65-78 | |
| 3<10 | ≤89.0 | 96 | ≤98.0 | 65-75 | |
| 10<30 | ≤89.0 | 96 | ≤98.0 | 65-75 | |
| ≥30 | ≤89.0 | 96 | ≤98.0 | 65-75 | |

Notes

1. Dust to binder range 0.8 to 1.6 for gradations passing below the restricted zone
2. If mix fails, use an approved antistrip and redesign with antistrip in the mix. All design tests must be with the antistrip in the mix.
3. For 9.5 nominal maximum aggregate size mixes and design ESAL ≥ 3 million, VFA range is 73 to 76 percent.
4. For 25 mm nominal maximum aggregate size mixes, the lower limit of the VFA range shall be 64% for design traffic levels <.3 million ESALs.
5. For 37.5 mm nominal maximum aggregate size mixes, the lower limit of the VFA range shall be 64% for all design traffic levels.

Once the design aggregate structure is identified, the design binder content must be determined. Starting with the design aggregate structure and the estimated binder content determined from Equation 2.20, samples are prepared at four levels of asphalt content:

- $P_{b,est}$ - 0.5%,
- $P_{b,est}$,
- $P_{b,est}$ + 0.5% and
- $P_{b,est}$ + 1.0%.

Two compaction and a maximum theoretical specific gravity specimens are prepared for each asphalt content. This produces the data for the volumetric analysis, which is identical to the analysis performed for the evaluation of the design aggregate structure. The design binder content is determined as the binder content that produces four percent air voids and meets all other Superpave criteria.

All of the samples compacted for determining the design binder content are compacted to the design level of revolutions. The volumetric properties of the samples are evaluated and plotted as with the Marshall procedure. The optimum binder content is determined as the asphalt content that produces four percent air voids while meeting all other mix design criteria.

To ensure the mix will not over densify under traffic, two samples are prepared with the design aggregate structure and optimum binder content and are compacted to the maximum level of revolutions. The void content of these samples is determined and compared to the Superpave criteria.

Finally, the moisture susceptibility of the mixture is evaluated. Six samples are prepared at the design aggregate structure and optimum binder content. Three samples are conditioned. The tensile strength of all samples is measured and the ratio of the average tensile strength of the conditioned samples divided by the average strength for the unconditioned samples is computed and compared to the Superpave criteria.

Superpave has some similarities to the Marshall procedure, but there are significant differences as highlighted in the following section.

### *2.2.3 WVDOH Marshall Versus Superpave Specifications*

Asphalt concrete specifications include the controls on the materials, binder and aggregate, and the controls on the mixture. Although the Marshall method was developed and implemented when the AC asphalt grading system was in favor, the WVDOH is currently using the PG specifications for binders for mixes designed under either the Marshall or Superpave methods. The specifications and selection rules are independent of the mix design method. The aggregate specifications and mix design specifications do vary between the two design methods.

Aggregate specifications vary in both gradation requirements and aggregate evaluation tests. Design aggregate gradation requirements for Wearing I asphalt concrete for both methods are presented in Figure 2.1. The Superpave requirements are slightly tighter than the Marshall for

the 3/8" sieve. Superpave allows a wider range of material passing the #8 sieve than is allowed in the Marshall specification. Up to 67 percent of the aggregate can pass the #8 sieve under the Superpave specification, where as only 55 percent is allowed to pass under the Marshall sieve. Superpave also allows slightly more material passing the #200 sieve, however, the upper limit of the amount of #200 material in a mix can be limited by the dust to binder ratio. When the restricted zone was in the Superpave specification there was a control point of 47.2% passing for the No. 8 sieve. To date, Superpave mixes constructed in West Virginia have gradations that pass below the restricted zone. This in essence restricted the allowable range of material passing the No. 8 sieve to 32.0 to 47.2 percent, which is much tighter than the allowable Marshall range.

The WVDOH Marshall specifications do not differentiate between source and consensus properties. However, under the Superpave method, source properties are aggregate specifications other than those controlled by the consensus aggregate specifications. Under this philosophy, the WVDOH aggregate specifications that carry over to the Superpave method as source properties include:

- Shale content,

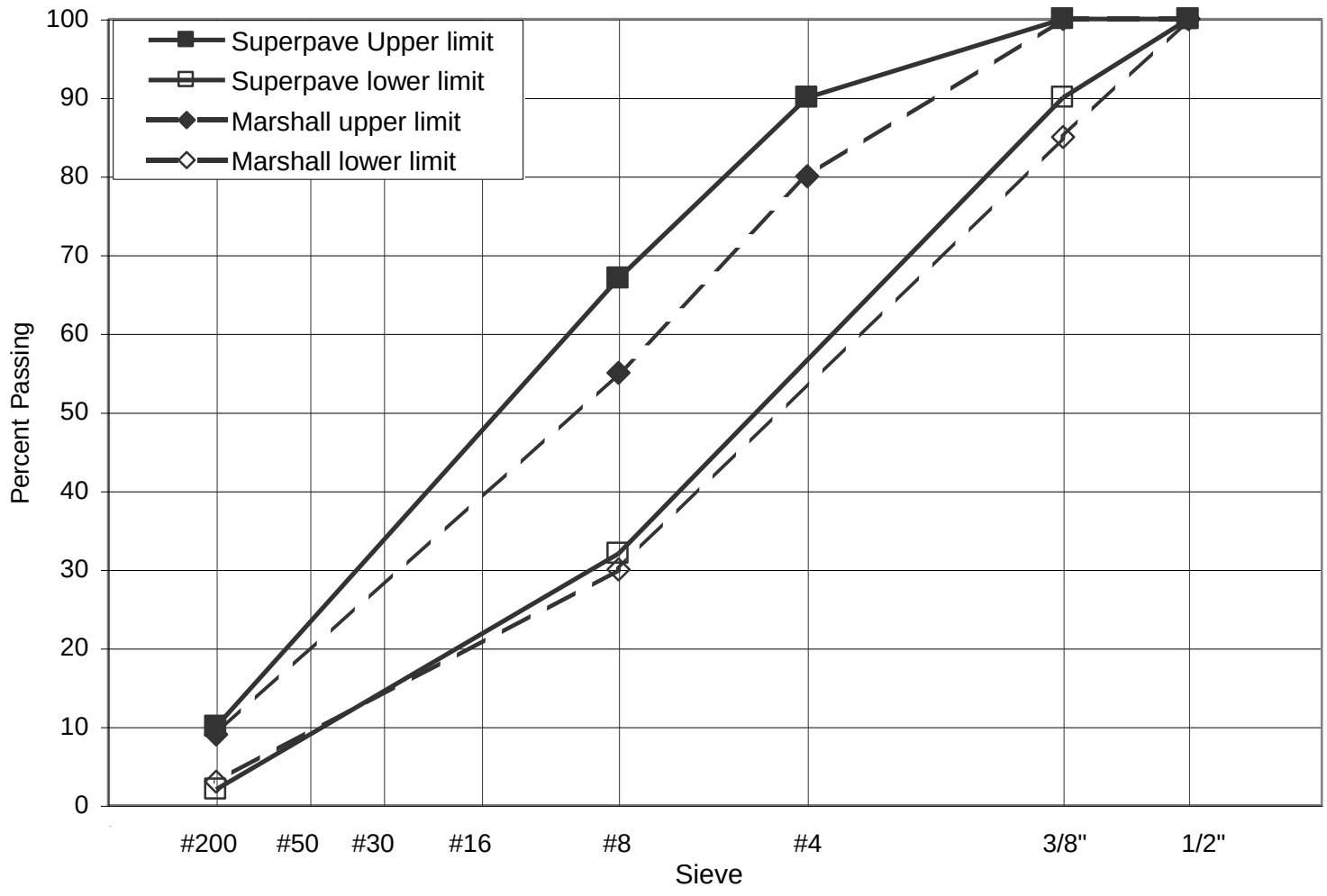


Figure 2.1 Comparison of Marshall and Superpave Gradation Limits for Wearing I and 9.5 mm Mixes

- Coal and other lightweight deleterious materials,
- Friable particles,
- Percent wear, and
- Soundness.

The WVDOH Marshall aggregate specifications that are comparable to the Superpave consensus properties are:

- Thin or elongated particles, and
- Crushed particles.

Although both Marshall and Superpave have specifications for these parameters, the test method and criteria for the thin or elongated particles are different. The specification criteria for crushed particles (Marshall) or fractured faces (Superpave) are different. The WVDOH Marshall specification for Wearing I mixes requires a minimum of 80% particles with two fractured faces. The Superpave fractured face specification for 9.5mm mixes is on both one and more than one fractured face and the limits vary by design traffic level and depth of the mix from the pavement surface.

The Superpave method requires two consensus aggregate properties that are not considered in the Marshall method:

- Fine aggregate angularity, and
- Sand equivalency.

The WVDOH mix design criteria for both the Marshall and Superpave methods include VMA, VFA, VTM, and D/B as shown in Table 2.6. The VMA values are equal for the Superpave method. The VFA criteria are very similar. The Marshall requirement for VTM show a range of 3 to 5% and the Superpave requirements are for exactly 4.0%. However, the Marshall method calls for designing for the median value of this range, 4%. Both the Marshall and Superpave methods have restrictions on the dust to binder ratio. However, the Marshall method uses the total binder content in the denominator whereas Superpave uses the effective binder content.

Table 2.6 WVDOH Marshall and Superpave Design Criteria Requirements for Wearing –I Mixes

| | Marshall | | Superpave | | |
|---|---|---|---|---|---|
| Design Criteria | Heavy | Medium | Heavy | Medium | Low |
| VMA (%) | 15 (9.5mm mix) | | 15 (9.5 mm mix) | | |
| VFA (%) | 65 - 76 | 65 - 78 | 65 - 75 | 65 - 78 | 70 - 80 |
| VTM (%) | 3 - 5 | 3 - 5 | 4 | 4 | 4 |

The Marshall method has requirements for stability and flow that are not considered in Superpave. The Superpave method has requirements for the initial and maximum compaction densities that are not considered in the Marshall method. In addition, Superpave requires evaluation of the mix for moisture susceptibility, which is not a requirement for the Marshall method.

### *2.2.4 Comparison of Marshall and Superpave*

Although numerous studies have been conducted that look at comparing specific aspects of Marshall design to Superpave design, limited research has been done to compare the complete mix design methods and results. This is especially true of studies of mixes for low volume roads. Habib et al studied the suitability of Superpave mix design as compared to Marshall design for low volume roads and shoulders (Habib, 1998).

The experimental design for this study included five aggregate blends, see Table 2.7 (Habib, 1998), and three binders, PG 52-28, PG 58-28 and PG 70-28. All five gradations were located below the restricted zone and had a 19mm nominal maximum aggregate size.

Mix samples were compacted with the Superpave gyratory compactor and Marshall hammer using the compactive effort required for low traffic volume design for each mix design method. The three main parameters examined during this study are estimated asphalt content, VMA and VFA.

Table 2.7 Aggregate Blend Proportions

| | Proportions (%) | | | | |
|---|---|---|---|---|---|
| Aggregate type | Blend 1 | Blend 2 | Blend 3 | Blend 4 | Blend 5 |
| Crushed limestone | 66 | 66 | 66 | 66 | 66 |
| Coarse river sand | 8 | 5 | 10 | 15 | 20 |
| Fine river sand | 21 | 29 | 24 | 19 | 14 |
| Manufactured sand | 5 | 0 | 0 | 0 | 0 |

Results from the experiment are shown in Table 2.8 and 2.9. First, only the blend with the maximum amount of coarse river sand, Blend 5, complies with all the mix design criteria. All other mixes fail the VFA criteria for the Superpave mixes or fail the stability criteria for the Marshall method. All the Superpave mixes required lower asphalt content than the Marshall mixes. However, this comparison was only meaningful for Blend 5.

Table 2.8 Habib Superpave Analysis Results and Criteria

| Superpave Parameter | Blend 1 | Blend 2 | Blend 3 | Blend 4 | Blend 5 | Criteria |
|---|---|---|---|---|---|---|
| VMA | 15.1 | 13.2 | 14.1 | 15.0 | 16.6 | 13 min. |
| VFA | 74.0 | 69.6 | 71.5 | 73.4 | 75.9 | 75 - 80 |
| AC (%) | 5.5 | 5.1 | 5.7 | 6.3 | 7.3 | -- |
| N ini | 86.9 | 88.3 | 87.9 | 88.2 | 88.1 | 89 max. |
| N max | 97.5 | 97.1 | 97.4 | 97.5 | 97.5 | 98 max. |
| Dust/Binder ratio | 0.73 | 0.73 | 0.64 | 0.60 | 0.46 | 0.6 - 1.2 |

Table 2.9 Habib Marshall Analysis Results and Criteria

| Marshall Parameter | Blend 1 | Blend 2 | Blend 3 | Blend 4 | Blend 5 | Criteria |
|---|---|---|---|---|---|---|
| VMA | 15.4 | 15 | 15.9 | 17 | 18.3 | 13 min. |
| VFA | 74 | 72 | 75 | 75 | 76 | 70 - 80 |
| AC (%) | 6.3 | 5.8 | 6.5 | 7.1 | 7.9 | -- |
| Stability (N) | 3560 | 3200 | 3130 | 4180 | 5340 | 5340 min. |
| Flow (mm) | 3.0 | 2.8 | 3.1 | 3.7 | 3.8 | 2 - 4.6 |

## 2.3 FINE AGGREGATE ANGULARITY

The SHRP researchers developing the Superpave method were very concerned with minimizing potential pavement deformation or rutting failure of mixtures. The relationship between fine aggregate angularity and texture to rutting potential was well understood. Natural sand possessing a round shape and smooth texture was known to contribute to mixes susceptible to rutting. Some states limited the amount of natural sand in a mix to control rut susceptibility. The SHRP researchers sought a test-based method for limiting the use of fine aggregates with undesirable characteristics. Hence, the Uncompacted Void Content of Fine Aggregate, AASHTO T304-96, was developed and consensus specifications were developed.

Implementation of Superpave, with the fine aggregate angularity requirement, has created concern in the asphalt paving industry. The influence of fine aggregate angularity on mix performance was evaluated in two research projects (Huber, 1998 and Casanova, 2000). Both studies found problems with the fine aggregate angularity specification.

Huber used a reference coarse aggregate with four fine aggregates whose FAA ranged from 38 to 48 percent air voids. Mix performance was evaluated with the Asphalt Pavement Analyzer using beam samples loaded for 8000 cycles. The characteristics of this device are presented later in the chapter. Huber's results are summarized in Table 2.10. The natural sand sample with the lowest FAA had the best performance. Regression analysis demonstrated no correlation between rut depth and FAA. Huber

Table 2.10 Results of Huber's APA tests

| Aggregate Source | FAA | Avg. Rut Depth |
|---|---|---|
| Georgia granite | 48 | 3.96 |
| Alabama limestone | 46 | 3.04 |
| Indiana crushed sand | 42 | 4.17 |
| Indiana natural sand | 38 | 2.81 |

supports the concept of using a test method to restrict use of round materials with low texture, but questions the validity of Superpave's current method and specification.

Casanova et. al. Studied the FAA of nine aggregate types. Each aggregate type was evaluated with methods A, B and C of AASHTO T304-96. These methods require different gradation blends. Method A is specified by Superpave. The aggregate were also evaluated under a microscope to achieve a visual measure of angularity and texture. Direct shear tests were used to assess the strength of each aggregate type and gradation. The results showed the FAA test correlated well with the visual assessment of angularity and texture. However, there was not a good correlation between FAA and the shear strength. The FAA would reject aggregates with high shear strength and vice versa. The researchers suggested supplementing the FAA test with direct shear measurements (Casanova, 2000).

**2.4 VOIDS IN THE MINERAL AGGREGATE**

Voids in the Mineral Aggregate percentages have been considered one of the major indicators of asphalt concrete quality since the development of volumetric analysis for mix design. Recently, concern as been expressed with designers not being able to achieve the current minimum VMA values specified in the Superpave design method (Coree, 1999 and Kandal, 1998). These minimum values range from 11% for pavements with a nominal maximum aggregate size of 37.5 mm to 15% for a 9.5 mm nominal maximum aggregate size asphalt concrete. In 1992, Aschenbrener set out to better quantify the relationship between the VMA value and the placement of the gradation curve in relation to the maximum density line (Aschenbrener, 1992). For this study, 101 mixes used by the Colorado Department of Transportation were examined to find the most appropriate method for placing the maximum density line in reference to the Fuller curve.

It was found that the reference gradation line, the line drawn from the origin to the actual percent passing on the nominal maximum aggregate size, gave the best indication of the measured VMA values. It was found that by staying away from the maximum density line at the #30 sieve and the fourth largest sieve to retain material would yield higher VMA values. This is

theoretically correct in that the farther the gradation curve is kept from the maximum density line, the more voids that would be in the mix.

Twenty-four laboratory samples were also made up for this project to study the effects of gradation, quantity of material passing the #200 sieve and the FAA value of the fine aggregate. The researchers hypothesized that these variables have the greatest effect on VMA. Gradation had the largest effect on VMA. The quantity of material passing the #200 and FAA had significant affects on VMA. One interesting finding of this study was that FAA affected the VMA of coarse mixes more than the fine mixes, but the amount of minus #200 material affected the VMA of the fine mixes more than the coarse mixes.

Coree and Hislop examined the historical aspect of the VMA criteria (Coree, 1999). Coree found that a minimum VMA value was not used until the 1950s and in the 1960s it was specified as a mix design parameter in Marshall mix design. They stated that many researchers have identified problems meeting the current Superpave VMA specifications. These researchers feel that they often have to "fail" mixes that would have been acceptable in pavement performance because of the VMA criteria. Also changing the gradation to get an improved VMA value will sometimes increase the optimum asphalt content leading to higher construction costs.

During Coree's research several problems were encountered with the VMA, including:

- no field data could be located that was used to set the original VMA values,
- the original and current VMA values are based on Marshall mix design, and
- the precision of tests used to determine the VMA values is not good enough to allow for strict enforcement of the minimum VMA values.

Recommendations of this research are: (a) the minimum VMA values need to be validated against pavement performance, including factors such as particle shape, texture and gradation, (b) since there is a lack of precision of the tests used to determine the VMA criteria, rigid enforcement should be discouraged at this time, and (c) minimum average film thickness needs to be verified and correlated to pavement performance.

There has also been concern expressed about the relationship between the VMA values, the Superpave restricted zone and asphalt film thickness. It was found that the decreased VMA values, as compared to Marshall VMA values, while designing under Superpave could be attributed to the higher compactive effort of the Superpave gyratory compactor as compared to the Marshall compaction hammer. This in turn has led to the use of coarser mixes in order to achieve the required VMA percentage. The problem arises in that this VMA requirement for Superpave's coarser mixes is the same as those for Marshall's mixtures.

Experiments during this research indicate that average film thickness yields a better picture of the mix being developed and encompasses more mix types (Kandal, 1998). This allows for higher pavement durability since film thickness is optimized. The method for achieving the

optimum asphalt is straightforward and an example is presented in the review. Mix types used for this research included mixes that were either all crushed material or 80% crushed – 20% Natural Sand. Also mixes were developed above, below and through the restricted zone. It is interesting to note that all the mix types, except an “above the restricted zone – natural sand” and a “through the restricted zone – natural sand” met VMA and all other design requirements. This raises a question about the validity of enforcing the Superpave restricted zone for all aggregate types.

**2.5 ASPHALT PAVEMENT ANALYZER**

The Asphalt Pavement Analyzer (APA) is a commercial version of the Georgia Loaded Wheel Tester (LWT) that has been used for the evaluation of rutting susceptibility of asphalt mixtures. The Georgia Department of Transportation and Georgia Tech began development of the LWT in 1985 (Collins et al, 1995). This was accomplished basically by modifying a slurry seal test machine already in use by GDOT. Research in the development of the device focused on determining correct amounts of loading, contact pressures and repetitions. Since successful completion of the development research, GDOT has implemented the LWT as part of their mix design method. Experience with this device has lead to the development of the "GDOT Method of Test for Determining Rutting Susceptibility Using the Loaded Wheel Tester" and improved testing devices such as the APA. Other state transportation agencies and laboratories are using this device for asphalt concrete evaluation.

The prototype of the Asphalt Pavement Analyzer was developed for the Georgia Department of Transportation, GDOT. This device was refined and marketed commercially by Pavement Technologies Inc. The PTI version of the APA consists of the following:

1. Temperature controlled test chamber,
2. A sample frame capable of holding six cylindrical capsules or three beam samples,
3. Three pressurized loading hoses placed across the sample during testing,
4. Three loading wheels that traverse the pressurized hoses during testing,
5. Controls and instrumentation.

Cylindrical samples may be field cores or fabricated in the laboratory. The sample size is 75mm tall by 150mm in diameter. The laboratory cylindrical samples may be compacted with the Superpave gyratory compactor. Rectangular samples are compacted with the vibratory compactor. All samples must be compacted to a void content of $7 \pm 0.5\%$ air.

In 2000, Choubane reported on the suitability of the APA to accurately and repeatedly predict pavement rutting potential (Choubane, 2000). Their report stated that the APA is an effective tool for ranking asphalt concrete based on rutting potential, but the APA exhibits significant variability between tests of the same mix design and between different testing positions within

the machine. This variability was quantified by analyzing the amount of significant differences indicated from Student t-tests.

Sample types tested for Choubane's research included both beam and gyratory samples and both laboratory prepared and core samples. Variability in depth measurements ranged from 4.7mm for beam samples and 6.3mm for gyratory samples. Also, variability seemed to be mix dependent and increased with the number of cycles. However, the ranking of pavements tested in the APA correlated with their in-field rankings, meaning that even though there is high variability between tests, the APA yields relatively good ranking in terms of rutting potential between a set of different mixtures. In general it was found that variability in the APA could occur between test runs, within the same test and between test position in the machine. Also the magnitude of variability may also differ between tests and test positions.

The researchers recommended that the APA be used to identify relative rutting potential values between a known “well-performing” mixture and a mix that is being designed. There is too much variability between APA tests to establish variability or precision statements, thus the APA test cannot currently be implemented as a pass/fail test criteria for mix design.

Mohammad, Huang and Cea did another study into the effectiveness of the APA in 2001 (Mohammad, 2001). This research was similar to that of Choubane’s with respect to testing different aggregate type mixtures in the APA. These types included both limestone and sandstone mixtures and had a nominal maximum aggregate size of 19 mm. They also varied the asphalt binder type in some of the mixes to see if any differences could be observed by varying the asphalt type. Binder types included in the study were PG 64-22, PG 70-22, PG 70-22 Modified, and PG 76-22.

Results of this study showed that mixtures containing the sandstone aggregate rutted less than limestone aggregate mixes. Among the mixes with the same aggregate blends, those that were mixed with the PG 76-22 binder rutted the least followed by those mixed with PG 70-22, PG 70-22 Modified and PG 64-22 asphalt cement. This was expected since the higher graded asphalt cement should withstand rutting to higher temperatures and since the temperature was held constant during these tests, the results are congruent to what was expected. High variance between samples of the same mix type was also experienced during this research confirming Choubane's observations.

Tarefder and Zaman performed research similar to the previous two studies in experimental design and data collected (Tarefder, 2001). This research looked at using the APA to determine a correlation between certain aggregate characteristics of a mixture and rutting potential in fine and coarse mixes.

The results of this project show that the rut resistances of fine mixtures are sensitive to the amount of material passing the #200 sieve. Coarse mixtures were found to be sensitive to aggregate size. This paper also recommends that a correlation between rut depths achieved by

the APA and those experienced in the field should be developed. This would better allow APA test results to be used as pass/fail criteria for mix design.

## 2.6 SUMMARY

The issue of comparing and evaluating mixtures of both Marshall and Superpave mix design methods is a complex and difficult one, especially with the numerous differences in both the design method and specifications.

The material presented in this section demonstrates that the concerns and questions of this research project have, at some time, been addressed by other projects and reviews. However, none of the questions have been fully answered but enough supporting information is available to better investigate and describe the findings of this research.

# CHAPTER 3 EQUIPMENT

## 3.1 INTRODUCTION

This research required the use of various equipment and apparatus to develop the required mix designs and rut test results. All of the equipment that required calibration was calibrated before their use. Proper use of all equipment was also learned and practiced. The following sections present brief descriptions of the equipment used and an overview of the procedures for both calibration and use of this equipment. Equipment described includes the Marshall Compaction Hammer, Marshall Testing Machine, Superpave Gyratory Compactor and the Asphalt Pavement Analyzer.

## 3.2 MARSHALL COMPACTION HAMMER

Pine Instrument Company of Grove City, PA City manufactured the Marshall compaction hammer used for this research. It is comprised of a specimen mold, compaction hammer, lifting apparatus, and counter. For asphalt pavement mixtures containing aggregate up to 1-inch maximum size, a mold with a diameter of 4 inch is used. Since the mixes for this research are wearing type mixtures, containing a nominal maximum aggregate size of 3/8 in., the 4 in. mold was used. The compaction hammer is comprised of a hammer with a flat, circular tamping surface with a diameter of 3 7/8 in. and has a sliding weight of 10 $\pm$0.02 lb. The free fall drop of the hammer was 18 $\pm$0.06 in. The lifting apparatus is basically a rotating chain that repeatedly lifts the compaction hammer to the proper height and releases to allow the hammer to free-fall to the sample. The counter automatically stops the compaction once a set number of drops is reached. For Marshall mix design this set number of blows varies with the traffic level of the pavement being designed. This research used 50 blows per side for the medium traffic mix and 75 blows per side for the heavy traffic mix as per WVDOH specifications. The AASHTO procedure for calibrating the hammer was not used, as it is not practiced in West Virginia. More detailed information on the Marshall Compaction Hammer can be found in AASHTO T 245-97.

## 3.3 MARSHALL TESTING MACHINE

The Marshall Testing Machine is a device used to determine the resistance to plastic flow and stability of Marshall specimens compacted with the Marshall Compaction Hammer (AASHTO T 245-97). The testing machine used for this research was a Pine Instruments AF850T Marshall Testing Machine. This apparatus is made up of a compression device, load head, load cell, x-y plotter and water bath.

To properly test a Marshall sample for flow and stability the samples must first be conditioned in a water bath at 140 $\pm$2°F for 30 to 40 minutes. This water bath has a resting surface for the samples that is 2 in. above the bottom of the bath. After the samples have soaked for the proper time they are dried and placed into the load head that resembles a cradle-like surface. The load head is comprised of two pieces so the sample can be loaded onto the bottom half of the load head and then the top half can be put on top to enclose the sample. The load head and

sample are then placed into the compression device. The compression device loads the sample at a deformation rate of two inches per minute. A load cell is activated and sends a signal to the x-y plotter that records a load-deformation curve for the sample. The stability and flow of the sample are determined from this graph.

To verify the calibration of the Marshall Testing Machine, a proving spring provided by the manufacturer is placed in the testing machine, and with a calibration paper in the x-y. The proving spring is then loaded. If the graphed line stays within two parallel lines pre-printed on the calibration paper, then the machine's calibration is verified. Calibration was verified several times throughout the development of the Marshall mix designs and the machine was always within tolerance.

### 3.4 SUPERPAVE GYRATORY COMPACTOR

The Superpave Gyratory Compactor is a relatively new device for use in the compaction of asphalt pavement specimens. This compactor was developed during the Strategic Highway Research Program, SHRP. The gyratory compactor uses a shearing action to compact the specimens. This is accomplished by constant tilting of the mold about a load head. The mold is held at a slight angle to achieve the shearing action. This method of compaction was found to best simulate in-field compaction practices due to its ability to correctly orient the aggregates in the mix. (Roberts, 1996)

The Superpave gyratory compactor used during this research was a Pine Instruments AFGC125X Gyratory Compactor. This apparatus is self-contained and fully automated. The operator ensures that the compactor is set to the correct compaction mode or number of gyrations. Then the mold containing a specimen is placed into the compaction chamber and the start button pressed. Once compaction is complete, and the load ram is returned to the rest position, the mold is removed and placed over the extracting device until the sample is cool enough for extraction.

Calibration of the gyratory compactor is a complicated procedure and is only required once every year. However, a simple verification procedure is performed to confirm the machine is calibrated. Verification should be performed every six months under normal operation. The calibration and verification processes ensure the compactor is within the tolerances set by both the manufacturer and the Superpave mix design method. Verification and calibration are required for the speed of gyration, ram force, ram position and angle of gyration.

### 3.5 ASPHALT PAVEMENT ANALYZER

The Asphalt Pavement Analyzer, APA, was used to evaluate the potential performance of the mixes with respect to rutting. All samples were prepared to a 7 $\pm$0.5% void content. The following operational parameters were used for all tests:

Temperature 40°C

| | |
|---|---|
| Hose Pressure | 100 psi |
| Wheel Load | 100 lbs |

The only calibration that is needed for the APA is that of the load placed on the samples by the rollers. This is accomplished by placing a load cell under one of the rollers and adjusting the pressure displayed on the APA gauges with the pressure reading from the load cell. This is to be done with each of the three rollers.

**3.6 BUCKET MIXER DESCRIPTION AND USE**

Due to the large amount of asphalt pavement samples needed and the fact that most of those were Superpave samples, a large Kol Brand bucket mixer was used. This mixer was used to prepare all Superpave samples. The bucket mixer has a ½ horsepower motor that rotates the five-gallon mixing bucket at a rate of 60 RPM. The bucket can be tilted from its vertical position to a plane parallel with the floor. A mixing paddle placed into the bucket and secured by a support rod ensures agitation of the mix.

Hughes performed an extensive study into the use of the bucket mixer (Hughes, 1999). His paper outlines procedures for correctly using the mixer, allowable capacities and mixing techniques. It was found that the bucket mixer could properly mix asphalt mix samples ranging in size from 1200g to 18,000g. It was also determined that there may be problems with mixing large samples of low asphalt content, but no problem was encountered during any mixing for this research. The mixing procedure developed by Hughes was followed during this research. This process is described in Appendix A.

# CHAPTER 4 FINE AGGREGATE ANGULARITY TESTING

## 4.1 INTRODUCTION

A major part of this research was analyzing the feasibility of using high percentages of natural sand in mixes designed for low volume roads. Therefore, of Fine Aggregate Angularity (FAA) tests were conducted for blend ratios of 100:0, 75:25, 68:32, 50:50, 25:75, and 0:100, crushed limestone sand to natural sand. These tests provided a baseline for evaluating the effect of blending on the FAA of the combined sands.

Evaluating the FAA of the actual blends used for the mix designs was the second part of the FAA testing. Mix specific FAA tests were conducted after the appropriate design aggregate structure was determined for each mix design. This ensured that the correct sand percentages would be tested. The results of these tests were also used to determine if the developed mixes would meet WVDOH Superpave specifications for FAA values for medium and heavy traffic level roadways. The current minimum value for heavy traffic design in Superpave is 45% while the value for medium traffic level design is 40%. Low volume roads do not have Superpave a FAA requirement.

## 4.2 SIGNIFICANCE AND USE OF FAA TESTS

The applicable standard for this test is AASHTO T 304-96, Uncompacted Void Content of Fine Aggregate (AASHTO, 2000). This test method outlines the procedure for determining the uncomplicated void content of a sample of fine aggregate. Results from this test on samples of a known gradation provide an indication of the aggregate's angularity, sphericity and surface texture when compared with other aggregates possessing the same gradation. This test can also provide an indication into the effect of the fine aggregate on the workability of a mixture in which it may be used when the void content is measured on an as-received grading. Tests for this research focused on determination of the physical characteristics of the fine aggregate. Three procedures, Methods A, B and C, are included in AASHTO T 304-96. Methods A and B provide percent void content determined under standardized conditions which will yield results that depend on particle shape and texture of the fine aggregate. If the results, by these procedures, show an increase in void content then that indicates greater angularity, less sphericity or rougher surface textures. A decrease in the void content value indicates a more rounded, spherical or smooth surfaced aggregate. Method C measures the uncompacted void content of the minus 4.75-mm (#4) portion of an as-received material. Method A was the procedure selected for testing the aggregate for this research since it is specified by WVDOH.

## 4.3 FAA TEST METHOD AND PROCEDURE

Method A was selected as the test method to determine uncompacted void percentages for this research (AASHTO T 304-96). The testing apparatus used for all methods of the FAA test is basically a one-pint Mason jar without a bottom and a cone of standard volume attached to the

mouth. This jar rests on a holder positioned over a 100 mL cylinder. The entire device is placed inside of a pan used to retain fine aggregate particles.

Sampling for these tests was conducted according to ASTM D 75 and ASTM C 702 (ASTM, 2000). Washing, sieving and drying was done in accordance with ASTM C 117 and ASTM C 136. Once this was completed the sample was weighed out. Method A specifies proportions of four different aggregate sizes as:

| Sieve | Weight (g) |
|---|---|
| #16 | 44 |
| #30 | 57 |
| #50 | 72 |
| #200 | 17 |
| Total | 190 |

The bulk dry specific gravity was also needed to complete the calculations for determining the uncompacted voids content. This was determined by taking a larger sample of the same proportions shown above and testing them according to ASTM C 128, Standard Test Method for Specific Gravity and Absorption of Fine Aggregate.

The testing procedure began with mixing the test sample until it was homogeneous. The jar and funnel were then placed in the stand and the 100 mL measure placed directly under the funnel opening. The sample was placed into the jar and leveled; a finger was placed at the tip of the funnel to retain the sand. The finger was then removed and allowing the sample to fall freely into the measuring cylinder. After the funnel empties, excess fine aggregate was struck off the cylinder. The measure was then weighed to determine the mass of fine material contained in the measure. This process was run twice for each mixture of fine material. The uncompacted void content is computed as:

$$U = 100\left(\frac{V - \frac{F}{G_{sb}}}{V}\right) \qquad [4.1]$$

Where,

U = uncompacted voids, percent, of the material.

V = volume of measure, mL,

F = net mass, g, of fine aggregate in measure,

$G_{sb}$ = bulk dry specific gravity of fine aggregate,

**4.4 FAA TEST RESULTS**

Tests were run on the six combinations of limestone and natural sands. The experimental data are presented in Appendix B. Results for each combination were analyzed and are displayed in Table 4.1. Column 3 shows the results for obtained by testing the blended sands. Column 4 shows the results obtained by computing the blended FAA based on the FAA of the limestone and the natural sand and using Equation 2.11. The 100% LS sand had a FAA of 43.5 percent. This is less than the minimum requirement Superpave heavy traffic designs, which requires an uncompacted voids of 45%. Thus, none of the blends meet the requirements for high volume roads. However, all the blends meet the requirements for other traffic levels.

Table 4.1 Results of Fine Aggregate Angularity Tests.

| Mix Type | Specific Gravity | Test Results Uncompacted Voids (percent) | Computed Results Uncompacted Voids (percent) |
|---|---|---|---|
| 100% LS | 2.618 | 43.5 | - |
| 75% LS - 25% NS | 2.596 | 42.5 | 42.5 |
| 68% LS - 32% NS | 2.591 | 41.6 | 42.2 |
| 50% LS - 50% NS | 2.575 | 41.2 | 41.5 |
| 25% LS - 75% NS | 2.554 | 40.2 | 40.4 |
| 100% NS | 2.534 | 39.4 | - |

Comparison of the test results from the blended material and the computed results shows only minor differences. However, in three of four cases, the computed values were higher than the measured values.

**4.5 CONCLUSION**

The FAA test is fairly simple and can be performed rapidly once the specific gravity of the sand is known. The results obtained were consistent with the expectations. The FAA value for the crushed limestone sand was 43.5 percent. This is less than the required specification for high traffic volume Superpave mixes. However, the supplier of these aggregates routinely uses them for Superpave mixes. As shown in Equation 4.1, the uncompacted void content is sensitive to the bulk specific gravity. Determining the bulk specific gravity of crushed limestone sand is

problematic, as the saturated surface dry condition of the aggregate is not consistently identified with the standard test method.

# CHAPTER 5 MIX DESIGN, SAMPLE PREPARATION AND APA TESTING

## 5.1 MARSHALL MIX DESIGN

To ensure the research results are applicable to local conditions, mixes evaluated during the research used locally available materials and were proportioned in accordance with WVDOH procedures and specifications, as presented in Table 2.2. Mix designs were prepared for both the medium and heavy traffic levels.

### *5.1.1 Type of Mixes Developed*

Four Marshall mix designs were needed for this research, the combinations were:

| Traffic | Aggregate | Designation |
|---|---|---|
| Heavy | 100% limestone | M HVY 100%LS |
| Medium | 100% limestone | M MED 100%LS |
| Heavy | Maximum allowable natural sand | M HVY 13%NS |
| Medium | Maximum allowable natural sand | M MED 13%NS |

The WVDOH design practice is to use the medium traffic level for the Marshall mix designs when the design traffic is less than 3 x $10^6$ ESALs. Thus, the medium traffic level design is used for low volume roads.

Mix designs prepared by J. F. Allen were used for the heavy and medium traffic level designs with 100% limestone aggregate. Specific design criteria values, percentages and aggregate properties for all developed mix designs are presented in the Appendix C. These designs were confirmed by making samples containing the design aggregate blend and optimum asphalt content indicated in the J. F. Allen mix design. These samples were checked for stability, flow and volumetric parameters.

The second set of Marshall designs was developed to contain the maximum amount of natural sand as permitted by volumetric requirements. These Marshall mixes were designed in conjunction with the Superpave designs containing a maximum amount of natural sand. It was discovered that the same gradation was acceptable and optimal for both Marshall and Superpave.

### *5.1.2 Aggregate Preparation and Gradation Development*

Before any mixes could be developed, the aggregate acquired from both sources needed to be sieved into proper aggregate size classifications and cleaned. Aggregate was sieved into 3/8”, #4, #8, #16, #30, #50, #200 and Pan sizes. Sieving was accomplished by using a Mary Ann

Mechanical Laboratory Sieve. After the material was sieved it was washed and dried according to AASHTO specifications. The washed and dried material was then separated into bins according to sieve size.

The first task in the mix design was to determine a blend of the stockpile aggregates that provided a gradation conforming to the Marshall specifications. An Excel spreadsheet was developed for this analysis. The 100% Limestone mixes were based on mix designs prepared by J.F. Allen. So their data were used to verify the program worked correctly. The gradation curves for all Marshall designs are presented in Figure 5.1. The blend percentages of all Marshall mix designs are presented in Table 5.1.

Based on experience, the sample weight for the compacted Marshall samples was estimated to be 1220 g.. The required aggregate and asphalt binder weights were calculated from the estimated total sample weight by the following equations:

$$W_b = \frac{P_b}{100} W_t \qquad [5.1]$$

$$W_s = W_t - W_b \qquad [5.2]$$

Where,

$W_b$ = weight of asphalt needed, g,

$P_b$ = percent binder in mix.

$W_t$ = the total weight of the sample, g,

$W_s$ = weight of aggregate needed for the indicated total sample weight, g,

Table 5.1 Blend Percentages for Marshall Mix Designs

| | Stockpile Types | | | | |
|---|---|---|---|---|---|
| **Traffic Level** | Skid | N. Sand | L. Sand | #9 | BH Fines |
| Heavy (100% L. Stone) | 35 | 0 | 46 | 18 | 1 |
| Medium (100% L.Stone) | 34 | 0 | 50 | 15 | 1 |
| Heavy (13% nat. sand) | 20 | 13 | 28 | 38 | 1 |
| Medium (13% nat. sand) | 20 | 13 | 28 | 38 | 1 |

The mix designs from J. F. Allen indicated optimum asphalt contents were 5.2% and 5.5% for the heavy and medium traffic levels respectively. Calculations were performed to determine the required aggregate and asphalt weights based on a mix sample weight of 1200 g. The required aggregate weight was input into the spreadsheet to get the weight required on each sieve.

J.F. Allen's mix design indicated the 100% crushed limestone mixtures had VMA values of 15.0 for the heavy traffic level and 15.1 for the medium traffic level, right at the minimum value of 15. This raised a question of what the effect of natural sand would have on the VMA. It was hypothesized that if the gradation of the mixes containing sand were similar to the 100% limestone mixtures, the VMA would decrease. This would put the mixture out of specification. A trial mix with 15% natural sand and a gradation similar to the 100% limestone mix was prepared with an asphalt content of 5.5%. The resulting VMA was 13.1. This confirmed the need to modify the gradation of the mixes with natural sand.

Through a trial and error process, it was determined that the maximum amount of sand that could be used in the mix and have acceptable volumetric properties was 13 percent sand. Using stockpile blend proportions that held the gradation curve farther away from the maximum density line counteracted the earlier problem of low VMA. In theory, keeping the gradation curve farther away from the maximum density line would provide for more space between the aggregates in the mix, thus resulting in higher VMA values. Resulting stockpile proportions for both Marshall heavy and medium mixtures containing natural sand can be found in Table 5.1. Coincidentally, the same gradation

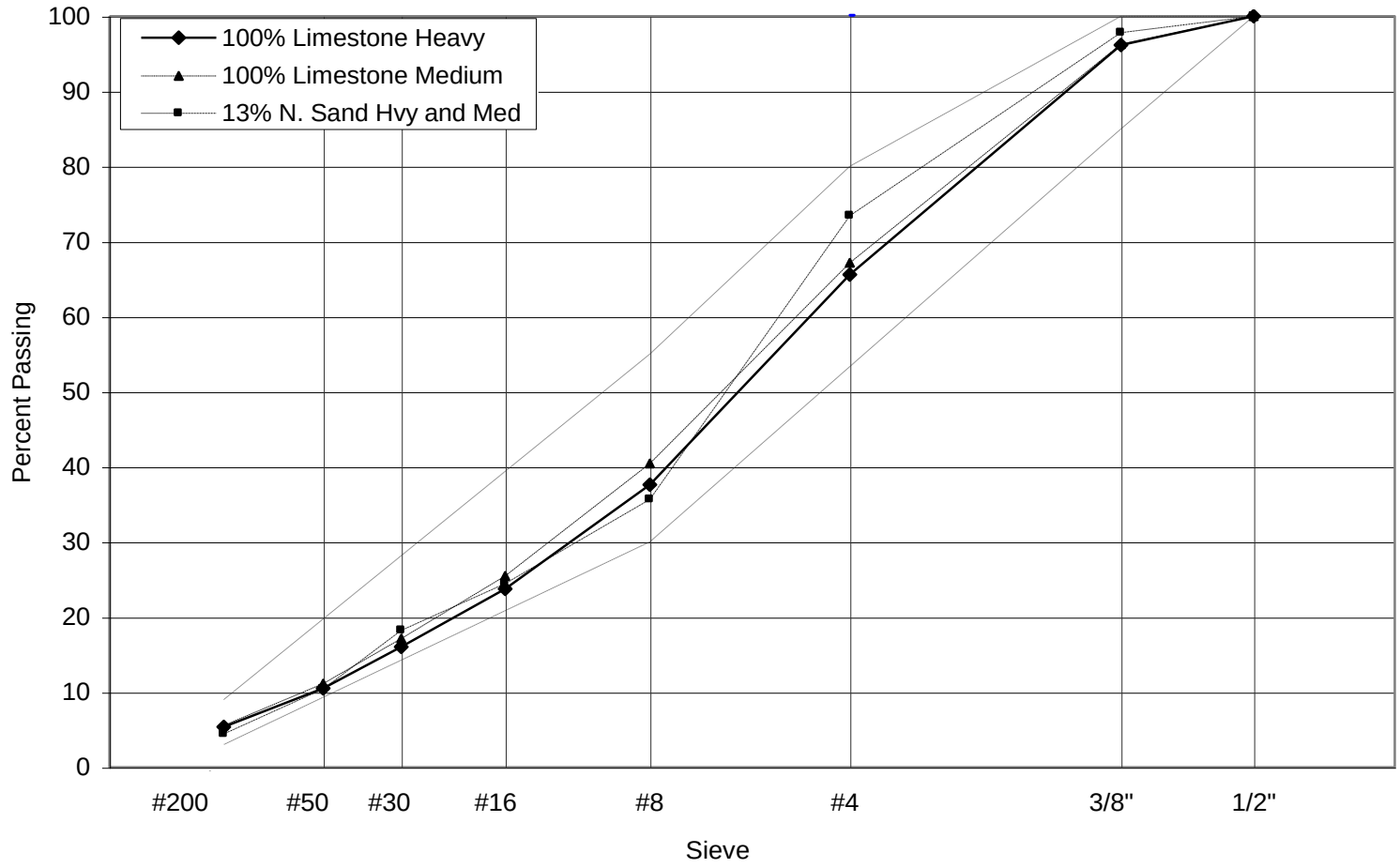


Figure 5.1 Marshall gradation curves

was acceptable for both Marshall and Superpave mix designs at both medium and heavy traffic levels.

Asphalt contents were calculated for these mixtures using Equations 2.12 to 2.16. The asphalt content estimates calculated from these equations were consistently too high. Using experience gained after completing a few mix evaluations achieved better estimates than were produced with the equations.

### *5.1.3 Specimen Fabrication and Testing*

As prescribed under Marshall mix design, test specimens were prepared over a range of different asphalt percentages to determine the optimum asphalt content. This range consists of ½ percent increments with two asphalt contents above and two below the estimated asphalt content. Also duplicate samples of each asphalt content were made. Two maximum specific gravity, or Rice, samples were also required at the estimated asphalt content according to AASHTO T209, making the total number of samples needed, 12 per mix design. Maximum specific gravity test samples were not needed for all asphalt contents since the Marshall method allows for estimation of the maximum specific gravity of the other asphalt contents from the one measured value. Equations 2.1 to 2.10 are used for this analysis.

Once the aggregates for the mixtures had been combined for correct weight, they were heated to the mixing temperature of 162°C. A sufficient amount of PG 64-22 asphalt binder was also heated to this temperature shortly before the mixing process. The mixing bowl and mixing wand were also heated to the compaction temperature. Mixing temperature was indicated in the binder evaluation data from the Citgo Asphalt Data Sheet. This evaluation sheet also indicated that the compaction temperature was 149°C. In a separate oven, the compaction molds were heated to the compaction temperature and the Marshall hammer was placed on a hotplate.

The heated aggregate mixture was then placed into the mixing bowl and the required amount of asphalt binder was added. This was immediately placed in the tabletop mixer and mixed until the aggregate and binder was thoroughly mixed. After mixing, the entire specimen was placed in the mold, spaded 25 times with a spatula, and placed on the compaction pedestal. The retaining ring was placed over the mold, the compaction hammer placed in the mold and attached to the automatic lifting device. The lifting device was then activated to apply the applicable number of blows to the specimen. The correct number of blows per side for Marshall medium and heavy mixtures is 50 and 75, respectively. After the compaction to one side of the specimen was complete, the mold was then flipped over and the compaction process repeated for the same amount of blows. Once the compaction process was complete, the sample and mold were removed and placed into the specimen extraction device. The specimen was removed from the mold and allowed to cool. This entire process was repeated for the ten specimens used for determining the optimum asphalt content.

Maximum specific gravity is a required value for determining the percent air voids of compacted samples of that same mixture. Mixing samples for the maximum specific gravity is similar to making the Marshall samples. AASHTO T 209-94 was followed to determine the maximum specific gravity.

After test specimens were compacted, the bulk specific gravity and stability and flow were measured following AASHTO T 166-00 and T 245-97, respectively. The analog plots of load versus time were used to determine the stability and flow for each sample.

### *5.1.4 Mix Design Results and Summary*

After the samples were mixed, compacted and tested the volumetric analysis was performed as reviewed in Chapter 2. An Excel spreadsheet was developed to compile and analyze the data. For the Marshall mix design the volumetric parameters are VMA, VFA and VTM. These results were graphed according to the Marshall mix design method.

Other values such as stability and flow were acquired from the Marshall Testing Machine graphs and input into the spreadsheet. The Excel program also calculated the stability correction for height after the measured height of each sample was input. Full-page printouts and design graphs for each mix design are presented in the Appendix C.

Table 5.2 contains the volumetric summary for the Marshall mix designs. WVDOH required values for properties listed are found in Table 2.2. As mentioned before the VMA for the two 100% LS designs are right at the WVDOH minimum value. By adjusting the gradation curve away from the maximum density line the VMA natural sand mixtures is 16.1%. VFA values are all within WVDOH specifications, although they are all toward the upper limit of the requirement. The 13% natural sand Medium design had a stability of 8075 lb., which is close to the minimum criteria of 8000 lb. All other mixes had stability values well above the minimum requirement. As expected, the stability values decreased in the medium design of each mixture type and also decreased with the addition of natural sand content. Conversely, flow values did the opposite, increasing in the medium level mixture and with increased sand content.

Table 5.2 Marshall Mix Design Volumetric Summary

| Mix Type | Asphalt (percent) | VMA (percent) | VFA (percent) | Stability (N) | Flow (mm) |
|---|---|---|---|---|---|
| MR HVY 100% LS | 5.2 | 15.0 | 74.0 | 10231 | 13.9 |
| MR MED 100% LS | 5.5 | 15.1 | 72.5 | 9341 | 14.9 |
| MR HVY 13% NS | 5.9 | 16.1 | 75.0 | 9450 | 11.3 |
| MR MED 13% NS | 6.0 | 16.1 | 75.5 | 8075 | 16.0 |

## 5.2 SUPERPAVE MIX DESIGNS

As with the Marshall mixes, the Superpave mixes were designed to be applicable to local conditions. The same aggregate stockpiles and asphalt cement were used for both mix types. The Superpave mix design procedure allows for more traffic levels than the Marshall procedure. The research plan called for developing Superpave mix designs comparable to the Marshall designs. In addition, a 100% crushed limestone mix and a mix with the maximum amount of natural sand was developed for the light traffic level. Since the consensus aggregate requirements are significantly relaxed for light traffic volume roads, it was possible to develop mix designs with high natural sand contents.

The dust to binder ratio controls the amount of dust is used in a Superpave mixture. This ratio affects the gradation limits for Pan material specified by Superpave as 2.0 to 10.0 percent. However, the dust to binder ratio effectively limits this range as a function of the percent effective binder. For example, if the effective binder content is 5 percent, the amount of material passing the #200 sieve must be in the range of 3.0 to 6.0 percent for the mix to meet the D/B criteria. Thus, the D/B criterion is a limiting factor on the number of acceptable mixtures which can be made with available aggregate stockpiles. The Superpave low traffic mixtures which were designed to be above the restricted zone were directly affected by the D/B ratio. In all cases, the D/B criteria limited the range of material passing the #200 sieve to less that the aggregate specification limits. Hence, if the D/B criterion is enforced, essentially controls this portion of the aggregate blend.

### *5.2.1 Types of Mixes Developed*

Eight Superpave mixes were designed for this project. The blends of stockpile materials are shown in Table 5.3. Four of these mixes mimic the Marshall mixes, two 100% limestone mixtures and two 13% natural sand mixes at traffic levels of medium and high. The two mixes containing 13% natural sand contain the exact same blends and gradations as the comparable Marshall mixes. The blends gradations for the heavy and medium traffic Superpave mixes with 100% limestone were adjusted to better meet the Superpave criteria. Four Superpave light traffic designs were developed. One contained the maximum amount of natural sand that could be used while meeting the Superpave consensus aggregate specifications. One contained approximately half this amount of sand, but the exact proportion was determined during the mix design process. Two light traffic mixes were designed with 100% limestone. One was the finest mix that could be developed based on the stockpile gradations. One was prepared with the same gradation as the mixes with natural sand. These were designed above the restricted zone and two contained large amounts of natural sand. Of the two remaining mixes one contained 100% limestone but was passed through the restricted zone due to major difficulties in combining the research stockpiles into a 100% limestone mixture above the restricted zone. The final mixture is one that mimics the 100% natural sand mixture. This was accomplished by altering the gradation of the limestone sand stockpile to match that of the natural sand

gradation. This allowed for direct comparison of a natural and limestone sand mix with the same proportions of sand.

Table 5.3 Blend Percentages for Superpave Mixtures

| | | Stockpile Types | | | | |
|---|---|---|---|---|---|---|
| **Designation** | **Traffic Level** | Skid | N.Sand | L.Sand | #9 | BH Fines |
| SP HVY 13%NS | Hvy 13% N. Sand | 20 | 13 | 28 | 38 | 1 |
| SP MED 13%NS | Med 13% N. Sand | 20 | 13 | 28 | 38 | 1 |
| SP HVY 100%LS | Hvy 100% L. Sand | 15 | 0 | 45 | 39 | 1 |
| SP MED 100%LS | Med 100% L. Sand | 15 | 0 | 45 | 39 | 1 |
| SP LGT 100%LS | Lgt 100% L. Sand | 15 | 0 | 78 | 7 | 0 |
| SP LGT 40%NS | Lgt 40% N. Sand | 15 | 39.6 | 40 | 3 | 2.4 |
| SP LGT 64%NS | Lgt 64% N. Sand | 32 | 64 | 0 | 0 | 4 |
| SP LGT 100%LS | Lgt 100% LS mod | 32 | 0 | 64 | 0 | 4 |

A search for existing Superpave mix designs in use by companies across the state found no mixes of interest for this project so all Superpave mixes used were developed in the laboratory.

### *5.2.2 Determining the Design Aggregate Structure*

Aggregates used for the Superpave portion of the research were the same as used during the Marshall tests, meaning the aggregate was sieved, washed and dried in the same way. Also, the same Excel spreadsheet, with modifications to better match Superpave design, was utilized to aid in developing the aggregate mixtures and gradation curves. The stockpile percentages and gradation curves for all Superpave mixtures can be seen in Table 5.3 and Figures 5.2 and 5.3.

The asphalt contents for all the Superpave mixtures were estimated using Equations 2.12 to 2.16. The estimated asphalt contents were consistently higher than the optimum percent binder determined from the mix design procedure. However, the estimates were a reasonable starting point for mix design.

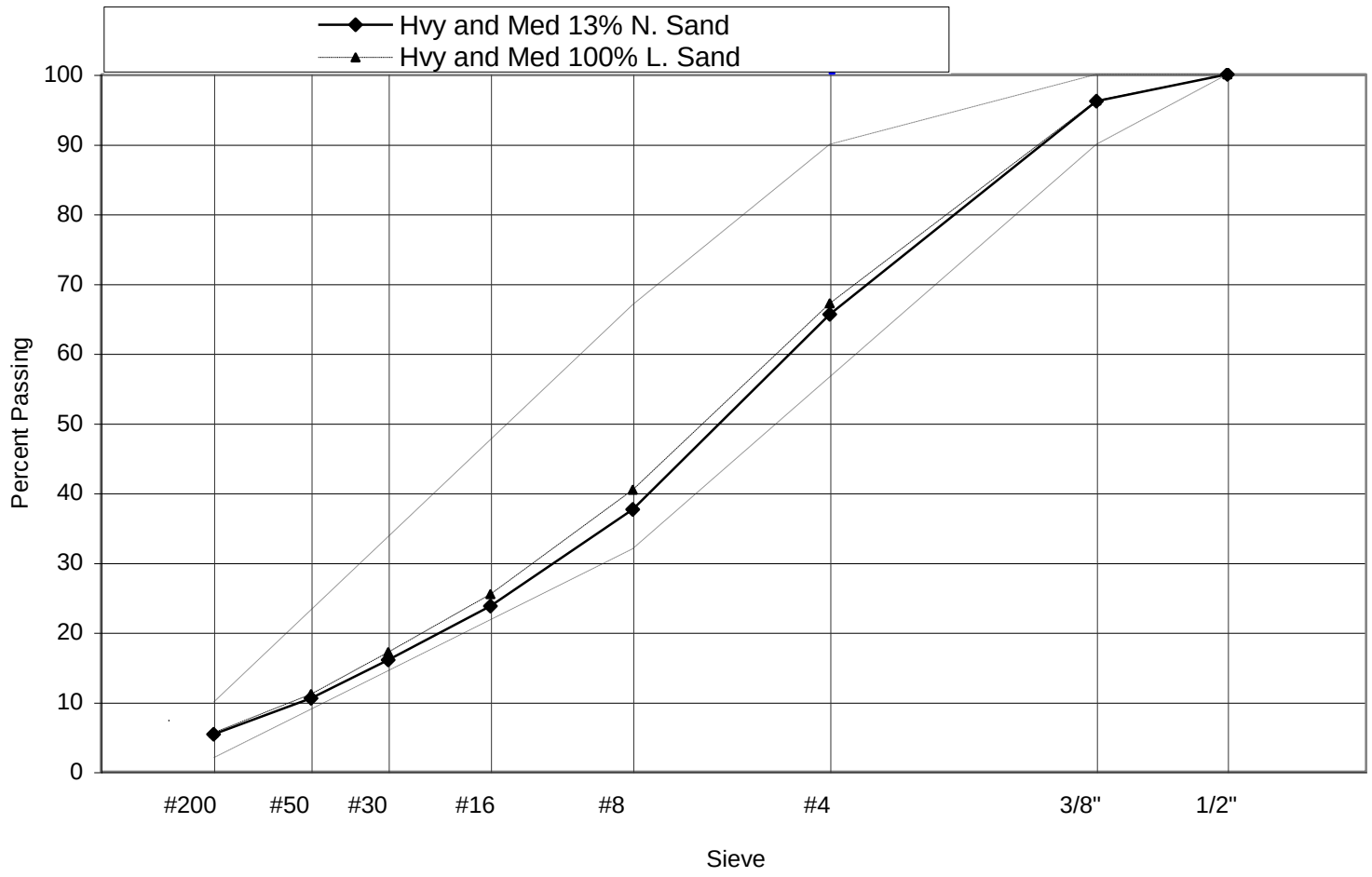


Figure 5.2 Gradation of Heavy and Medium Superpave mixtures

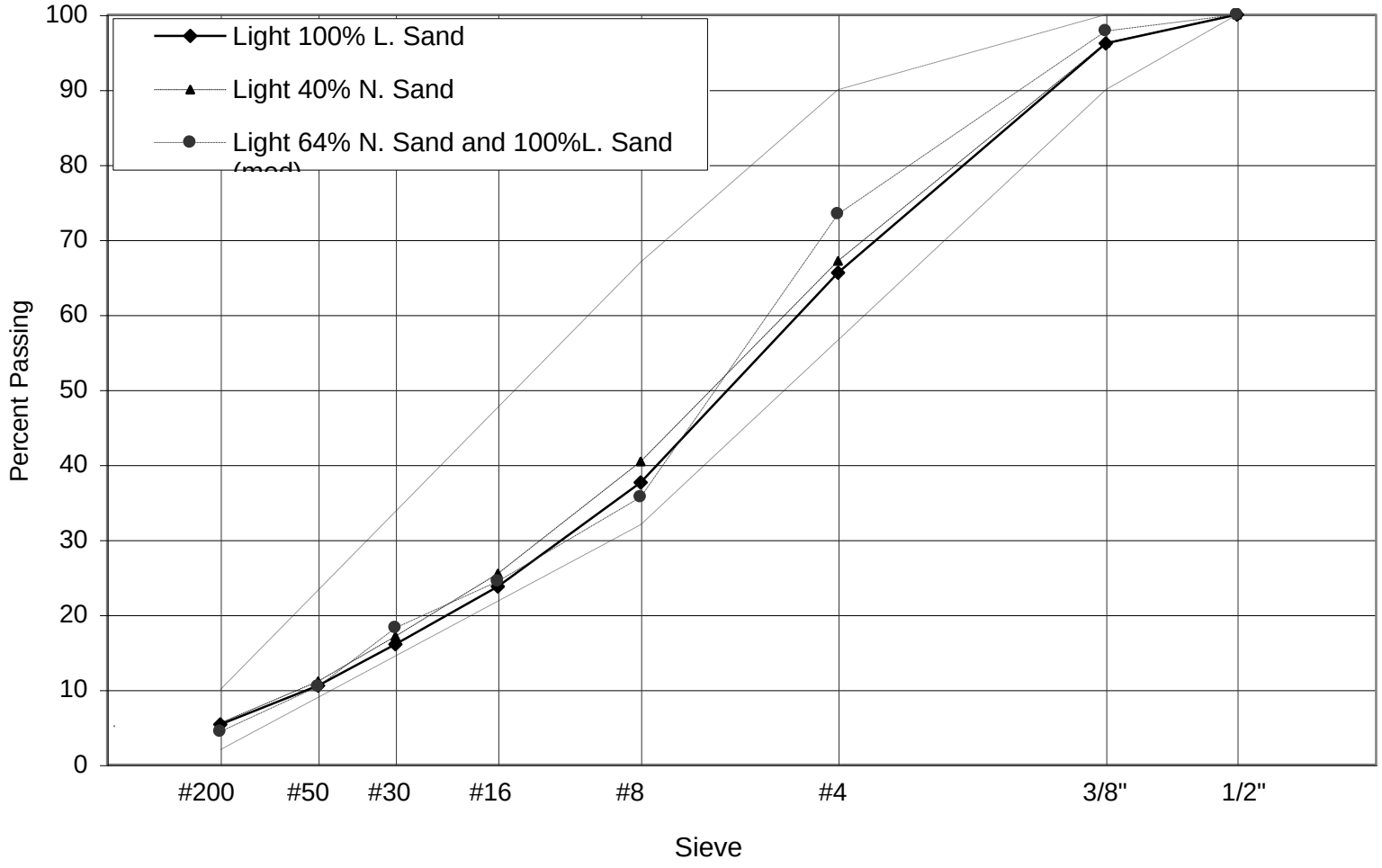


Figure 5.3 Gradation of Superpave Light mixtures

The first Superpave mixes developed were those containing 13% natural sand. This was done in conjunction with Marshall mixtures of the same gradation, thus problems encountered with the Marshall development also occurred with the Superpave.

VMA was a concern with the Superpave mixes because past experience, documented in Chapter 2, indicated mixtures compacted in the gyratory compactor exhibit lower VMA values than those compacted with the Marshall compaction hammer. However, trial blends demonstrated that VMA was not a problem with the 13% natural sand aggregate blend. The VMA was 15.0 for the heavy traffic mixture and 15.4 for the medium. These VMA values are close to WVDOH limit of 15.0 indicating that 13% natural sand was the maximum amount that could be used for these designs.

Next the 100% limestone aggregate Superpave mixtures were designed. At first, trial mixes were evaluated with gradations similar to the Marshall designs. However, the VMA was less than the required minimum, so the gradation was adjusted to allow for more distance between the upper part of the gradation curve and the maximum density line. This increased the VMA to an acceptable level.

Finally, the Superpave light-traffic volume mixtures were designed. The first mix developed was the Superpave light-traffic mix with 100% limestone. Initially, two problems were encountered, inadequate VMA and too much #200 material to pass the D/B criteria. Using the available stockpile gradations, there was no combination of aggregates that passed all criteria, including avoidance of the restricted zone. At the national level, mixes with 100% crushed material are allowed to pass through the restricted zone. Hence, it was decided to allow the 100% limestone mix for light-traffic to pass through the restricted zone. This allowed for a reasonable amount of pan material to be in the mix while still staying away from the maximum density line to achieve proper VMA.

The next mix developed was one that contained a half-and-half mixture of limestone and natural sand. This was done by simply taking the gradation of the 100% limestone sand design and splitting the limestone sand portion in half. Adjustments had to be made to the #9 and baghouse fines stockpiles to allow for an acceptable gradation above the restricted zone. This gradation was also hard to design in that to meet the percent passing requirement of the #50 sieve in the restricted zone, the percent passing the #8 sieve was pushed out of specification. This was eventually corrected by fine-tuning the gradation percentages. However, this did hold the gradation far enough away from the maximum density line to allow for a VMA of 15.2.

The next mixture designed was one that contained 100% natural sand. Various trial blends were tested that closely resembled that of the 100% limestone sand mixture using natural sand instead of limestone. These blends were found to exhibit low VMA values and it was also difficult to meet the minimum percent passing the #200 sieve requirement. This was mainly attributed to the gradation laying so closely to the upper limits on other sieves making it difficult to adjust the gradation a sufficient amount. This problem was over come by allowing a higher

percentage of aggregate from the SKID stockpile into the mix. After more trial blends with this adjusted gradation it was found that the highest allowable amount of natural sand stockpile in the mix was 64%.

The final Superpave light mixture developed was one that was exactly like the 64% natural sand mix but with the sand portion consisting of limestone mixed at the same gradation as the natural sand. This mix was developed to allow for a direct comparison of identical gradations using different material. It was decided that volumetric requirements for this mix design would not be considered. This was done so the gradation curves could remain identical. However, this mix design only had a VMA of 13.9.

### *5.2.3 Specimen Fabrication*

Superpave mix design is covered and outlined by two standards published by AASHTO: Standard Practice for Superpave, PP28-99, and Specification for Superpave, MP2 –99. The design process started by first developing trial blends for determining the proper aggregate structure or testing one that has previously been shown to be a good blend for other traffic volumes. Next, estimated asphalt content was calculated using the same process used with the Marshall samples. The trial blends were then tested at the estimated asphalt content and tested for each specimen's volumetric properties. The trial blend that yielded the best result, based on volumetric properties, was selected as the design aggregate blend.

The next step in the design process was to determine the design asphalt content, which yields 4 percent air voids. Using the newly determined design aggregate structure and estimated asphalt content as a starting point, samples also were prepared at 0.5 percent above and below estimated asphalt content and also 1.0 percent above. Duplicate samples at each asphalt content percentage were also made along with maximum specific gravity samples for each asphalt content. These samples were made up by first mixing the proper proportions of aggregates for each blend, then heating them to the mixing temperature of 162°C. The aggregate and corresponding weight of asphalt for each asphalt content percentage was then combined and mixed in the large bucket mixer until all aggregate was thoroughly coated. This loose mixture was then placed in an oven at the compaction temperature of 149°C for two hours. The mix was stirred at half hour intervals.

After the proper soak time, the mix was removed from the oven and placed in the gyratory compactor mold, placed in the compactor that has been set to the correct number of gyrations for the type of sample being compacted and the compactor activated. Once the specimen was compacted, the mold was removed from the compactor and specimen removed from the mold with an extracting jack. The specimens were cooled to room temperature. After the specimens cooled they were ready for volumetric determination and testing.

### 5.2.4 Specimen Testing

Superpave mix design relies solely volumetric properties of the mix. No physical test is currently required. However, the APA test developed by the Georgia DOT is gaining popularity with various state agencies and researchers.

Testing was conducted on all specimens along the range of asphalt contents tested and values inputted into an Excel spreadsheet programmed specifically for Superpave. This program then calculated the air voids, VMA and VFA from the measured bulk weights of each specimen and graphs made of each of these properties versus asphalt content.

From the graphs developed by the spreadsheet, the asphalt content corresponding with 4% air voids was determined. This asphalt content was the design asphalt content. VMA and VFA values of the mix were determined by finding the values for each that corresponded with the design asphalt content. Volumetric values were then checked for compliance with required values set forth by Superpave.

Once the optimum asphalt content has been found, a set of $N_{max}$ specimens were prepared. If the sample met Superpave specifications, then the mix was determined to be an acceptable mix.

### 5.2.5 Mix Design Results

Results of the Superpave designs were calculated using an Excel spreadsheet. Tables and graphs containing the full mix design data for each Superpave mix design are presented in Appendix C and are summarized in Table 5.4.

All properties were within WVDOH specifications except for those indicated by the heavy boxes. As indicated in Chapter 4 the fine aggregate used did not meet the specifications for heavy traffic volume design. As expected the 100% limestone mixes exhibited a higher FAA value than that of the mixes containing 13% natural sand. Another source for sand was not sought to raise this value above the minimum of 45 needed to meet requirements due to the need to keep the sand content consistent throughout the research. This allowed for accurate comparisons to be made without the added complication of considering variations in material properties.

Table 5.4 Summary of Volumetric and Design Properties for Superpave Mixtures

| Type | Percent Asphalt | FAA | VMA | VFA | D/B ratio |
|---|---|---|---|---|---|
| SP HVY 100% LS | 5.7 | 43.5 | 15.3 | 73.5 | 0.96 |
| SP MED 100% LS | 6.3 | 43.5 | 16.9 | 74.0 | 0.87 |
| SP HVY 13% NS | 5.5 | 41.6 | 15.0 | 72.6 | 0.80 |
| SP MED 13% NS | 5.8 | 41.6 | 15.4 | 74.0 | 0.76 |
| SP LOW 100% LS | 5.6 | 43.5 | 15.0 | 73.5 | 1.13 |
| SP LOW 40% NS | 6.1 | 41.5 | 15.2 | 74.0 | 0.98 |
| SP LOW 64% NS | 6.1 | 39.4 | 15.5 | 74.5 | 0.82 |
| SP LOW 100% LS (modified) | 5.1 | 43.5 | 13.9 | 72.0 | 0.98 |

All mixes had VMA values above 15 except for the modified Superpave light 100% limestone sand mix. This was expected since the gradation was not developed to meet specifications but was meant to allow a direct comparison between using different fines content with the exact same gradation. The Superpave medium 100% limestone sand mixture was found to have a very high VMA value of 16.9 as compared to similar mixtures of the same aggregate structure which have VMA values near the mid – 15s. This is mainly attributed to the higher optimum asphalt content. VFA values were found to all be within the set ranges for each traffic volume level, however, like the Marshall mixes, these were also toward the upper limits of the requirements. Also, the dust to binder ratios were all within the limits set by WVDOH and Superpave. As expected asphalt content increased as the fines content increased. This was especially true as the natural sand content increased.

## 5.3 APA TESTING

The Asphalt Pavement Analyzer, APA, is a relatively new tool used to test the rutting potential of bituminous pavement mixtures. Although this device is a required test procedure, much interest and research are being put into this apparatus as a viable test method for evaluating mixture performance. The Georgia DOT has written a specification for the apparatus and testing method contained in the GDOT specification manual under GDT – 115: Method of Test for Determining Rutting Susceptibility using the Loaded Wheel Tester (APA Manual and Collins, 1996). Research is ongoing into reducing the high variability observed among test results of samples of the same mix design and air content. There has also been high variability between testing positions within the machine of which there are three: left, center and right.

The APA was used to develop test results containing information on the rut depths experienced by each mix type. These data were used rank the pavements based on rutting potential and analyze the effects of natural sand content on rut depths. The data also gave insight into rut depths versus asphalt content, air voids, fine aggregate angularity and VMA. Also, variability

among the tests results of the same mixture was also observed and examined during and after the APA testing.

### *5.3.1 Procedure for Determining Sample Weights for Correct Air Voids*

The procedure for the APA test was fairly straightforward. First, the weight of sample for 7 ±0.5 percent air voids was estimated using Equation 5.3.

$$W_{est} = G_{mm}\ C_1 \left( \frac{V_{samp}}{C_2} \right) \qquad [5.3]$$

Where,

$W_{est}$ = estimated weight to achieve 7.0% air voids

$G_{mm}$ = maximum theoretical specific gravity of specific mixture

$V_{samp}$ = volume of APA sample with height of 75mm = 1325.3mm$^3$

$C_1$ = percent sample of total volume at 7.0% voids = 0.93

$C_2$ = constant observed in lab accounting for voids at sample surface = 1.03.

Estimated weights were calculated for each mix design with the above equation and trial blends were made up. It was found that these weights resulted in the air voids being just slightly over 7.5 percent in some of the mixes. If a mix was within range but very close to either limit then it was adjusted also to reduce the effects of having to reject a sample that went above or below the limits due to variability in the mix. Most of the mixtures required adding 20 g to the estimated weight to achieved the proper air content. Table 5.5 contains the calculated and adjusted weights for each mix design.

The next step in preparing for the APA samples was the making of the required number of specimens for proper testing of each mix design. In the preliminary stages of this research it was decided that three samples of each mix design would be necessary to correctly test the mix designs. A sample would consist of two specimen pills each, making a total of 6 specimen pills per mix design and with 12 mix designs that number comes to 72 pills required. The samples were blended, mixed and compacted in accordance with the particular specimen's mix design method with the exception of using the gyratory compactor for the compaction of Marshall specimens. Since samples were tested randomly in the APA, testing could not begin until all samples had been made.

Table 5.5 Calculated and Adjusted Weights for APA Test Samples

| Mix Design | Calculated Weight | Adjusted Weight |
|---|---|---|
| MR HVY 100% LS | 2978 | 2998 |
| MR MED 100% LS | 2969 | 2989 |
| MR HVY 13% NS | 2946 | 2956 |
| MR MED 13% NS | 2941 | 2951 |
| SP HVY 100% LS | 2971 | 2991 |
| SP MED 100% LS | 2956 | 2976 |
| SP HVY 13% NS | 2975 | 2995 |
| SP MED 13% NS | 2966 | 2986 |
| SP LOW 100% LS | 2966 | 2986 |
| SP LOW 50% NS | 2910 | 2930 |
| SP LOW 64% NS | 2910 | 2930 |
| SP LOW 100% LS (mod) | 2988 | 3008 |

### *5.3.2 Test Procedure*

Once all the APA samples were compacted to the proper height of 75mm and air content of between 6.5 and 7.5 percent, the APA tests were performed. The tests were conducted by randomly testing two specimens of each mix design in a random position in the testing tray. To begin, each specimen was placed into the specimen retaining molds and secured in the testing tray in the proper positions. Once the testing tray was secured in the APA, the soak time and temperature was set at 3 hours and 140°F, respectively. Pressing the start button then started the automated testing process. After the three-hour soak time, hoses pressurized to 100 psi were automatically lowered unto the samples. Then wheels loaded to 100 pounds were lowered onto the hoses and the repetitive loading process started. This process consisted of 8000 cycles of the wheels rolling back and forth across the hoses and specimens. The APA automatically shut down once it completed these cycles and the samples were allowed to cool.

Once the samples were cool and removed from the APA, a measuring template was placed over the sample retaining mold and a deflectometer was passed over two equally spaced positions on each specimen pill making a total of four measurements per sample. After measurements

were made, the samples were removed from the retaining molds and discarded. This process was repeated for twelve APA runs and data recorded for all test runs.

### *5.3.3 APA Testing Results*

Rut depths were measured and recorded for each sample of every mix design tested. The four rut depths per sample were averaged and these values for the triplicate samples were also averaged to get one average rut depth for each mix design. Standard deviation was also calculated over the sample set of data points consisting of the individual rut depths on each sample. Table 5.6 contains these results and data on average percent air voids for each sample. These results show that the hypothesis of mixes that contain natural sands would exhibit greater rut depths than mixes that contain all limestone was correct, however, some interesting and contradicting results were also observed. One interesting result was that the Superpave medium 13% natural sand mix incurred an average rut depth of 9.43mm while the heavy design of the same natural sand content had an average rut depth of 10.35mm. In theory, a heavy mix design should be less likely to rut than a medium traffic design of the same gradation. Another unexpected result was that both Superpave light 100% limestone sand mixtures performed better than all the other mixes, with the exception of the 100% limestone sand Marshall designs. This is especially interesting in that the Superpave light 100% limestone sand design was passed through the restricted zone. By doing this, the mixture should have exhibited the characteristics of a tender mix (i.e. high rut depths).

As expected the designs containing very high percentages of natural sand exhibited very high rut depths. This was particularly true with the Superpave light 40% natural sand and 68% natural sand mixtures. These mixes resulted in the deepest rut depths of all the mix designs. It should be noted that most of the samples tested failed the Georgia DOT requirement if a maximum of 7.5mm rut depth. However, well performing mixtures designed for the WVDOH typically exhibit average rut depths greater than 7.5mm. This shows that the maximum rut depth requirement would need reexamined if this test was ever implemented in West Virginia. Rut depth data, along with all other test results and data developed during this research, will be further analyzed in the next chapter.

Table 5.6 Results of APA Tests

| | Air voids percent | Rut Depth (mm) |
|---|---|---|
| **MR HVY 100% LS** | 6.9 | 6.40 |
| **MR MED 100% LS** | 7.0 | 6.22 |
| **MR HVY 13% NS** | 7.2 | 11.51 |
| **MR MED 13% NS** | 7.0 | 7.76 |
| **SP HVY 100% LS** | 7.0 | 8.89 |
| **SP MED 100% LS** | 6.9 | 10.16 |
| **SP HVY 13% NS** | 7.1 | 10.35 |
| **SP MED 13% NS** | 7.1 | 9.43 |
| **SP LOW 100% LS** | 7.2 | 7.01 |
| **SP LOW 40% NS** | 7.5 | 15.04 |
| **SP LOW 64% NS** | 7.3 | 17.33 |
| **SP LOW 100% LS (mod)** | 7.4 | 6.50 |

# CHAPTER 6 DATA ANALYSIS AND RESULTS

## 6.1 INTRODUCTION

Once data were collected from all mix designs, fine aggregate angularity tests and APA tests it was compiled into tables presented in the Appendix D. These tables contain the raw data, such as sample weights, as well as calculated results of corresponding tests. Graphs are presented in this chapter that show comparisons between rut depths versus various aggregate properties and mix design values. These include air voids of APA samples, FAA value, VMA, asphalt content and percent natural sand in the mix. Results of the APA test were tested statistically for significant differences and were compared with those results from the literature. Also, general observations, limitations and considerations were discussed with respect to the objectives set forth at the start of the research.

## 6.2 PRELIMINARY DATA ANALYSIS AND GENERAL OBSERVATIONS

*Fine Aggregate Angularity.* Preliminary analysis performed on the fine aggregate angularity tests showed that the results calculated from the tests met expectations and past experience. Uncompacted voids percentage increased as the amount of natural sand in the mix decreased. As mentioned before, none of the mixtures met the WVDOH requirement for FAA in Superpave Heavy mixtures. If a contractor wanted to use this material for a Superpave Heavy design in West Virginia this problem could only be overcome by blending another aggregate into the mix that exhibited an uncompacted void percentage higher than 45%. Also no 100% natural sand content mixtures could be designed at the medium traffic volume level since the natural sand itself had a FAA value of 39.4%, just under the WVDOH minimum specification of 40% for medium traffic designs.

*Superpave Mix Design.* Accommodation of direct comparisons between mix designs across traffic level and design method was attempted throughout the mix design process. This meant getting gradations as close to each other as possible, while still meeting volumetric and strength requirements for each mix design method. This was accomplished for the most part by at least keeping the gradations of similar design types and levels as close as possible. One place where this was not possible was in developing a Superpave Heavy or Medium design with a high level of natural sand. As mentioned before, the highest natural sand percentage that could be achieved in either mix design type at the heavy and medium level was 13% of the total mixture. Any more than that caused either a problem with volumetric values or with the gradation crossing through the restricted zone. If a higher sand content design could have been developed at these levels, then a more direct comparison could have been made between them and the Superpave Low 50% NS and 64% NS mix designs.

*Asphalt Pavement Analyzer Testing.* The data collected during this testing did follow expectations of the effects that natural sands would have on the rut depths (i.e. more natural sand, deeper rutting). However, there were many unexpected results after the data from this testing was first examined. At first it was expected that all the heavy traffic level mixtures would

exhibit lower rut depths than any of the other mixes and then the medium mixtures and finally the low volume mixes, this, however, was not the case. In fact, two Superpave Low mixtures performed better than three of the four heavy mixes. This was probably due to the fact that the low volume mixes did not contain any natural sand, while a few of the heavy mixes did. Most all of the pavement designs tested very well, even though the majority of them would have failed the Georgia DOT criteria for minimum rut depth, especially when compared to APA results of previous research involving natural sands and how most pavements in West Virginia fare in APA tests. It should also be mentioned that the equation used to aid in finding the proper weight to achieve 7% air voids in the APA samples worked very well, even though some slight adjustments did need made to the sample weights. This equation brought the estimate to within 20 to 30 grams of the correct weight of samples that average 3000 grams.

**6.3 DATA ANALYSIS**

Student t-tests were used for the statistical analysis. The two-tailed t-tests were conducted in the standard method prescribed by statistical data analysis. In all cases, the hypothesis tested was that the means of the populations are equal, and the null hypothesis is the means are not equal. A critical t-value was determined for each comparison based on the number of degrees of freedom and a confidence level of 95 percent. If the t-statistic value was within the range of plus or minus of the critical t-value then the null hypothesis of the population means being unequal was not rejected. An Excel spreadsheet was used to aid in the calculation of the large number of t-tests needed for this research.

Table 6.1 presents some global comparisons of the data. The comparison of all Marshall mixes versus the Superpave mixes shows the null hypothesis of equal means should be rejected. However, this conclusion is confounded by the fact that there were no Marshall light mixes in experiment. There was 40 and 64 percent natural sand in two of the Superpave light traffic mixes, with average rutting potential of 15 and 17 mm respectively. These two mixes are the reasons that the average rutting of the Superpave mixes was much greater than the average rutting of the Marshall mixes. Without these two mixes, the average rutting of the Marshall and Superpave mixes was fairly close and the t-statistic for comparing the mixes was 0.222, indicating that the null hypothesis should not be rejected. The comparison of the Heavy and Medium traffic mixes showed that the null hypothesis could not be rejected, this is evidence that the mixes performed equally well. However, there is not enough data to claim that the null hypothesis should be accepted. The data also suggests that there is not sufficient evidence to suggest a difference in the performance of the mixes based on the traffic level used in the design of Superpave mixes. This result is counter intuitive and should be studied further. It is likely that the forced inclusion of sand in some of the Superpave mixes confounded the results of this comparison. Comparison of mixes with limestone only to those with natural sand demonstrates the null hypothesis should be rejected. From inspection of the data it can be concluded that on the average mixes with natural sand rutted more than mixes with only limestone.

The various Superpave mixes are compared in Table 6.2. The overall comparison of Superpave mixes with and without natural sand indicated the null hypothesis should be rejected, supporting the conclusion that the inclusion of sand increased rutting potential. However further examination of the table shows that when the natural sand was limited to 13 percent, the null hypothesis could not be rejected in all but one case. This indicates that no difference in the performance of the mixes was detected. The case where the null hypothesis was rejected was for a mix with 13 percent sand for heavy traffic versus 100

Table 6.1 Global Comparisons of Rutting Potential

| **Comparison** | | **T-statistic** | **Critical T-value** | **Reject null hypothesis (Y / N)** |
|---|---|---|---|---|
| Marshall | Superpave | 2.107 | 2.074 | **Y** |
| Heavy Traffic | Medium Traffic | 1.013 | 2.074 | N |
| Limestone Sand | Natural Sand | -2.268 | 2.074 | **Y** |
| SP Heavy | SP Medium | -0.220 | 2.228 | N |
| SP Heavy | SP Low | -0.713 | 2.228 | N |
| SP Medium | SP Low | -0.627 | 2.228 | N |

percent limestone for light traffic, Table 5.6 shows the Superpave light traffic, 100 percent limestone, mix showed very little rutting potential relative to the other mixes. In all cases, the null hypothesis was rejected when the amount of sand in the Superpave mix was 40 percent or greater. The null hypothesis was not rejected for the comparison of the Superpave light traffic mixes with 40 and 64 percent sand.

Table 6.3 shows the comparisons of the Marshall mixes. The null hypothesis was rejected for the comparison of the heavy traffic mix designs with 100 percent limestone and 13 percent natural sand. In this case, the mix with 13 percent sand showed more rutting potential than other mixes. This mix also showed significantly more rutting potential that the Marshall medium traffic design with 13 percent sand.

Table 6.4 shows the comparisons between Marshall and Superpave mixes. The null hypothesis could only be rejected for four of the 16 comparisons. The Superpave heavy traffic with 13 percent natural sand had significantly more rutting than the Marshall heavy traffic design with 100 percent limestone. This Superpave mix also showed more rutting potential than the Marshall medium traffic design with 13 percent natural sand. The Superpave medium traffic

design had significantly more rutting potential than the Marshall medium traffic design with 13 percent natural sand and the Marshall heavy design with 100 percent limestone.

Table 6.2 Comparison of Superpave Mixes Rutting Potential

| **Comparison** | | **T-statistic** | **Critical T-value** | **Reject null hypothesis (Y / N)** |
|---|---|---|---|---|
| SP 100% LS | SP with NS | -2.549 | 2.120 | **Y** |
| SP H 100LS | SP H 13NS | -1.302 | 2.776 | N |
| SP H 100LS | SP H 13NS | -1.302 | 2.776 | N |
| SP H 100LS | SP L 100LS | 1.398 | 2.776 | N |
| SP H 100LS | SP L 40NS | -4.909 | 2.776 | **Y** |
| SP H 100LS | SP M 100LS | -1.202 | 2.776 | N |
| SP H 100LS | SP M 100LS | -1.202 | 2.776 | N |
| SP H 100LS | SP M 13NS | -0.370 | 2.776 | N |
| SP H 100LS | SP M 13NS | -0.370 | 2.776 | N |
| SP H 13NS | SP L 40NS | -4.820 | 2.776 | **Y** |
| SP H 13NS | SP M 13NS | 0.741 | 2.776 | N |
| SP H 13NS | SP M 13NS | 0.741 | 2.776 | N |
| SP M 100LS | SP H 13NS | -0.260 | 2.776 | N |
| SP M 100LS | SP H 13NS | -0.260 | 2.776 | N |
| SP M 100LS | SP L 100LS | 3.053 | 2.776 | **Y** |
| SP M 100LS | SP L 40NS | -5.384 | 2.776 | **Y** |
| SP M 100LS | SP M 13NS | 0.619 | 2.776 | N |
| SP M 100LS | SP M 13NS | 0.619 | 2.776 | N |
| SP M 13NS | SP L 40NS | -4.133 | 2.776 | **Y** |
| SP L 100LS | SP H 13NS | -3.052 | 2.776 | **Y** |
| SP L 100LS | SP L 100LS (MOD) | 0.463 | 2.776 | N |
| SP L 100LS | SP L 40NS | -6.517 | 2.776 | **Y** |
| SP L 100LS | SP L 40NS | -6.517 | 2.776 | **Y** |

| | | | | |
|---|---|---|---|---|
| SP L 100LS | SP L 64NS | -10.335 | 2.776 | **Y** |
| SP L 100LS | SP M 13NS | -1.678 | 2.776 | N |
| SP L 100LS (MOD) | SP L 40NS | 8.842 | 2.776 | **Y** |
| SP L 40NS | SP L 64NS | -2.644 | 2.776 | N |
| SP L 100LS (MOD) | SP L 64NS | 16.893 | 2.776 | **Y** |

Table 6.3 Comparison of Marshall Mixes Rutting Potential

| Comparison | | T-statistic | Critical T-value | Reject null hypothesis (Y / N) |
|---|---|---|---|---|
| MR H 100LS | MR H 13NS | -8.170 | 2.776 | **Y** |
| MR H 100LS | MR M 100LS | 0.130 | 2.776 | N |
| MR H 100LS | MR M 13NS | -3.220 | 2.776 | **Y** |
| MR H 13NS | MR M 13NS | 5.012 | 2.776 | **Y** |
| MR H 13NS | MR M 100LS | -3.430 | 2.776 | **Y** |
| MR M 100LS | MR M 13NS | -1.047 | 2.776 | N |

Table 6.4 Comparison of Superpave and Marshall Mixes

| **Comparison** | | **T-statistic** | **Critical T-value** | **Reject null hypothesis (Y / N)** |
|---|---|---|---|---|
| SP H 100LS | MR H 100LS | 2.572 | 2.776 | N |
| SP H 100LS | MR H 13NS | -2.280 | 2.776 | N |
| SP H 100LS | MR M 100LS | 1.562 | 2.776 | N |
| SP H 100LS | MR M 13NS | 1.076 | 2.776 | N |
| SP H 13NS | MR H 100LS | 7.004 | 2.776 | **Y** |
| SP H 13NS | MR H 13NS | -1.394 | 2.776 | N |
| SP H 13NS | MR M 100LS | 2.717 | 2.776 | N |
| SP H 13NS | MR M 13NS | 3.708 | 2.776 | **Y** |
| SP M 100LS | MR M 13NS | 4.014 | 2.776 | **Y** |
| SP M 100LS | MR H 100LS | 8.650 | 2.776 | **Y** |
| SP M 100LS | MR H 13LS | -1.784 | 2.776 | N |
| SP M 100LS | MR M 100LS | 2.672 | 2.776 | N |
| SP M 13NS | MR H 100LS | 2.755 | 2.776 | N |
| SP M 13NS | MR H 13NS | -1.647 | 2.776 | N |
| SP M 13NS | MR M 100LS | 1.797 | 2.776 | N |
| SP M 13NS | MR M 13NS | 1.425 | 2.776 | N |

These observations demonstrate the complexity of evaluating the rutting potential of asphalt concrete. In general, it can be concluded from these results that for similar design situations, the Superpave and Marshall mixes produce similar results, although for this data set, the overall rutting potential of Marshall mixes was slightly less than Superpave mixes. It can also be concluded that too much sand will increase rutting potential. This was clearly shown for the Superpave mixes where mixes with more than 40 percent natural sand showed more rutting potential than mixes with 13 percent natural sand. For the Marshall mixes, two of the three mixes with 13 percent sand showed more rutting potential than the mixes without natural sand.

Looking at the data as a whole, other correlations and relationships were observed. Figures 6.1 through 6.5 are graphs of rut depths versus design criteria such as asphalt content, VMA, FAA,

percent air voids and percent limestone sand. Linear regression was performed on the data contained in each of the following figures and their corresponding $R^2$ values can be found in Table 6.5. $R^2$ values near zero typically mean that there is no correlation between the data sets, whereas values near 1 represent high correlation between data.

By comparing the $R^2$ values and figures it can be observed that there are not any effects on the rut depth of a pavement mixture based on its asphalt content, percent air voids and especially VMA, which had an $R^2$ value of 0.09. It can be seen that there may be a high association between rut depth and both uncompacted voids percentage (FAA) and percent limestone sand. The comparison between rut depth and FAA value had a calculated $R^2$ value of 0.67, implying fairly high associations between these two mix design properties. The same can be said for the relationship between rut depth and percent limestone sand, which had a calculated $R^2$ value of 0.78. It should be noted that the charts of the two comparisons mentioned above appear very similar. This is due to the FAA value being dependant on the amount of limestone and natural sand contained in the mixture.

Table 6.5 Correlation Coefficients from Regression Analysis

| Comparison | R-square |
|---|---|
| Rut Depth vs Asphalt Content | 0.45 |
| Rut Depth vs VMA | 0.09 |
| Rut Depth vs FAA | 0.67 |
| Rut Depth vs % Air Voids | 0.34 |
| Rut Depth vs % Limestone Sand | 0.78 |

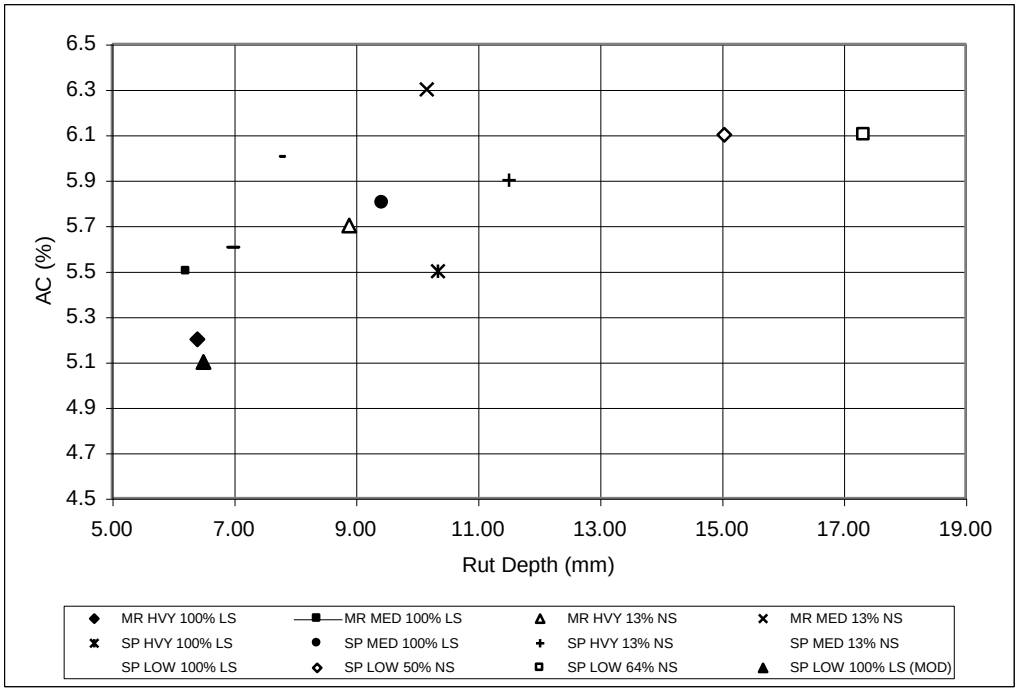


Figure 6.1 Rut Depth vs Asphalt Content

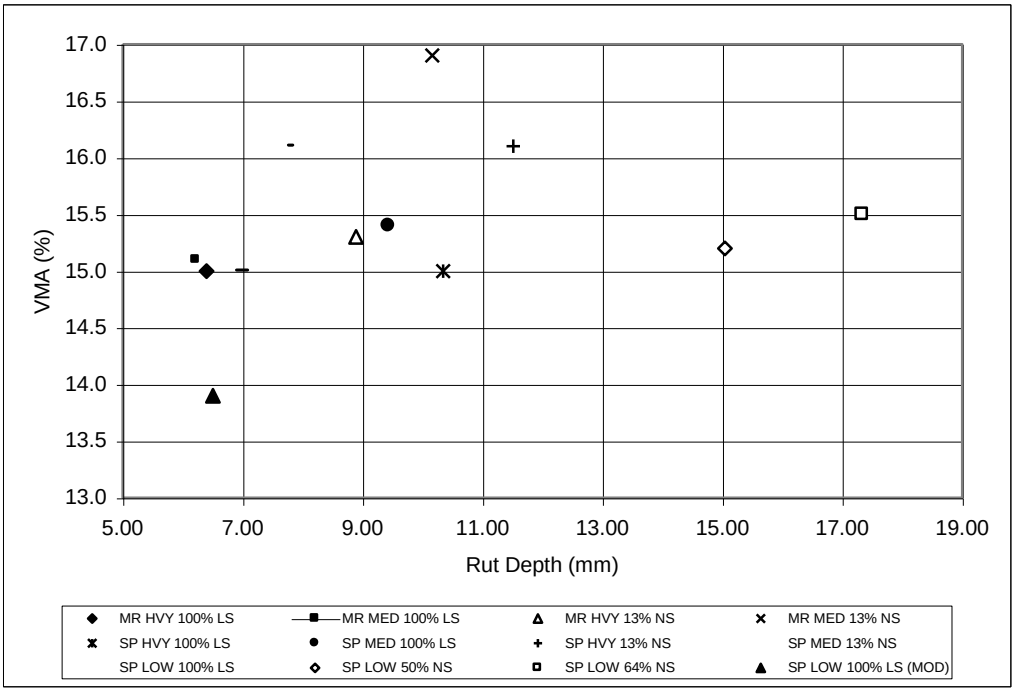


Figure 6.2 Rut Depth vs VMA

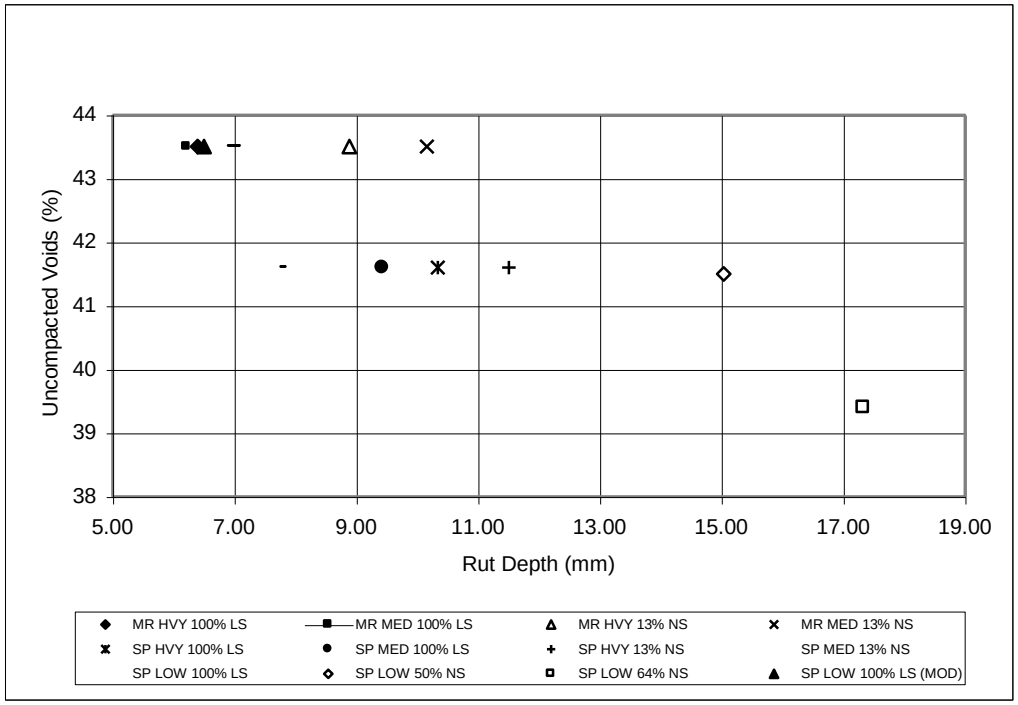


Figure 6.3 Rut Depth vs Fine Aggregate Angularity

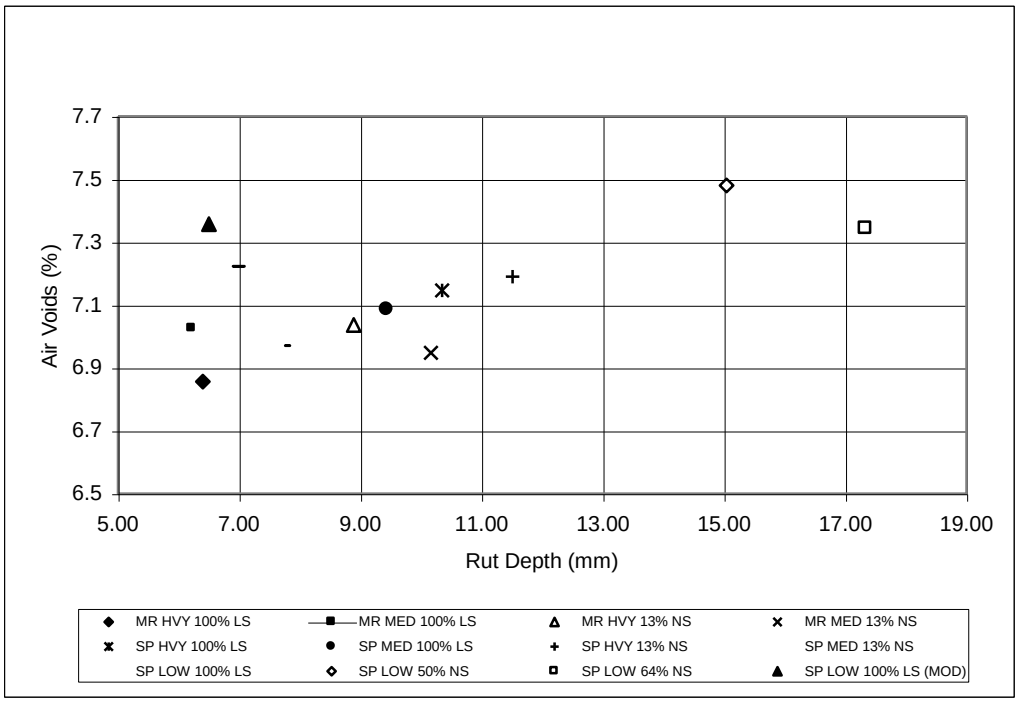


Figure 6.4 Rut Depth vs Air Voids

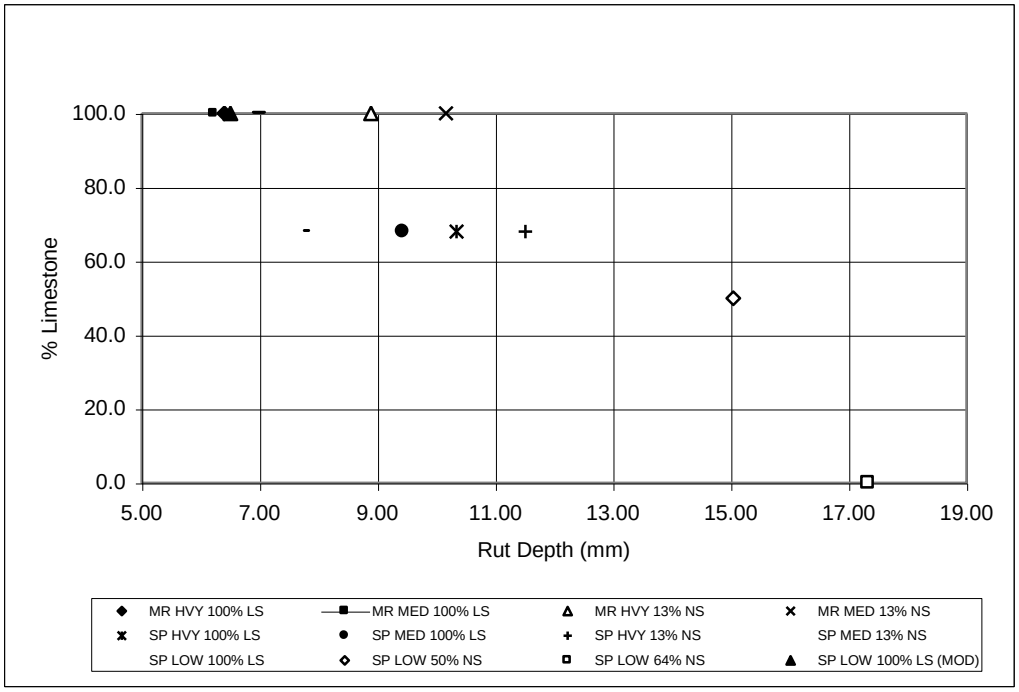


Figure 6.5 Rut Depth vs Percent Limestone Sand

## 6.4EVALUATION AND COMPARISON WITH OTHER STUDIES

Comparisons of results from this research with those of past studies are divided into the following sections: fine aggregate angularity, comparison of Marshall and Superpave mix methods, voids in the mineral aggregate and APA testing results.

*Fine aggregate angularity.* It was stated by both Huber (1998) and Casanova (2000) that it unclear if FAA is a fair and accurate indication of pavement performance. Huber found no correlation between FAA and rut depth results. However Casanova showed a correlation between FAA and rut depth measurements, but also found that FAA tests may not be enough since it tended to reject strong material and accept weaker aggregates. An $R^2$ value of 0.67 was found when comparing FAA values with rut depths for this research. This values shows that there is, at the least, a slight correlation between rutting potential and FAA, but the correlation is not strong enough to establish a clear trend. This could be partially the result of the experimental design used in this research. As shown on Figure 6.3 only a limited number of mixes were studied with a low FAA value. If more mixes were included with a FAA of less than 40, then the correlation would have probably been stronger.

*Comparison of Marshall and Superpave.* As mentioned in Chapter 2, Habib (1998) studied the differences between Marshall and Superpave design methods for low-volume roads. Habib found that values for asphalt content, VMA and VFA of the Superpave mix design were lower

than the Marshall mixes. Table 6.6 and Figure 6.6 display values for asphalt content, VMA and VFA for both methods use with this research. The Superpave mixes required a higher percent asphalt for the 100 percent limestone mixes, while the Marshall mixes required a higher asphalt with 13 percent sand in the mix. For the 100 percent limestone mixes, the VMA was higher for the Superpave mixes than for the Marshall mixes, but the opposite was true for the mixes with 13 percent sand. The VFA of the Marshall mixes was higher than the Superpave mixes in three of the four cases.

Table 6.6 Summary of Marshall and Superpave Design Parameters

| Mix Type | Percent Asphalt | VMA | VFA |
|---|---|---|---|
| SP HVY 100% LS | 5.7 | 15.3 | 73.5 |
| MR HVY 100% LS | 5.2 | 15.0 | 74.0 |
| SP MED 100% LS | 6.3 | 16.9 | 74.0 |
| MR MED 100% LS | 5.5 | 15.1 | 72.5 |
| SP HVY 13% NS | 5.5 | 15.0 | 72.6 |
| MR HVY 13% NS | 5.9 | 16.1 | 75.0 |
| SP MED 13% NS | 5.8 | 15.4 | 74.0 |
| MR MED 13% NS | 6.0 | 16.1 | 75.5 |

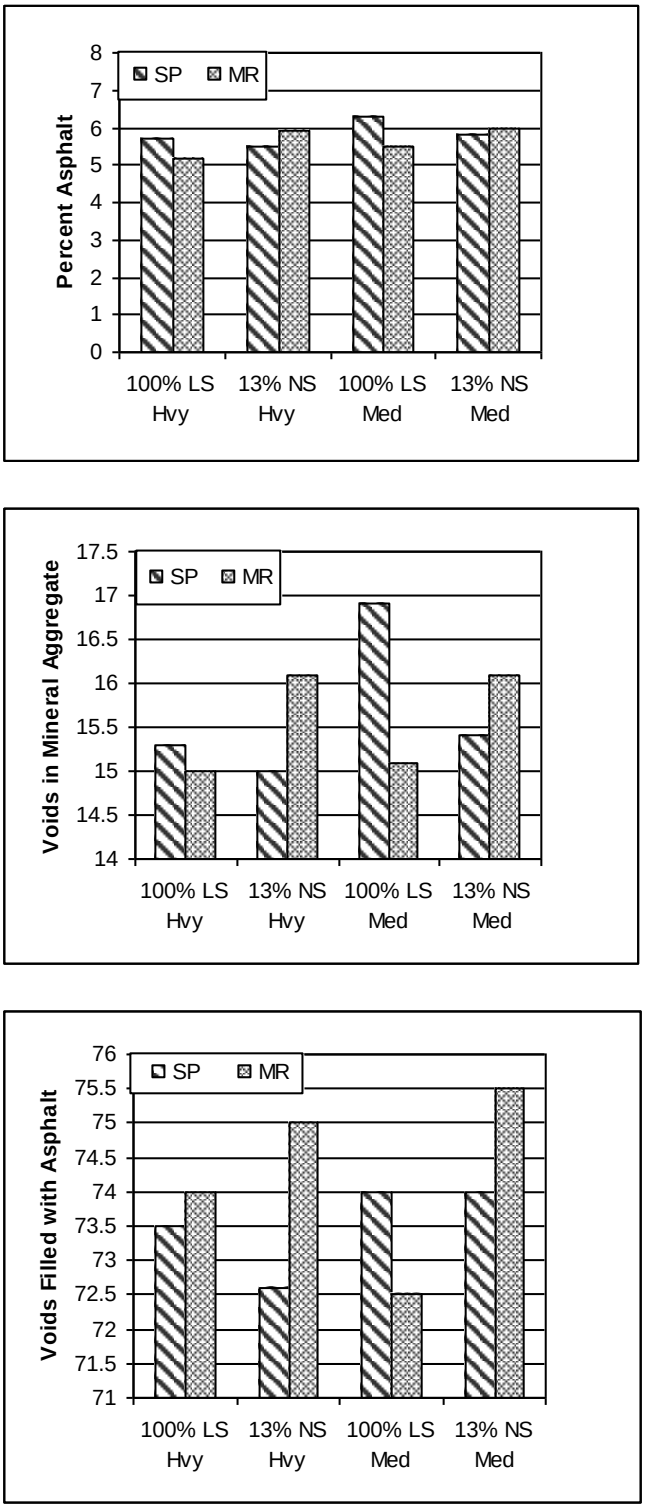


Figure 6.6 Volumetric properties of mixes.

*Voids in the Mineral Aggregate.* As described in Chapter 2, researchers and contractors have been experiencing difficulty in meeting VMA requirements, especially while designing for Superpave mixtures. Although no direct comparison of values can be made from this research, it should be noted that it was difficult to achieve the WVDOH minimum VMA of 15 during this research. This agrees with the studies performed by Coree (1999) and Kandal (1998). Both of these studies found that the difficulty in achieving minimum VMA requirements can be attributed to the higher compactive effort provided by the Superpave gyratory compactor. Kandal raised a question about the effectiveness of the Superpave restricted zone in relation to VMA values since only one of his designs that were passed through the restricted zone failed VMA requirements. Results of this research supported this question because the Superpave Low 100% LS mixture here was also passed through the restricted zone and found to have a VMA value of 15.0%, just on the line of the minimum requirement of 15.0 percent for 9.5mm mixtures.

# CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

## 7.1 CONCLUSIONS

The results of this study demonstrate varied differentials between the mixes and associated rutting potential of mixes prepared with the Marshall and Superpave mix design methods. For the mixes evaluated, there were some cases where the Marshall mixes performed better and other cases where Superpave mixes performed better. The net result was that a statistically significant difference was not identified for mixes prepared for the same design situation.

The evaluation of the effect of sand on the mix was inline with industry expectations, sand has a detrimental effect on the rutting potential of asphalt concrete. However, for the Superpave mixes, the rutting potential of mixes with 100 percent limestone and 13 percent natural sand were not statistically significantly different. On the other hand the Marshall mix with 13 percent sand showed greater rutting potential than the 100 percent limestone mix. The Superpave mixes for low traffic roads designed with high sand contents displayed very high rutting potential. Due to the experimental plan used in the research, the percent sand and Fine Aggregate Angularity factors were confounded, hence, conclusions drawn concerning the performance of the mix relative to sand content could also be associated with Fine Aggregate Angularity. The Superpave method totally relaxes the Fine Aggregate Angularity for low volume road design. The results produced in this research demonstrate that this will produce a mix with high rutting potential when high sand contents are used. However, low volume roads may not experience sufficient traffic to develop sever rutting.

The differences in the asphalt contents between the two mix design methods ranged from 0.2 to 0.8 percent. While this is an appreciable difference, there was no apparent trend with respect to the mix design method. For the 100 percent limestone mixes, the asphalt contents were higher for the Superpave mixes. For the mixes with 13 percent natural sand, the Marshall mixes required more asphalt. Not enough data were collected during the research to determine if this is a consistent trend.

## 7.2 RECOMMENDATIONS

The results of this research indicate that the performance of Marshall and Superpave mixes is comparable with respect to rutting performance. This demonstrates that correctly applying the methodology and criteria of a mix design method may be more important than which mix design method is used. At this time, there does not appear to be a pavement performance reason to use one mix design method over the other.

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# APPENDIX A BUCKET MIXER INSTRUCTIONS

Instructions outline the correct setup and use of the large bucket mixer used during the Superpave mix design process and the making of the APA test samples. These instructions have been derived from those developed during research performed by Michael S. Hughes (Hughes, 1999).

## MIXER SETUP

Install paddle arm so that it sits parallel to the axis about which the bucket rotates. Secure paddle to paddle arm so that both edges of the paddle sit flush to the side of the bucket and blade touches bottom of bucket.

## MIXING PROCEDURE

- Heat 5-gallon bucket and paddle attached to paddle arm in oven set to mixing temperature. Allow sufficient time for bucket and paddle to achieve proper temperature.
- Remove bucket and paddle from oven, weigh, and add heated aggregate and asphalt.
- Place bucket in mixer basket.
- Remove paddle from oven and slide over paddle securing rod.
- Turn on mixer, this should allow paddle to be pushed down to touch the bottom of the bucket.
- Unlock mixer from upright position and tilt bucket forward.
- While holding onto paddle arm, tilt mixer as far as possible being careful not to spill contents.
- Rock bucket back and forth to aid in mixing.
- After the aggregate and asphalt has been thoroughly mixed, lock mixer back into upright position.
- Turn off the mixer.
- Pull paddle off of securing rod and, with a hot spatula, completely scrape all of the material off the paddle into the bucket.
- Remove bucket from mixer and transfer contents.
- Scrape the inside of the bucket thoroughly and transfer this material. Weigh bucket and paddle and continue to remove material until the paddle and bucket weigh within 5 grams of the original weight.

- Return the bucket and paddle to the oven.

## APPENDIX B FINE AGGREGATE ANGULARITY TEST DATA

The specific gravity and uncompacted voids data in the following tables were collected during the fine aggregate angularity testing.

Table B-1 Weights Used for Testing Fine Aggregates for Fine Aggregate Angularity

| Sieve # | Wgt. (g) |
|---|---|
| #16 | 44.00 |
| #30 | 57.00 |
| #50 | 72.00 |
| #200 | 17.00 |

Percentage Specific Gradations and Weights

| | Sieve # | Wgt. (g) |
|---|---|---|
| 100% Limestone | #16 | 44.00 |
| or | #30 | 57.00 |
| 100% N.Sand | #50 | 72.00 |
| | #200 | 17.00 |

| | Sieve # | Wgt. (g) | |
|---|---|---|---|
| | | LS | NS |
| 50% Limestone | #16 | 22.00 | 22.00 |
| and | #30 | 28.50 | 28.50 |
| 50% N.Sand | #50 | 36.00 | 36.00 |
| | #200 | 8.50 | 8.50 |

| | Sieve # | Wgt. (g) | |
|---|---|---|---|
| | | LS | NS |
| 75% Limestone | #16 | 33.00 | 11.00 |
| and | #30 | 42.75 | 14.25 |
| 25% N.Sand | #50 | 54.00 | 18.00 |
| | #200 | 12.75 | 4.25 |

| | Sieve # | Wgt. (g) | |
|---|---|---|---|
| | | LS | NS |
| 25% Limestone | #16 | 11.00 | 33.00 |
| and | #30 | 14.25 | 42.75 |
| 75% N.Sand | #50 | 18.00 | 54.00 |
| | #200 | 4.25 | 12.75 |

Table B-2 Specific Gravity Determination

A= mass of oven-dry specimen in air, g
B= mass of pycnometer filled with water, g
C= mass of pycnometer with specimen and water, g
D= mass of saturated surface-dry specimen, g

| | | | | |
|---|---|---|---|---|
| 100% Limestone | A = | 488.3 | $G_{sb}$ = | 2.618 |
| | B = | 659.3 | | |
| | C = | 974.3 | | |
| | S = | 501.5 | | |
| 100% N.Sand | A = | 490.8 | $G_{sb}$ = | 2.534 |
| | B = | 659.3 | | |
| | C = | 966.7 | | |
| | S = | 501.1 | | |
| 50% Limestone | A = | 493.6 | $G_{sb}$ = | 2.550 |
| 50% N.Sand | B = | 659.3 | | |
| | C = | 968.8 | | |
| | S = | 503.1 | | |
| 75% Limestone | A = | 490 | $G_{sb}$ = | 2.561 |
| 25% N.Sand | B = | 659.3 | | |
| | C = | 968.4 | | |
| | S = | 500.4 | | |
| 25% Limestone | A = | 490.8 | $G_{sb}$ = | 2.534 |
| 75% N.Sand | B = | 659.3 | | |
| | C = | 967.6 | | |
| | S = | 502 | | |

Table B-3 Uncompacted Void Content Determination

| Weights per FAA test run and uncompacted voids percentages | Net weight in measure (g) | | $G_{sb}$ | U (%) |
|---|---|---|---|---|
| 100% Limestone | F1 = | 148.3 | 2.618 | 43.5 |
| | F2 = | 147.5 | | |
| | Favg = | 147.9 | | |
| 100% N. Sand | F1 = | 153.4 | 2.534 | 39.4 |
| | F2 = | 153.6 | | |
| | Favg = | 153.5 | | |
| 50% Limesotne | F1 = | 151.6 | 2.575 | 41.2 |
| 50% N. Sand | F2 = | 151.1 | | |
| | Favg = | 151.4 | | |
| 75% Limestone | F1 = | 149.2 | 2.596 | 42.5 |
| 25% N. Sand | F2 = | 149.3 | | |
| | Favg = | 149.3 | | |
| 25% Limestone | F1 = | 152.8 | 2.550 | 40.1 |
| 75% N. Sand | F2 = | 152.8 | | |
| | Favg = | 152.8 | | |

# APPENDIX C MIX DESIGN GRADATION AND DATA

The following tables and charts contain data collected during the mix design process and development of the design aggregate structures for each mix design. Design specific gradations, specific gravities for the blends and mix values for design properties are found in these tables.

**AGGREGATE DESIGN DATA**

Table C-1 Stockpile gradations

| Sieve size | SKID | N.SAND | L.SAND | # 9 | BH FINES | LS (mod) |
|---|---|---|---|---|---|---|
| 3/4" | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2" | 100 | 100 | 100 | 100 | 100 | 100 |
| 3/8" | 89 | 100 | 100 | 100 | 100 | 100 |
| #4 | 14 | 98 | 100 | 76 | 100 | 98 |
| #8 | 3 | 83 | 75 | 6 | 100 | 83 |
| #16 | 3 | 68 | 46 | 3 | 100 | 68 |
| #30 | 2 | 56 | 30 | 3 | 100 | 56 |
| #50 | 2 | 22 | 18 | 3 | 100 | 22 |
| #200 | 1.6 | 1.3 | 7.5 | 2.4 | 92 | 1.3 |
| Pan | 0 | 0 | 0 | 0 | 0 | 0 |
| $G_{sb}$: | 2.691 | 2.539 | 2.618 | 2.679 | 2.695 | 2.618 |
| $G_{sa}$: | 2.745 | 2.685 | 2.729 | 2.749 | 2.695 | 2.729 |

Table C-2 Stockpile Blends per Mix Design

| | Blend Percents | | | | |
|---|---|---|---|---|---|
| Type | SKID | N SAND | L SAND | #9 | BH FINES |
| M HVY 100% LS | 35 | 0 | 46 | 18 | 1 |
| M MED 100% LS | 34 | 0 | 50 | 15 | 1 |
| M HVY 13% NS | 20 | 13 | 28 | 38 | 1 |
| M MED 13% NS | 20 | 13 | 28 | 38 | 1 |
| SP HVY 100% LS | 15 | 0 | 45 | 39 | 1 |
| SP MED 100% LS | 15 | 0 | 45 | 39 | 1 |
| SP HVY 13% NS | 20 | 13 | 28 | 38 | 1 |
| SP MED 13% NS | 20 | 13 | 28 | 38 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| SP LGT 100% LS | 15 | 0 | 78 | 7 | 0 |
| SP LGT 50% NS | 15 | 39.6 | 40 | 3 | 2.4 |
| SP LGT 64% NS | 32 | 64 | 0 | 0 | 4 |
| SP LGT 100% LS (MOD) | 32 | 0 | 64 | 0 | 4 |

Table C-3 Computed Blend Gradations

| Sieve | M HVY 100% LS | M MED 100% LS | M HVY 13% NS | M MED 13% NS | SP HVY 100% LS | SP MED 100% LS |
|---|---|---|---|---|---|---|
| 3/4" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/8" | 96.2 | 96.3 | 97.8 | 97.8 | 98.4 | 98.4 |
| #4 | 65.6 | 67.2 | 73.4 | 73.4 | 77.7 | 77.7 |
| #8 | 37.6 | 40.4 | 35.7 | 35.7 | 37.5 | 37.5 |
| #16 | 23.8 | 25.5 | 24.5 | 24.5 | 23.3 | 23.3 |
| #30 | 16.0 | 17.1 | 18.2 | 18.2 | 16.0 | 16.0 |
| #50 | 10.5 | 11.1 | 10.4 | 10.4 | 10.6 | 10.6 |
| #200 | 5.4 | 5.6 | 4.4 | 4.4 | 5.5 | 5.5 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $G_{sb}$: | 2.655 | 2.652 | 2.645 | 2.645 | 2.653 | 2.653 |
| $G_{sa}$: | 2.738 | 2.737 | 2.734 | 2.734 | 2.739 | 2.739 |

| Sieve size | SP HVY 13% NS | SP MED 13% NS | SP LGT 100% LS | SP LGT 50% NS | SP LGT 64% NS | SP LGT 100% LS (MOD) |
|---|---|---|---|---|---|---|
| 3/4" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1/2" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/8" | 97.8 | 97.8 | 98.4 | 98.4 | 96.5 | 96.5 |
| #4 | 73.4 | 73.4 | 85.4 | 85.6 | 71.2 | 71.2 |
| #8 | 35.7 | 35.7 | 59.4 | 65.9 | 58.1 | 58.1 |
| #16 | 24.5 | 24.5 | 36.5 | 48.3 | 48.5 | 48.5 |
| #30 | 18.2 | 18.2 | 23.9 | 37.0 | 40.5 | 40.5 |
| #50 | 10.4 | 10.4 | 14.6 | 18.7 | 18.7 | 18.7 |
| #200 | 4.4 | 4.4 | 6.3 | 6.0 | 5.0 | 5.0 |
| Pan | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $G_{sb}$: | 2.645 | 2.645 | 2.633 | 2.600 | 2.592 | 2.592 |
| $G_{sa}$: | 2.734 | 2.734 | 2.733 | 2.714 | 2.704 | 2.704 |

**MIX DESIGN DATA**

Table C-4 Marshall Heavy 100% LS Design Data

| | | Density | | | | Stability (N) | | Flow |
|---|---|---|---|---|---|---|---|---|
| Specimen | % AC | kg/m3 | VMA | VTM | VFA | Actual | Adj. | (.25mm ) |
| A | 4.0 | 2344 | 15.8 | 7.5 | 50.5 | 11143 | 11143 | 12.9 |
| B | 4.5 | 2362 | 15.5 | 6.1 | 59.7 | 10431 | 10231 | 14.2 |
| C | 5.0 | 2382 | 15.2 | 4.6 | 69.1 | 10622 | 10622 | 13.4 |
| D | 5.5 | 2423 | 14.5 | 2.2 | 83.9 | 9408 | 9408 | 14.2 |

Table C-5 Marshall Medium 100% LS Design Data

| | | Density | | | | Stability (N) | | Flow |
|---|---|---|---|---|---|---|---|---|
| Specimen | % AC | kg/m3 | VMA | VTM | VFA | Actual | Adj. | (.25mm) |
| A | 4.2 | 2130 | 23.1 | 15.8 | 31.5 | 3541 | 2869 | 18.6 |
| B | 4.7 | 2229 | 20.0 | 11.2 | 43.9 | 5938 | 5525 | 15.7 |
| C | 5.2 | 2357 | 15.8 | 5.4 | 65.7 | 9288 | 9288 | 12.4 |
| D | 5.7 | 2409 | 14.3 | 2.6 | 81.8 | 8487 | 8487 | 15.8 |

Table C-6 Marshall Heavy 13% LS Design Data

| | | Density | | | | Stability (N) | | Flow |
|---|---|---|---|---|---|---|---|---|
| Specimen | % AC | kg/m3 | VMA | VTM | VFA | Actual | Adj. | (.25mm) |
| A | 5.5 | 2328 | 16.8 | 6.0 | 64.3 | 9164.0 | 8981 | 11.8 |
| B | 6.0 | 2369 | 16.0 | 3.6 | 77.3 | 9563.5 | 9517 | 11.3 |
| C | 6.5 | 2380 | 15.9 | 2.5 | 84.5 | 9564.0 | 9516 | 12.9 |

Table C-7 Marshall Medium 13% NS Design Data

| | | Density | | | | Stability (N) | | Flow |
|---|---|---|---|---|---|---|---|---|
| Specimen | % AC | kg/m3 | VMA | VTM | VFA | Actual | Adj. | (.25mm) |
| A | 5.5 | 2325 | 16.9 | 6.1 | 63.8 | 7651.0 | 7460 | 15.4 |
| B | 6.0 | 2361 | 16.1 | 4.0 | 75.4 | 8285.0 | 8075 | 16.0 |
| C | 6.5 | 2367 | 16.4 | 3.0 | 81.7 | 8340.5 | 8257 | 18.1 |

Table C-8 Superpave Heavy 100% LS Design Data

Summary of volumetrics:

| | | | | $\%G_{mm}$ | | |
|---|---|---|---|---|---|---|
| %AC | VMA | VTM | VFA | @ $N_{ini}$ | @$N_{des}$ | @$N_{max}$ |
| 5.50 | 15.2 | 4.5 | 70.4 | - | 95.5 | - |
| 6.00 | 15.5 | 3.4 | 77.7 | - | 96.6 | - |
| 6.50 | 15.9 | 3.4 | 78.8 | - | 96.6 | - |

Summary of $N_{max}$ volumetrics:

| | | | | $\%G_{mm}$ | | |
|---|---|---|---|---|---|---|
| %AC | VMA | VTM | VFA | @ $N_{ini}$ | @$N_{des}$ | @$N_{max}$ |
| 6.10 | 12.6 | 2.7 | 78.4 | 84.2 | 95.9 | 97.3 |

Table C-9 Superpave Medium 100% LS Design Data

Summary of volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 4.50 | 16.5 | 8.3 | 49.7 | - | 91.7 | - |
| 5.00 | 17.3 | 7.8 | 55.0 | - | 92.2 | - |
| 5.50 | 17.0 | 6.3 | 62.8 | - | 93.7 | - |
| 6.00 | 16.9 | 5.0 | 70.2 | - | 95.0 | - |

Summary of $N_{max}$ volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 6.30 | 15.6 | 2.5 | 78.4 | 88.6 | 95.6 | 97.5 |

Table C-10 Superpave Heavy 13% NS Design Data

Summary of volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.00 | 15.2 | 5.7 | 62.6 | - | 94.3 | - |
| 5.50 | 14.6 | 3.8 | 73.9 | - | 96.2 | - |
| 6.00 | 14.2 | 2.2 | 84.7 | - | 97.8 | - |

Summary of $N_{max}$ volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.50 | 12.8 | 2.0 | 84.4 | 85.6 | 96.2 | 98.0 |

Table C-11 Superpave Medium 13% NS Design Data

Summary of volumetrics:

| | | | | %$G_{mm}$ | | |
|---|---|---|---|---|---|---|
| %AC | VMA | VTM | VFA | @ $N_{ini}$ | @$N_{des}$ | @$N_{max}$ |
| 5.50 | 15.3 | 4.7 | 69.1 | - | 95.3 | - |
| 6.00 | 15.4 | 3.5 | 77.1 | - | 96.5 | - |
| 6.50 | 15.5 | 3.1 | 79.8 | - | 96.9 | - |

Summary of $N_{max}$ volumetrics:

| | | | | %$G_{mm}$ | | |
|---|---|---|---|---|---|---|
| %AC | VMA | VTM | VFA | @ $N_{ini}$ | @$N_{des}$ | @$N_{max}$ |
| 5.80 | 14.2 | 2.6 | 81.3 | 85.5 | 95.9 | 97.4 |

Table C-12 Superpave Light 100% LS Design Data

Summary of volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.00 | 15.2 | 6.0 | 60.4 | - | 94.0 | - |
| 5.50 | 15.0 | 4.4 | 70.5 | - | 95.6 | - |
| 6.00 | 14.8 | 2.5 | 83.2 | - | 97.5 | - |

Summary of $N_{max}$ volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.60 | 13.2 | 2.2 | 83.5 | 86.5 | 96.2 | 97.8 |

Table C-13 Superpave Light 50% LS Design Data

Summary of volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.50 | 15.3 | 5.6 | 63.7 | - | 94.4 | - |
| 6.00 | 15.2 | 4.1 | 72.8 | - | 95.9 | - |
| 6.50 | 14.8 | 2.8 | 80.9 | - | 97.2 | - |

Summary of $N_{max}$ volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 6.10 | 14.0 | 2.2 | 84.2 | 90.0 | 96.5 | 97.8 |

Table C-14 Superpave Light 64% NS Design Data

Summary of volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.50 | 15.4 | 5.5 | 64.2 | - | 94.5 | - |
| 6.00 | 15.5 | 4.2 | 73.1 | - | 95.8 | - |
| 6.50 | 15.6 | 3.3 | 79.0 | - | 96.7 | - |

Summary of $N_{max}$ volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 6.10 | 14.1 | 2.4 | 83.2 | 91.5 | 96.5 | 97.6 |

Table C-14 Superpave Light 100% LS (mod) Design Data

Summary of volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.00 | 13.9 | 4.3 | 69.2 | - | 95.7 | - |
| 5.50 | 13.7 | 2.6 | 80.8 | - | 97.4 | - |
| 6.00 | 13.6 | 1.5 | 89.3 | - | 98.5 | - |

Summary of $N_{max}$ volumetrics:

| %AC | VMA | VTM | VFA | %$G_{mm}$ @ $N_{ini}$ | %$G_{mm}$ @$N_{des}$ | %$G_{mm}$ @$N_{max}$ |
|---|---|---|---|---|---|---|
| 5.10 | 13.1 | 3.0 | 76.8 | 88.0 | 95.8 | 97.0 |

## APPENDIX D ASPHALT PAVEMENT ANALYZER TEST DATA

The follow data were collected during the production and testing of the APA samples. The calculations of the percent air in the sample and the measured rut depth are presented in the tables.

Table D-1 Air Content of APA Samples

| M HVY 100% LS | Weights | | | $G_{mm}$ = | 2.489 |
|---|---|---|---|---|---|
| Sample # | **Dry** | **Wet** | **SSD** | $G_{mb}$ | **% air** |
| **1** | 2967.3 | 1689.2 | 2975.0 | 2.308 | 7.27 |
| **2** | 2993.2 | 1714.5 | 3002.1 | 2.325 | 6.59 |
| **3** | 2989.9 | 1709.0 | 2997.1 | 2.321 | 6.75 |
| **4** | 2989.9 | 1711.5 | 2998.9 | 2.322 | 6.71 |
| **5** | 2992.7 | 1715.2 | 3003.6 | 2.323 | 6.67 |
| **6** | 2990.6 | 1713.3 | 3002.8 | 2.319 | 6.83 |
| M MED 100% LS | **Weights** | | | **Gmm=** | 2.481 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **Gmb** | **% air** |
| **1** | 2962.9 | 1685.9 | 2974.5 | 2.299 | 7.34 |
| **2** | 2959.8 | 1682.3 | 2968.2 | 2.302 | 7.21 |
| **3** | 2980.8 | 1703.2 | 2991.5 | 2.314 | 6.73 |
| **4** | 2979.1 | 1702.5 | 2990.1 | 2.314 | 6.73 |
| **5** | 2980.1 | 1702.9 | 2994.8 | 2.307 | 7.01 |
| **6** | 2979.9 | 1701.8 | 2990.3 | 2.313 | 6.77 |
| SP HVY 100% LS | **Weights** | | | $G_{mm}$= | 2.483 |
| **Sample #** | **Dry** | **Wet** | **SSD** | $G_{mb}$ | **% air** |
| **1** | 2961.7 | 1678.9 | 2968.8 | 2.296 | 7.53 |
| **2** | 2980.6 | 1697.4 | 2988.6 | 2.308 | 7.05 |
| **3** | 2981.4 | 1701.5 | 2989.7 | 2.314 | 6.81 |
| **4** | 2981.8 | 1700.0 | 2990.8 | 2.310 | 6.97 |
| **5** | 2981.4 | 1696.6 | 2989.8 | 2.305 | 7.17 |

| | | | | | |
|---|---|---|---|---|---|
| **6** | 2979.3 | 1696.7 | 2988.1 | 2.307 | 7.09 |

Table D-1 Air Content of APA Samples (Continued)

| SP MED 100% LS | **Weights** | | | **$G_{mm}$ =** | 2.470 |
|---|---|---|---|---|---|
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2943.5 | 1661.9 | 2950.0 | 2.285 | 7.49 |
| **2** | 2964.9 | 1684.3 | 2971.9 | 2.303 | 6.76 |
| **3** | 2960.4 | 1681.4 | 2968.4 | 2.300 | 6.88 |
| **4** | 2961.4 | 1683.3 | 2969.5 | 2.302 | 6.80 |
| **5** | 2961.4 | 1682.5 | 2968.8 | 2.302 | 6.80 |
| **6** | 2962.4 | 1682.6 | 2970.1 | 2.301 | 6.84 |
| SP HVY 13% NS | **Weights** | | | **$G_{mm}$=** | 2.486 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2977.2 | 1693.1 | 2986.1 | 2.303 | 7.36 |
| **2** | 2979.1 | 1696.3 | 2986.8 | 2.308 | 7.16 |
| **3** | 2980.6 | 1700.6 | 2988.9 | 2.314 | 6.92 |
| **4** | 2980.2 | 1697.5 | 2988.1 | 2.309 | 7.12 |
| **5** | 2983.6 | 1701.5 | 2994.2 | 2.308 | 7.16 |
| **6** | 2979.1 | 1697.8 | 2987.2 | 2.310 | 7.08 |
| SP MED 13% NS | **Weights** | | | **$G_{mm}$=** | 2.479 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2964.6 | 1683.2 | 2972.9 | 2.299 | 7.26 |
| **2** | 2973.3 | 1690.4 | 2980.8 | 2.304 | 7.06 |
| **3** | 2972.0 | 1693.8 | 2980.2 | 2.310 | 6.82 |
| **4** | 2974.0 | 1692.4 | 2982.6 | 2.305 | 7.02 |
| **5** | 2971.7 | 1687.5 | 2979.9 | 2.299 | 7.26 |
| **6** | 2971.1 | 1688.4 | 2979.7 | 2.301 | 7.18 |

Table D-1 Air Content of APA Samples (Continued)

| M HVY 13% NS | Weights | | | $G_{mm}$= | 2.462 |
|---|---|---|---|---|---|
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| 1 | 2946.7 | 1667.9 | 2956.6 | 2.287 | 7.11 |
| **2** | 2941.7 | 1664.1 | 2952.8 | 2.283 | 7.27 |
| **3** | 2937.3 | 1661.3 | 2946.6 | 2.285 | 7.19 |
| **4** | 2938.2 | 1661.6 | 2949.0 | 2.282 | 7.31 |
| **5** | 2942.7 | 1667.7 | 2953.4 | 2.289 | 7.03 |
| **6** | 2941.9 | 1662.3 | 2951.2 | 2.282 | 7.31 |
| M MED 13% NS | **Weights** | | | **$G_{mm}$=** | 2.458 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2939.1 | 1663.2 | 2947.9 | 2.288 | 6.92 |
| **2** | 2935.0 | 1660.6 | 2944.4 | 2.286 | 7.00 |
| **3** | 2939.7 | 1665.5 | 2948.8 | 2.291 | 6.79 |
| **4** | 2936.5 | 1664.1 | 2948.6 | 2.286 | 7.00 |
| **5** | 2931.5 | 1660.7 | 2945.7 | 2.281 | 7.20 |
| **6** | 2934.9 | 1658.6 | 2944.8 | 2.282 | 7.16 |
| SP LGT 100% LS | **Weights** | | | **$G_{mm}$=** | 2.479 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2968.1 | 1680.1 | 2973.0 | 2.296 | 7.38 |
| **2** | 2974.9 | 1689.4 | 2983.3 | 2.299 | 7.26 |
| **3** | 2985.6 | 1697.0 | 2994.3 | 2.301 | 7.18 |
| **4** | 2987.3 | 1697.4 | 2996.7 | 2.299 | 7.26 |
| **5** | 2988.5 | 1698.1 | 2996.0 | 2.303 | 7.10 |
| **6** | 2988.7 | 1697.7 | 2997.1 | 2.300 | 7.22 |
| SP LGT 50% NS | **Weights** | | | **$G_{mm}$=** | 2.432 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |

| | | | | | |
|---|---|---|---|---|---|
| **1** | 2912.7 | 1620.8 | 2917.9 | 2.246 | 7.65 |
| **2** | 2917.0 | 1625.3 | 2922.0 | 2.250 | 7.48 |
| **3** | 2930.8 | 1633.8 | 2935.8 | 2.251 | 7.44 |
| **4** | 2931.8 | 1637.8 | 2938.0 | 2.255 | 7.28 |
| **5** | 2930.6 | 1635.0 | 2937.6 | 2.250 | 7.48 |
| **6** | 2929.5 | 1630.5 | 2935.1 | 2.246 | 7.65 |

Table D-1 Air Content of APA Samples (Continued)

| SP LGT 64% NS | **Weights** | | | **$G_{mm}$=** | 2.432 |
|---|---|---|---|---|---|
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2909.3 | 1618.6 | 2913.8 | 2.246 | 7.65 |
| **2** | 2916.2 | 1625.9 | 2920.1 | 2.253 | 7.36 |
| **3** | 2931.3 | 1636.3 | 2935.5 | 2.256 | 7.24 |
| **4** | 2928.6 | 1635.4 | 2933.5 | 2.256 | 7.24 |
| **5** | 2929.3 | 1632.2 | 2934.2 | 2.250 | 7.48 |
| **6** | 2928.1 | 1631.5 | 2933.9 | 2.248 | 7.57 |
| SP LGT 100% LS (MOD) | **Weights** | | | **$G_{mm}$=** | 2.497 |
| **Sample #** | **Dry** | **Wet** | **SSD** | **$G_{mb}$** | **% air** |
| **1** | 2993.2 | 1701.1 | 2999 | 2.306 | 7.65 |
| **2** | 2995.9 | 1702.4 | 3001.7 | 2.306 | 7.65 |
| **3** | 3009.4 | 1719.6 | 3017.8 | 2.318 | 7.17 |
| **4** | 3009.3 | 1718.1 | 3017.4 | 2.316 | 7.25 |
| **5** | 3009.3 | 1715.6 | 3018.5 | 2.310 | 7.49 |
| **6** | 3007.9 | 1713.3 | 3015.1 | 2.311 | 7.45 |

Table D-2 Rut Depths for Each APA Specimen

Mix: M HVY 100% LS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 7.88 | 7.65 | 7.50 |
| 1 | 5.45 | 5.60 | 5.82 |
| 2 | 5.76 | 6.10 | 6.16 |
| 2 | 6.79 | 6.50 | 5.60 |
| | L | L | C |

| Date Tested: | 7/22/01 | 7/26/01 | 7/28/01 | AVG | SD |
|---|---|---|---|---|---|
| Averages: | 6.47 | 6.46 | 6.27 | 6.40 | 0.113 |

Mix: M MED 100% LS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 4.36 | 8.50 | 7.80 |
| 1 | 2.90 | 6.25 | 7.30 |
| 2 | 3.22 | 7.60 | 8.30 |
| 2 | 3.10 | 7.73 | 7.55 |
| | C | L | C |

| Date Tested: | 7/28/01 | 7/28/01 | 8/3/01 | AVG | SD |
|---|---|---|---|---|---|
| Averages: | 3.40 | 7.52 | 7.74 | 6.22 | 2.447 |

Mix: SP HVY 100% LS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 7.20 | 12.10 | 9.20 |
| 1 | 6.80 | 10.30 | 8.90 |

| | | | |
|---|---|---|---|
| 2 | 8.40 | 10.80 | 7.40 |
| 2 | 7.90 | 9.90 | 7.80 |
| | C | L | R |

| | | | | | |
|---|---|---|---|---|---|
| Date Tested: | 7/26/01 | 8/2/01 | 8/2/01 | AVG | SD |
| Averages: | 7.58 | 10.78 | 8.33 | 8.89 | 1.674 |

Table D-2 Rut Depths for Each APA Specimen (Continued)

Mix: SP MED 100% LS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 9.30 | 12.90 | 11.20 |
| 1 | 11.00 | 12.00 | 12.05 |
| 2 | 8.90 | 7.50 | 10.10 |
| 2 | 8.20 | 8.90 | 9.90 |
| | R | L | R |

| | | | | | |
|---|---|---|---|---|---|
| Date Tested: | 8/2/01 | 8/2/01 | 8/3/01 | AVG | SD |
| Averages: | 9.35 | 10.33 | 10.81 | 10.16 | 0.745 |

Mix: SP HVY 13% NS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 8.85 | 10.85 | 11.75 |
| 1 | 8.00 | 10.30 | 10.40 |
| 2 | 9.80 | 9.75 | 12.45 |
| 2 | 10.90 | 10.40 | 10.70 |
| | R | L | L |

| | | | | | |
|---|---|---|---|---|---|
| Date Tested: | 7/27/01 | 7/27/01 | 8/3/01 | AVG | SD |
| Averages: | 9.39 | 10.33 | 11.33 | 10.35 | 0.969 |

Mix: SP MED 13% NS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 11.30 | 8.50 | 11.00 |

| | | | |
|---|---|---|---|
| 1 | 9.50 | 6.90 | 11.50 |
| 2 | 9.79 | 7.15 | 10.85 |
| 2 | 10.30 | 6.50 | 9.90 |
| | R | R | C |

| Date Tested: | 7/28/01 | 8/2/01 | 8/3/01 | AVG | SD |
|---|---|---|---|---|---|
| Averages: | 10.22 | 7.26 | 10.81 | 9.43 | 1.902 |

Table D-2 Rut Depths for Each APA Specimen (Continued)

Mix: M HVY 13% NS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 13.46 | 12.60 | 12.95 |
| 1 | 13.19 | 11.40 | 12.55 |
| 2 | 12.19 | 9.97 | 9.40 |
| 2 | 12.18 | 9.75 | 8.50 |
| | R | L | C |
| Date Tested: | 7/22/01 | 8/2/01 | 8/2/01 |
| Averages: | 12.76 | 10.93 | 10.85 |

| AVG | SD |
|---|---|
| 11.51 | 1.078 |

Mix: M MED 13% NS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 6.19 | 9.75 | 9.80 |
| 1 | 6.06 | 8.90 | 7.60 |
| 2 | 8.11 | 6.20 | 8.20 |
| 2 | 7.50 | 6.90 | 7.90 |
| | L | C | C |
| Date Tested: | 7/28/01 | 8/2/01 | 8/2/01 |
| Averages: | 6.97 | 7.94 | 8.38 |

| AVG | SD |
|---|---|
| 7.76 | 0.722 |

Mix: SP LGT 100% LS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 |
|---|---|---|---|
| 1 | 10.00 | 7.20 | 6.65 |
| 1 | 8.40 | 5.88 | 5.85 |
| 2 | 8.56 | 5.45 | 6.40 |

| | | | | | |
|---|---|---|---|---|---|
| 2 | 8.55 | 5.20 | 5.95 | | |
| | L | R | R | | |
| Date Tested: | 7/27/01 | 8/2/01 | 8/3/01 | AVG | SD |
| Averages: | 8.88 | 5.93 | 6.21 | 7.01 | 1.626 |

Table D-2 Rut Depths for Each APA Specimen (Continued)

Mix: SP LGT 50% NS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 | | |
|---|---|---|---|---|---|
| 1 | 16.50 | 13.50 | 14.50 | | |
| 1 | 17.00 | 15.00 | 16.30 | | |
| 2 | 16.50 | 12.50 | 13.80 | | |
| 2 | 16.00 | 14.00 | 14.90 | | |
| | C | C | R | | |
| Date Tested: | 7/22/01 | 7/26/01 | 7/28/01 | AVG | SD |
| Averages: | 16.50 | 13.75 | 14.88 | 15.04 | 1.383 |

Mix: SP LGT 64% NS

| Pill Reading | Sample 1 | Sample 2 | Sample 3 | | |
|---|---|---|---|---|---|
| 1 | 17.50 | 16.50 | 18.50 | | |
| 1 | 16.50 | 17.00 | 18.00 | | |
| 2 | 17.00 | 17.00 | 17.00 | | |
| 2 | 16.50 | 18.00 | 18.50 | | |
| | R | L | R | | |
| Date Tested: | 7/26/01 | 7/26/01 | 7/26/01 | AVG | SD |
| Averages: | 16.88 | 17.13 | 18.00 | 17.33 | 0.588 |

Mix: SP LGT 100% LS (MOD)

| Pill Reading | Sample 1 | Sample 2 | Sample 3 | | |
|---|---|---|---|---|---|
| 1 | 6.70 | 7.15 | 8.00 | | |
| 1 | 5.63 | 5.90 | 8.10 | | |
| 2 | 6.01 | 5.70 | 7.10 | | |
| 2 | 5.30 | 5.30 | 7.15 | | |
| | C | R | L | | |
| Date Tested: | 7/27/01 | 7/27/01 | 8/3/01 | AVG | SD |
| Averages: | 5.91 | 6.01 | 7.59 | 6.50 | 0.942 |