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EFFECT OF FINE AGGREGATE ANGULARITY ON ASPHALT MIXTURE PERFORMANCE

Chih-Jen Lee
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July 1999

Indiana
Department
of Transportation

Purdue
University

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16. Abstract

Superpave aggregate qualification includes the fine aggregate angularity (FAA). Fine aggregate angularity levels used in the Superpave system are below 40, 40 to 45 and above 45. The higher values are specified for layers near the surface and for higher traffic levels.

The objective of this study was to address the effect of fine aggregate angularity on asphalt mixture rutting performance. A total of 18 mixtures were designed according to the Superpave volumetric design criteria. A surface mixture utilizing a partially crushed 9.5mm coarse aggregate and a single PG 64-22 binder were utilized. The poor quality coarse aggregate was used to maximum the effects of the various fine aggregates. Tests conducted included PURWheel Laboratory Wheel Tracking Device, Simple Shear Test (SST), Compacted Aggregate Resistance (CAR) test, and Florida Bearing Value.

Test results indicated that the use of fine aggregate angularity (FAA) does not be itself assure good mixture rutting performance. Other factors such as mixture gradation, asphalt content, dust amount and mixture compactibility also influence mixture rutting performance. A performance test such as the PURWheel laboratory wheel tracking device can be used to assure that mixtures will exhibit the desired level of rutting performance.

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IMPLEMENTATION REPORT

Fine aggregate characteristics are significant to the performance of hot mix asphalt. The current study has addressed means of measuring fine aggregate characteristics and their contribution to rutting performance. Tests on the fine aggregate included fine aggregate angularity (FAA), compacted aggregate resistance (CAR) and Florida bearing value. Performance tests conducted included the Purdue University laboratory wheel (PURWheel) track tester and the Superpave simple shear test (SST). PURWheel tests included hot/dry and hot/wet tests. Simple shear tests conducted were the frequency sweep, constant height (FSCH) and repeated shear, constant height (RSCH) tests.

A number of asphalt mixture variables were studied. These included several fine aggregates, which collectively represent a significant range of FAA values. Mixtures were also tested with blends of two of these fine aggregates. The blends were with natural sand and crushed gravel. The natural sand was also added to other mixtures to study its effect on mixture compactability. Dust/asphalt ratio was varied in selected mixtures. The purpose was to determine if additional dust would decrease the design asphalt content. Effect of gradation modification was also studied.

As in previous studies, the PURWheel has proven to be an effective tool for evaluating asphalt mixtures. Specifically in this study results of PURWheel tests exhibit a sensitivity to FAA, shape and texture of fine aggregate, design asphalt content, dust/asphalt ratio, amount of natural sand and gradation. It is recommended that the Indiana Department of Transportation (INDOT) fund fabrication of a PURWheel tester and that it continue to be used to evaluate performance of asphalt mixtures. It is desirable that performance criteria for the PURWheel test be developed. The criteria should be related to field performance. PURWheel tests were conducted on a number of Superpave mixtures constructed in 1997. It is recommended that the rutting performance of these pavements be evaluated along with the corresponding PURWheel test results to develop the desired criteria.

The initial SST test utilized was the FSCH test. However, the complex modulus varied inversely with asphalt content. As a result, the natural sand mixture with the lowest asphalt content along with the poorest PURWheel performance had the highest complex modulus. The RSCH test was added to the study. But the results were not significant in explaining rutting performance. At this time neither the FSCH or RSCH SST tests are recommended as performance tests. It is recommended that research be considered to evaluate the effect of compaction on the RSCH results as well as research on other SST tests.

Fine aggregate characteristics were evaluated using FAA, CAR and Florida bearing value. The FAA showed the best correlation with rutting performance. However, the use of fine aggregate angularity (FAA) does not by itself assure good mixture rutting performance. Asphalt mixtures are complex systems and other factors such as mixture gradation, asphalt content, dust amount and mixture compactability also influence their rutting performance. The data indicates that mixtures with fine aggregate having FAA values less than 45 can exhibit rutting performance equal to or better than mixtures with FAA values as high as 48. A performance test such as the PURWheel laboratory wheel tracking device should be used to assure that mixtures will exhibit the desired level of rutting performance. This approach would compliment any FAA criteria.

Increasing the dust asphalt ratio appears to decrease the design asphalt content. Rutting performance is improved. In the case of slag the increase is substantial. Addition of natural sand, which increases compactability also decreases asphalt content. Rutting performance for mixtures with slag sand was greatly improved. However, there was very little effect on mixtures with limestone sand. Gradation change to obtain a denser mineral aggregate structure caused significant improvement in rutting performance. It is recommended that gradations be used that will generate a denser mineral aggregate structure. The current coarse or open gradations recommended per Superpave do not do that. Further research into the gradation change effects is recommended.

Increasing the dust/asphalt ratio will improve rutting performance. However, replacing asphalt with dust can cause a loss of durability. This issue deserves additional research. Improved compactability achieved through addition of natural sand should be done selectively. In this case performance testing is recommended (PURWheel).

In this study, mixtures were designed utilizing Superpave mixture design criteria. The volumetric criteria include a fixed four percent air voids (AV) at N_{design}, minimum VMA of 15, and VFA within the range of 65 to 75 percent for the surface mixtures. Voids filled with asphalt (VFA) is defined as the ratio of the difference of VMA and AV to VMA, i.e., VFA=(VMA-AV)/VMA. The lower limit of VFA is redundant since there are specific criteria on VMA and AV. Actually, if VMA is equal to the minimum limit of 15, VFA is equal to 73.3 percent, which narrows the acceptable range of VFA to 73.3 to 75 percent. This criteria is difficult to satisfy.

Of the mixtures with film thicknesses less than 8 microns some exhibited good PURWheel performance and some did not. Mixtures with film thicknesses above 12 microns exhibited poor performance. The three best performing mixtures had an average film thickness of 8.2 microns. The literature indicates various ranges of desirable film thickness. Acceptable film thickness may vary with maximum aggregate size. In this study a 9.5mm maximum aggregate size was utilized. An acceptable film thickness range appears to be 8 to 10 microns.

Research is recommended that would develop criteria for an upper limit of voids in the mineral aggregate (VMA) or as an alternative a range of asphalt film thickness. This may include adopting a range of air voids (AV) for the mix design process rather than the current fixed four percent AV. In fact, the fixed AV criterion is the single most important item associated with Superpave mixture design and performance problems. It is recommended that research be conducted on the effect of an AV range on mixture performance. The above criteria may also vary by maximum aggregate size (i.e., 9.5mm, 12.5mm and 19mm, etc.) and gradation type (coarse and fine).

CHAPTER 1 INTRODUCTION

Hot mix asphalt (HMA) is widely used in maintenance, rehabilitation and construction of new pavements. Improvement of HMA material specifications and mixture design procedures would contribute significantly to construction of better pavements with longer performance life. In 1987, with this goal, the Strategic Highway Research Program (SHRP) sponsored major, multiyear research in asphalt binder, aggregates and HMA. A major product of the SHRP asphalt research program is a new system referred to as Superpave which stands for Superior Performing Asphalt Pavements. Superpave is a system which includes specifications for component materials, asphalt mixture design and analysis, pavement performance prediction, test equipment, and criteria.

1.1 Fine Aggregate Angularity

One of the material qualification requirements of the Superpave mix design process is the Fine Aggregate Angularity (FAA). The numerical value of the FAA is the voids in the mineral aggregate of the loosely packed fine aggregate. Higher and lower values of FAA represent fine aggregate with high and low packing characteristics, respectively. For a given gradation, the degree of packing depends on the aggregate particle shape and texture. Inference is that higher packing is associated with increased rutting resistance.

Fine aggregate angularity levels used in the Superpave system are below 40, 40 to 45 and above 45. The higher values are specified for layers near the surface and for higher traffic levels. Past and current experience shows that there are fine aggregates below the specified levels in mixtures that are performing well. There are also fine aggregates above these levels that are being used in mixtures that are not exhibiting desired performance. This study was purposed and is being conducted to address the association of FAA level and mixture performance.

1.2 Approach

Asphalt mixtures have three major components: coarse aggregate, fine aggregate and binder. Each component contributes to the performance of the mixture. However, careful planning is required to quantify the effect of one of the components because the effects of the other two may confound the results. In this study, the goal is to distinguish the performance of mixtures with different fine aggregate. Therefore, a single binder (PG 64-22) and a poor quality coarse aggregate were adopted with the hope that the difference in mixture performance would be a reflection of the different fine aggregate qualities. Fine aggregates used in the study have FAA values ranging from a low of 39 to a high of around 48.

Mixture performance was addressed through tests with the Purdue University Laboratory Wheel (PURWheel) Tracking Device (WTD). Additional tests on aggregate and mixture included Compacted Aggregate Resistance (CAR) Test, Florida Bearing Ratio and Superpave shear tests (SST).

There are two phases in this study. In the first phase, individual mix designs were conducted for each fine aggregate combination. In addition mixtures were evaluated with blends of natural sand and crushed gravel sand. The blends were targeted to obtain FAA values of 43, 45 and 46, respectively. Totally, nine mixtures were incorporated in the first phase. Six of the mixtures included a single sand while three mixtures included the blended sands.

In the second phase of the study, different approaches were adopted to redesign the two mixtures that had poor rutting performance in the first phase. The two mixtures were a slag sand mix and a stone sand mix with an S-shaped gradation. The modifications included adding mineral filler, replacing part of the original sand with natural sand, and changing gradation of the aggregate blend. Nine additional mixtures were included in the second phase tests.

1.3 Scope

The report contains seven chapters. A review of literature on fine aggregate is included in Chapter Two. Chapter Three includes the properties of materials incorporated in this study. The Superpave mixture design procedures and results are presented in Chapter

Four. Chapter Five and Chapter Six describe the tests and test results, respectively. Conclusions and recommendations are presented in Chapter Seven.

1.4 Summary

In summary, this study uses performance-based tests to determine the influence of fine aggregate angularity on asphalt mixture rutting performance. Superpave volumetric mixture designs were conducted on eighteen mixtures with fine aggregate having FAA values ranging from 39 to 49. Separate designs were conducted for each mixture. In the latter nine mixtures, three modifications were adopted to redesign two of the original nine mixtures that exhibited poor rutting performance. The modification included adding mineral filler, replacing the original fine aggregate with natural sand, and changing the gradation of the aggregate blend.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature regarding the effect of fine aggregate properties on hot asphalt mixture performance. Several methods have been proposed for fine aggregate evaluation.

Superpave defines fine aggregate angularity (FAA) as "the percent air voids present in loosely compacted aggregates smaller than 2.36mm". Three levels of FAA are specified depending upon traffic level and proximity to the pavement surface as shown in Table 2.1. These fine aggregate angularity criteria were intended "to ensure a high degree of fine aggregate internal friction and rutting resistance."

Based on past experience, the particle shape of fine aggregate is apparently more important than that of coarse aggregate. Particle shape of fine aggregate can be one of the most important factors affecting mixture stability and the capability to resist permanent deformation. Historically, various indices have been utilized to quantify the particle shape and surface texture of fine aggregate and therefore control the geometric properties of fine aggregate utilized in hot mix asphalt. The current criteria for fine aggregate angularity as specified in Superpave are obviously a confirmation of this effort.

2.2 Effects of Fine Aggregate Geometric Properties on Mixtures

Significant research has been conducted on the effect of aggregate shape and surface texture on asphalt mixture performance. In 1954, Herrin and Goetz reported the effect of aggregate shape on stability of bituminous mixtures and concluded that the addition of crushed gravel in the coarse aggregate increased the strength for one-size aggregate mixture. Later, in 1956, Lottman and Goetz reported the effect of crushed gravel fine aggregate on the strength of asphalt surface mixtures. One of the conclusions stated was: "The increased strength of bituminous surface mixtures made with crushed-gravel fine aggregate, or crusher dust, when compared to similar mixtures made with natural-sand fine aggregate, was thought to be due to the angularity and surface texture of the crushed aggregate". In 1957, Griffith and Kallas studied the effect of aggregate type on mixture void characteristics and concluded that generally the asphalt demand is lower for mixtures with natural gravel aggregate than for crushed stone mixtures. This is because natural gravel is more compactible than crushed stone for the same gradation. The result is that the compacted VMA of the gravel is lower than the VMA of crushed stone. In 1961, Wedding and Gaynor studied the effects of using crushed gravel as the coarse and fine aggregate in dense graded bituminous mixtures and concluded that mixture stability can be significantly increased when crushed gravel is used in place of uncrushed gravel. In 1964, Shklarsky and Livneh presented an extensive study on the use of gravel for bituminous paving mixtures. Tests including Marshal stability and flow, triaxial shear strength, laboratory-scale moving wheel loading, splitting-tensile strength, immersion-compression strength ratio and permeability. These tests were conducted on five mixtures with crushed and uncrushed gravel for both coarse and fine aggregates. They concluded that "replacement of the natural sand with crushed fines improves incomparably the properties of the product, increases its stability, reduces rutting, improves water-resistance, reduces bitumen sensitivity, increases the voids ratio and brings the mixture almost to the quality level of one with crushed coarse and fine aggregate. On the other hand, replacement of the coarse material with crushed coarse aggregate entails no such decisive effect". In 1979, Moore and Welke conducted Marshal mix designs using 110 sands from locations throughout the state of Michigan. The coarse aggregate and mineral filler were held constant. They concluded that fine aggregate angularity and mixture gradation are the two critical factors affecting mixture stability. The more angular the fine aggregate, the higher the stability. As for gradation, they concluded that the closer the gradation curve is to the maximum density curve, the higher the stability. In 1982, Kalcheff and Tunnicliff studied the effects of crushed stone aggregate size and shape on properties of asphalt concrete. Conclusions in this study reconfirmed the advantage of using mixtures containing crushed coarse and fine aggregate. The advantages included higher resistance to permanent deformation from repeated traffic loading, and less susceptibility to the effects of temperature and high initial void content than comparable mixtures containing natural sand. In 1984, Button, et al. studied the influence of aggregate on rutting of asphalt concrete pavements. They noted that the main factors associated with rutting were excessive asphalt content, excessive fine aggregate, and the round shape and smooth texture of uncrushed aggregate particles. In 1989, Meier and Elnicky used the Hveem stability test to evaluate the relationship between mixture performance and several aggregates with varying shape and texture. It was found that the Hveem stability of asphalt mixtures was linearly related to fine aggregate shape and surface texture values.

2.3 Fine Aggregate Shape and Surface Texture Tests

Since the 50's, several methods have been proposed to quantify the shape, angularity, and surface texture of aggregate particles. Researchers have focused on the comparisons of these methods as well as relationships of the test results and asphalt mixture performance. Brief descriptions of tests on fine aggregate particles are:

- Direct Shear Test (ASTM Method D3080-90): This test is used to measure the internal friction angle of a fine aggregate under different normal stress conditions. A prepared sample of the aggregate under consideration is consolidated in a shear mold. The sample is then placed in a direct shear device and sheared by a horizontal force while a known normal stress is applied.
- Index of Aggregate Particle Shape and Texture (ASTM Method D3398-81): This test provides an index value of the relative particle shape and texture characteristics of aggregates. A single fraction of aggregate is compacted in a mold using two different compactive efforts (10 and 50 drops). The test is completed on six different aggregate fractions between the No. 4 sieve and No. 200 sieve. An index value is obtained for each aggregate fraction. The average index for the composite aggregate is obtained by using the proportions of each aggregate fraction and its index value.

- Rex and Peck Time Index (Rex and Peck, 1956): The test is performed by placing a 0.11-lb sample of a one-sized fraction of aggregate (No. 20 to No. 30) into a glass jar with a cone-shaped lid and orifice. The jar is inverted, the stopper in the orifice removed, and a timer started. The rate of flow for the sample is then compared to the rate of flow for standard Ottawa sand of the same gradation.
- Specific Rugosity by Packing Volume (Tons and Goetz, 1968): In this test, an aggregate sample is separated into four sizes (No.8 to No.10, No.20 to No.30, No.60 to No.80, and No.200 to No.270) and each placed in a cone-shaped bin and then poured into a calibrated constant-volume container. Packing specific gravity is computed using the weight of this calibrated volume of aggregate. The macro- and micro-surface voids are computed using the apparent, bulk, and packing specific gravities. The specific rugosity is computed by adding the macro-surface and micro-surface voids.
- Method of Test for Flat and Elongated Particles in Fine Aggregate, Corps of Engineers' Method CRD-C120-55: In this method, particle shape is evaluated by observation with a microscope. The sample is separated into five sizes and the number of particles having a length-to-width ratio of more than 3 in each group is counted and reported as a percentage. This method measures the particle shape only and not the surface texture of the particles.
- Laughlin Method (Laughlin, 1960): This method was developed for fine aggregate used in Portland cement concrete. Measurements are made using enlarged photographs of particles retained on various sieves. The radii of curvature of the

particles and the radius of an inscribing circle are measured. Using these measurements, a parameter referred to as the roundness of the particle is then computed. Again, this method measures the particle shape only and not the surface texture of the particles.

- Void Ratio by Western Technologies (Meier and Elnicky, 1989): The test is performed by placing a known volume of a single aggregate fraction into a graduated cylinder in a standard manner. The void ratio is calculated from the measured and absolute volumes of the aggregate. The test should be repeated for three different-sized aggregate fractions (No.4 to No.8, No.20 to No.30, and No.100 to No.200) and an average void ratio computed.
- Florida Bearing Ratio: The test (Indiana State Highway Commission Test Method 201-72) is used to determine the bearing value of a fine aggregate. Fine aggregate is mixed with water and compacted into a cup in lifts with a specified compressive load. The filled cup is placed in a compression testing machine and compacted with a load of 1,500-lb applied at a rate of 2.4 in./min. The compacted specimen is then placed in the Florida bearing value machine with a 1-in^2 bearing plate centered on the specimen. A compressive load is applied through the bearing plate by addition of steel shot at a standard rate. When the rate of deformation reaches 0.01-in in five seconds, the loading is discontinued and the weight of shot up to that moment is determined. The bearing ratio is calculated from the weight of shot.
- Test Method for Measuring Fine Aggregate Angularity, Michigan Test Method 118-90: The test provides an angularity index (AI). In the test 100-mL of distilled water is

placed into a 250-mL capacity graduated cylinder. Subsequently, 250-g of sand are poured into the cylinder. The volume of the solids is equal to the total volume minus the 100-mL of water. The volume of voids is equal to the volume of the sample in water minus the volume of the solids. The angularity void ratio is the ratio of the volume of voids to the volume of solids. The AI is then calculated as follows:

AI = (10.0)(angularity void ratio – 0.6)..(2.1)

In 1967, Boutilier studied the relation between aggregate particle index and the physical properties of aggregate blends for bituminous mixtures. He concluded that the particle index could be a very valuable method for predicting the properties of bituminous paving mixtures such as optimum asphalt content, VMA, and VFA. In 1968, Tons and Goetz measured specific rugosity and packing volume of aggregates. The packing volume concept was implemented by Ishai and Tons in 1977. The test they developed was a pouring test "for the fast, simple, and practical bulk measurement" of a sands packing volume. In 1982, Ishai and Gelber studied the effects of aggregate geometric irregularity on the properties and behavior of bituminous concrete. They found that "the geometric irregularity of the aggregate, as defined by the packing volume parameters, was highly and meaningfully correlated with the relevant bituminous mixture parameters. Optimum bitumen content, Marshall stability and flow, and mixture density at optimum bitumen content were quantitatively and directly related to the geometric irregularity of the aggregate". In 1981, Mcleod and Davidson presented test data showing that 2 and 3-in.

diameter molds could be used to determine the particle index values for fine aggregate. In 1987, Huang developed a particle index test to reflect the discernible geometric characteristics of an aggregate.

In the 80's and 90's, several studies were presented to address the effectiveness of different aggregate tests. In 1989, Meier and Elnicky evaluated shape and surface texture of fine aggregate with 7 methods. They were:

- NAA Test for Particle and Texture
- Index of Aggregate Particle Shape and Texture
- Rex and Peck Time Index
- Void Ratio
- Florida Bearing Ratio
- Direct Shear Test
- Specific Rugosity by Packing Volume

In these tests, the NAA Test for Particle Shape and Texture, Rex and Peck Time Index, and Specific Rugosity by Packing Volume were found to have good correlation with Hveem stability results. A recommendation was made that these tests could be used to screen fine aggregate properties for use in asphalt concrete mixtures.

In 1992, Kandhal, et al compared ASTM D 3398, Standard Test Method for Index of Particle Shape and Texture with the National Aggregate Association's (NAA) Method of Test for Particle Shape and Texture of Fine Aggregate Using Uncompacted Void Content. It should be noted that the National Aggregate Association's method has three variations. Method A uses a sample with a specified gradation. In Method B, the void content is averaged using the void content results of three individual size fractions: Nos. 8 to 16, Nos. 16 to 30, and Nos. 30 to 50. Method C involves testing the as-received gradation. The NAA method has been adopted as ASTM C 1252. In turn the Superpave system utilizes Method A as a standard test to measure the fine aggregate angularity. The purpose of this current study is to evaluate the effect of fine aggregate angularity on HMA mixture performance. Therefore a brief description of the test is included here.

In the FAA determination, the fine aggregate particles fall freely from a specified height through the orifice of a funnel into a 100-cm^3 cylinder. The excess material is struck off and the cylinder with the aggregate is weighed. Uncompacted void content of the sample is then computed using this weight and the bulk dry specific gravity of the aggregate as in the following:

$$FAA = \frac{vol - \left[\frac{mass}{bulk}\right]}{vol} \times 100 \quad (2.2)$$

Where

FAA = fine aggregate angularity, uncompacted voids in fine aggregate (%)

$mass$ = mass of aggregate in cylinder (G)

$bulk$ = bulk specific gravity of fine aggregate, and

vol = volume of cylinder (cm^3)

Kandhal, et al studied 18 sands and concluded that a particle index value of 14 divided the natural sand and manufactured sand when using ASTM D 3398. For NAA Method A and B, uncompacted values of 44.5 and 48.3 divided natural and manufactured sands, respectively. Both NAA Method A and B showed high correlation with ASTM D 3398 and the correlation indicated the viability of substituting the NAA method for ASTM D3398 as the standard method for determining particle shape and texture of fine aggregates.

In 1994, Stuart and Mogawer evaluated natural sands used in asphalt mixtures. Marshall stability and flow, the U.S. Army Corps of Engineers gyratory testing machine (GTM), Georgia loaded-wheel tester (GLWT), and the French Laboratoires des Ponts et Chaussees (LPC) pavement rutting tester were used to evaluate the performance of asphalt mixtures. Five different tests were conducted on the fine aggregate to evaluate the ability of these methods to distinguish good- from poor-performing sands. They were:

- National Aggregate Association (NAA) Method A
- Direct Shear Test (ASTM Method D3080-90)
- ASTM Method D 3398
- Michigan Department of Transportation Method (MTM) 118-90
- Flow Rate Method: This method was developed by the Bureau of Public Roads (now FHWA) but was later modified (Jimenez, 1990). This method was performed according to the NAA procedure using the NAA apparatus with the exceptions that 500-g of sand was used instead of 190-g and the time for the sand to flow out of the funnel was recorded instead of determining its uncompacted void content. The flow rate of the sand is calculated by dividing the volume of the sand (cm^3) by the flow time (sec).

One of the conclusions of this study was that NAA Method A did not differentiate the sands perfectly. Poor- and good-quality sands were grouped at an uncompacted void content of around 44.7.

Cross et al. studied fine aggregate angularity using National Aggregate Association methods. They used the U.S Army Corps of Engineers gyratory testing machine (GTM) to evaluate mixture performance. It was found that NAA Method A, compared with Method C, was more repeatable.

In 1996, Ahlrich studied the influence of aggregate properties on performance of heavy-duty hot-mix asphalt mixtures. The aggregate particles were characterized with the particle index (ASTM D 3398), uncompacted void content for fine aggregate (ASTM C 1252), modified ASTM C 1252 for coarse aggregate, and unit weight and voids in aggregate (ASTM C 29). A confined repeated-load deformation (triaxial cyclic creep) test was used to evaluate rutting potential of HMA mixtures. It was found that Method A of ASTM C 1252 produced a stronger relationship with percent crushed fine particles and the natural sand content than Method C. It was also proposed that ASTM C 1252 be used to characterize aggregate particle and texture in specifications instead of percent crushed particles.

Table 2.1 Fine Aggregate Angularity Criteria

Traffic (ESAL)	Depth from Surface	
	< 100 mm	> 100 mm
$< 3 \times 10^5$	-	-
$< 1 \times 10^6$	40	-
$<3 \times 10^6$	40	40
$<3 \times 10^7$	45	40
$< 1 \times 10^8$	45	45
$> 1 \times 10^8$	45	45

CHAPTER 3 MATERIALS

3.1 Introduction

This chapter describes the materials (asphalt cement and aggregate) used in the study. A PG 64-22 asphalt cement was provided by Koch Materials, Terre Haute, Indiana. The coarse aggregate was a 9.5mm (3/8 inch) nominal maximum size, partially crushed gravel. Eight candidate fine aggregates were identified by the Indiana Department of Transportation and the Indiana Mineral Aggregate Association. After considering the fine aggregate types and characteristics, six of the original eight were selected for inclusion in the study.

The Compacted Aggregate Resistance (CAR) and Florida Bearing Value tests were also conducted on the mineral aggregate. The procedures and results of both tests are included in this chapter.

3.2 Asphalt and Aggregate

3.2.1 Asphalt

The asphalt cement utilized was a PG 64-22 from Koch Materials, Terre Haute, Indiana. The asphalt binder was tested according to AASHTO PP6, "Practice for Grading or Verifying the Performance Grade of an Asphalt Binder" to ensure that it met the desired grade. Table 3.1 shows the test results for the asphalt.

3.2.2 Aggregate

Basically, three different aggregates were incorporated in each mix: coarse aggregate, fine aggregate and mineral filler. The coarse aggregate was a partially crushed gravel with 80% one crushed face. The maximum particle size of this material was 9.5 mm (3/8 inch). Eight fine aggregates were originally considered but the number was reduced to six to avoid tautology. Table 3.2 lists the aggregate characteristics including the mineral filler.

In addition to the selected six single fine aggregates, there are mixtures with blends of two fine aggregates. Mixtures B1, B2 and B3 include blends of natural sand (#2497) and crushed gravel sand (#2164). A combination of 74%, 64%, and 44% of crushed gravel sand with a corresponding 26%, 36%, and 56% of natural sand resulted in blended fine aggregates with FAA values of 46, 45, and 43, respectively. The Compacted Aggregate Resistance (CAR) and Florida Bearing Value tests were also conducted on these blended fine aggregates.

In Phase II of this study, five mixtures with slag sand (#2478) and four mixtures with an S-shaped gradation produced with limestone sand (#2314) were included. Among them, mixtures #2478n2, #2478n4, #2314n1 and #2314n2 utilized blended fine aggregates. The blended fine aggregates were a combination of the original slag sand or the limestone sand with the natural sand (#2497). In addition, mixture #2314n4 included limestone sand with an artificial gradation. The Compacted Aggregate Resistance (CAR) and Florida Bearing Value tests were also conducted on these blended fine aggregates or the fine aggregate with the modified gradation.

3.2.3 ASTM Tests on Aggregate

A number of standard tests as specified in ASTM as well as petrographic analysis were conducted on the aggregates. Tests conducted on aggregates were:

- ASTM C128-84: "Specific Gravity and Absorption of Fine Aggregate"
- ASTM C136-84a: "Sieve Analysis of Fine and Coarse Aggregate"
- ASTM C117-87: "Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing ".
- ASTM C 1252-93 "Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)

This test was performed on each of the eight candidate sands. The test was performed using a standard grading (Method A). This approach is utilized in the Superpave system. The results are included in Table 3.2.

- ASTM D 5821-95 "Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate"

Percent of fractured faces was determined on the #11 crushed gravel (coarse aggregate) from Indiana source #2415. The procedure was performed once for each of the 9.5-12.5 mm and 4.75-9.5mm sieve size ranges. Results are shown in Table 3.3. The test method is designed to determine the percentage of particles that have more than a specified number of fractured faces. Because the specified number may vary depending on requirements of the pavement mix, particles were sorted into five categories of fractured faces. These are 0, 1, 2, and 3 or greater fractured faces, as well as those particles for which the number of fractured faces was questionable. The percentage of particles with fractured faces was then calculated for each sorted fraction.

- ASTM D 4791-89 "Standard Test Method for Flat and Elongated Particles in Coarse Aggregate"

This test was also performed on the #11 crushed gravel (coarse aggregate) from source #2415. The procedure was performed once for each of the 9.5-12.5 mm and 4.75-9.5mm sieve size ranges. Results are shown in Table 3.4. The test was performed with a caliper ratio set to 1:3. With the caliper ratio set to 1:3 or 1:5, all particles were neither flat nor elongated.

3.2.4 Petrographic Analysis

Petrographic analysis of the aggregates were conducted by Dr Robert Pettinger and Dr. Terry West in the School of Geology at Purdue University. For each sample, particles were sorted by rock type, and the percent (by particle count) of each rock type was determined for both the 9.5-12.5 mm and 4.75-9.5mm particle size ranges. Petrographic analysis was performed on the 2.36-4.75 mm and 1.18-2.36 mm sieve size ranges for each of the eight aggregates.

For natural sand sources #2497, #2591, and #2164, particles were sorted by rock type. Initial rock type categories included the following:

- Limestone - all carbonate particles that dissolve vigorously in hydrochloric acid.
- Dolomite - all carbonate particles that exhibit significant dolomitization
- Mafic - all dark, or green igneous rocks, such as basalt, peridotite, and dunite, as well as dark colored metamorphic rocks.
- Felsic - light and pink color igneous rocks such as granite, rhyolite, and andesite as well as light colored metamorphic rocks.
- Quartz - quarts crystals or quartzite
- Chert - all light and dark color chert, chalcedony, or flint
- Clastics - cemented sedimentary rocks such as sandstone or siltstone
- Oxides - All particles exhibiting significant iron oxides.

If warrented, following initial separation, each group may have been further divided into other categories based on specific rock type, color, or weathering where applicable.

For stone sand sources #2423, #2311, #2314, and dolomite sand source #2211, particles were sorted into the above categories. However, because of the abundance of limestone (or dolomite for the dolomite sand), an emphasis was placed on sorting by limestone characteristics such as color or weathering. Particles were sorted when wet to better distinguish particle characteristics.

For slag sand source #2478, particles were sorted by characteristics such as color and texture. Particles of these aggregate were also sorted when wet to better distinguish particle characteristics.

The results of the petrographic analysis are given in Table 3.5 to Table 3.13.

3.3 Compacted Aggregate Resistance (CAR) Test

The CAR test was developed by David Jahn, Martin Marietta for evaluating the penetration or shear resistance of compacted fine aggregate materials in their "as received" condition. The test is a modification of the CBR test. A 38.1-mm diameter rod is used instead of the 49.5-mm diameter rod in the CBR test. Load and penetration are plotted. Figure 3.1 shows the test results for all the fine aggregates included in this study. Peak load during the test, load at a deformation of 1.27mm (0.05-inch), and slope of the load deformation curve, are listed in Table 3.14.

This procedure is intended for use on the combined fine aggregate materials to be used in the paving mixture. The performance of individual components can be judged provided engineering judgement is used. The test procedure is included in Appendix A.

3.4 Florida Bearing Value

Florida Bearing Value tests were conducted using Indiana Test Method or Procedure No. 201-89 and was described in the previous chapter. Details of the procedure can be found in Appendix B. Tests were conducted on the six single fine aggregates as well as the blended fine aggregates. The results are shown in Figure 3.2 and listed in Table 3.15.

The comparison of Compacted Aggregate Resistance (CAR) test results and results of Florida Bearing Value is shown in Figure 3.3. The reader is referred to Chapter 4 for a description of Phase II aggregates.

Table 3.1 Binder Properties (PG 64-22)

	Binder Properties	Test Result	Specifications (Asphalt Institute, SP-1)
Original Binder	Flash Point Temp, T-48 (^{0} C)	230+	Min. 230^0 C
	Viscosity, ASTM D 4402, Pa-s	0.383	Max. 3 Pa-s @135^0 C
	Dynamic Shear, TP-5, Kpa	1.41	Min. 1 Kpa @ 64^0 C
Rolling Thin Film Oven (AASHTO T-240)	Mass Loss, % Max.	0.993	Max. 1% @ 64^0 C
	Dynamic Shear, TP-5, Kpa	4.48	Min. 2.2 Kpa @ 64^0 C
Pressure Aging Vessel Residue (PP-1)	PAV Aging Temperature, ^{0} C	100	100
	Dynamic Shear, TP-5, Kpa	4591	Max. 5000 Kpa @ 25^0 C
Physical Hardening	Creep Stiffness, TP-1, S-Value, MPa	220	Max. 300 Mpa @ -12^0 C
	Creep Stiffness, TP-1, m-Value	0.324	Min. 0.300 @ -12^0 C
	Direct Tension, TP-3, Failure Strain	N/A	Min. 1.0 % @ -12^0 C

Table 3.2 Properties of Stockpiles

	Coarse Aggregate	Fine Aggregate						Mineral Filler
Source Number	#2415	#2311	#2497	#2164	#2211	#2478	#2314	N/A
Source	Logansport, IN	Indian-apolis, IN	Logans-port, IN	West Leba-non, IN	Hunting-ton, IN	East Chica-go, IN	Indian-apolis, IN	Swayzee, IN
Type of Material	#11 Gravel (80/85% Crush Count)	Stone Sand	Natural Sand	Crushed Gravel Sand	Dolomite Sand	Slag Sand	Stone Sand	Mineral Filler
FAA		***45.14***	***38.73***	***48.97***	***48.11***	***46.98***	***44.15***	***N/A***
Apparent SG	2.7307	2.7257	2.7111	2.7475	2.8546	2.8924	2.6854	N/A
BSG	2.6091	2.6449	2.5990	2.6387	2.7528	2.7639	2.5917	2.700
Sieve Size(mm)	% passing by weight							
9.5	83.4%	100%	100%	100%	100%	100%	100%	100%
4.75	28.5%	100%	100%	100%	100%	100%	100%	100%
2.36	3.0%	88.4%	82.3%	73.5%	77.5%	87.4%	47.3%	100%
1.18	1.2%	54.7%	59.8%	42.7	44.4%	63.9	19.7%	100%
0.6		32.6%	33.1%	25.65	24.8%	31.4%	9.0%	100%
0.3		18.5%	11.3%	15.4%	11.9%	17.8%	3.9%	96.6%
0.15		9.7%	3.7%	7.7%	5.0%	10.3%	1.9%	71.3%
0.075		5.5%	1.3%	3.0%	2.6%	6.4%	1.3%	21.9%

Table 3.3 ASTM D 5821-95 Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate

Source: #2415

Sieve Size: 9.5-12.5 mm

	Quantity					
Value	0 Faces	1 Face	2 Faces	>=3 Faces	Questionable	Total
Mass w/ Container (g)	117.7	145.4	86.7	176.0	41.7	
Net Mass (g)	104.2	131.9	73.2	162.5	28.2	500.0
Count	54	72	39	95	20	280
Average Mass/Particle	1.93	1.83	1.88	1.71	1.41	1.79
	Percentage					
	0 Faces	1 Face	2 Faces	>=3 Faces	Questionable	Total
Net Mass (g)	20.84%	26.38%	14.64%	32.50%	5.64%	100.00%
Count	19.29%	25.71%	13.93%	33.93%	7.14%	100.00%

1 Fractured Face				
	Meets or Exceeds Criteria	Questionable	Does Not Meet Criteria	Percent
Value	(F)	(Q)	(N)	
By Mass (g)	367.6	28.2	104.2	76.34%
By Count	206	20	54	77.14%
2 Fractured Faces				
	Meets or Exceeds Criteria	Questionable	Does Not Meet Criteria	Percent
Value	(F)	(Q)	(N)	
By Mass (g)	235.7	28.2	236.1	49.96%
By Count	134	20	126	51.43%
3 Fractured Faces				
	Meets or Exceeds Criteria	Questionable	Does Not Meet Criteria	Percent
Value	(F)	(Q)	(N)	
By Mass (g)	162.5	28.2	309.3	35.32%
By Count	95	20	165	37.50%

Table 3.3 (Continued)

Source: #2415
Sieve Size: 4.75-9.5 mm

	Quantity					
Value	0 Faces	1 Face	2 Faces	>=3 Faces	Questionable	Total
Mass w/ Container (g)	76.1	44.2	21.3	69.7	7.1	
Net Mass (g)	73.3	41.4	18.5	66.9	4.3	204.4
Count	172	114	45	227	19	577
Average Mass/Particle	0.43	0.36	0.41	0.29	0.23	0.35
	Percentage					
	0 Faces	1 Face	2 Faces	>=3 Faces	Questionable	Total
Net Mass (g)	35.86%	20.25%	9.05%	32.73%	2.10%	100.00%
Count	29.81%	19.76%	7.80%	39.34%	3.29%	100.00%

1 Fractured Face				
	Meets or Exceeds Criteria	Questionable	Does Not Meet Criteria	Percent
Value	(F)	(Q)	(N)	
By Mass (g)	126.8	4.3	73.3	63.09%
By Count	386	19	172	68.54%
2 Fractured Faces				
	Meets or Exceeds Criteria	Questionable	Does Not Meet Criteria	Percent
Value	(F)	(Q)	(N)	
By Mass (g)	85.4	4.3	114.7	42.83%
By Count	272	19	286	48.79%
3 Fractured Faces				
	Meets or Exceeds Criteria	Questionable	Does Not Meet Criteria	Percent
Value	(F)	(Q)	(N)	
By Mass (g)	66.9	4.3	133.2	33.78%
By Count	227	19	331	40.99%

Table 3.4 ASTM D 4791 - 89 Standard Test Method for Flat or Elongated Particles in Coarse Aggregate

Source: #2415
Sieve Size: 9.5-12.5 mm
Caliper Ratio 2:1

	Quantity				Percentage		
Value	Flat	Elongated	Neither	Total	Flat	Elongated	Neither
Mass (g)	11.3	0	236.8	248.1	4.55%	0.00%	95.45%
Count	9	0	130	139	6.47%	0.00%	93.53%
Average Mass/Particle	1.26		1.82	1.78			

Sieve Size: 4.75-9.5 mm
Caliper Ratio 2:1

	Quantity				Percentage		
Value	Flat	Elongated	Neither	Total	Flat	Elongated	Neither
Mass (g)	7.8	0.6	58.8	67.2	11.61%	0.89%	87.50%
Count	20	1	128	149	13.42%	0.67%	85.91%
Average Mass/Particle	0.39		0.46	0.45			

Table 3.5 Petrographic Analysis of #2415

Sieve Range:	9.5 - 12.5 mm		4.75 - 9.5 mm	
	Count	Percentage	Count	Percentage
Chert	19	6.76%	26	9.42%
Chalcedony	3	1.07%	1	0.36%
Quartz	3	1.07%	3	1.09%
Quartzite	3	1.07%	15	5.43%
Siliceous Siltstone	19	6.76%	28	10.14%
Soft Siltstone	21	7.47%	28	10.14%
Shale (Black)	2	0.71%	0	0.00%
Felsic	30	10.68%	28	10.14%
Mafic	45	16.01%	26	9.42%
Limestone	31	11.03%	43	15.58%
Dolomite	102	36.30%	73	26.45%
Sandstone	0	0.00%	1	0.36%
Oxides	3	1.07%	4	1.45%
Total	281	100.00%	276	100.00%

Table 3.6 Petrographic Analysis of #2591

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Mafic	21	6.77%	Mafic	41	16.14%
Limestone	89	28.71%	Carbonate (Dark)	20	7.87%
Dolomite	38	12.26%	Carbonate (Light)	67	26.38%
Dolomite (weathered)	34	10.97%	Carbonate (Weathered)	35	13.78%
Quartzite	6	1.94%	Quartzite	1	0.39%
Quartz (crystalline)	9	2.90%	Quartz (Crystalline)	8	3.15%
Chalcedony	30	9.68%	Chalcedony	5	1.97%
Chert (light)	19	6.13%	Chert (Light)	22	8.66%
Oxides/Ironstones	8	2.58%	Chert (Dark)	2	0.79%
Felsic	25	8.06%	Felsic	53	20.87%
Black Shale	3	0.97%	Total:	254	100.00%
Clastic (cemented)	17	5.48%			
Clastic (fissile)	11	3.55%			
Total:	310	100.00%			

Table 3.7 Petrographic Analysis of #2497

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Limestone	94	28.23%	Mafic	59	15.61%
Dolomite	81	24.32%	Carbonate (Dark)	35	9.26%
Mafic	38	11.41%	Carbonate (Light)	50	13.23%
Felsic	18	5.41%	Carbonate (Weathered)	37	9.79%
Quartz (Crystalline)	60	18.02%	Ironstone	1	0.26%
Chert	18	5.41%	Quartz (Crystalline)	47	12.43%
Clastics	24	7.21%	Siliceous Siltstone	56	14.81%
Oxides	0	0.00%	Chert (Weathered)	31	8.20%
			Chert (Unweathered)	32	8.47%
			Clastic (Soft Siltstone)	4	1.06%
			Felsic	26	6.88%
Total:	333	100.00%	Total:	378	100.00%

Table 3.8 Petrographic Analysis of #2164

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Clastic	19	5.67%	Clastics	23	4.36%
Limestone	74	22.09%	Carbonate (Dark)	12	2.28%
Dolomite	47	14.03%	Carbonate (Light)	174	33.02%
Dolomite (weathered)	26	7.76%	Carbonate (Weathered)	77	14.61%
Quartz	23	6.87%	Quartz (Crystalline)	38	7.21%
Quartzite	2	0.60%	Quartzite	11	2.09%
Chert	16	4.78%	Chert (Weathered)	37	7.02%
Clastic (weathered)	32	9.55%	Chert (Unweathered)	15	2.85%
Mafic	53	15.82%	Mafic	98	18.60%
Felsic	33	9.85%	Felsic	42	7.97%
Oxidized Igneous	10	2.99%			
Total:	335	100.00%	**Total:**	527	100.00%

Table 3.9 Petrographic Analysis of #2423

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Limestone (Light)	88	23.10%	Limestone (Light)	221	54.84%
Limestone (Medium)	200	52.49%	Limestone (Medium)	155	38.46%
Limestone (Dark)	73	19.16%	Limestone (Dark)	16	3.97%
Crystaline Calcite	5	1.31%	Crystaline Calcite	2	0.50%
Felsic	4	1.05%	Felsic	4	0.99%
Mafic	1	0.26%	Mafic	0	0.00%
Quartz	1	0.26%	Quartz	0	0.00%
Quartzite	1	0.26%	Quartzite	0	0.00%
Chert	8	2.10%	Chert	5	1.24%
Total:	381	100.00%	**Total:**	403	100.00%

Table 3.10 Petrographic Analysis of #2311

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Limestone (Light)	4	1.50%	Limestone (Light)	21	6.31%
Limestone (Medium)	257	96.25%	Limestone (Medium)	285	85.59%
Limestone (Dark)	4	1.50%	Limestone (Dark)	27	8.11%
Crystaline Calcite	1	0.37%	Crystaline Calcite	0	0.00%
Dolomitic	1	0.37%	Dolomitic	0	0.00%
Total:	267	100.00%	Total:	333	100.00%

Table 3.11 Petrographic Analysis of #2314

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36	
	Count	Percentage		Count	Percentage
Limestone (Light)	116	32.04%	Limestone (Light)	89	26.02%
Limestone (Medium)	199	54.97%	Limestone (Medium)	227	66.37%
Limestone (Dark)	26	7.18%	Limestone (Dark)	22	6.43%
LS (Argillaceous)	7	1.93%	LS (Argillaceous)	0	0.00%
LS (Weathered)	2	0.55%	LS (Weathered)	0	0.00%
LS (Sparry)	4	1.10%	LS (Sparry)	0	0.00%
Calcite Crystal	1	0.28%	Calcite Crystal	0	0.00%
Chert	7	1.93%	Chert	4	1.17%
Total:	362	100.00%	Total:	342	100.00%

Table 3.12 Petrographic Analysis of #2478

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Vesicular/Non-Fibrous	98	31.92%	Vesicular/Non-Fibrous	113	37.05%
White/Silver Bladed Fibers Present	177	57.65%	White/Silver Bladed Fibers Present	171	56.07%
Oxides	4	1.30%	Oxides	1	0.33%
Black Sphere	1	0.33%	Black Sphere	0	0.00%
Yellow Crystal	1	0.33%	Yellow Crystal	0	0.00%
Massive, Non to Slightly Vesicular, Angular	26	8.47%	Massive, Non to Slightly Vesicular, Angular	20	6.56%
Total:	307	100.00%	Total:	305	100.00%
Notes: Sorted by wet color					

Table 3.13 Petrographic Analysis of #2211

Sieve Range:	2.36 - 4.5 mm			1.18 - 2.36 mm	
	Count	Percentage		Count	Percentage
Dk. Gray Dolomite	97	22.66%	Dk. Gray Dolomite	45	14.52%
Lt. Gray Dolomite	192	44.86%	Lt. Gray Dolomite	152	49.03%
Yellow/Orange/Tan Dolomite	136	31.78%	Yellow/Orange/Tan Dolomite	113	36.45%
Flint	3	0.70%	Flint	0	0.00%
Total:	428	100.00%	Total:	310	100.00%
Notes: Washed and sorted by color when dry					

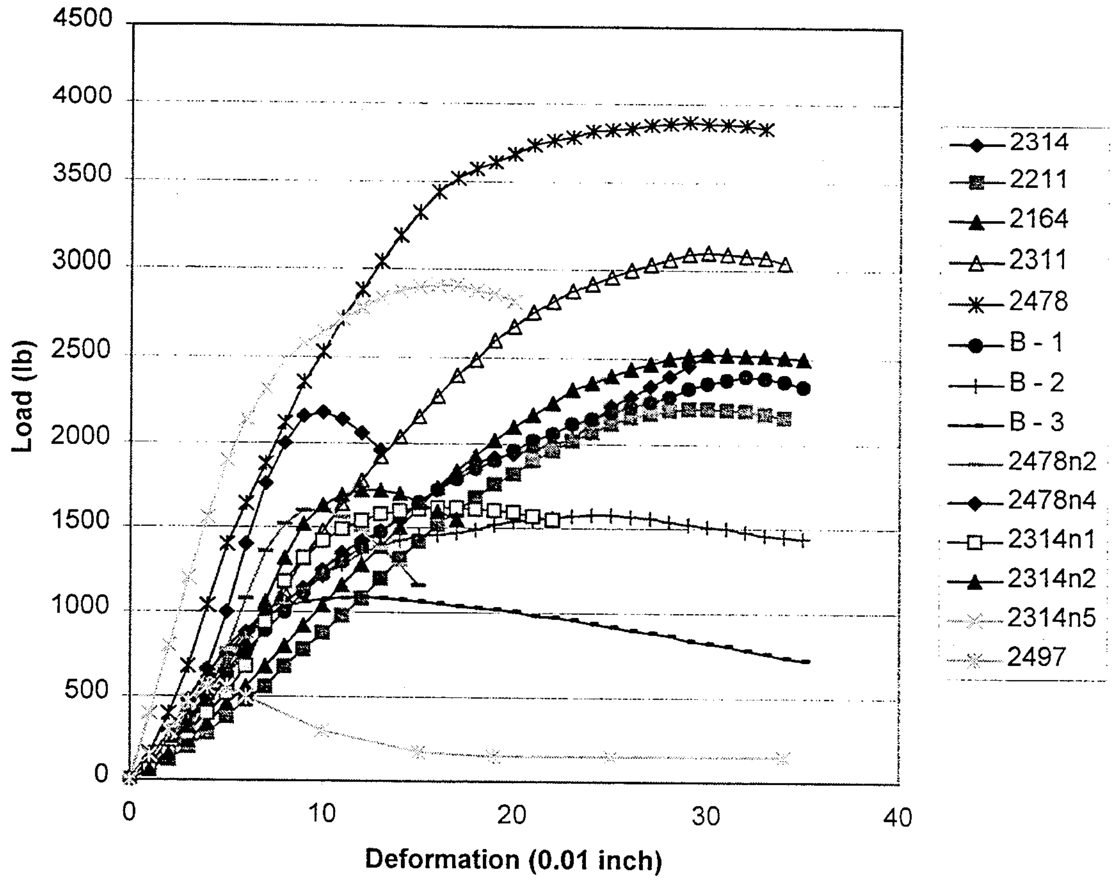

Figure 3.1 Compacted Aggregate Resistance Test Results

Table 3.14 Compacted Aggregate Resistance Test Results

Fine aggregate	Peak Load (lb)	Load at 0.05 inch	Slope (lb/inch)	Fine aggregate	Peak Load (lb)	Load at 0.05 inch	Slope (lb/inch)
#2311	3100	680	14770	B2	1580	730	12100
#2497	560	560	14000	B3	1090	790	10750
#2164	3025	460	10630	#2478n2	1605	780	26667
#2211	2210	380	9260	#2478n4	2180	1000	40000
#2478[1]	3880	1400	25300	#2314n1	1620	520	24000
#2314[2]	2525	750	11830	#2314n2	1730	640	26300
B1	2400	620	12200	#2314n4	2970	1900	40000

1 Mixtures #2478, #2478n1, #2478n3 and #2478n5 utilized identical fine aggregate: slag sand with source number #2478.

2 Mixtures #2314 and #2314n3 utilized identical fine aggregate: limestone sand with source number #2314.

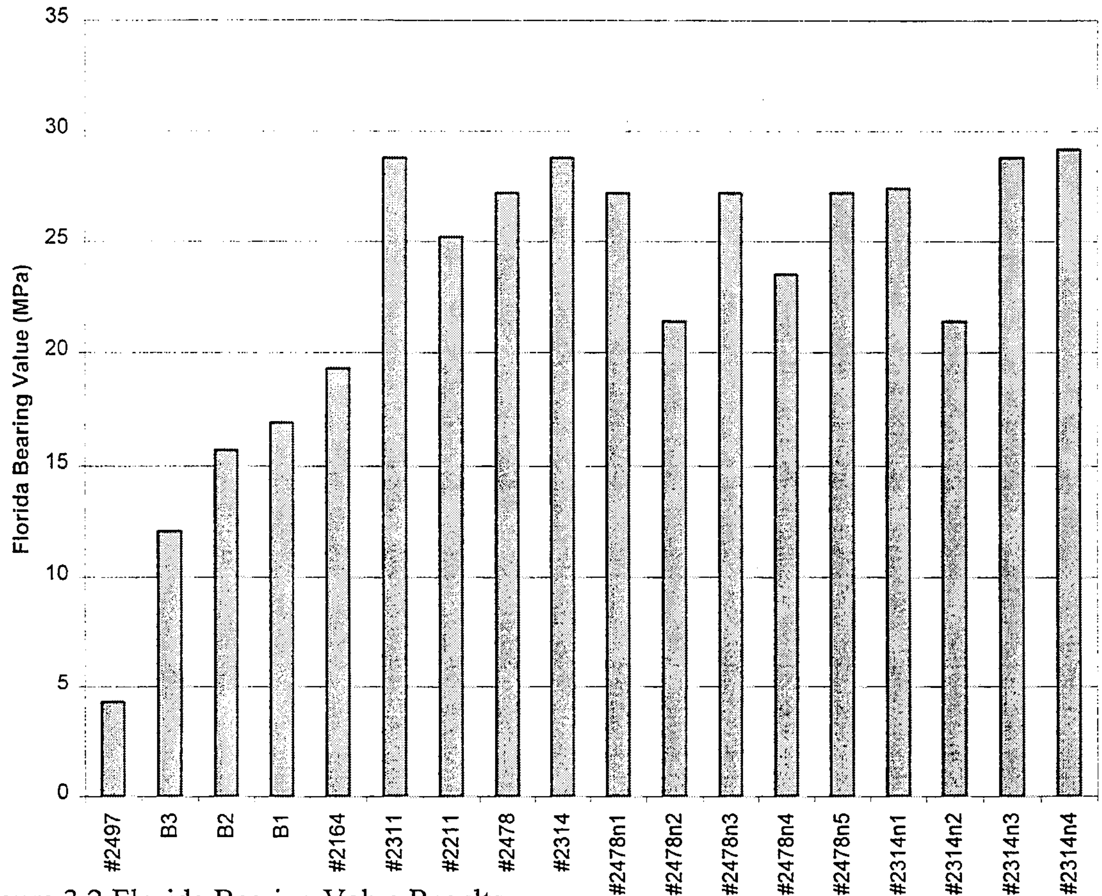

Figure 3.2 Florida Bearing Value Results

Table 3.15 Florida Bearing Value Results

Fine aggregate	Florida Bearing Value	Fine aggregate	Florida Bearing Value
#2311	28.8	B2	15.7
#2497	4.3	B3	12.1
#2164	19.3	#2478n2	21.4
#2211	25.2	#2478n4	23.5
#2478[1]	27.2	#2314n1	27.4
#2314[2]	28.8	#2314n2	21.4
B1	16.9	#2314n4	29.2

1 Mixtures #2478, #2478n1, #2478n3 and #2478n5 utilized identical fine aggregate: slag sand with source number #2478.

2 Mixtures #2314 and #2314n3 utilized identical fine aggregate: limestone sand with source number #2314.

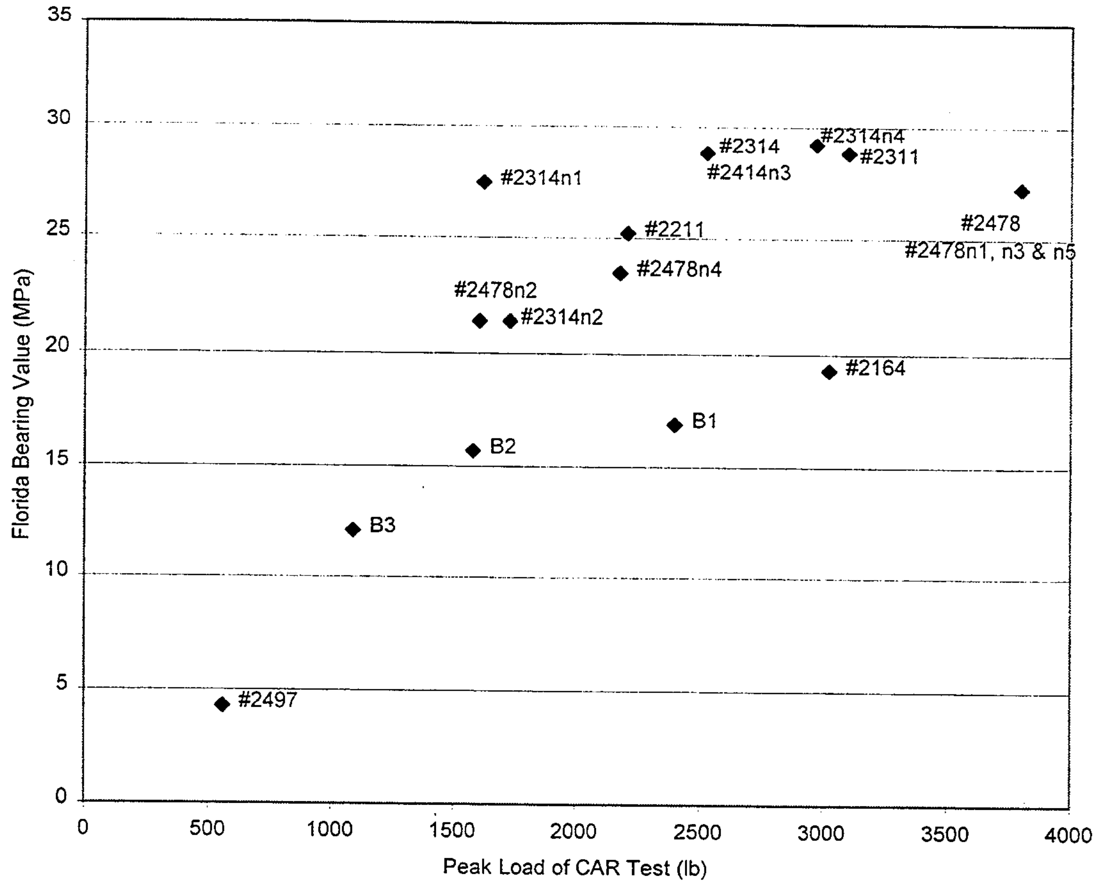

Figure 3.3 Florida Bearing Value versus Compacted Aggregate Resistance Test

CHAPTER 4 MIXTURE DESIGNS

This chapter describes the mixture design procedures and results. A total of eighteen mixtures were designed using Superpave volumetric procedures.

4.1 Gradations

There were nine asphalt mixtures tested in Phase I. Six of these mixtures included a single sand. The remaining three mixtures included blends of different percentages of the same two sands (#2164 and #2497) to achieve FAA values of 46, 45 and 43, respectively. The proportions to achieve these FAA values were obtained by varying the proportion of #2164 and #2497 in a blend and then measuring the corresponding FAA value. From a plot of FAA vs. percentage, combinations of 74%, 64%, and 44% of #2164 sands with corresponding 26%, 36%, and 56% of #2497 sands were selected to produce the FAA values of 46, 45, and 43, respectively.

In Phase II, five mixture designs were conducted for the slag sand (#2478) and four mixture designs were conducted for the S-shaped gradation obtained using limestone sand (#2314). This additional work was done to evaluate the effects of varying dust/asphalt ratio, gradation and natural sand on rutting performance.

The mixtures included in this study were all 9.5mm surface mixtures. Tables 4.1 and 4.2 show the gradations of the mixtures in Phase I and II, respectively. The gradation for #2311 mixture (stone sand) was selected in Phase I as a target gradation and gradations of the other eight mixtures were adjusted to be as close to the target as possible. With the exception of the one S-gradation (mixture #2314) the aggregate blends were close. The nine gradations met the Superpave criteria for 9.5mm nominal size mixture. The gradations are illustrated in Figure 4.1.

In Phase II, five new designs were conducted for the slag sand (#2478). These mixtures were identified as #2478n1 to #2478n5. Among the five mixtures, mixtures #2478n1 and #2478n3 included 22% and 16% natural sand, respectively. Mixtures #2478n2 and #2478n4 had 4% and 6% mineral filler, respectively. Gradation of mixture #2478n5 goes above the restricted zone as identified in Superpave. Gradations of the five slag mixtures are given in Table 4.2 and plotted in Figure 4.2.

In addition to the five slag mixtures, Phase II of the study also included four mixtures for the #2314 stone sand: #2314n1 to #2314n4. Mixtures #2134n1 and #2314n2 included 10% and 15% natural sand and #2314n3 contained 10% mineral filler. Mixture #2314n4 was a special mixture with an artificial gradation. The artificial gradation was utilized to straighten the original S-shaped curve. Gradations of mixtures #2314n1 to #2314n4 are also listed in Table 4.2 and illustrated in Figure 4.3.

4.2 Mixture Design Procedures

All mixture designs were conducted using Superpave volumetric tests and criteria. Samples were prepared using a Pine Superpave Gyratory Compactor (SGC) as shown in Figure 4.4. The number of gyrations were selected as $N_{initial} = 8$, $N_{design} = 96$ and $N_{maximum}$

= 152, which corresponds to a design traffic level of 3-10 million equivalent single axle loads (ESAL) and an average design high air temperature of less than 39°C.

The Superpave mixture design criteria requires that the percent air voids be fixed at four percent. Minimum *Voids in the mineral aggregate* (VMA) for 9.5-mm surface mixtures is15 percent. The range for *voids filled with asphalt* (VFA) is 65 to 75 percent. Allowable dust to asphalt ratio ranges from 0.6 to 1.2. Other restrictions include degree of compaction to be less than 89 percent of G_{mm} at $N_{initial}$ and less than 98 percent of G_{mm} at $N_{maximum}$.

There are four major steps in a Superpave volumetric mixture design testing and evaluation process:

1. Selection of materials,
2. Selection of a design aggregate structure,
3. Selection of a design asphalt binder content,
4. Evaluation of moisture sensitivity of the design mixture.

Step one includes requirements for the fine aggregate. The minimum fine aggregate angularity (FAA) for a surface mixture and the selected traffic level is 45. Coarse aggregate fractured face requirements include a minimum of ninety-five percent 1+ fractured faces and a minimum of ninety percent 2+ fractured faces. The coarse aggregate fractured face requirements were violated in this study because of the specific aggregate choice. The second step includes preparation of several trial blends. A mixture with acceptable, estimated volumetric properties is selected from the trial blends. In the current study, only mixture #2311 was evaluated. Subsequent mixture gradations were selected to agree with this gradation as closely as possible. The fourth step of the mixture design process was not addressed in this study.

4.3 Mixture Design Results

Table 4.3 shows a summary of the mixture design results in Phase I. There is variation from Superpave volumetric criteria. This variation was accepted to keep from modifying the stockpiles. To do so would have created artificial materials. The *voids in the mineral aggregate* (VMA) for the #2497 natural sand mixture was lower than the criteria. Also, the air voids for aggregate sources #2478 (slag) and #2314 (stone sand) were higher than the criteria. Had the air void criteria of four percent been met for these mixtures, then the *voids filled with asphalt* (VFA) would have been exceeded. Since the asphalt content was already high, a decision was made to hold the VFA at 75 percent and violate the air voids requirement. This resulted in a reduced asphalt content for these two mixtures.

A summary of the mixture design results for Phase II is shown in Table 4.4. There are also variations from Superpave mixture design criteria among these mixtures. However, some of the mixtures with air voids of 4.1 or 4.2 percent are not considered to be in violation of Superpave criteria. The reason is that the design asphalt content is obtained from interpolation of two adjacent asphalt contents with a difference of 0.5 percent, a precise 4 percent air voids content is not easily achieved. Air voids vary significantly with asphalt content. And from interpolation, the design asphalt content is going to be over one decimal place different.

Figure 4.5 shows the relationship of VMA vs. asphalt content for all the mixtures included in this study. One can see that the relation between VMA and asphalt content is approximately linear. Figure 4.6 and Figure 4.7 show the relationship between asphalt content and FAA and VMA and FAA. It can be seen that there is a general trend that both VMA and asphalt content increase with increasing value of FAA. And either VMA or asphalt content is reduced for mixtures #2478 and #2314 with modifications.

Figure 4.8 and Figure 4.9 show the effect of natural sand and mineral filler on the mixtures with slag sand. An increase of natural sand or mineral filler effectively reduces the asphalt demand of the original mixture. Figure 4.10 and Figure 4.11 illustrate the effect of natural sand and mineral filler on the originally S-shaped stone sand mixture. Again, adding natural sand and mineral filler proved to be two effective means of decreasing the VMA and corresponding asphalt content.

Natural sand facilitates compaction and may provide a denser "packing" of the gradation. In both cases the VMA decreases and the asphalt demand decreases for a constant air voids criteria. Mineral filler can replace some of the asphalt and fill in the interstices of larger particles. In either case asphalt demand is reduced.

Detailed information for each mixture design can be found in Appendix C.

Table 4.1 Mixture Design Gradations in Phase I

Source/Mix Number	#2311	#2497	#2164	#2211	#2478	#2314	B1	B2	B3
FAA	**45**	**39**	**49**	**48**	**47**	**44**	**46**	**45**	**43**
Course Aggregate, %	55	54	54	54	55	58.7	53	53	53
Fine Aggregate 1, % (#2497 for B1-B3)	44	40	40	40	44	36.2	10.9	15.1	23.5
Fine Aggregate 2, % (#2164 for B1-B3)							31.1	26.9	18.5
Mineral Filler, %	1	6	6	6	1	5.1	5	5	5
Optimal Asphalt Content, %	5.3	4.4	5.4	5.0	6.9	7.5	5.5	5.3	5.0
Sieve Size (mm)	Percent Passing								
12.5	100	100	100	100	100	100	100	100	100
9.5	90.9	91.0	91.0	91.0	90.9	94.0	91.2	91.2	91.2
4.75	60.6	61.4	61.4	61.4	60.6	74.1	62.1	62.1	62.1
2.36	41.5	40.5	37.0	38.6	41.1	33.9	38.4	38.8	39.5
1.18	25.7	30.5	23.7	24.4	29.7	17.0	25.4	26.1	27.5
0.6	15.9	19.8	16.8	16.2	15.4	10.7	17.1	17.4	18.0
0.3	9.5	10.9	12.6	11.1	9.3	7.7	11.4	11.3	10.9
0.15	5.5	6.9	8.6	7.4	5.8	5.7	7.4	7.2	6.9
0.075	3.3	4.2	4.9	4.8	3.7	3.9	4.2	4.2	4.0

Table 4.2 Mixture Design Gradations in Phase II

Source/Mix Number	#2478n1	#2478n2	#2478n3	#2478n4	#2478n5	#2314n1	#2314n2	#2314n3	#2314n4
Course Aggregate, %	55	52	52	52	32	22	22	36	55
Fine Aggregate	39	22	44	28	60	58	53	54	42
Natural Sand Added (#2497)	0	22	0	16	0	10	15	0	0
Mineral Filler, %	6	4	4	4	8	10	10	10	3
Optimal Asphalt Content, %	5.9	5.8	6.6	6.5	6.3	6.1	6.0	6.7	5.2
Sieve Size (mm)	Percent Passing								
12.5	100.0	100.0	100	100	100	100	100	100.0	100
9.5	90.9	91.4	91.4	91.4	94.7	96.3	96.3	94.0	90.9
4.75	60.6	62.8	62.8	62.8	77.1	84.3	84.3	74.2	60.6
2.36	41.7	42.9	44.0	43.2	61.4	46.3	48.1	36.6	41.7
1.18	31.5	31.8	32.7	32.0	46.7	27.6	29.6	21.0	26.6
0.6	18.8	18.7	18.4	18.6	27.2	18.7	19.9	15.2	17.2
0.3	13.4	10.8	12.2	11.2	18.9	13.6	13.9	12.4	11.2
0.15	9.5	6.8	8.3	7.2	13.2	10.1	10.2	9.8	7.0
0.075	6.2	4.3	5.4	4.6	8.6	6.7	6.7	6.6	4.3

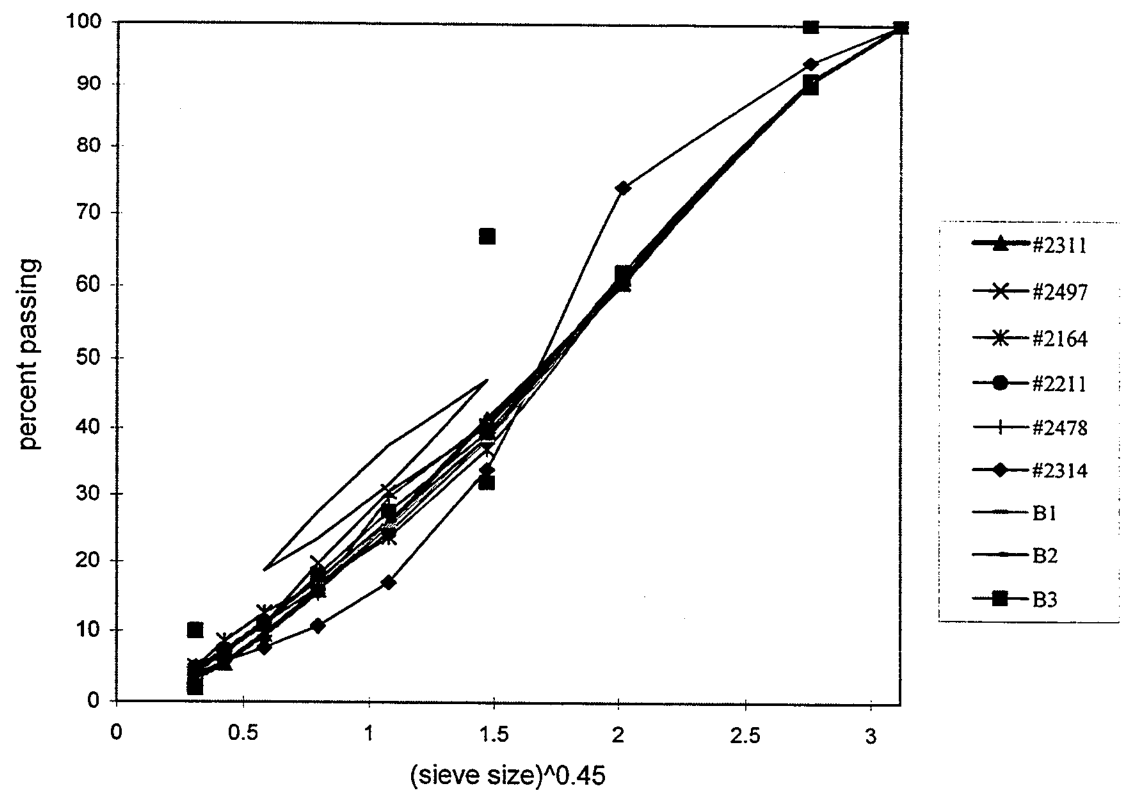

Figure 4.1 Mixture Design Gradations in Phase I

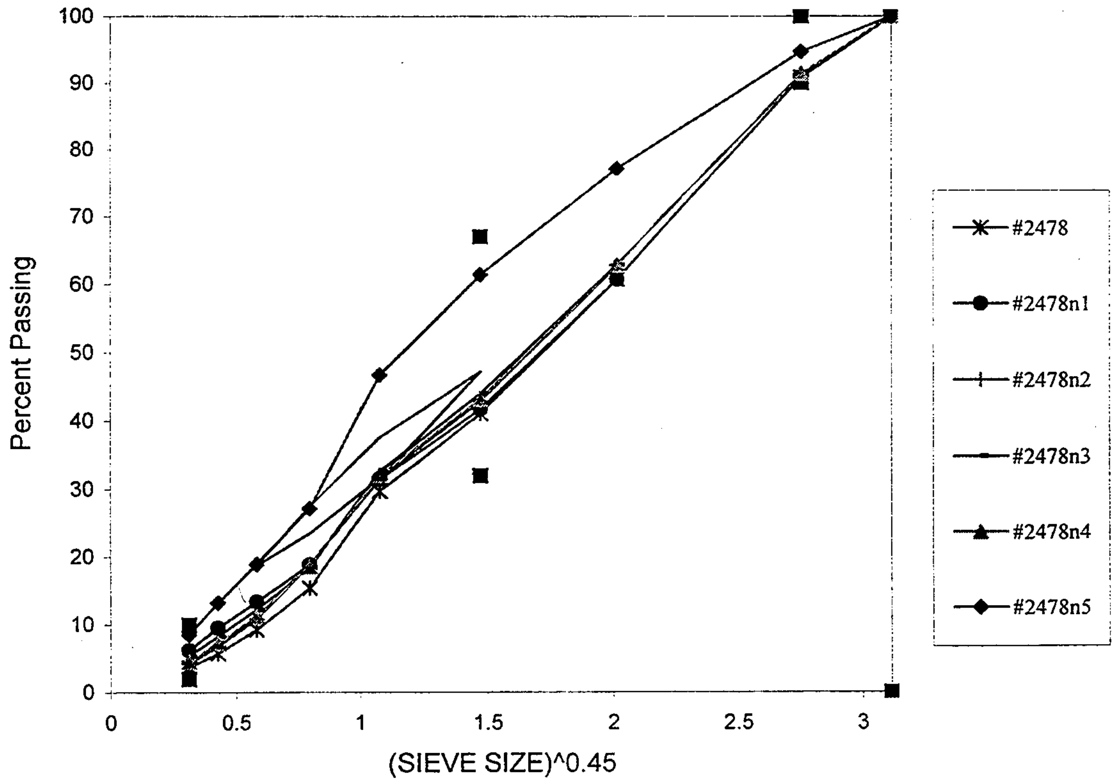

Figure 4.2 Gradations for Mixtures #2478 and #2478n1 to #2478n5

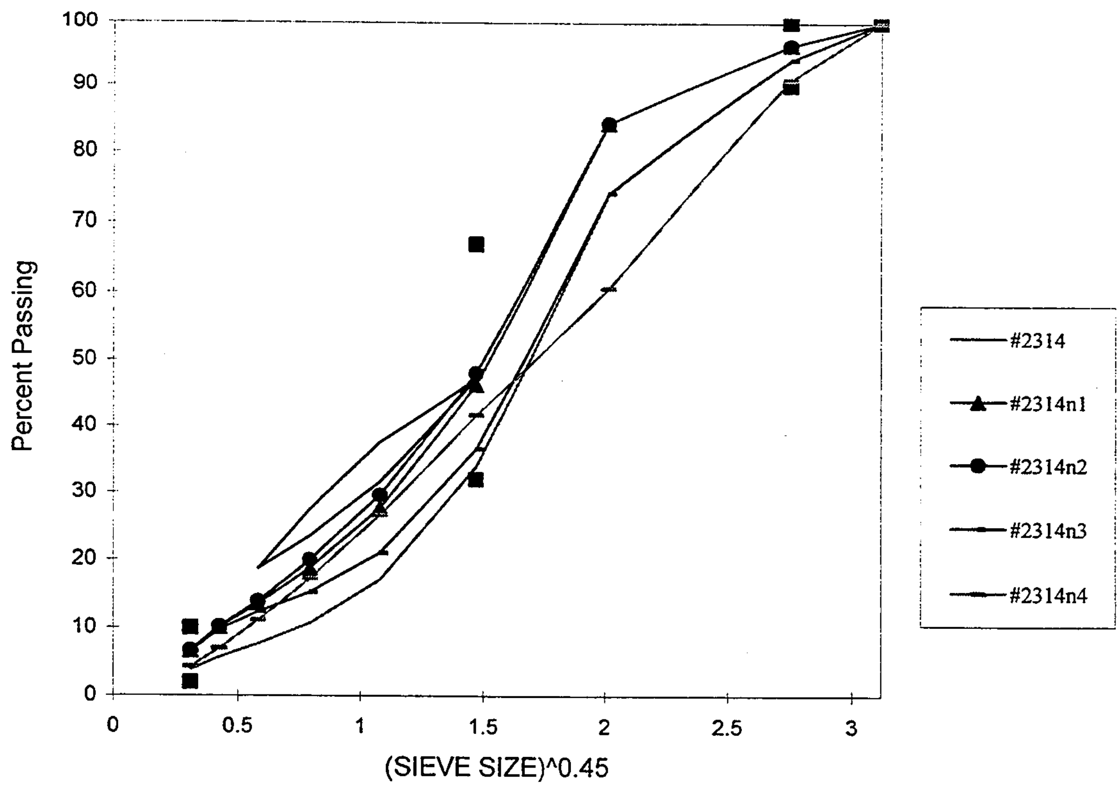

Figure 4.3 Gradations for Mixtures #2314 and #2314n1 to #2314n4

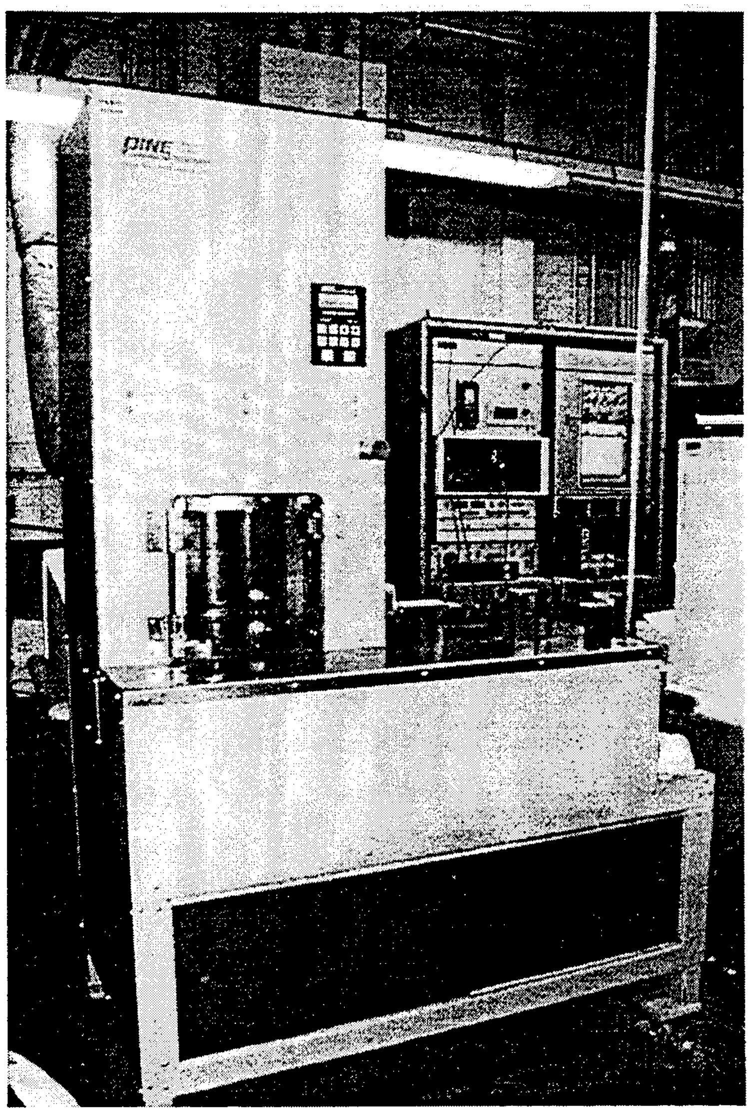

Figure 4.4 Pine Superpave Gyratory Compactor

Table 4.3 Mixture Design Results in Phase I

	FAA	Air Void(%)	AC(%)	MTSG	VMA(%)	VFA(%)	D/A
#2311	45	4.0	5.3	2.472	15.1	73.6	0.6
#2497	39	4.0	4.4	2.488	12.4*	68.8	1.1
#2164	49	4.0	5.4	2.455	15.0	73.4	1.0
#2211	48	4.0	5.0	2.481	15.3	73.3	1.0
#2478	47	4.4*	6.9	2.474	17.8	75	0.7
#2314	44	4.6*	7.5	2.402	18.6	75	0.6
B1	46	4.0	5.5	2.454	15.0	73.4	0.9
B2	45	4.0	5.3	2.453	14.8*	72.7	0.9
B3	43	4.0	5.0	2.441	14.4*	72.3	0.8

* These items do not meet Superpave criteria

Table 4.4 Mixture Design Results in Phase II

	FAA	Air Void(%)	AC(%)	MTSG	VMA(%)	VFA(%)	D/A
#2478n1	47	4.2	5.9	2.484	16.2	74.1	1.2
#2478n2	45.7	4	5.8	2.466	16.7	75.9*	0.9
#2478n3	47	4.3*	6.6	2.47	17.4	75.1	0.9
#2478n4	46.5	4.1	6.5	2.469	16.5	75.2	0.9
#2478n5	47	4.2	6.3	2.513	16.7	74.8	1.6
#2314n1	43.6	4.1	6.1	2.456	15.2	72.9	1.4
#2314n2	43	4.1	6.0	2.463	14.8	72.4	1.4
#2314n3	44	4.2	6.7	2.434	16.7	74.5	1.4
#2314n4	44	4.2	5.2	2.494	13.0*	67.7	1.1

* These items do not meet Superpave criteria

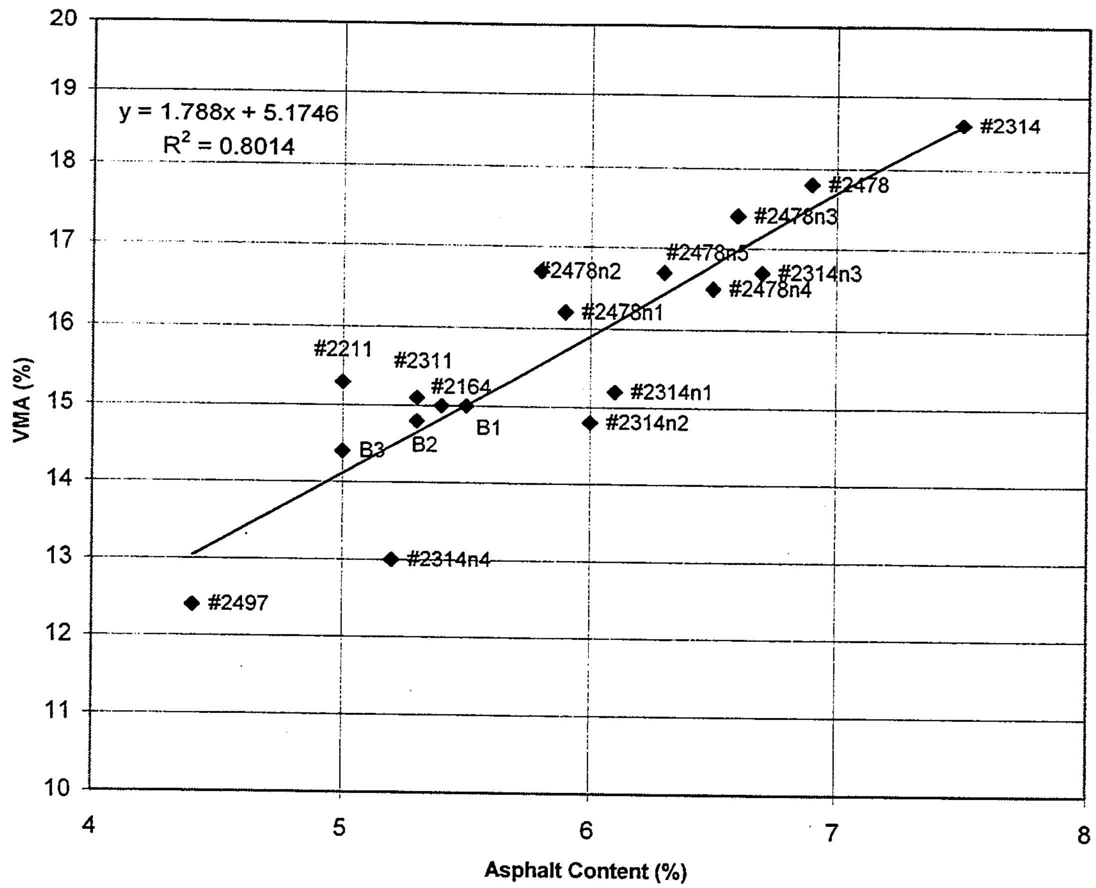

Figure 4.5 Relationship of VMA versus Asphalt Content

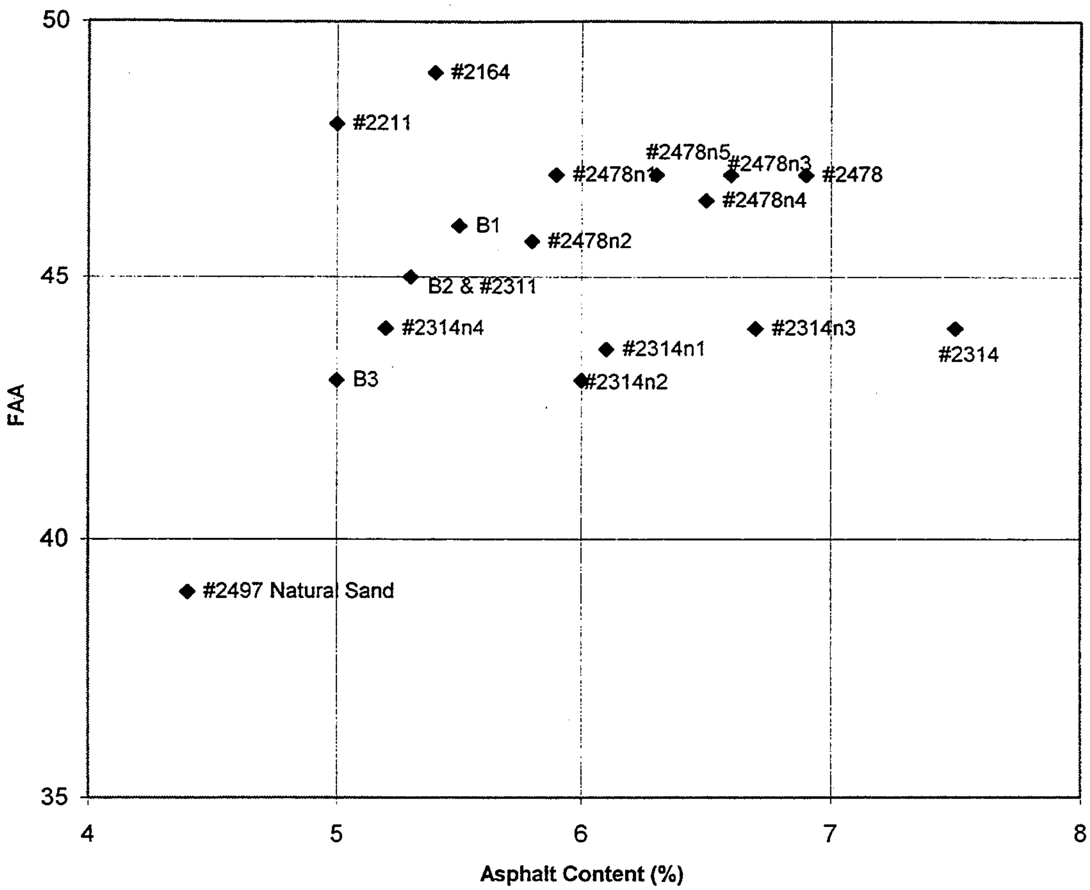

Figure 4.6 Relationship of FAA versus Asphalt Content

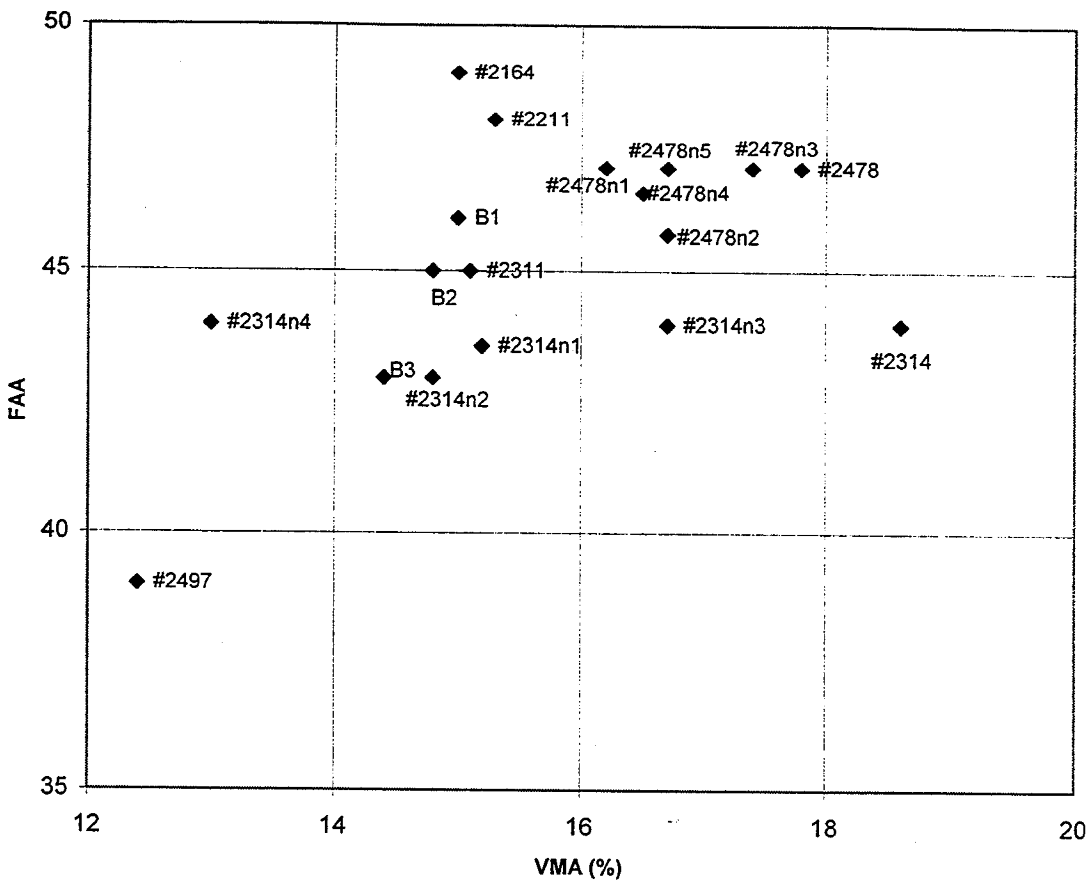

Figure 4.7 Relationship of FAA versus VMA

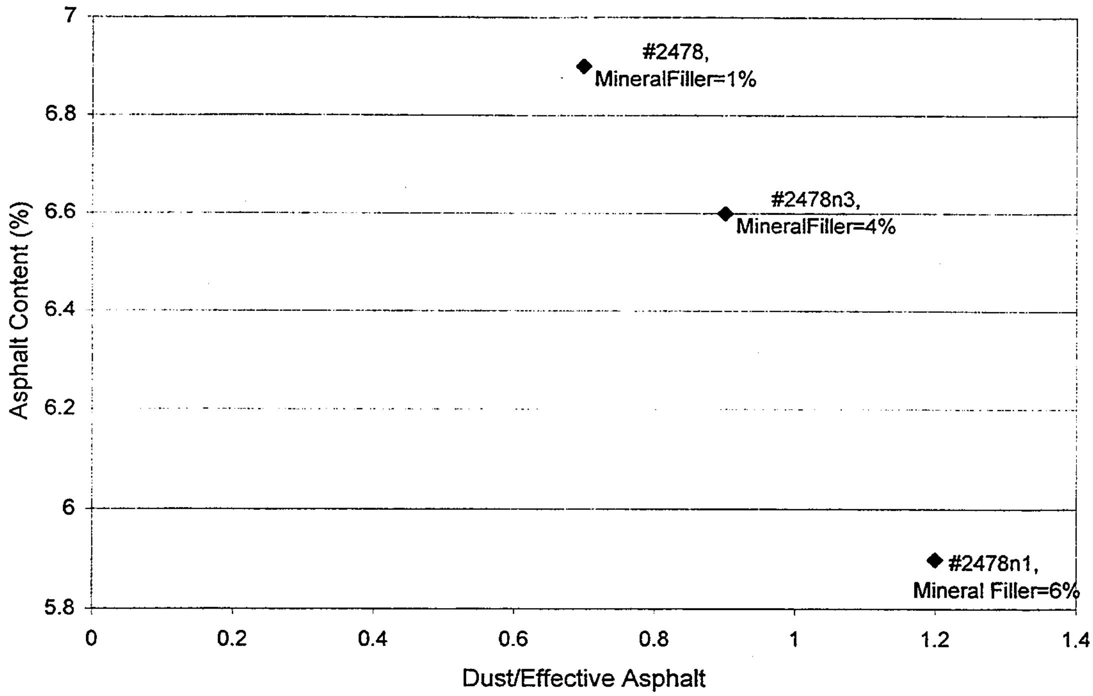

Figure 4.8 Dust Proportion versus Asphalt Content for Slag Mixtures

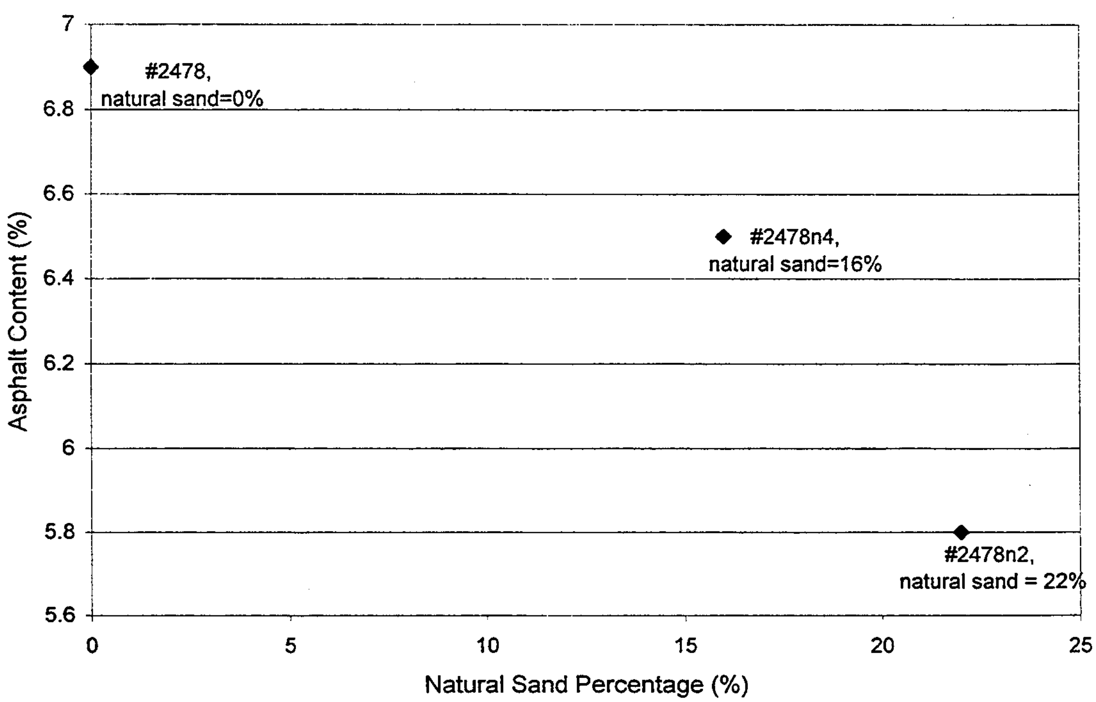

Figure 4.9 Natural Sand Percentage versus Asphalt Content for Slag Mixtures

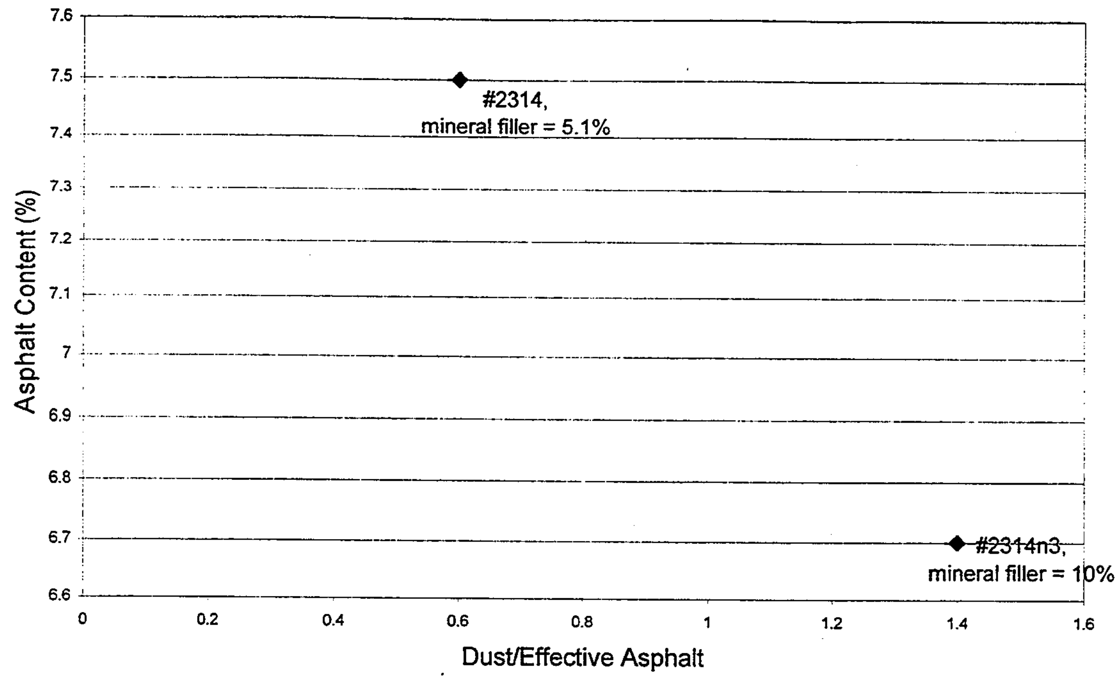

Figure 4.10 Dust Proportion versus Asphalt Content for Stone Sand Mixtures

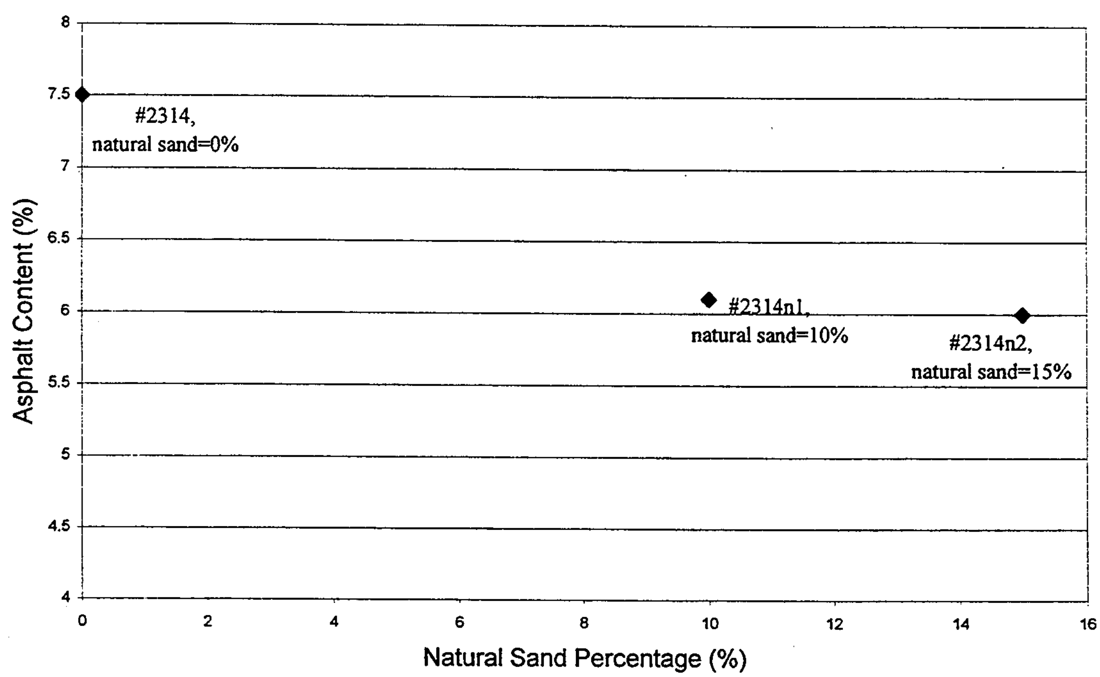

Figure 4.11 Natural Sand Percentage versus Asphalt Content for Stone Sand Mixtures

CHAPTER 5 PERFORMANCE TESTS ON MIXTURES

This chapter presents results of performance tests incorporated in this study. Tests included PURWheel Laboratory Tracking Device (WTD) and Simple Shear Test (SST). In the latter, frequency sweep, constant height and repeated shear, constant height tests were conducted.

5.1 Purwheel Laboratory Tracking Test

Two major pieces of equipment were developed for the laboratory wheel track testing. They are laboratory linear compactor and PURWheel Laboratory Tracking Device (WTD). The linear compactor was designed as a general tool to produce samples for PURWheel testing, bending fatigue tests and nuclear density test.

5.1.1 Compaction Device

PURWheel samples were prepared using the laboratory linear compactor shown in Figure 5.1. The design concept of this compactor is based on a similar device developed for Koch Materials. That compactor was used to prepare samples for the Hamburg Steel Wheel Tester (Habermann, 1994). Essential features of this compactor include a 304.8 mm x 622.3 mm rectangular steel mold attached to an air cylinder, a set of steel plates, a loading frame with a steel roller, and a hydraulic ram to apply a compactive force (Figure 5.2). The compactive force is applied to the steel plates through the loading frame and attached roller. Hydraulic pressure for the ram is provided by an electric powered hydraulic pump. With the hydraulic loading, asphalt mixtures can be compacted into slabs up to 127 mm thick. Target density can be achieved by compacting a specific amount of material into a certain volume.

Plan dimensions of slabs prepared for this study were 304.8 mm wide and 622.3 mm long. Since mixtures in this study were all surface mixtures, the slabs were compacted to 38 mm.

5.1.2 Wheel Tracking Device

The PURWheel Laboratory Wheel Tracking Device was originally designed as a flexible, general-purposed tester. The test environment can be either hot/wet or hot/dry. Test temperatures can vary from room temperature to 65°C. The wheel assembly provides for mounting different types of wheels (steel, rubber coated, or pneumatic). A close view of the assembly with a pneumatic wheel and sample box is shown in Figure 5.3. Figure 5.4 shows a general view of the PURWheel testing device.

In this study, a pneumatic wheel was used with a contact pressure of 793 kPa. The wheel was loaded to achieve a contact pressure of 620 kPa. The wheel velocity was 33 ± 2 cm /sec and the test conditions were dry/45°C, wet/45°C, dry/60°C, and wet/60°C for the nine mixtures in the first phase of this study. From results of the first phase, it was found that the dry/60°C test condition was effective in distinguishing the performance of mixtures. Therefore, in Phase II, each mixture was tested in the dry/60°C condition only.

Each specimen was subjected to 20,000 wheel passes or until 20 mm downward wheel path rutting developed. Figure 5.5 shows the transducer used to measure the downward wheel path rutting of the sample.

Two systems are used for dry heating. One involves circulation of hot water through machined channels in the faces of a set of plates bolted together. The plates are located in the bottom of the sample box. This allows the sample to be heated from the bottom. A second system uses air heaters as shown in Figure 5.6. The air heating system reduces the sample surface temperature differential and reduces the heating time.

5.1.3 Sample Preparation and Testing

The aggregate is first batched out in two steel pans, each holding about 7 to 8 kg of dry aggregate for every 19 mm (0.75 in.) thickness of slab. The pans of aggregate are placed in a forced draft oven and heated to the mixing temperature. When the mixing temperature is achieved, the aggregate and required amount of asphalt are combined and mixed using a mechanical drum mixer shown in Figure 5.7. After mixing, the mixture is placed in a pan and cured at 145°C for 1 to 2 hours in a forced draft oven prior to compaction. Procedures for using the linear compactor are as follows:

1. Preheat the mold to about 145°C by using an infrared heater,
2. Place a precut piece of brown wrapping paper at the bottom of the mold and then load the batches of mixture, carefully leveling the surface,
3. Place in consecutive order on the leveled mixture another piece of paper, a galvanized sheet metal plate, and the set of kneading plates,

4. Lower the loading frame and connect the hydraulic ram,
5. Lower the side cage panels and start compaction,
6. Compact the specimen to the desired thickness,
7. Allow the specimen to cool for about 2 to 3 hours,
8. Remove the specimen from the mold and cut the specimen in half, resulting in two test specimens,
9. Dry the specimens at room temperature, weigh and measure the length, width and thickness at eight locations (two on each edge),
10. Compute the volumetric density and voids relations.

Each half of the slab is placed in the wheel tracking device and grouted in place with plaster-of-Paris. After the plaster cures for about 30 minutes, the hood is closed and the control program is initiated. The following information is entered in the program for regular test conditions:

1. Type of test (wet or dry),
2. Test temperature (60°C for surface, 57.5°C for binder, and 54°C for base mixtures),
3. Pneumatic tire pressure (793 kPa inflation pressure),
4. Wheel path (fixed for these tests),
5. Total mass in load box (85kg for surface and binder mixtures, 56 kg for base mixtures),
6. Deformation measurements (average of 9 points near the center of the sample, 10 mm between each measurement point),
7. Data recording frequency (every 250 wheel passes),

8. Test criteria (sooner of 20,000 wheel passes or 20 mm of wheel path rutting), and

9. Conditioning time (20 minutes for wet testing and 60 minutes for dry testing after reaching target test temperature).

During the test, data are displayed on the monitor including number of wheel passes, wheel path rutting for each sample and elapsed test time. The control program ends the test based on the above test criteria. Data files can be transferred to a spreadsheet software for analysis and graphical presentation.

5.1.4 Wheel Track Testing Evaluation

Generally, pavement rutting includes two components. According to Huang (1995) and Pan (1997), these two components are wheel path rutting and plastic shear (uplift). The first component, the wheel path rutting occurs where the deformed surface is lower than the original pavement surface. The second component is where the deformed surface is higher than the original pavement surface. It is often referred to as "uplift" or "heave" and occurs between or outside the wheel paths.

Wheel Path rutting during PURWheel test is measured with a transducer as shown in Figure 5.5 and recorded. The data recorded includes only the wheel path rutting. Total or "stringline" rutting is measured manually after completion of the test. Difference in the total rut and wheel path rutting is the plastic or "heave" rutting component. A relationship was developed (Pan, 1997) between wheel track rutting measured by the transducer and total rutting. This data represents numerous types of mixtures. This relationship has a goodness fit of 0.96. The relationship is:

Total Rut Depth = 0.0153(Wheel Path Rut) ^{2} + 1.3144(Wheel Path Rut)............(5.1)

Where:

Wheel Path Rut = Wheel track deformation as measured by the transducer, mm

Total Rut Depth = Total rut depth under the straight edge, mm

For each mixture, quadruplicate samples were prepared and tested to include the effect of sample variation. The data were normalized in two ways for each mixture. First, the number of wheel passes to produce a 6.35-mm rut depth is determined. This corresponds to a wheel path rut of 4.6-mm according to Equation 5.1. Selection of the rutting level to use was predicated on the level being reasonable and sensitive to the mixtures being tested in the study. For samples with measured wheel path rut of 4.6-mm before 20,000 wheel passes, the first number of wheel passes to reach or exceed 4.6-mm is used. For samples with measured wheel path rut not reaching 4.6-mm, a linear rate of deformation is determined using the data points from 5,000 to 20,000 wheel passes. The number of wheel passes at 4.6-mm wheel path rut can be calculated from the linear function. This procedure is illustrated in Figure 5.8 for mixture #2478n5.

Secondly, wheel path rut depth at a specific percent air voids is determined. This was done by regression analysis of the wheel passes and air voids of the four tested samples. Although the compaction level for each sample was targeted at 6 percent air voids, variation does occur. Since, from past experience, the rutting performance is sensitive to air voids, the normalization is done to ensure the mixtures can be compared on the same basis. This procedure for mixture #2478n5 is shown in Figure 5.9 as an example. The wheel passes for each test sample and after normalization are shown in Table 5.1 and Table 5.2 for Phase I and II, respectively.

5.1.5 Test Results

Results from PURWheel laboratory tests are shown in Figure 5.10 to Figure 5.36. Figure 5.10 to Figure 5.27 show Phase I mixture PURWheel test results for both dry/60°C and wet/60°C conditions. Although test conditions of dry/45°C and wet/45°C were conducted on the mixtures of Phase I, the results did not delineate differences in mixture performance. Tests conducted in dry/45°C and wet/45°C are shown in Appendix D.

Figure 5.28 to Figure 5.36 show test results for the nine mixtures in Phase II. Mixtures in Phase II were tested dry/60°C because tests conducted for this condition were effective in distinguishing the rutting performance of mixtures in Phase I.

5.2 Simple Shear Test

5.2.1 Introduction

Test procedures followed AASHTO Designation: TP7-94, "Standard Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device". According to this standard, six tests are typically conducted with the Simple Shear Test Device:

- volumetric test,

- uniaxial strain test,
- repeated shear test at constant height,
- repeated shear test at constant stress ratio,
- simple shear test at constant height, and
- frequency sweep test at constant height.

The volumetric and uniaxial strain tests were recommended for what was termed the Superpave Level Three Mixture Design. The repeated shear test at constant height (RSCH) is a stand-alone test and it is not a part of the Superpave mixture design and analysis system. Level Two (also part of the original Superpave terminology) and Level Three designs used repeated shear at constant stress ratio, simple shear at constant height, and frequency sweep at constant height tests (FSCH). In this study, the frequency sweep at constant height and repeated shear at constant height tests were conducted.

5.2.2 Sample Preparation

Samples for the shear test were prepared following SHRP Method of Test M-003 (Harrigan et. al. 1994) using a Pine Superpave Gyratory Compactor (SGC). The number of gyrations was estimated from the mix design information of each mix to obtain seven percent air voids. The specimens were cut to a thickness of 50 mm. Table 5.3 lists the number of gyrations used to prepare the samples and the bulk specific gravity of each sample.

Samples were epoxyed to aluminum loading platens with adhesive before testing. A platen-specimen assembly device was used to facilitate bonding the top and bottom ends of the specimen to the loading platens. The gluing operation as well as the platen-specimen assembly device are shown in Figure 5.37. Figure 5.38 shows the testing chamber of the shear test device.

5.2.3 Frequency Sweep, Constant Height Test

In the frequency sweep, constant height test, a repeated sinusoidal shearing load is applied to the specimen to achieve a controlled shearing strain of 0.005 percent. One hundred cycles are used for the test at each of the following frequencies: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz.

As the specimen shears, dilation occurs, which increases its height. The vertical load actuator uses the signal from the vertical axial LVDT to apply sufficient axial stress to maintain the specimen height constant. During the test, axial and shear loads and horizontal deformation are measured and recorded. Figure 5.39 illustrates the shearing strains and axial stresses applied during the test.

5.2.4 Repeated Shear, Constant Height Test

The repeated shear, constant height test is not a Superpave requirement. The test is conducted by applying a load cycle for 0.7-second, which includes an impulse 0.1-second shear load and followed by a 0.6-second rest period. The test is stopped when the sample is subjected 5,000 load cycles or until the permanent shear strain reaches five percent. Figure 5.40 shows the stress pulses applied during the test.

5.2.5 Test Results

Figure 5.41 shows the relationship of complex modulus from the frequency sweep, constant height test at 10 Hz and mixture asphalt content. It is believed that the applied strain level is so low that only the effect of the asphalt is reflected. The effect of the aggregate and aggregate structure is minimal in this test.

Figures 5.42 to 5.44 show the results of the repeated shear, constant height test. The results for Phase I mixtures are shown in Figure 5.42. Figure 5.43 shows the results of all the slag sand (#2478) mixtures. Figure 5.44 shows results of all of the limestone sand (#2314) mixtures. Numbers of loading cycles at one and two percent shear strains as well as the shear strain at end of test are listed in Table 5.4

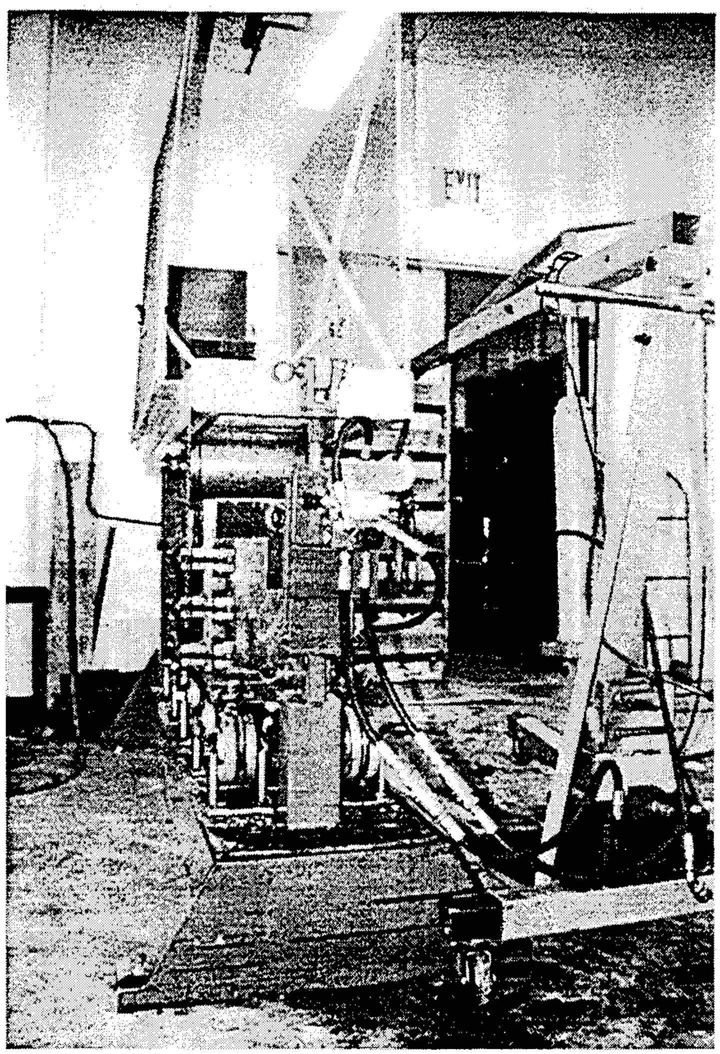

Figure 5.1 Purdue Laboratory Linear Compactor

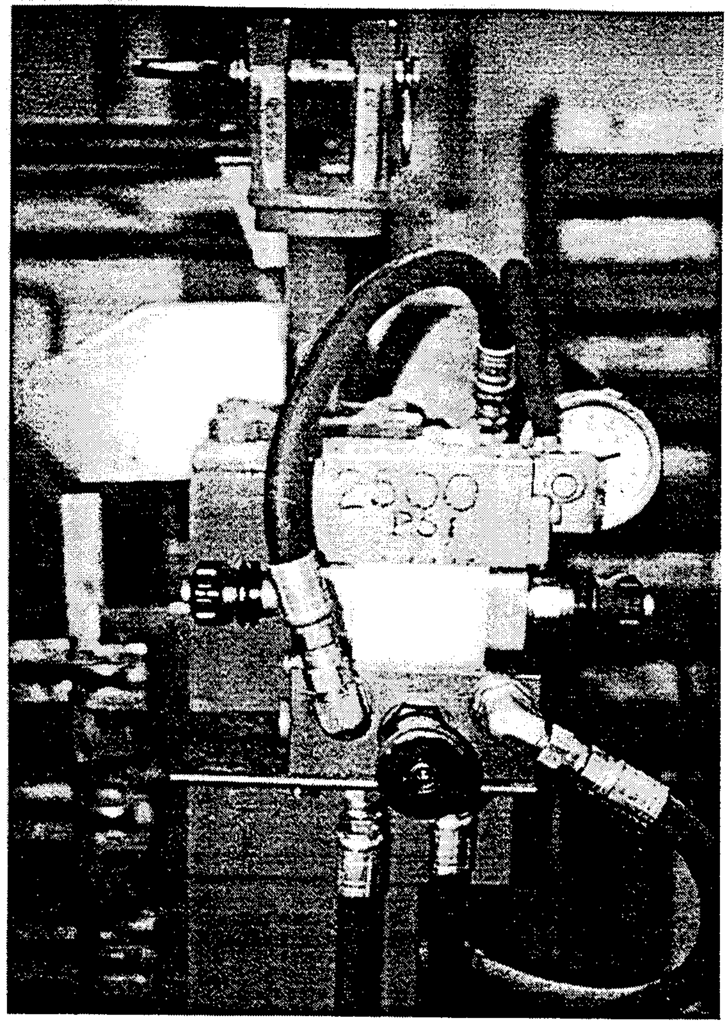

Figure 5.2 Hydraulic Loading Ram

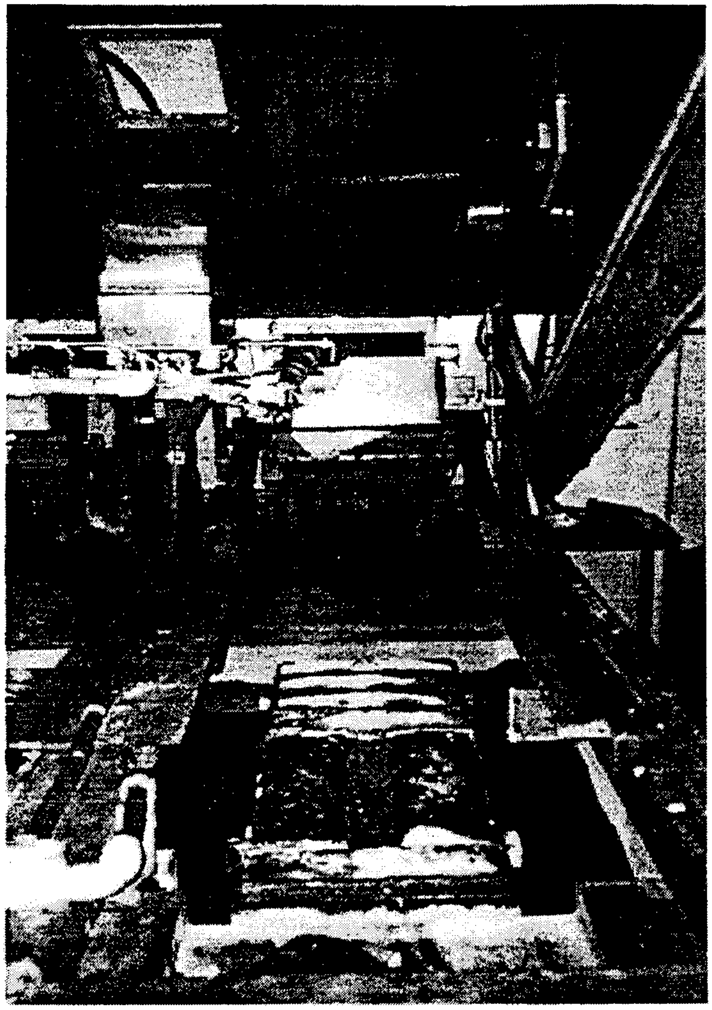

Figure 5.3 Pneumatic Wheel Assembly and Sample Mounting Box in PURWheel

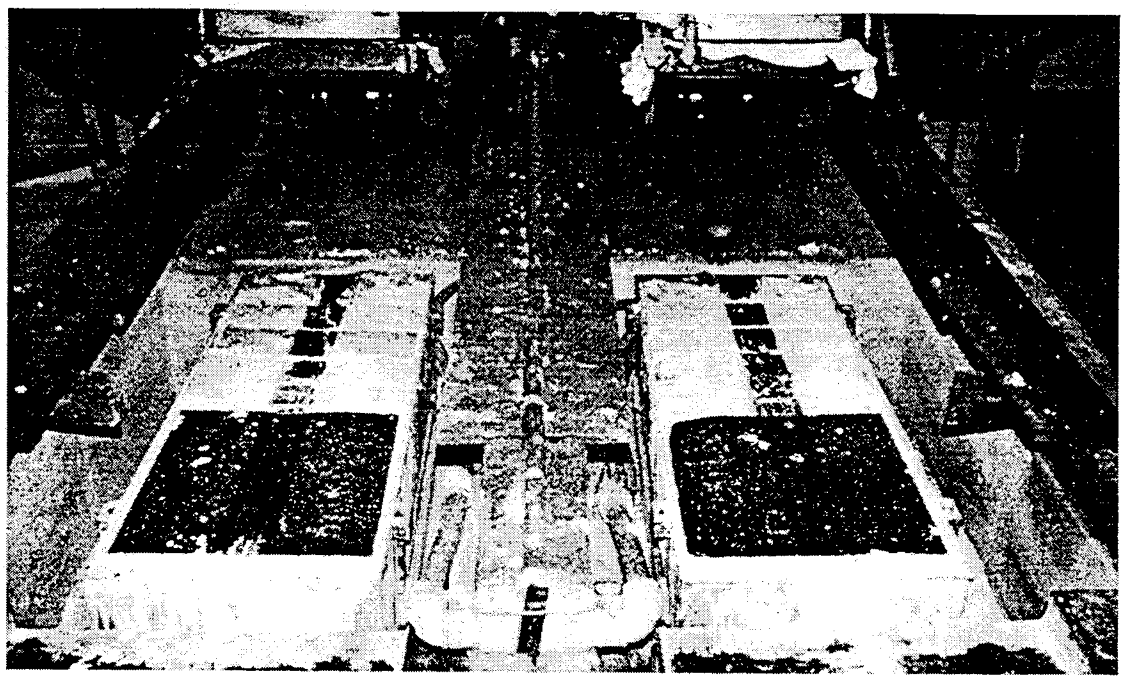

Figure 5.4 PURWheel Testing Device

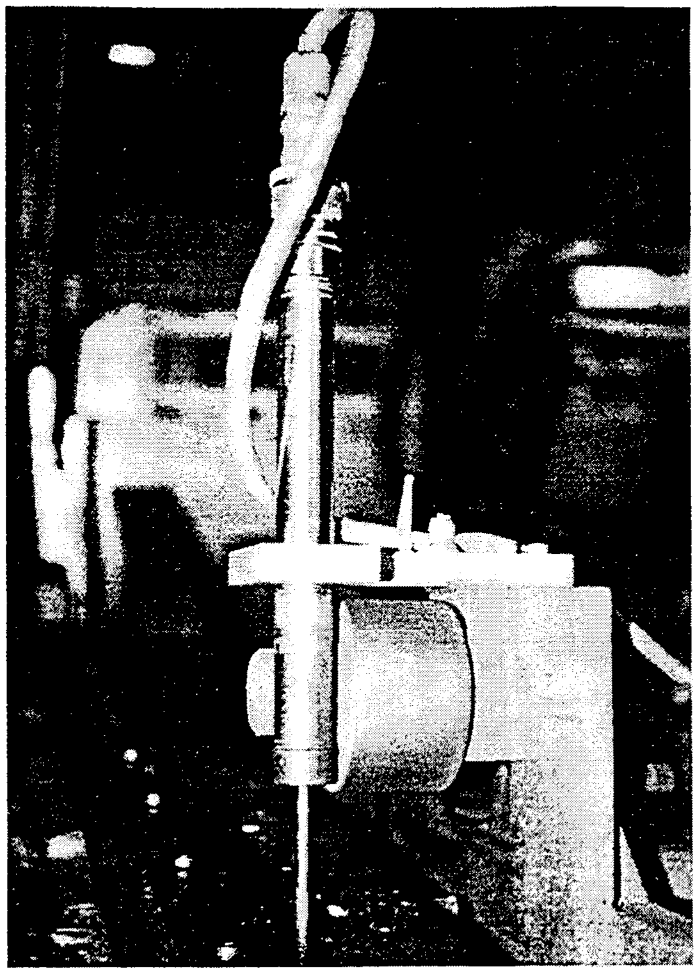

Figure 5.5 PURWheel Transducer

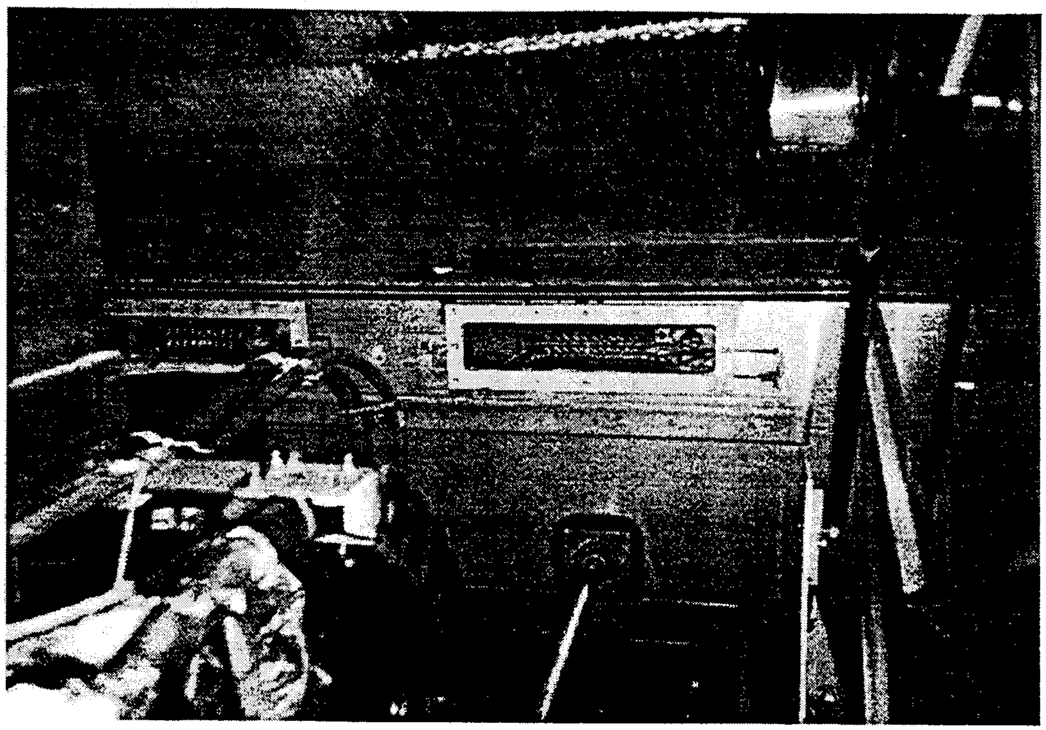

Figure 5.6 PURWheel Air Heater

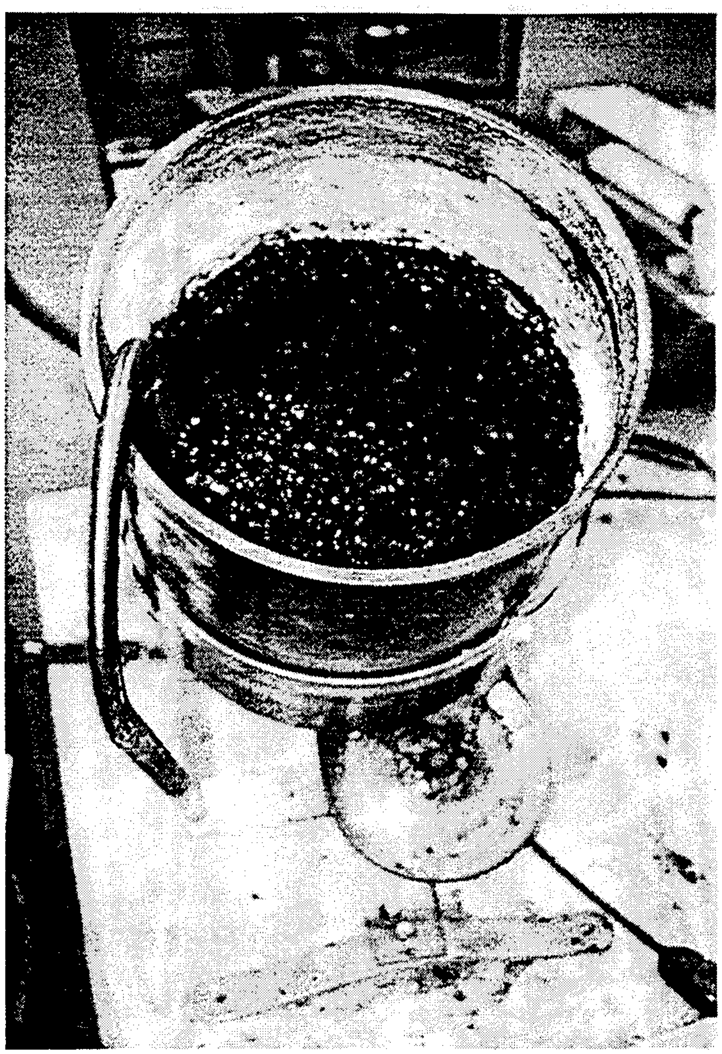

Figure 5.7 Mechanical Drum Mixer

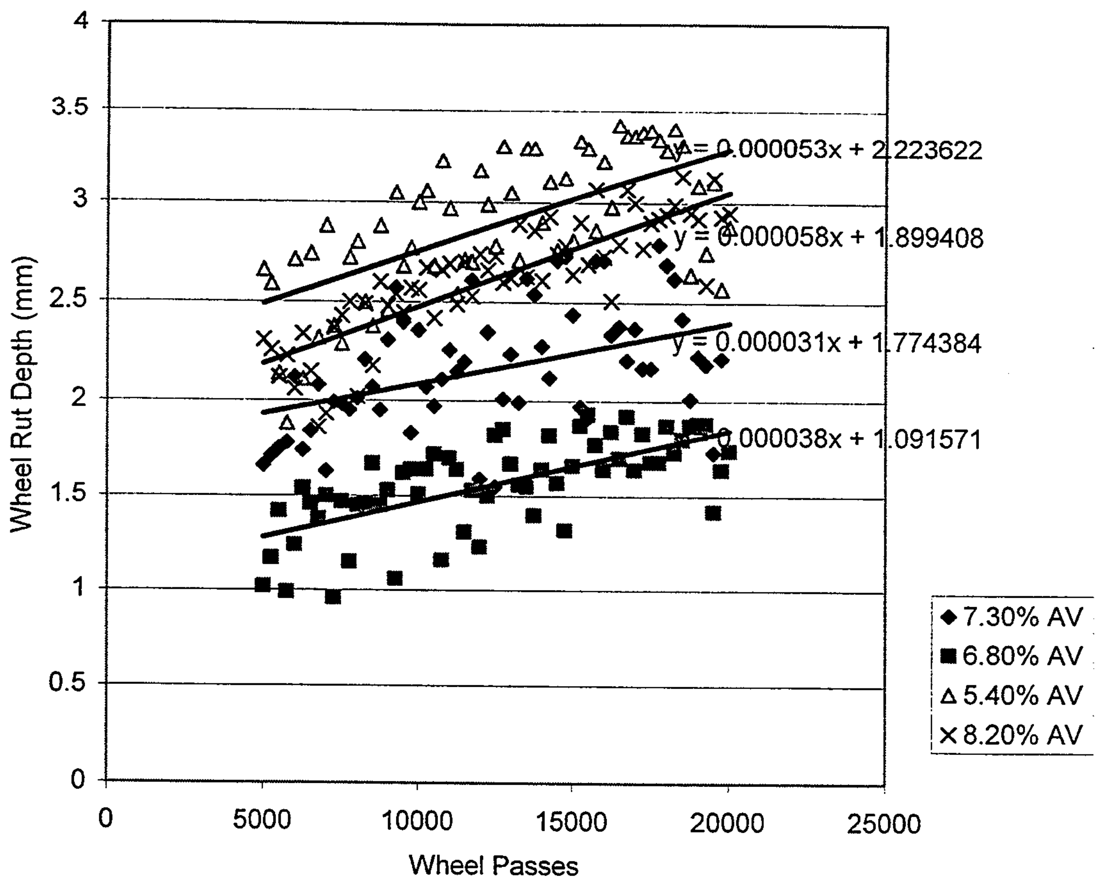

Figure 5.8 Regression Analysis to Determine the Number of Wheel Passes to 4.6-mm Wheel Path Rut for Mixture #2478n5

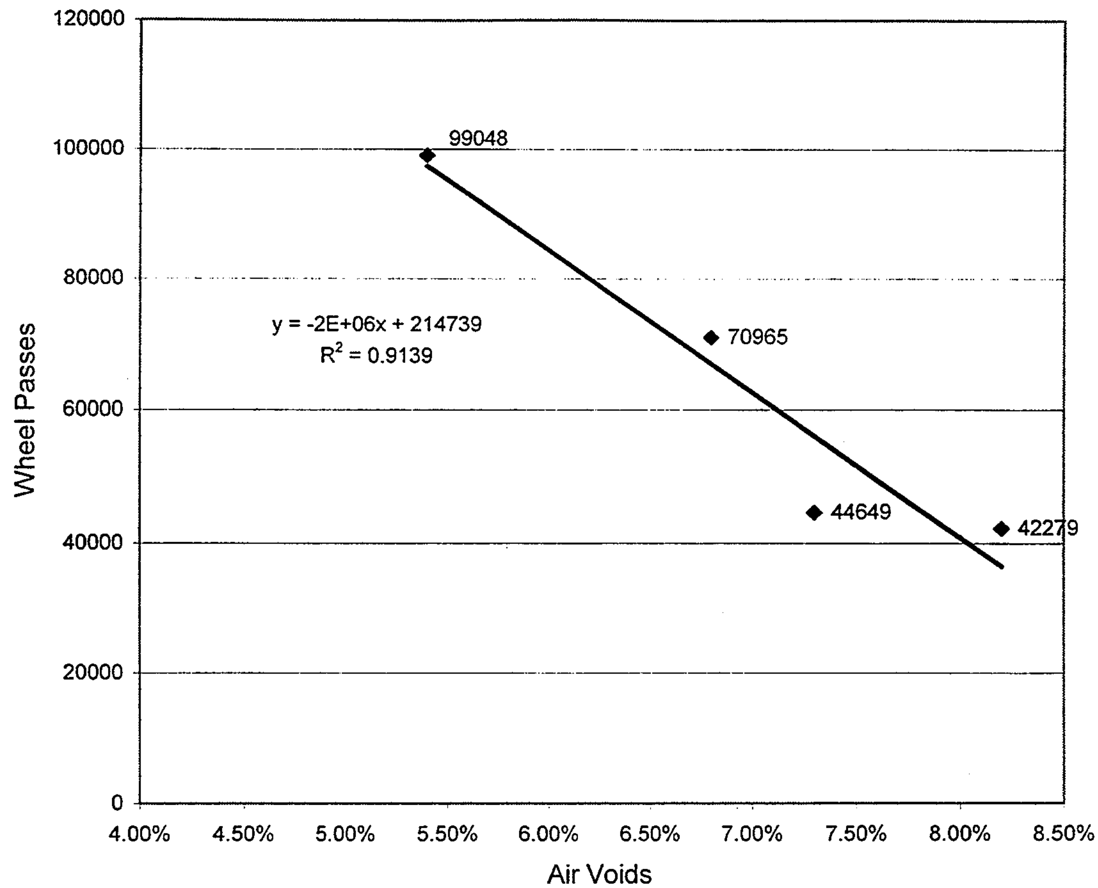

Figure 5.9 Regression Analysis to Determine the Number of Wheel Passes at a Specific Air Void for Mixture #2478n5

Table 5.1 PURWheel Test Results in Phase I

Mix ID	*FAA*	*AC(%)*	*VMA*	*60 °C Dry Test (Air Void, %)*	*Passes @ 6% Air Void*	*60 °C Wet Test (Air Void, %)*	*Passes @ 6% Air Void*
#2311 Limestone Sand	45	5.3	15.1	18748(6.53)	53063	19500(7.57)	18282
				51067(6.66)		18000(6.5)	
				73104(6.13)		9750(7.18)	
				67000(7.08)		8750(9.57)	
#2497 Natural Sand	39	4.4	12.4	13500(5.9)	8169	3750(6.06)	2938
				5500(5.04)		2250(7.24)	
				5500(7.08)		1500(6.38)	
				13750(7.2)		1250(6.95)	
#2478 Slag Sand	47	6.9	17.8	6500(6.35)	4327	1750(7.98)	3703
				5750(8.92)		4000(6.45)	
				3250(5.83)		2250(7.05)	
				3750(6.78)		1250(7.01)	
#2211 Dolomite Sand	48	5.0	15.3	38205(7.21)	43709	6750(6.83)	14191
				35620(7.99)		13000(6.81)	
				41236(6.66)		17500(5.77)	
				69405(8.77)		5750(9.16)	
#2164 Crushed Gravel Sand	49	5.4	15.0	27178(9.51)	131539	9750(6.01)	12424
				100000(7.55)		7250(6.58)	
				100163(5.08)		3500(6.97)	
				102997(7.86)		16250(5.81)	
#2314 Limestone Sand	44	7.5	18.6	46287(5.51)	32493	3750(7.98)	4547
				25052(6.28)		4000(7.20)	
				12250(9.75)		1250(8.34)	
				18904(6.78)		6500(3.55)	
B1 (26% of 2497 & 74% of 2164)	46	5.5	15.0	11250(8.92)	73366	10250(5.89)	11910
				32910(7.77)		16250(7.06)	
				81707(6.17)		10500(7.35)	
				12250(7.05)		9750(8.0)	
B2 (36% of 2497 & 64% of 2164)	45	5.3	14.8	30493(9.06)	69115	3750(8.07)	9213
				38581(7.44)		11750(5.67)	
				107590(5.10)		6000(7.62)	
				7250(9.8)		6500(6.15)	
B3 (56% of 2497 & 44% of 2164)	43	5.0	14.4	50043(6.55)	51228	2000(5.65)	7656
				40956(9.56)		1750(7.36)	
				51227(6.42)		3250(6.73)	
				44352(7.38)		6000(6.56)	

Table 5.2 PURWheel Test Results in Phase II

Mix ID	*FAA*	*AC(%)*	*VMA*	*60℃ Dry Test (Air Void,%)*	*Passes @ 6% Air Void*
#2478n1 (Mineral Filler = 6%)	47	5.9	16.2	40945(6.2) 13750(9.1) 59279(4.2) 68997(3.8)	43867
#2478n2 (22% of Natural sand)	45.7	5.8	16.7	54094(5.6) 33170(7.2) 35370(5.3) 5000(7.7)	37901
#2478n3 (Mineral Filler = 4%)	47	6.6	17.4	12250(5.4) 11000(6.7) 7750(8.6) 15750(5.4)	12719
#2478n4 (16% of Natural sand)	46.5	6.5	16.5	25690(6.0) 18250(7.1) 28820(5.1) 16750(8.1)	24872
#2478n5 (Gradation above restricted zone)	47	6.3	16.7	44649(7.3) 70965(6.8) 99048(5.4) 42279(8.2)	84339
#2314n1 (10% of Natural sand)	43.6	6.1	15.2	13000(8.8) 41590(4.0) 12250(6.3) 25737(6.4)	25341
#2314n2 (15% of Natural sand)	43	6.0	14.8	11250(6.4) 44384(4.4) 27708(6.5) 23112(7.3)	28230
#2314n3 (Mineral Filler = 10%)	44	6.7	16.7	45691(6.0) 11250(6.4) 70965(5.0) 11000(7.2)	39155
#2314n4 (Artificial Gradation)	44	5.2	13.2	68568(6.3) 35620(6.6) 24459(7.3) 139182(5.1)	84776

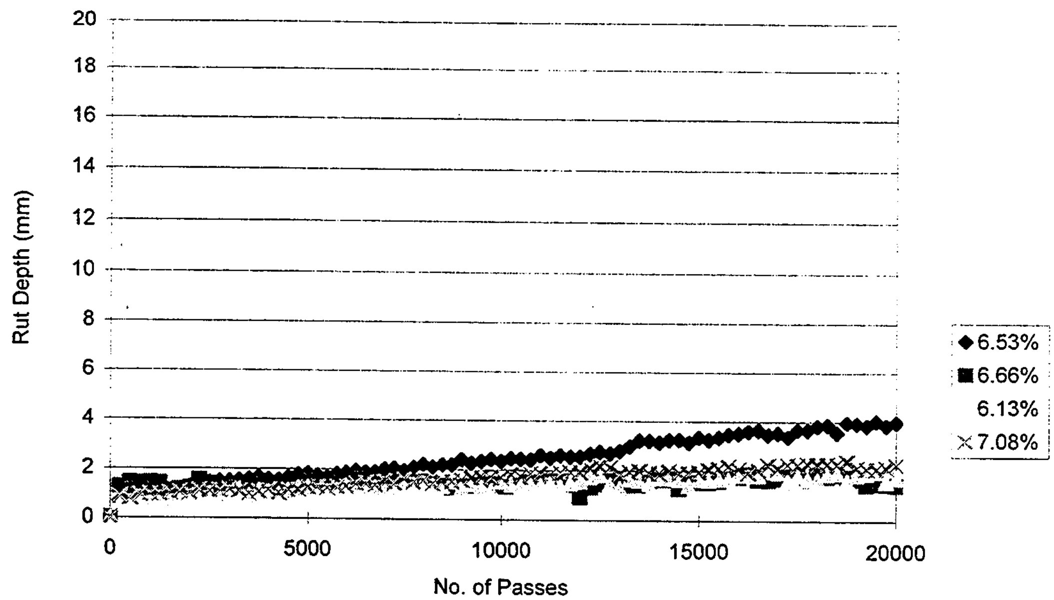

Figure 5.10 PURWheel Test Result for #2311 in Dry/60°C

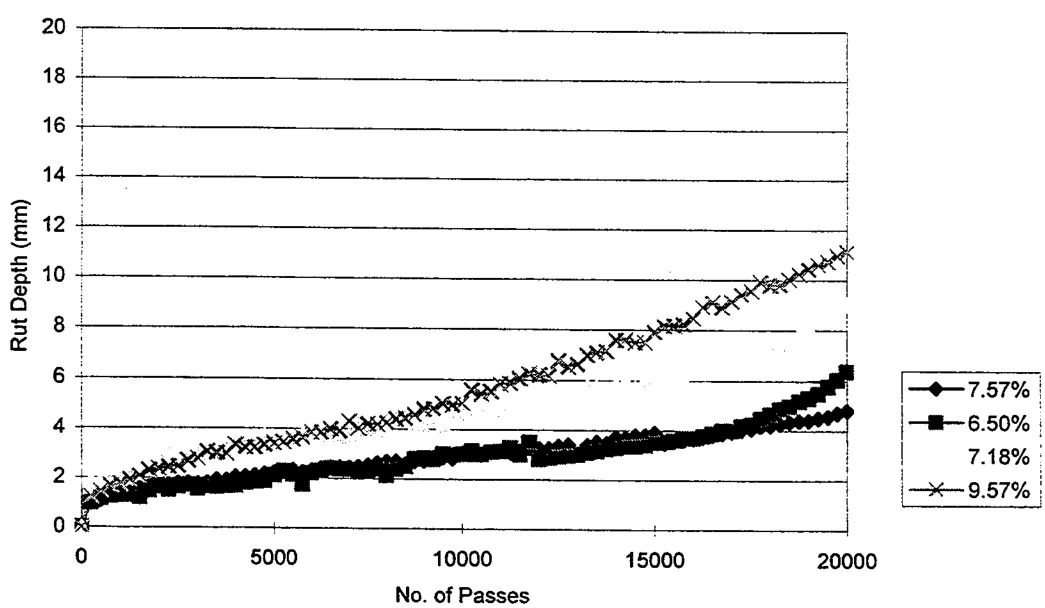

Figure 5.11 PURWheel Test Result for #2311 in Wet/60°C

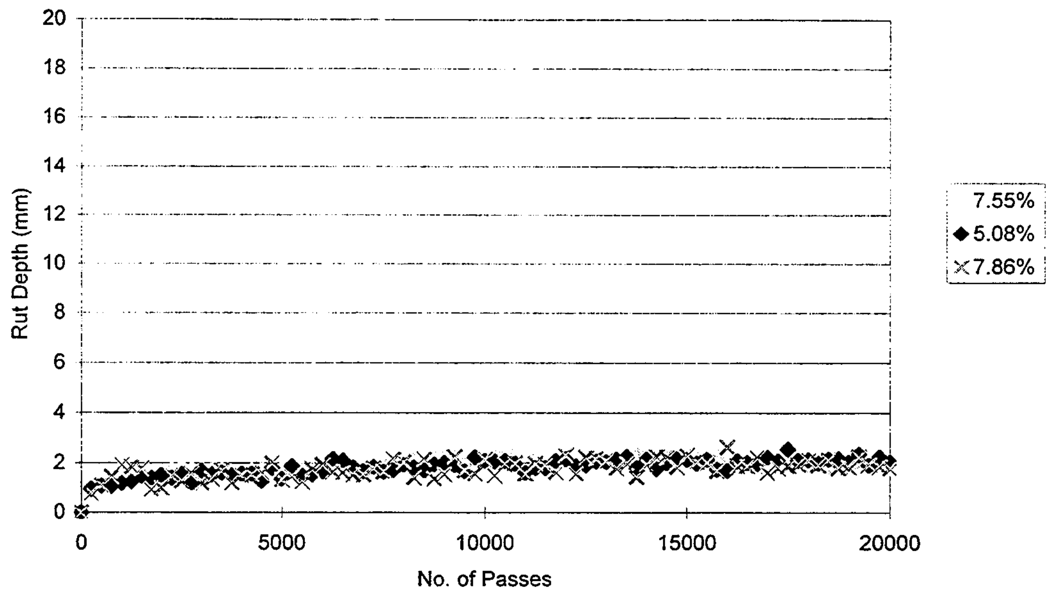

Figure 5.12 PURWheel Test Result for #2164 in Dry/60°C

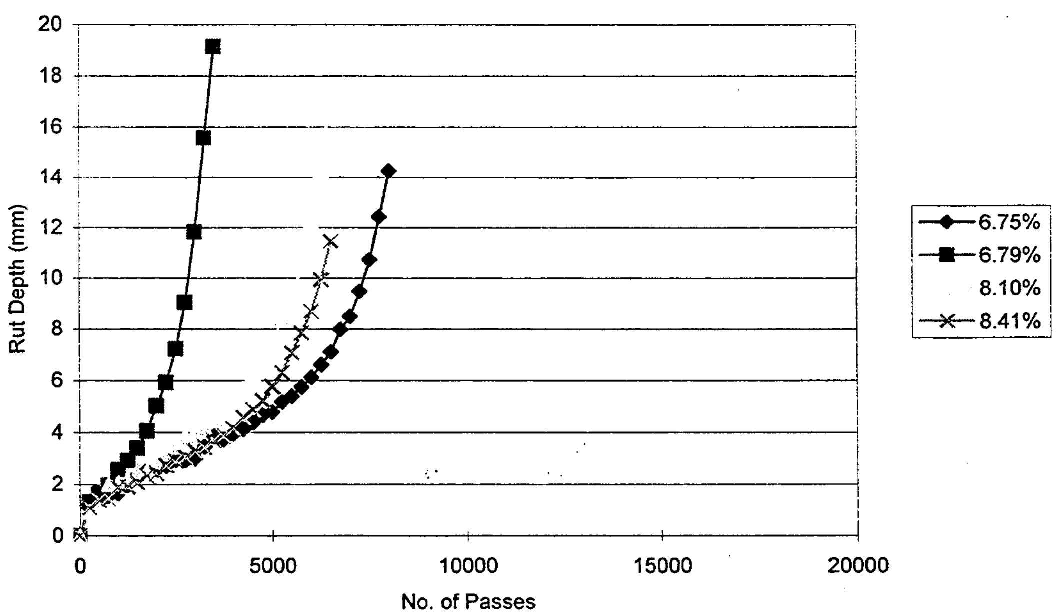

Figure 5.13 PURWheel Test Result for #2164 in Wet/60°C

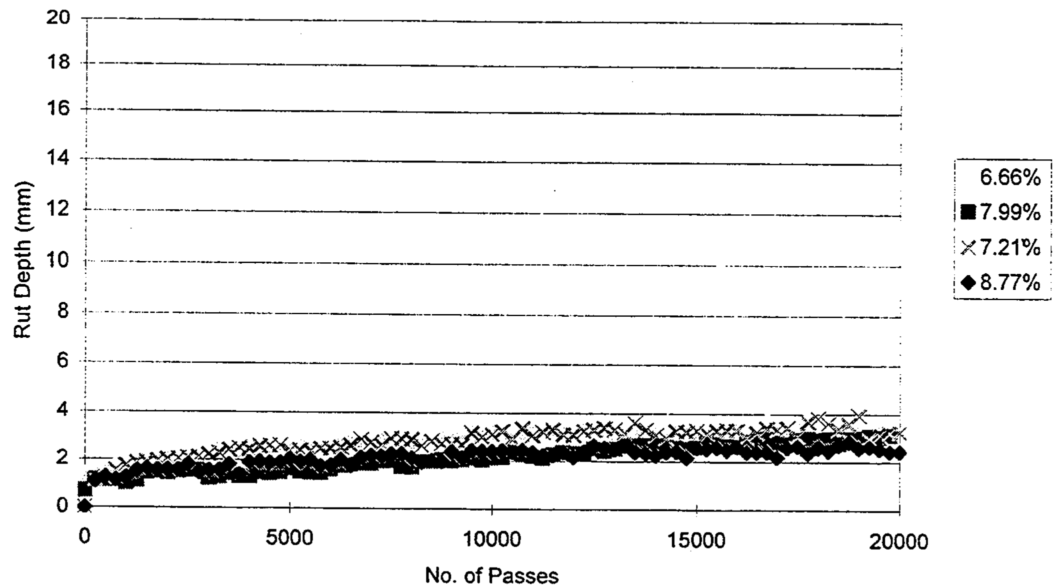

Figure 5.14 PURWheel Test Results for #2211 in Dry/60°C

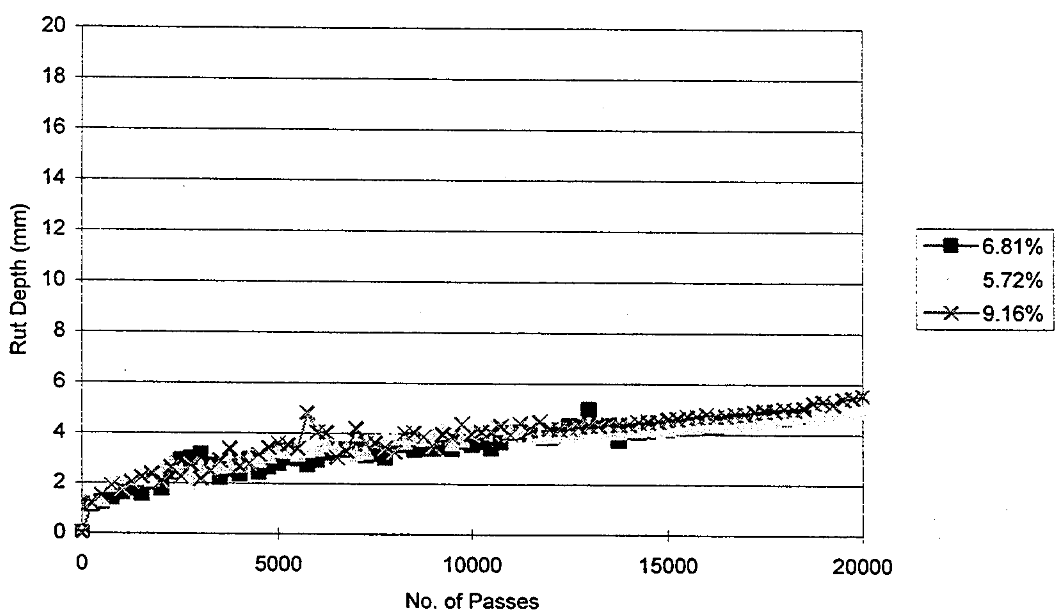

Figure 5.15 PURWheel Test Results for #2211 in Wet/60°C

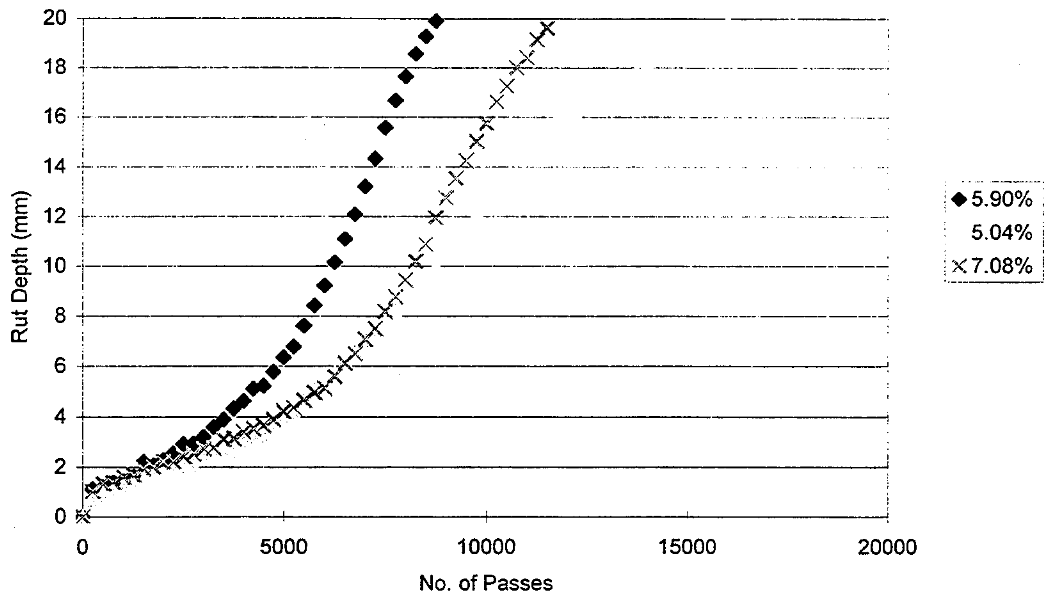

Figure 5.16 PURWheel Test Results for #2497 in Dry/60°C

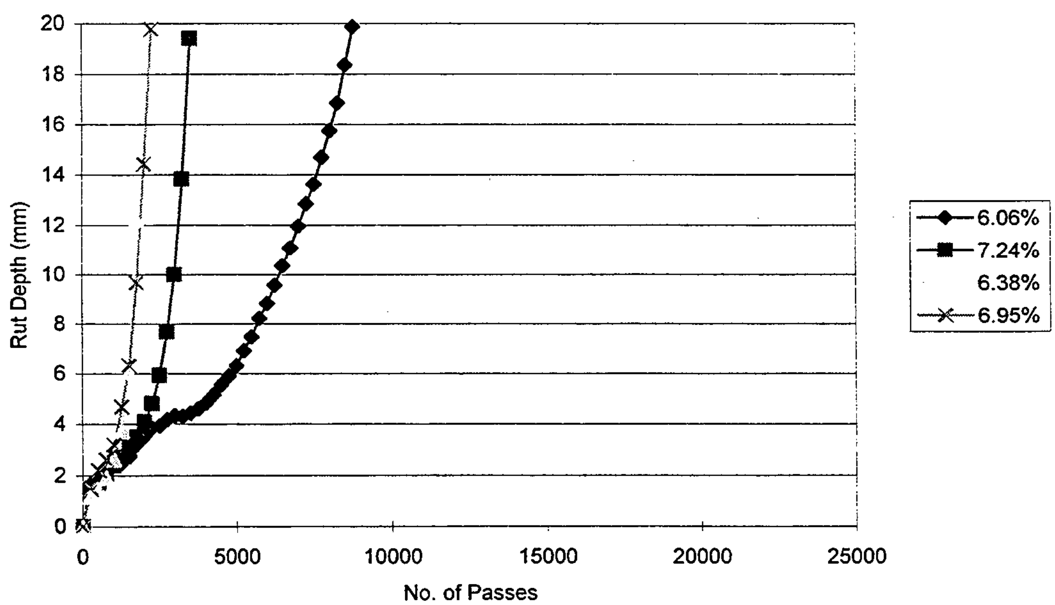

Figure 5.17 PURWheel Test Results for #2497 in Wet/60°C

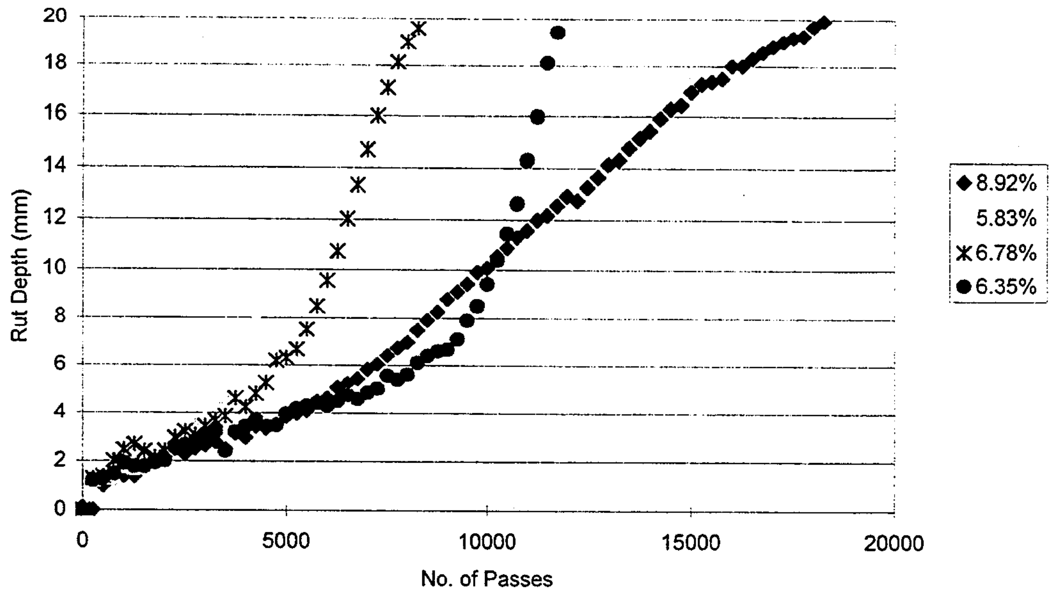

Figure 5.18 PURWheel Test Results for #2478 in Dry/60°C

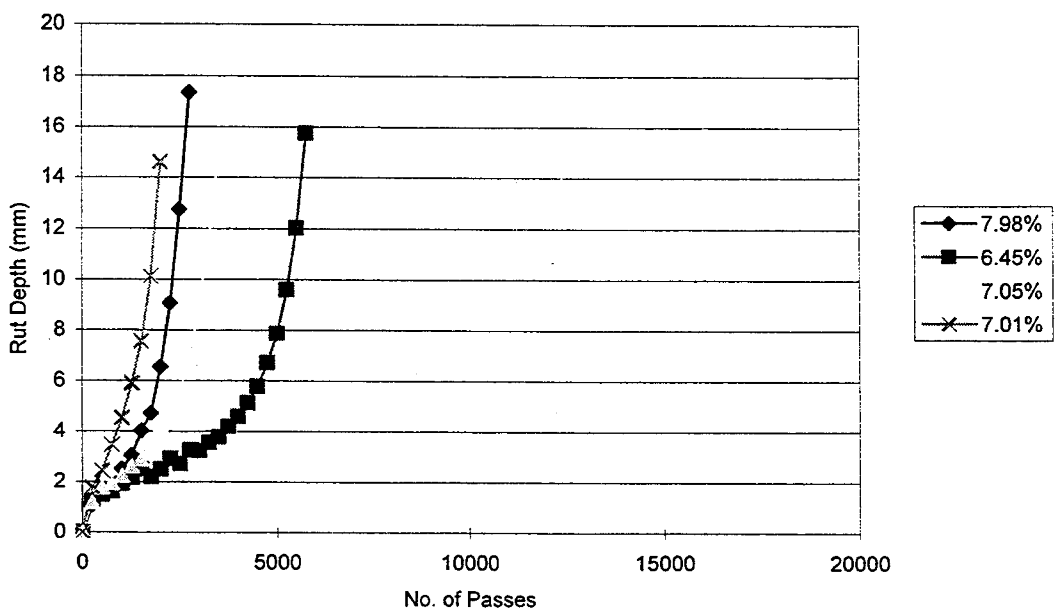

Figure 5.19 PURWheel Test Results for #2478 in Wet/60°C

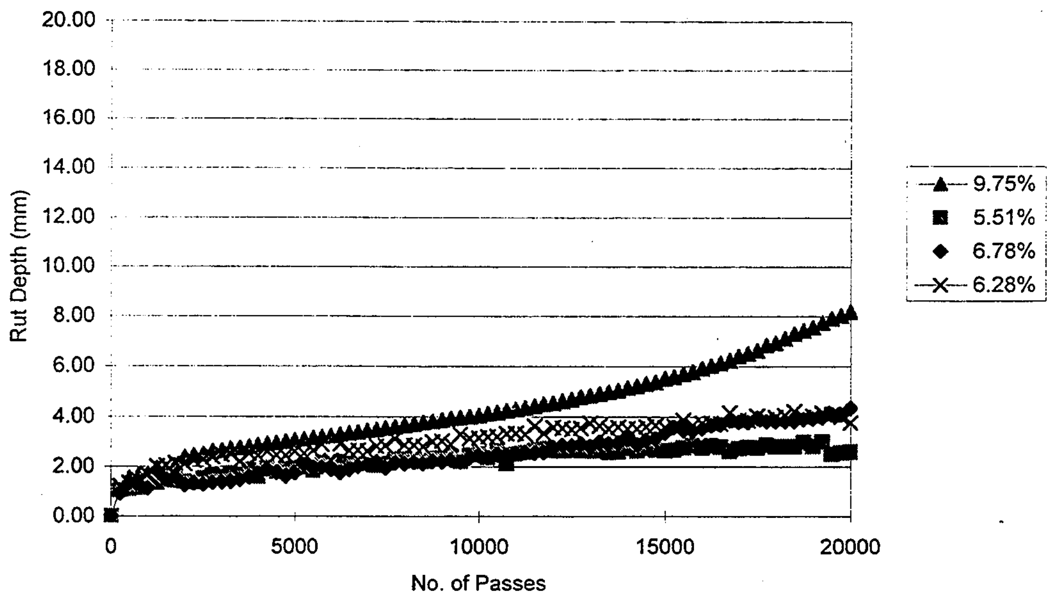

Figure 5.20 PURWheel Test Results for #2314 in Dry/60°C

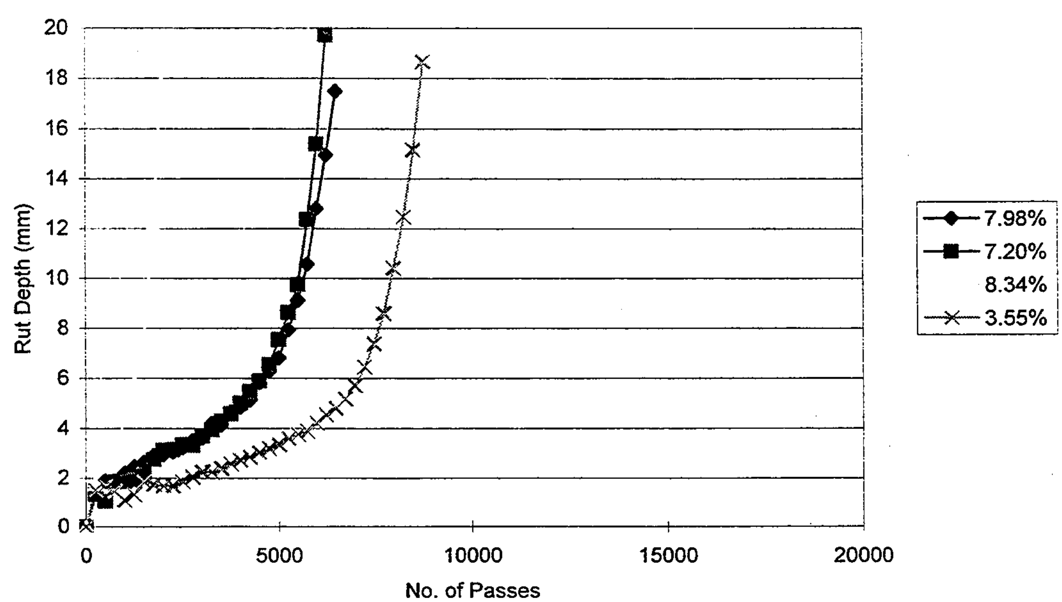

Figure 5.21 PURWheel Test Results for #2314 in Wet/60°C

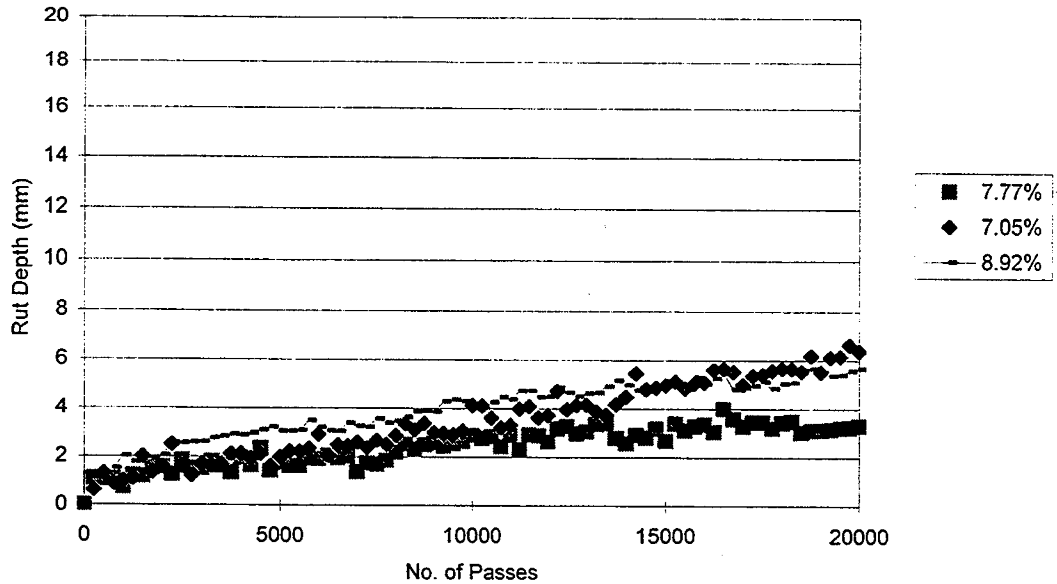

Figure 5.22 PURWheel Test Results for B1 in Dry/60°C

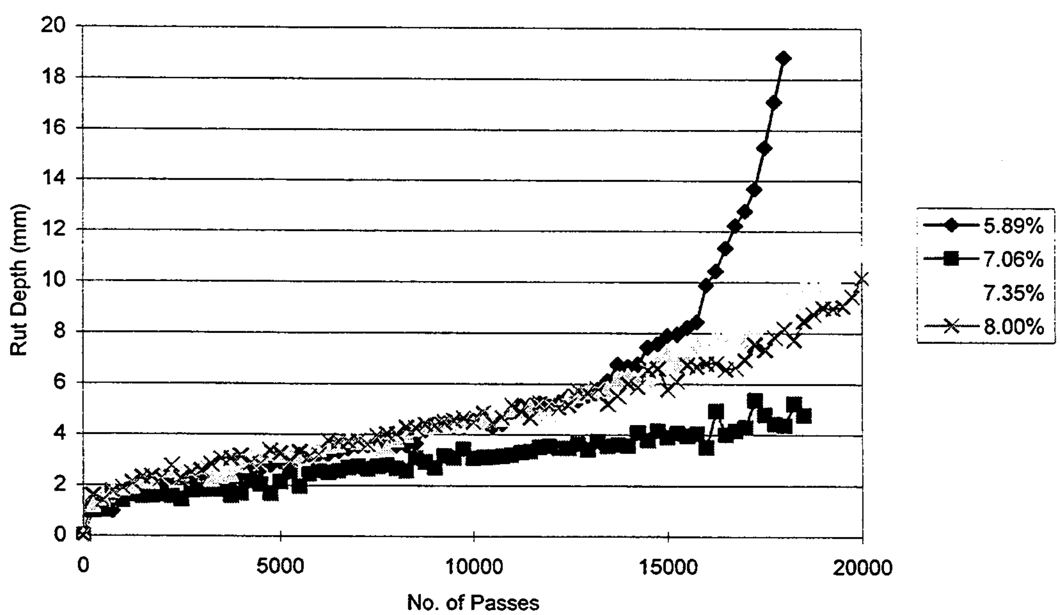

Figure 5.23 PURWheel Test Results for B1 in Wet/60°C

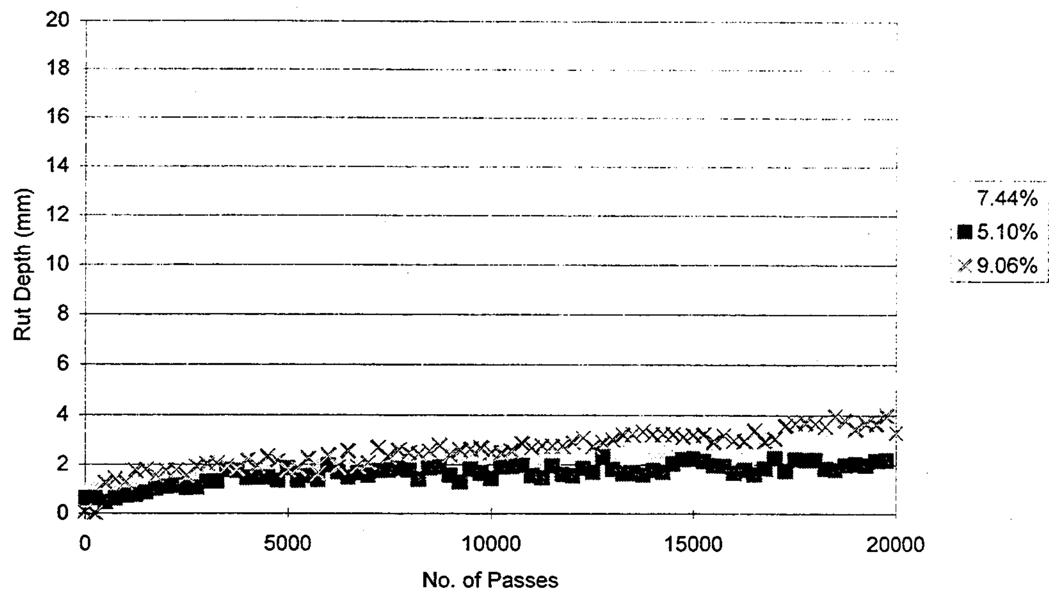

Figure 5.24 PURWheel Test Results for B2 in Dry/60°C

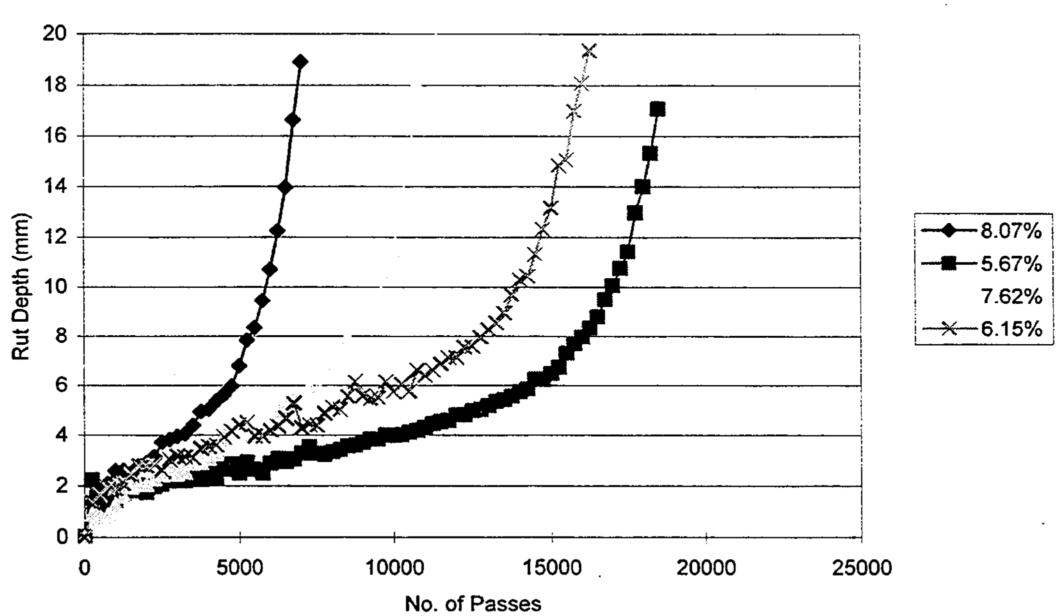

Figure 5.25 PURWheel Test Results for B2 in Wet/60°C

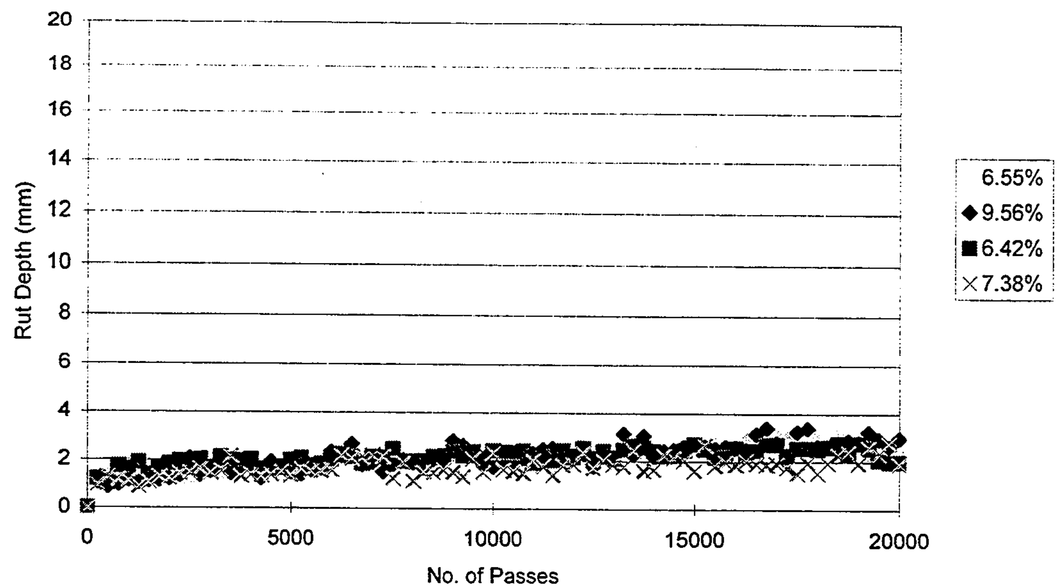

Figure 5.26 PURWheel Test Results for B3 in Dry/60°C

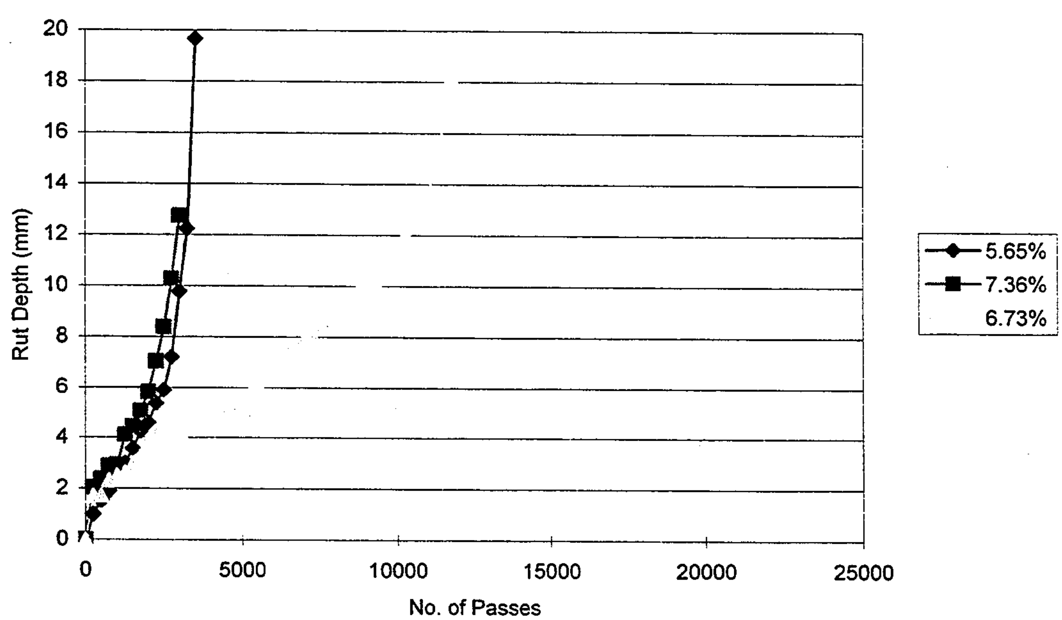

Figure 5.27 PURWheel Test Results for B3 in Wet/60°C

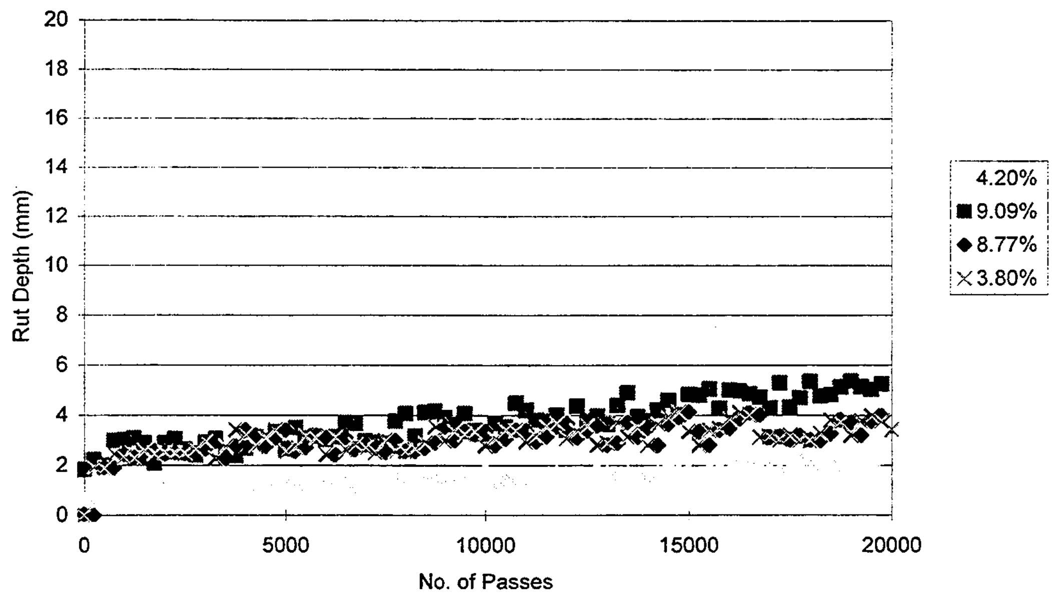

Figure 5.28 PURWheel Test Result for #2478n1

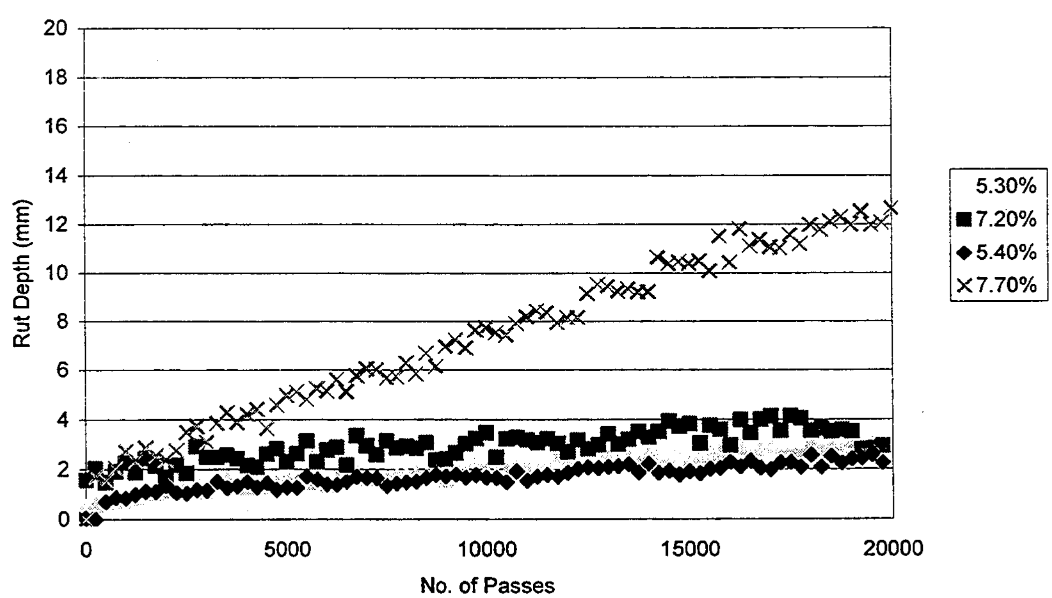

Figure 5.29 PURWheel Test Result for #2478n2

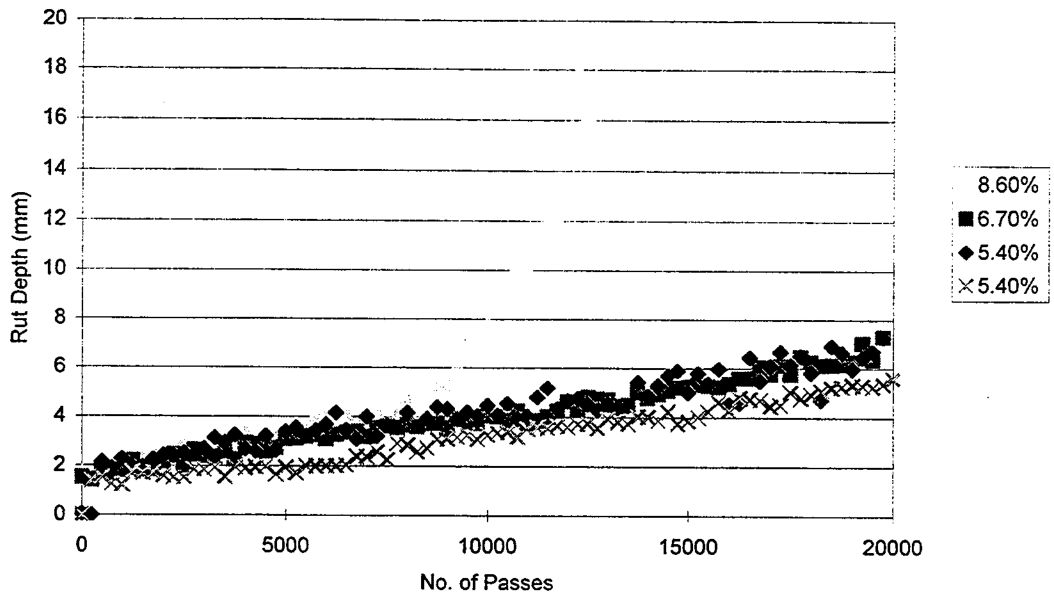

Figure 5.30 PURWheel Test Results for #2478n3

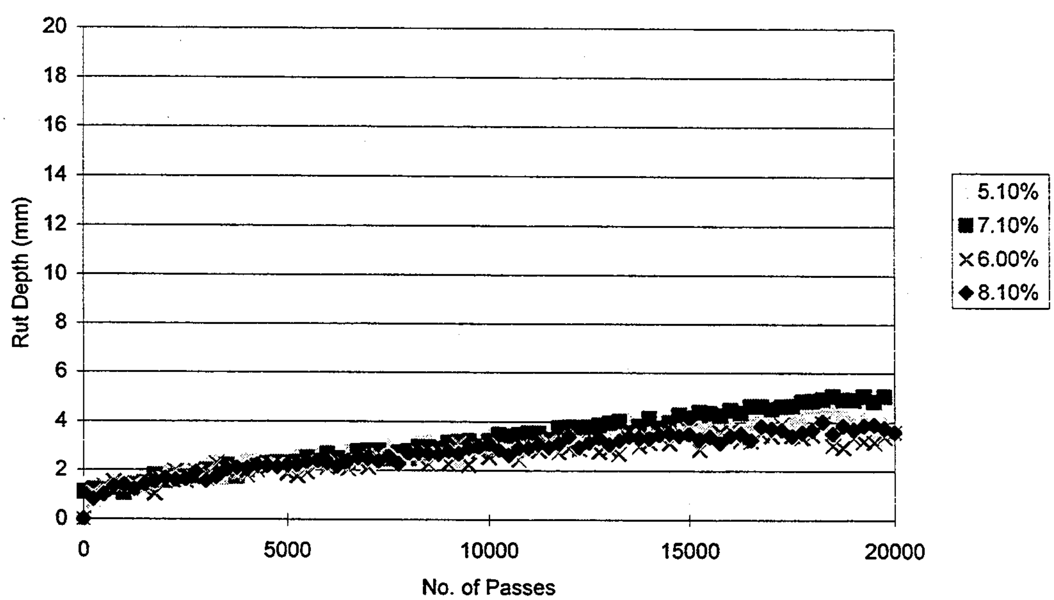

Figure 5.31 PURWheel Test Results for #2478n4

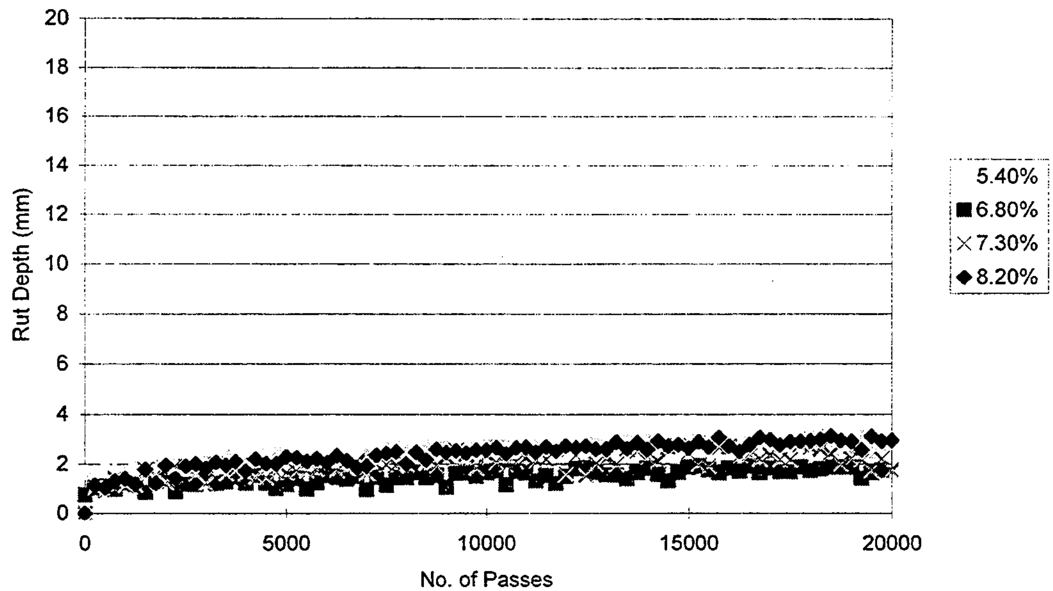

Figure 5.32 PURWheel Test Results for #2478n5

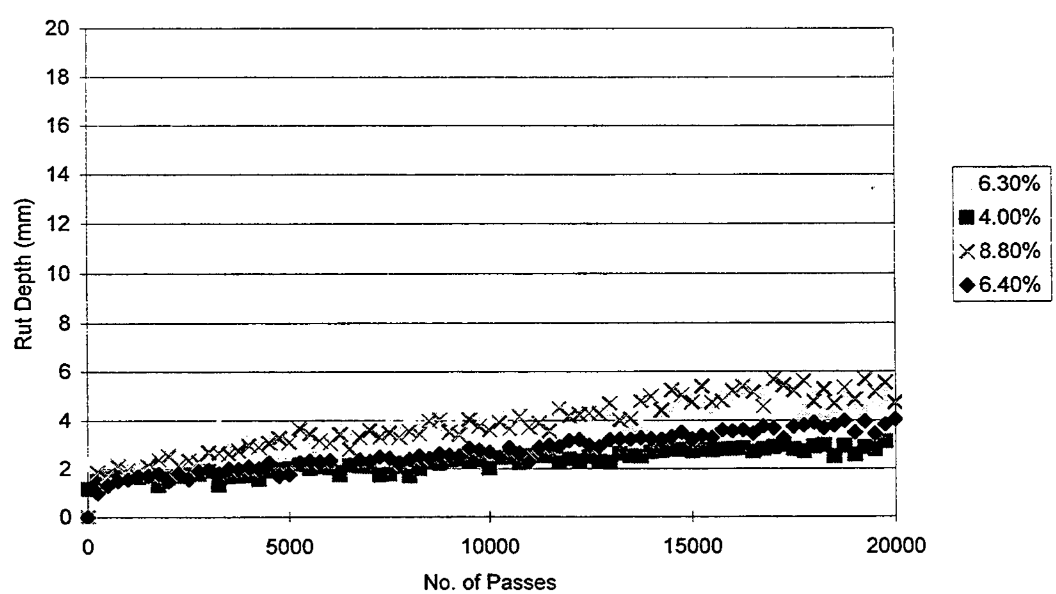

Figure 5.33 PURWheel Test Results for #2314n1

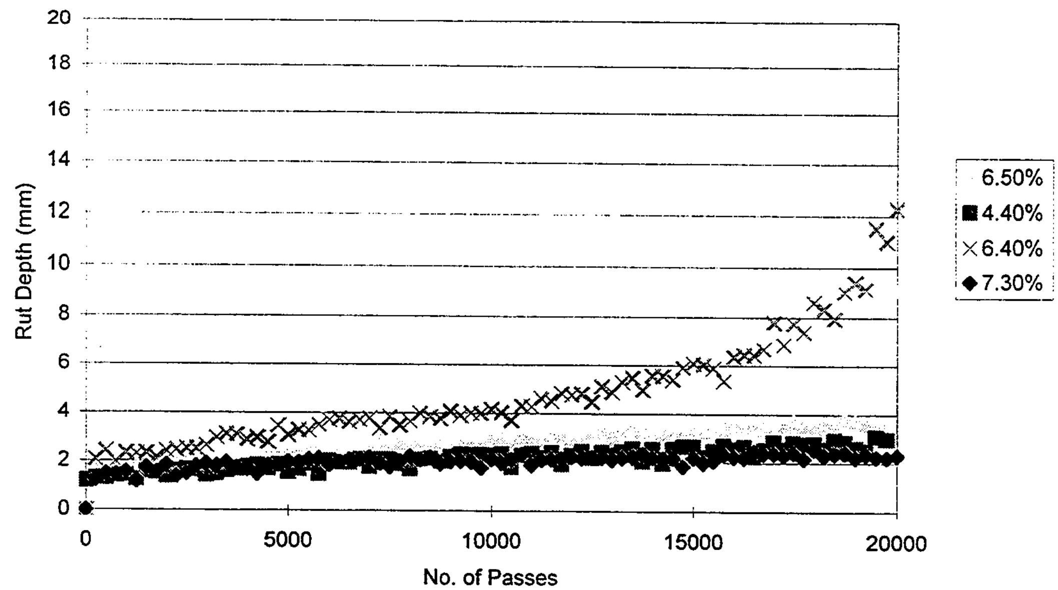

Figure 5.34 PURWheel Test Results for #2314n2

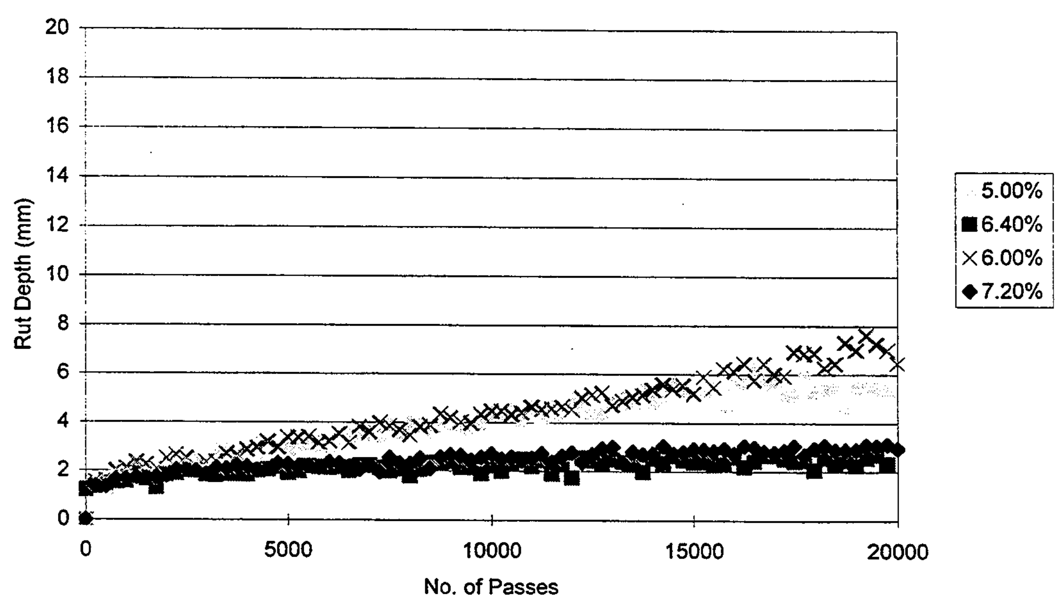

Figure 5.35 PURWheel Test Results for #2314n3

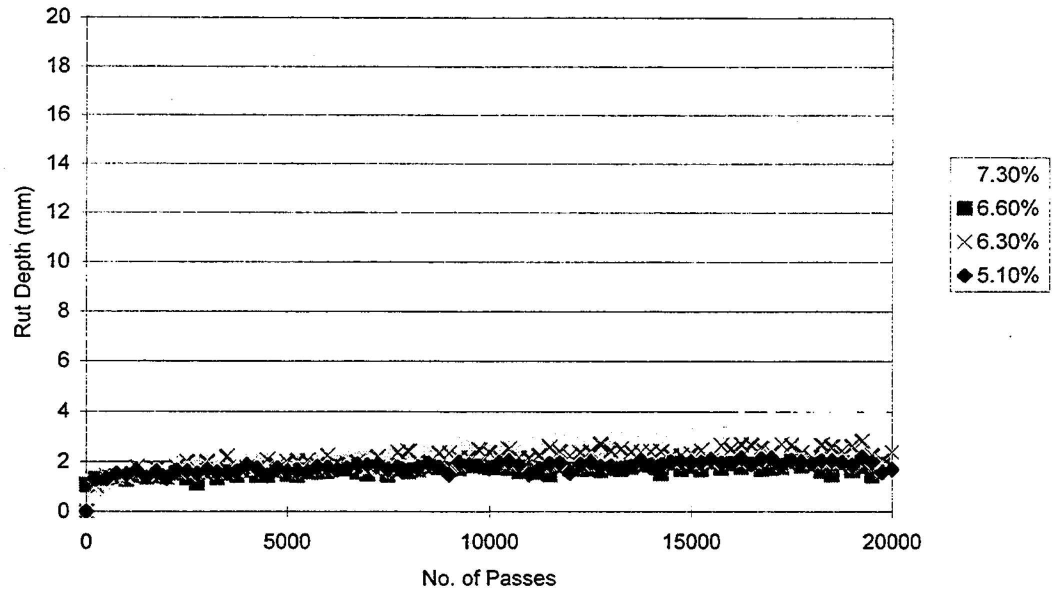

Figure 5.36 PURWheel Test Results for #2314n4

Table 5.3 SST Sample Properties

	No. of Gyration	BSG	MTSG	AC(%)	Air Void (%)
#2311	40	2.308	2.472	5.3	6.6
#2497	30	2.358	2.488	4.4	5.2
#2164	40	2.330	2.455	5.4	5.1
#2211	40	2.361	2.481	5.0	4.8
#2478	40	2.326	2.474	6.9	6.0
#2314	60	2.273	2.402	7.5	5.4
B1	40	2.346	2.454	5.5	4.4
B2	40	2.326	2.453	5.3	5.2
B3	35	2.305	2.441	5.0	5.6
#2478n1	40	2.311	2.484	5.9	7.0
#2478n2	40	2.293	2.466	5.8	7.0
#2478n3	45	2.301	2.470	6.6	6.8
#2478n4	40	2.336	2.469	6.5	5.4
#2478n5	45	2.403	2.513	6.3	4.4
#2314n1	50	2.285	2.456	6.1	7.0
#2314n2	50	2.310	2.463	6.0	6.2
#2314n3	55	2.304	2.434	6.7	5.3
#2314n4	45	2.316	2.494	5.2	7.1

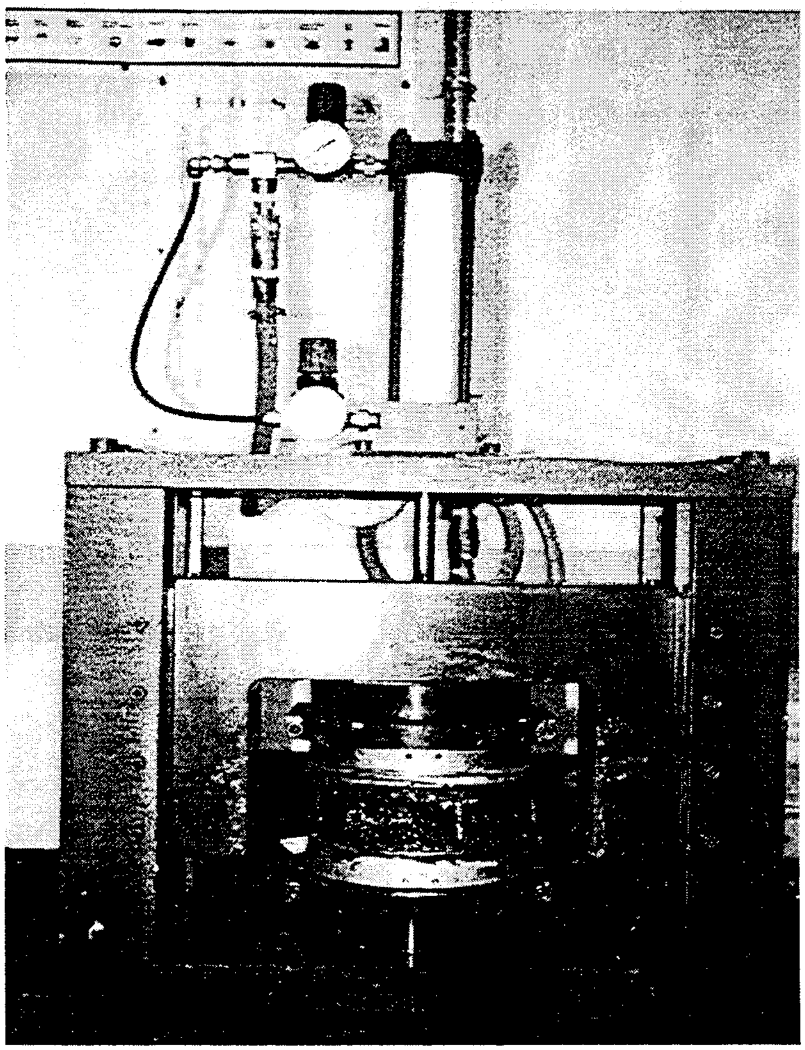

Figure 5.37 Platen-Specimen Assembly Device

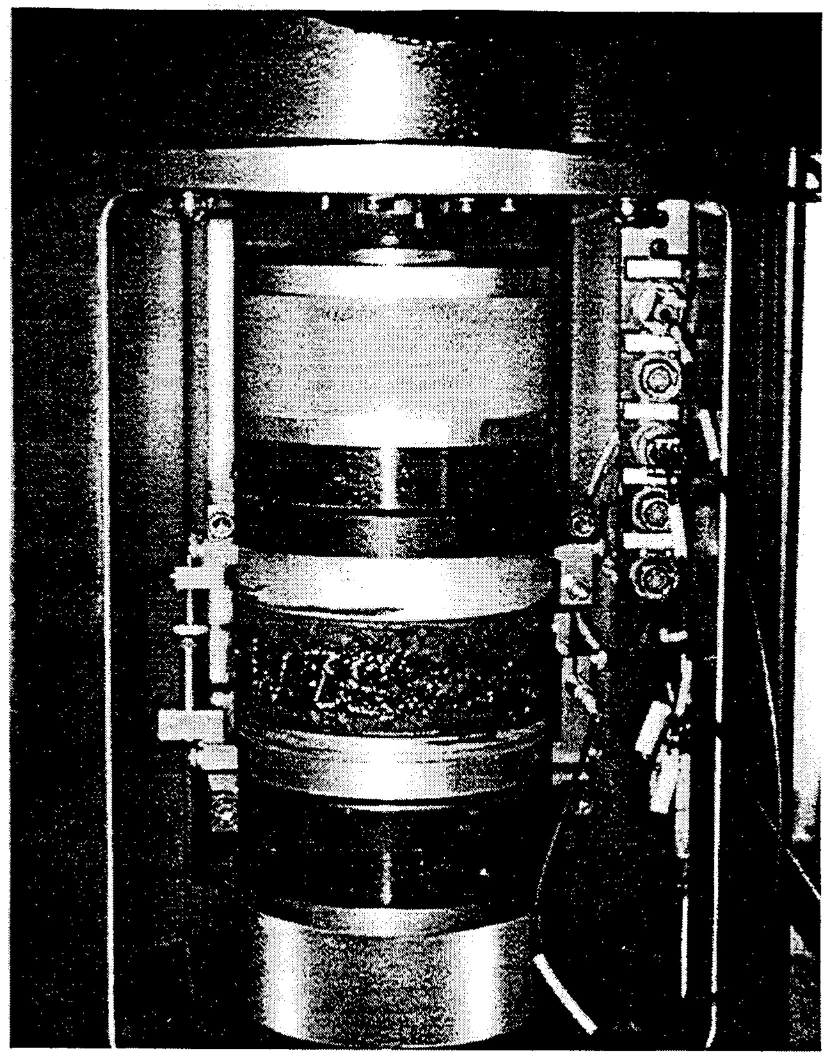

Figure 5.38 Specimen in the Testing Chamber of Simple Shear Test (SST) Device

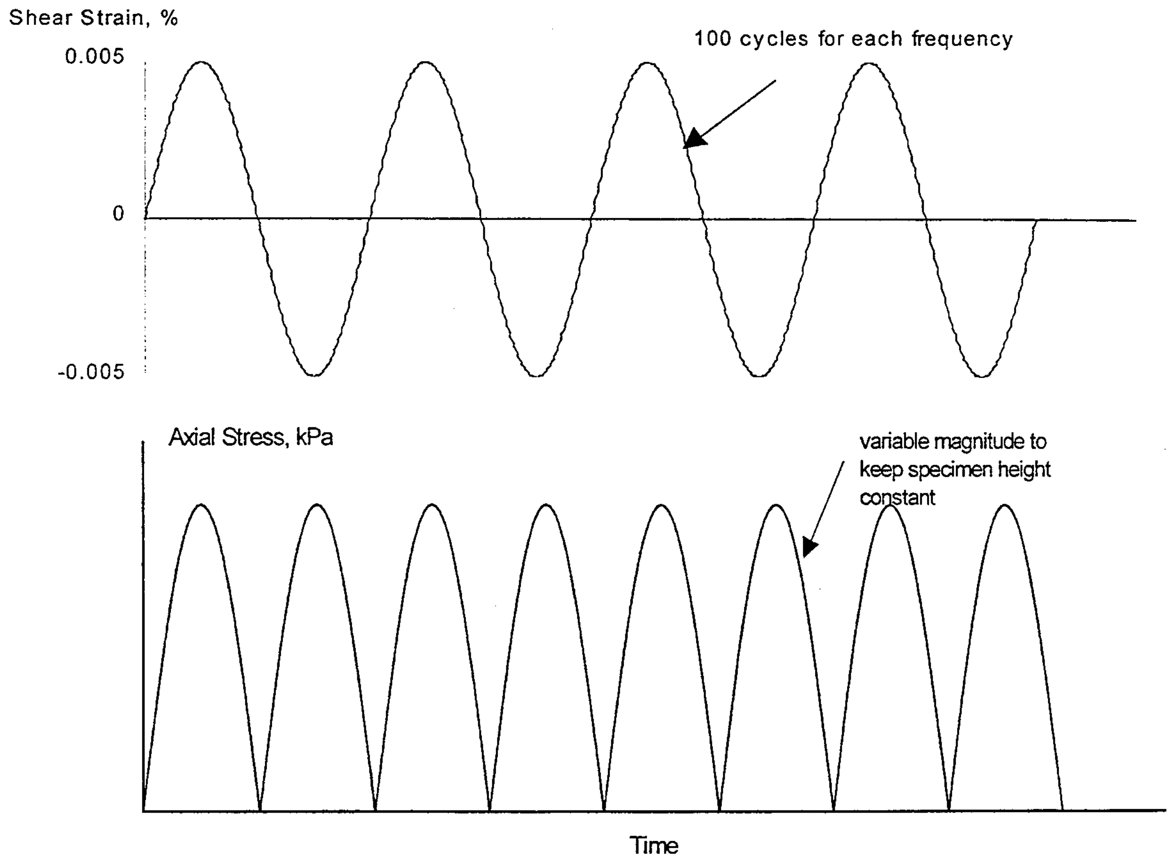

Figure 5.39 Shear Strain and Axial Stress Applications in Frequency Sweep Test

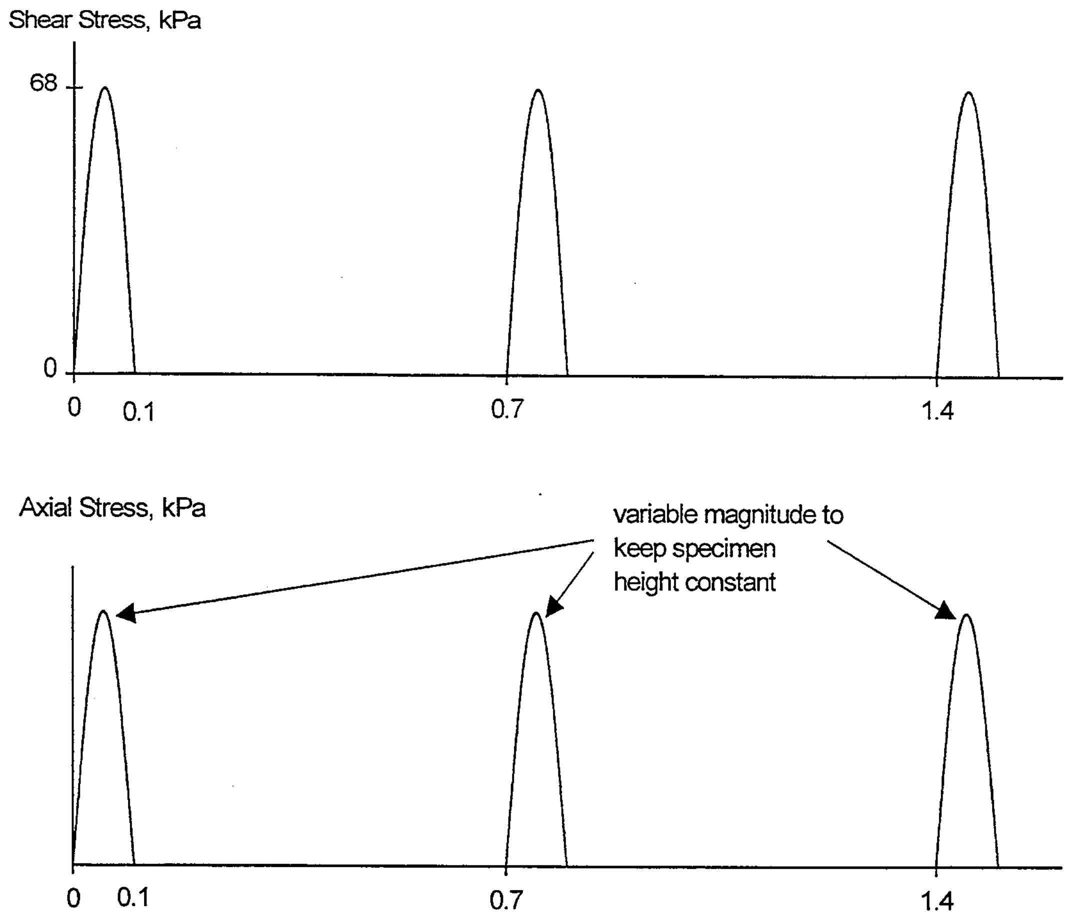

Figure 5.40 Stress Pulses in Repeated Shear Test at Constant Height

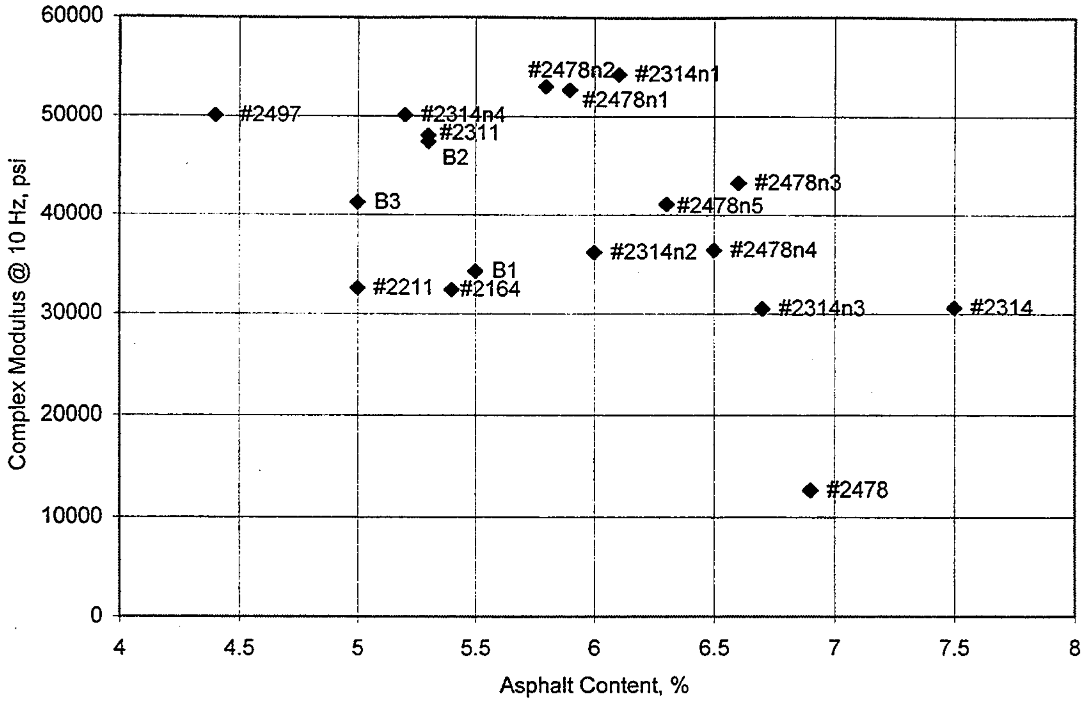

Figure 5.41 Relationship of Complex Modulus at 10 Hz and Asphalt Content

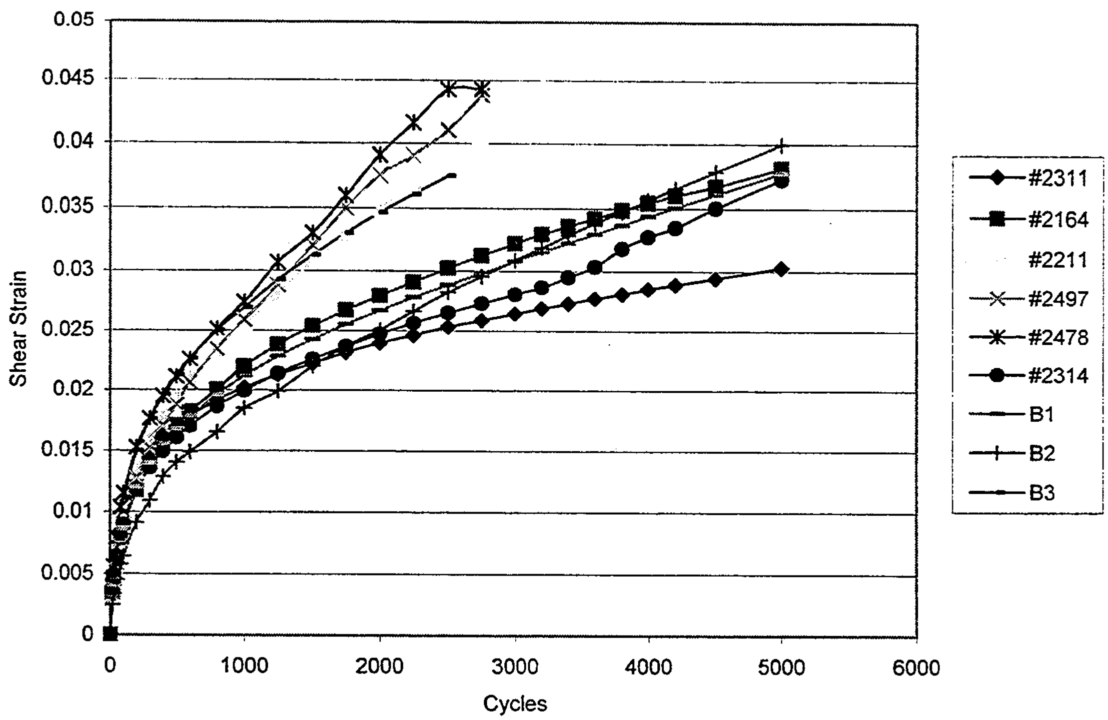

Figure 5.42 Repeated Shear at Constant Height Test Results for Phase I Mixtures

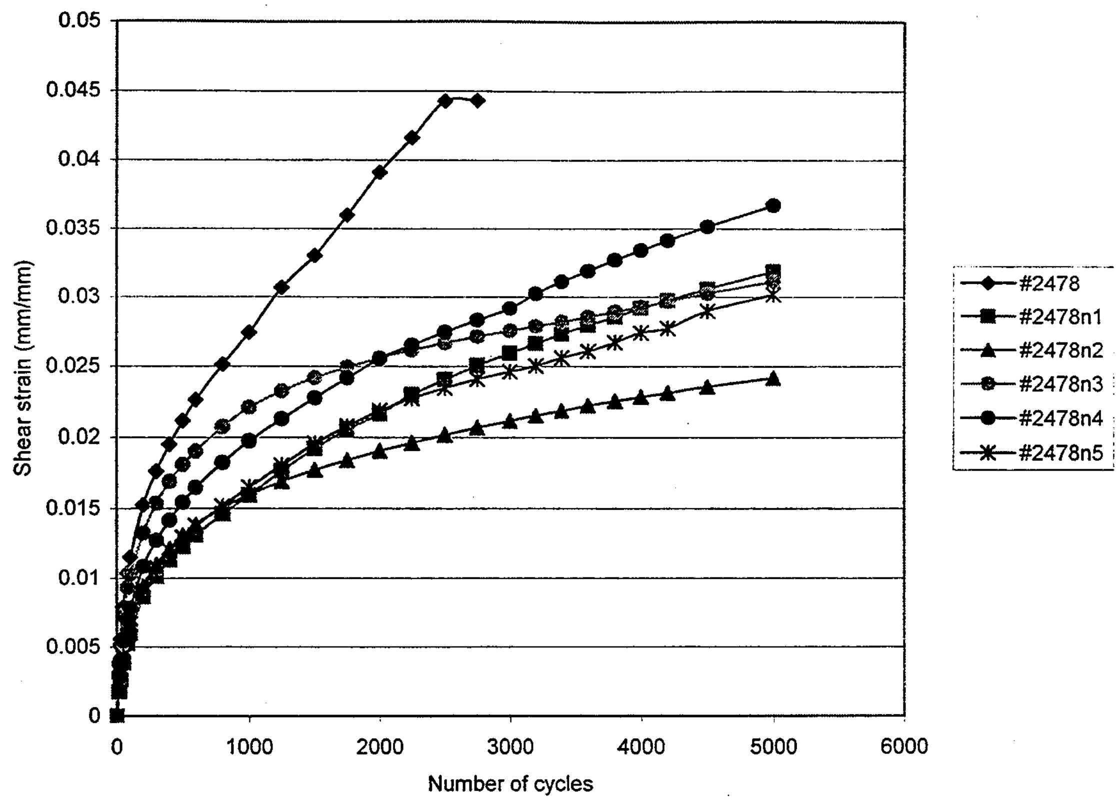

Figure 5.43 Repeated Shear at Constant Height Test Results of Slag Sand (#2478) Mixtures

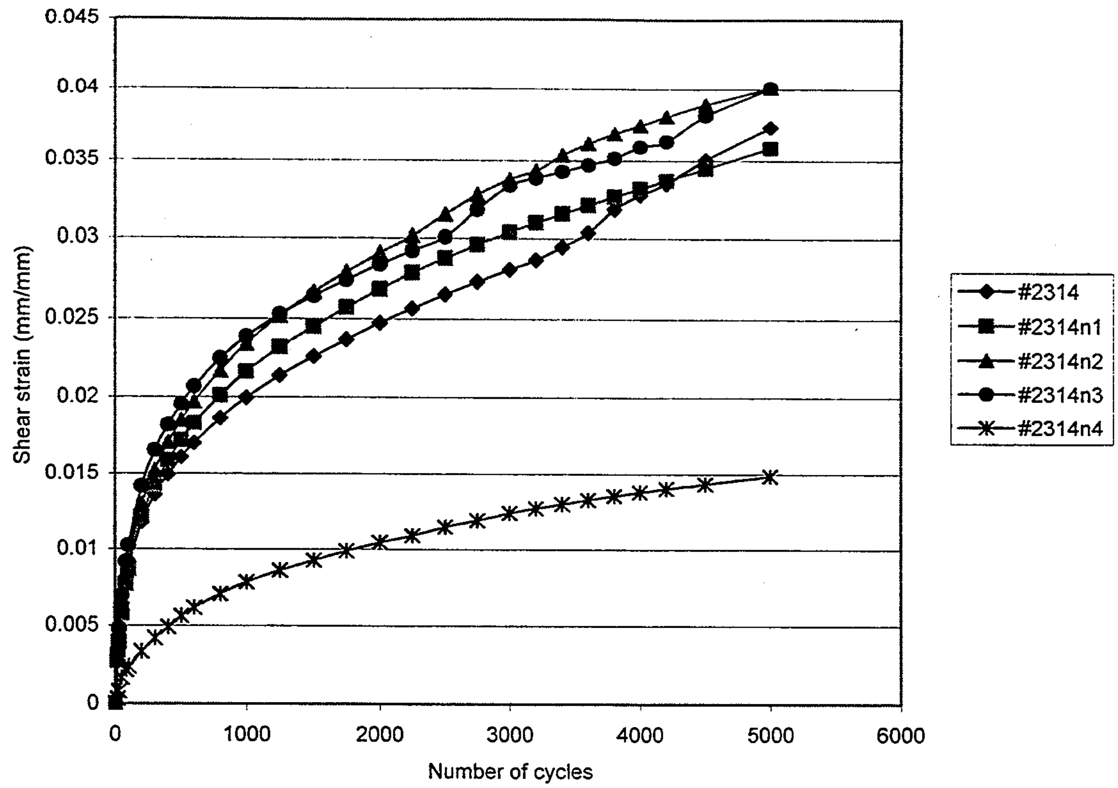

Figure 5.44 Repeated Shear at Constant Height Test Results of Stone Sand (#2314) Mixtures

Table 5.4 Results of Repeated Shear Test at Constant Height

Mix ID	Loading Cycles to 1% Shear Strain	Loading Cycles to 2% Shear Strain	Shear Strain at End of Test
#2311	118	958	0.02366
#2497	128	565	0.04379
#2164	142	793	0.03814
#2211	115	540	0.04432
#2478	75	430	0.04431
#2314	136	1005	0.03729
B1	140	849	0.0378
B2	128	1007	0.03998
B3	80	422	0.03749
#2478n1	293	1643	0.03189
#2478n2	236	2420	0.02419
#2478n3	94	714	0.03115
#2478n4	172	1041	0.03673
#2478n5	252	1591	0.0302
#2314n1	138	788	0.03585
#2314n2	113	629	0.04008
#2314n3	95	539	0.04005
#2314n4	1801	>5,000	0.01488

CHAPTER 6 ANALYSIS OF EXPERIMENTAL DATA

PURWheel test results were evaluated with respect to HMA compacted volumetric properties as well as asphalt film thickness and fine aggregate angularity characteristics. Analysis was conducted with the aid of Statistical Analysis Software (SAS) [SAS Institute, Inc, 1991]. A stepwise regression and analysis of covariance (ANCOVA) was performed in order to determine the significance of factors influencing the mixture performance.

6.1 Film Thickness

It is known that thicker binder films tend to produce mixtures that are flexible and durable while thinner binder films produce mixtures which are brittle, tend to crack and ravel excessively (Campen, et al, 1959). However, durability and stability, although both important for a HMA, are somewhat contradictory characteristics. Thick binder films tend to protect the aggregate and produce more durable HMA, however, a thicker film also acts as a lubricant between aggregate particles and results in a less stable HMA. In contrast, thin binder films produce less durable HMA but the aggregate skeleton remains a more stable structure when the mixture is subjected to external loads.

Campen, et al., 1959, presented a relationship between air voids, surface area, film thickness and HMA stability. On the basis of their data, film thicknesses ranging from 6 to 8 microns were found to provide the most desirable pavement mixtures. Kandhal, et al.(1998) suggested a minimum average asphalt film thickness of 8 microns be used to ensure mix durability instead of a minimum VMA requirement. In the current study, lower and upper film thicknesses of 8 and 10 microns, respectively, were evaluated. The film thicknesses of the eighteen mixtures incorporated in this study ranges from 6.6 microns to 16.3 microns as shown in Figure 6.1. The calculations followed the procedures in "Hot Mix Asphalt Materials, Mixture Design and Construction" (NAPA, 1991) and detailed results are shown in Table 6.1.

Almost all the mixtures shown in Figure 6.1 have film thickness ranging between 8 to 12 microns. For those of mixtures with film thickness lower than 8, some exhibited good PURWheel performance but some did not. However, the two mixtures with film thickness higher than 12 did not exhibit good performance in the PURWheel.

In Table 6.1, it can be seen that both mixtures with high asphalt content - mixture #2478 and mixture #2314 - have very thick binder films. Mixture #2497 has a relatively low film thickness, which reflects ease-of-compaction of the natural sand. Two of the above three mixtures, mixture #2478 and mixture #2497, exhibited the worst performance in the PURWheel as compared to the other mixtures. It is believed that the poor performance of mixture #2478 was due to the high asphalt content/thick binder film. Mixture #2497 with natural sand would have poor internal frictional characteristics as indicated by its low FAA value. Although the performance of mixture #2314 was reasonable, asphalt flushed to the sample surface during the PURWheel test

The film thickness estimated for mixture #2478n5 is 6.6 microns. This mixture is a modification of the original mixture #2478 and has a gradation passing above the restricted zone. This mixture exhibited good rutting performance in the PURWheel. It is believed that the low film thickness is due to the high surface area of the aggregate blend. As shown in Table 6.1, with the minus No. 200 sieve proportion of 8.6 percent, the aggregate blend has a surface area of 3.79 m^2 (40.8 ft^2) which is about twice the surface area of other mixtures.

6.2 PURWheel Performance Test

Data from tests of all mixtures were used to develop relationships between wheel passes and asphalt content, wheel passes and VMA, and wheel passes and FAA. The data are shown in Figures 6.2 to 6.4. From Figures 6.2 and 6.3, there appear to be upper limits of 6.5 percent for asphalt content and 17 percent for VMA. Above these limits the performance is poor, such as that exhibited by mixtures #2478 and #2478n3. These mixtures had number of wheel passes less than 20,000. From Figure 6.4, wheel passes increase with increasing value of FAA. However, this is a general trend that is confounded with factors other than FAA, such as excessive asphalt content. Figure 6.5 combines Figures 6.2 and 6.4 and shows a three-dimensional plot of wheel passes versus both asphalt content and FAA.

In Phase II of this project, nine additional mixtures were designed and tested. Five mixture designs were developed using the slag sand (#2478) and four mixtures were developed focused on the S-gradation with the limestone sand (#2314). Variations included blending various amounts of natural sand, increasing the amount of dust, and varying the gradation. Figure 6.6 shows the effect of dust/asphalt ratio on the PURWheel performance of the slag mixtures. It is obvious that the performance improves with increasing amount of dust. Figure 6.7 shows the effect of natural sand on the PURWheel performance of slag mixtures. Replacement of the original slag sand with natural sand improves the PURWheel performance over the range of sand amount tested. It is believed that by adding natural sand in the slag mixture, the mixture compactibility increases, and the VMA as well as the corresponding asphalt demand decreases. Less asphalt content results in a more stable mixture.

Figures 6.8 and 6.9 show the effect of amount of dust and natural sand on performance of the S-shaped gradation mixtures with limestone sand (#2314). Increasing the dust proportion improves mixture PURWheel performance. However, there is no significant effect when part of the #2314 sand is replaced with natural sand. This is true even with the addition of 10 and 15 percent natural sand which lowers the asphalt demand from a high of 7.5 percent to 6.1 and 6 percent, respectively. It is believed that with the addition of natural sand, the gradation of the new aggregate blends is still S-shaped. The lack of integrity in the aggregate structure remains the same, and therefore, the rutting performance was not improved.

Mixture #2314n4 is a dense gradation that is artificially produced from the individual sieve sizes of sand #2314. It appears that modifying the gradation is the most effective means of improving performance of this sand.

Table 6.2 lists ranking of the PURWheel test results for each mixture included in this study. For comparison purpose, ranking for the results of the repeated shear test at constant height is also shown. From Table 6.2, it can be seen that rankings for both of the performance tests are quite different.

Among the eighteen mixtures, mixture #2211 is a dolomite sand mixture with an asphalt content of 5.0 percent and a film thickness of 10.0 microns. And it meets all the Superpave requirements. The normalized PURWheel performance of this mixture is 43709 wheel passes to 6.35mm rut depth at six percent air voids. If the assumption is made that this mixture is acceptable and would be expected to exhibit good rutting performance, then mixtures with ranking better than mixture #2211should also have good rutting performance. Mixtures with ranking poorer than mixture #2211 would be susceptible to rutting. Relative ranking is given in Table 6.2.

The reason for selection of mixture #2211 is to distinguish the mixtures involved in this study into two groups. In Figure 6.10, Relationship for VMA and Asphalt Content, mixtures with better ranking than mixture #2211 are labeled with bold characters. These mixtures all fall in the asphalt content range of 5.0 to 6.5 percent. And with the exception of mixture #2314n4 (its artificial gradation results in a dense mixture), all these rutting-resistant mixtures have values of VMA ranging from 14 to 17.

6.3 Statistical Analysis

Rutting is related to loading and environmental conditions as well as mixture properties. In PURWheel tests, loading and environmental conditions are constant. As a result, the effect of mixture variations can be determined.

In the statistical analysis of PURWheel test data, the dependent variable was taken as the number of passes (Y) to reach a rut depth of 6.35-mm. The independent variables included in the analysis of all mixtures were fine aggregate angularity (FAA), asphalt content (AC), air void (AV), dust/asphalt ratio (DA), gradation (GRAD), and the interaction between fine aggregate angularity and asphalt content (FAA*AC). Results from the repeated shear test at constant height was also included in the statistical model to evaluate the shear test (SST).

In Phase II, independent variables were different treatments (TRT) to the original #2478 and #2314 mixtures. The treatments were the natural sand content, dust proportion and change of gradation. Air voids of each sample was considered a covariate in the statistical model. An analysis of variance (ANOVA) was performed in order to determine significance of the treatments.

Tests conducted on fine aggregate, such as: fine aggregate angularity (FAA), Compacted Aggregate Resistance (CAR), and Florida Bearing Value were correlated with tests conducted on mixtures such as Repeated Shear at Constant Height (RSCH) and rutting performance in the PURWheel. Correlation analysis showed that among the three tests conducted on fine aggregate, FAA had the best correlation with mixture rutting performance.

6.3.1 Regression on All Mixtures

There are a total of eighteen surface mixtures in this study. Four samples were tested in the PURWheel for each of the eighteen mixtures. The independent variables of the statistical anaylsis were fine aggregate angularity (FAA), asphalt content (AC), air void (AV), dust/asphalt ratio (DA), gradation (GRAD), and the interaction between fine aggregate angularity and asphalt content (FAA*AC). Results from the repeated shear at constant height test were also included in the statistical model. Number of loading cycles to two percent shear strain was taken as an independent variable (SST). Ususally, there are three parameters to quantify results from repeated shear at constant height test. They are: numbers of loading cycles to one percent shear strain, numbers of loading cycles to two percent shear strain, and shear strain at 5000 loading cycles. Since not all of the mixtures passed 5000 cycles, the number of loading cycles to two percent shear strain was selected as "SST" to represent RSCH test result.

Various measures of gradation curve shape and offsets from the Superpave maximum density line were evaluated. However, the distance from the mixture gradation curve to the maximum density line at the 50 percent passing level showed the best coorelation. This value was also used by Williams, 1996. Parameters for each mixture used in the statistical analysis are listed in Table 6.3. The following model was assumed in the analysis.

$$\log(Y) = \beta_0 + \beta_1(FAA) + \beta_2(AC) + \beta_3(AV) + \beta_4(DA) + \beta_5(GRAD) + \beta_6(FAA * AC) + \beta_7(SST) + \varepsilon \qquad \text{..............(6.1)}$$

Where:

$\log(Y)$ = dependent variable, logrithmic value of the number of wheel passes to 6.35-mm rut depth

β_0 = intercept of the linear model

β_1 to β_7 = coefficients of the independent variables

ε = experimental error

A stepwise regression was performed with the significance level at 0.15 (a default value of SAS). With the exception of dust/asphalt ratio (DA), all other factors entered the statistical model. The summary of the analysis is shown in Table 6.4 and the summary of the stepwise procedure is shown in Table 6.5. Parameter estimates after the last step are shown in Table 6.6. It is noted that coefficients of air voids (AV) and interaction of fine aggregate angularity and asphalt content (FAA*AC) are both negative, which means that high values of AV and FAA*AC are detrimental to the mixture rutting performance. It should also be noted that the significance level of SST (RSCH) is the lowest among all factors.

Another stepwise regression analysis was performed with SST as the dependable variable. The folllowing model was assumed.

$$SST = \beta_0 + \beta_1(FAA) + \beta_2(AC) + \beta_3(AV) + \beta_4(DA) + \beta_5(GRAD) + \beta_6(FAA * AC) + \varepsilon \quad \text{..............(6.2)}$$

Parameters for each mixture used in this analysis are listed in Table 6.7. This analysis was conducted to evaluate the rutting predictability of the repeated shear at constant height test. With the default significance level of 0.15, none of the factors entered in this model.

6.3.2 Slag Sand Mixtures

Among the eighteen mixtures in this study, six include slag sand. Mixture #2478, #2478n1 and #2478n3 contain only slag sand along with dust/asphalt ratios of 0.6, 1.2 and 0.9, respectively. Mixtures #2478n2 and #2478n4 have 22 and 16 percent natural sand (based on the total weight of aggregate) blended with the slag sand. Mixture #2478n5 has a gradation which goes above the restricted zone. Therefore, the six slag sand mixtures were separated into three groups for analysis. The first group includes mixtures #2478, #2478n1 and #2478n3. The second group includes mixtures #2478, #2478n2 and #2478n4. The third group include #2478 and #2478n5. Treatment in the first group is dust/asphalt ratio. Treatment in the second group is amount of natural sand. And treatment in the third group is change of gradation. All of the three groups have "treatment" (TRT) as the independent variable. The following model was assumed in the analysis.

$$\log(Y_{ij}) = \mu + \tau_i + \beta(x_{ij} - \underline{x}) + \varepsilon_{ij} \qquad (6.3)$$

Where:

$\log(Y_{ij})$	= dependent variable, logrithmic value of the number of wheel passes to 6.35-mm rut depth
μ	= overall mean
τ_i	= effect of treatment
β	= slope of air void and the dependent variable, log(wheel passes)
x_{ij}	= air void of each test sample, i=1,2,(3), j=1..4
$\underline{x}$	= a covariate
ε_{ij}	= experimental error, i=1,2,(3), j=1..4

An ANOVA was performed with the first group of the slag sand mixtures and the results are summarized in Table 6.8. The main effect (dust/asphalt ratio) and air voids are both significant. This suggests that rutting is dependent on the mixture dust proportion and the sample air voids.

Table 6.9 shows the ANOVA results for the second group of the slag sand mixtures. The main effects, amount of natural sand and air voids, are significant. This suggests that rutting of the slag sand mixtures is dependent on both amount of natural sand and air voids.

Table 6.10 shows the ANOVA results for mixtures #2478 and #2478n5. The main effect (change of gradation) is significant, which means that change of gradation has a strong effect on rutting performance. The effect of air voids is also significant.

6.3.3 Limestone Sand Mixtures

Totally, five limestone sand (#2314) mixtures were incorporated in this study. They were mixture #2314 and mixtures #2314n1 to #2314n4. As in the previous section, the five limestone sand mixtures were separated into three groups based on three different treatments and the same model was assumed. The first group included mixture #2314 and mixture #2314n3. The treatment in this group is the dust/asphalt ratio. Mixtures #2314 and #2314n3 have dust/asphalt ratios of 0.6 and 1.4, respectively

Mixtures #2314, #2314n1 and #2314n2 were analyzed as a group with varying percentage of natural sand. The natural sand percentages for mixtures #2314, #2314n1 and #2314n2 are 0, 10 and 15 percent, respectively.

The third group included mixtures #2314 and #2314n4. Treatment in this group is the change of gradation. Mixture #2314n4 included the same fine aggregate (#2314 limestone sand) but the gradation of the aggregate was artificially modified to approximate the gradation of the other limestone sand (#2311).

Table 6.11 to Table 6.13 show the ANOVA results for the three groups. The main effects in the first and the second group are not significant. This means that the treatments of adding natural sand and increasing dust proportion effectively lowered the asphalt demand of the original mixture but did not improve the rutting performance. However, the main effect in the third group, gradation change, is significant. Among the three treatments, the artificially changed gradation is the only effective means to improve the rutting performance.

The effect of air voids is significant in the analysis of the second and the third group. The effect of air voids in the first group is significant with a p-value of 0.05.

6.3.4 Correlation Between Aggregate Tests and Mixture Tests

Correlation analysis was conducted of fine aggregate tests (FAA,CAR, and Florida Bearing Value) and mixture test results. Table 6.14 lists the values for each parameter included in the analysis. Table 6.15 shows the correlation matrix of FAA, CAR, Florida Bearing Value, SST (RSCH), and PURWheel results.

From Table 6.15, it can be seen that the correlations between FAA and CAR, FAA and Florida Bearing Value, CAR and Florida Bearing Value are all very good. Among the three, CAR and Florida Bearing Value have the best correlation because both of the tests measure the shear strength of compacted fine aggregate in a similar way.

Compared with CAR, Florida Bearing Value, and SST, FAA has the best correlation with PURWheel rutting performance.

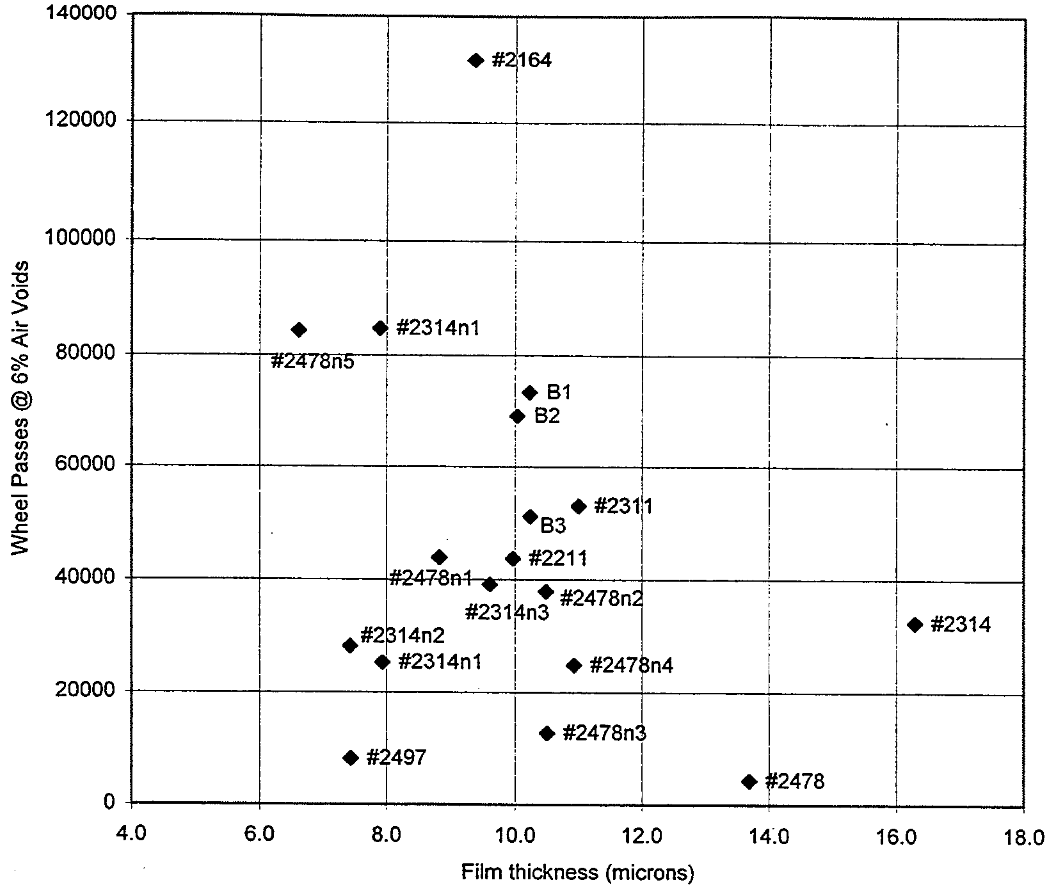

Figure 6.1 Film Thickness and Wheel Passes

Table 6.1 Film thickness

Mix ID	SA (ft^2)	P_b (%)	MTS G	G_{se}	G_{sb}	Unit Wt (pcf)	Total P_b (ft^3)	P_{ba}	Vol of P_{ba} (ft^3)	Vol. of P_{be} (ft^3)	Film thick ness (mic rons)
#2311	20.6	5.3	2.472	2.682	2.626	147	0.121	0.008	0.018	0.103	11.0
#2497	24.2	4.4	2.488	2.661	2.607	149	0.102	0.008	0.018	0.084	7.4
#2478	21.6	6.9	2.474	2.761	2.676	148	0.158	0.012	0.025	0.133	13.7
#2211	24.4	5	2.481	2.680	2.671	149	0.116	0.001	0.003	0.113	10.0
#2164	25.7	5.4	2.455	2.666	2.623	147	0.124	0.006	0.014	0.110	9.4
#2314	19.7	7.5	2.402	2.693	2.601	143	0.167	0.014	0.028	0.139	16.3
B1	23.8	5.5	2.454	2.669	2.622	147	0.126	0.007	0.015	0.111	10.2
B2	23.7	5.3	2.453	2.659	2.620	147	0.121	0.006	0.012	0.109	10.0
B3	23.4	5	2.441	2.631	2.616	146	0.114	0.002	0.005	0.109	10.2
#2478n1	29.7	5.9	2.484	2.725	2.673	148	0.136	0.007	0.016	0.120	8.8
#2478n2	24.3	5.8	2.466	2.698	2.643	148	0.133	0.008	0.017	0.116	10.5
#2478n3	27.5	6.6	2.470	2.741	2.671	148	0.151	0.010	0.021	0.130	10.5
#2478n4	25.1	6.5	2.469	2.735	2.653	148	0.149	0.012	0.025	0.125	10.9
#2478n5	40.8	6.3	2.513	2.782	2.707	150	0.147	0.010	0.023	0.125	6.6
#2314n1	31.2	6.1	2.456	2.699	2.612	147	0.139	0.013	0.027	0.112	7.9
#2314n2	31.8	6	2.463	2.703	2.607	147	0.138	0.014	0.030	0.107	7.4
#2314n3	28.9	6.7	2.434	2.698	2.608	146	0.152	0.013	0.028	0.124	9.6
#2314n4	23.9	5.2	2.494	2.705	2.602	149	0.121	0.015	0.033	0.088	7.9

Note:

- SA : Surface area
- Pb : Asphalt content
- Gse : Effective specific gravity (determined from MTSG)
- Gsb : Bulk specific gravity of aggregate
- Total Pb : Total volume of asphalt cement
- Pba : Asphalt absorbed (by weight of aggregate)
- Volume of Pbe: Effective volume of asphalt

Table 6.2 Mixture Performance Rankings for PURWheel Tests and Repeated Shear Test at Constant Height

Mix ID	FAA	AC(%)	Description	Ranking in PURWheel	SST
#2311	45	5.3	Limestone sand	6	8
#2497	39	4.4	Natural sand	17	14
#2211	48	5.0	Dolomite sand	9	10
#2164	49	5.4	Crushed gravel sand	1	17
#2478	47	6.9	Slag sand, 1% MF	18	15
#2314	44	7.5	Limestone sand, S-shaped gradation, 5.1% MF	12	7
B1	46	5.5	26% #2497 + 74% #2164	4	9
B2	45	5.3	36% #2497 + 64% #2164	5	5
B3	43	5.0	56% #2497 + 44% #2164	7	18
#2478n1	47	5.9	Slag sand, 6% MF	8	3
#2478n2	45.7	5.8	Slag sand, 22% #2497, 4% MF	11	2
#2478n3	47	6.6	Slag sand, 4% MF	16	12
#2478n4	46.5	6.5	Slag sand, 16% #2497, 4% MF	15	6
#2478n5	47	6.3	Gradation above the restricted zone, 8% MF	3	4
#2314n1	43.6	6.1	#2314 + 10% #2497, 10% MF	14	11
#2314n2	43	6.0	#2314 + 15% #2497, 10% MF	13	13
#2314n3	44	6.7	#2314, 10% MF	10	16
#2314n4	44	5.2	Artificial gradation, 3% MF	2	1

Table 6.3 Parameters in Stepwise Regression Analysis

Mix ID	*FAA*	*AC(%)*	*D/A*	*GRAD*[1]	*Air Void (%)*	*SST*[2]	*Wheel Passes*
#2311	45	5.3	0.6	5.5	6.5	958	18748
					6.7		51067
					6.1		73104
					7.1		67000
#2497	39	4.4	1.1	6.5	5.9	565	13500
					5.0		5500
					7.1		5500
					7.2		13750
#2478	47	6.9	1.0	6.0	6.4	430	6500
					8.9		5750
					5.8		3250
					6.8		3750
#2211	48	5.0	0.7	8.0	7.2	540	38205
					8.0		35620
					6.7		41236
					8.8		69405
#2164	49	5.4	1.0	9.0	9.5	793	27178
					7.6		100000
					5.1		100163
					7.9		102997
#2314	44	7.5	0.6	10.0	5.5	1005	46287
					6.3		25052
					9.8		12250
					6.8		18904
B1	46	5.5	0.9	8.0	8.9	849	11250
					7.8		32910
					6.2		81707
					7.1		12250
B2	45	5.3	0.9	8.0	9.1	1254	30493
					7.4		38581
					5.1		107590
					9.8		7250
B3	43	5.0	0.8	7.1	6.6	422	50043
					9.6		40956
					6.4		51227
					7.4		44352

Table 6.3 (Continued) Parameters in Stepwise Regression Analysis

Mix ID	*FAA*	*AC(%)*	*D/A*	*GRAD*[1]	*Air Void (%)*	*SST*[2]	*Wheel Passes*
#2478n1	47	5.9	1.2	5.7	6.2	1643	40945
					9.1		13750
					4.2		59279
					3.8		68997
#2478n2	45.7	5.8	0.9	4.0	5.6	2420	54094
					7.2		33170
					5.3		35370
					7.7		5000
#2478n3	47	6.6	0.9	3.5	5.4	714	12250
					6.7		11000
					8.6		7750
					5.4		15750
#2478n4	46.5	6.5	0.9	4.0	6.0	1041	25690
					7.1		18250
					5.1		28820
					8.1		16750
#2478n5	47	6.3	1.6	14.0	7.3	1591	44649
					6.8		70965
					5.4		99048
					8.2		42279
#2314n1	43.6	6.1	1.4	2.0	8.8	788	13000
					4.0		41590
					6.3		12250
					6.4		25737
#2314n2	43	6.0	1.4	3.7	6.4	629	11250
					4.4		44384
					6.5		27708
					7.3		23112
#2314n3	44	6.7	1.4	7.5	6.0	539	45691
					6.4		11250
					5.0		70965
					7.2		11000
#2314n4	44	5.2	1.1	5.0	6.3	5000	68568
					6.6		35620
					7.3		24459
					5.1		139182

[1] GRAD is the parameter to quantify gradation. It is the percent from the mixture gradation curve to the maximum density line at the 50 percent passing level.

[2] SST is the number of loading cycles to two percent shear strain in Repeated Shear test at Constant Height.

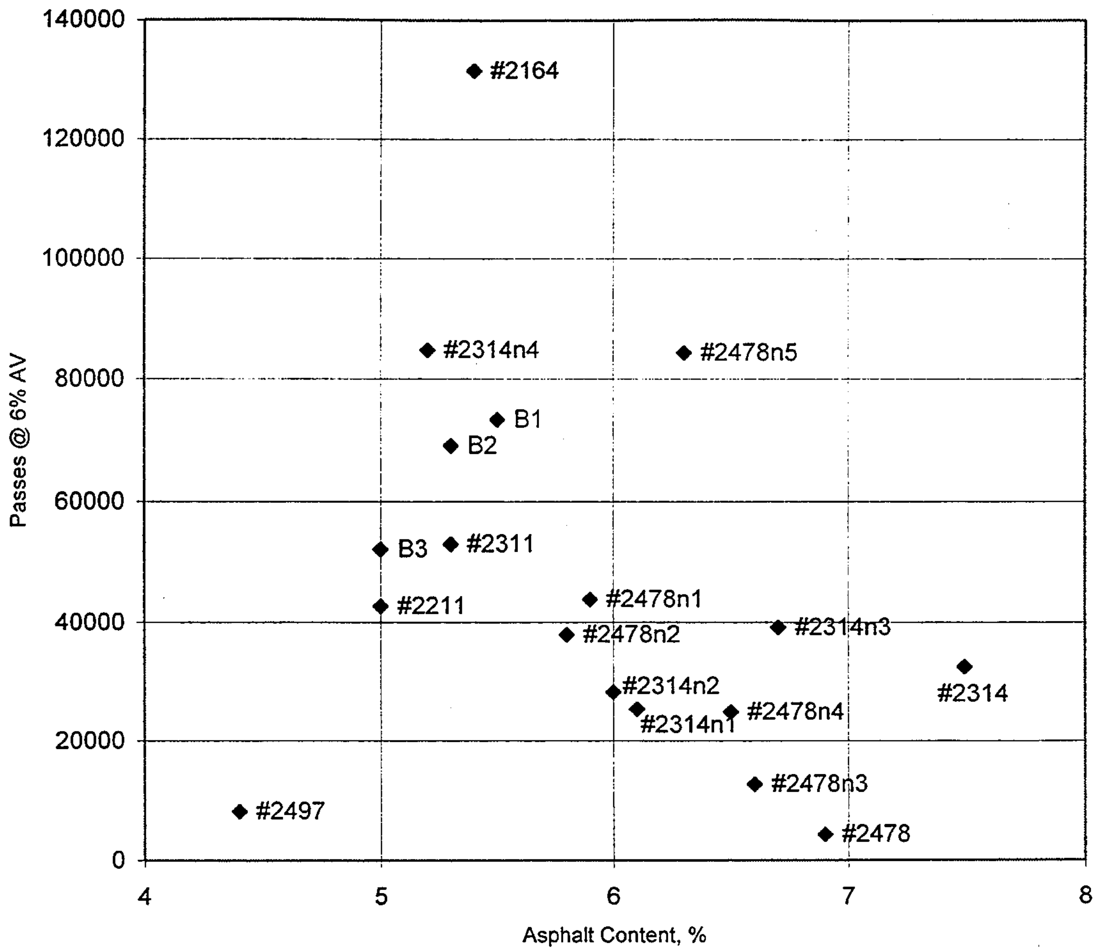

Figure 6.2 Asphalt Content vs. Wheel Pass at 6% Air Voids

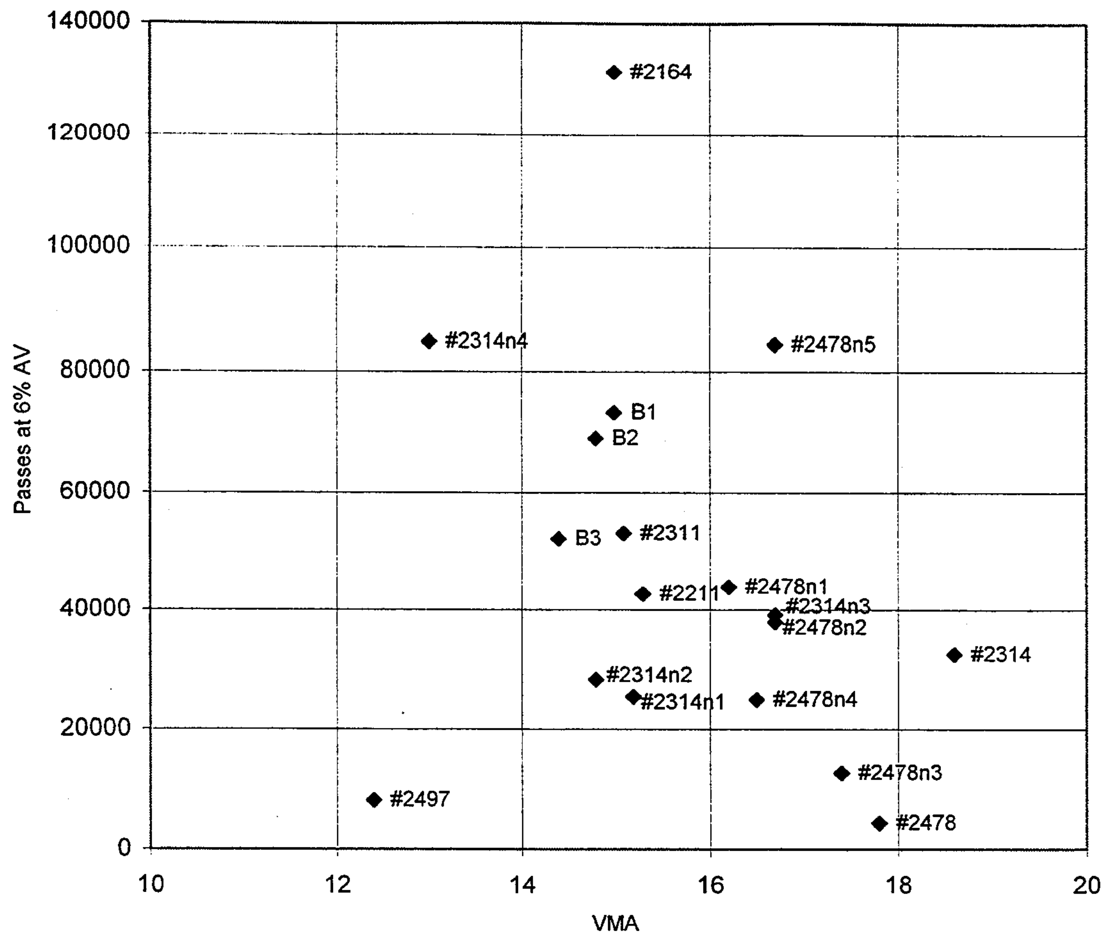

Figure 6.3 VMA vs. Wheel Pass at 6% Air Voids

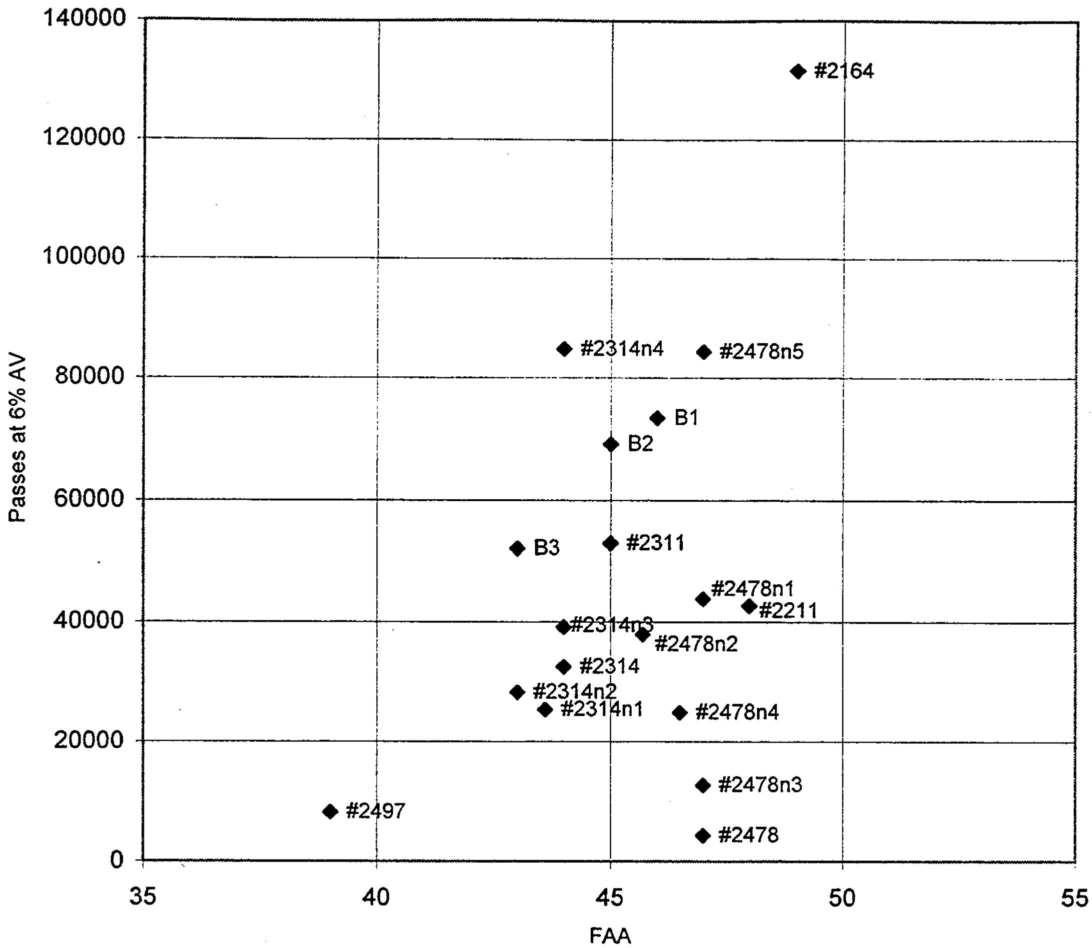

Figure 6.4 FAA vs. Wheel Pass at 6% Air Voids

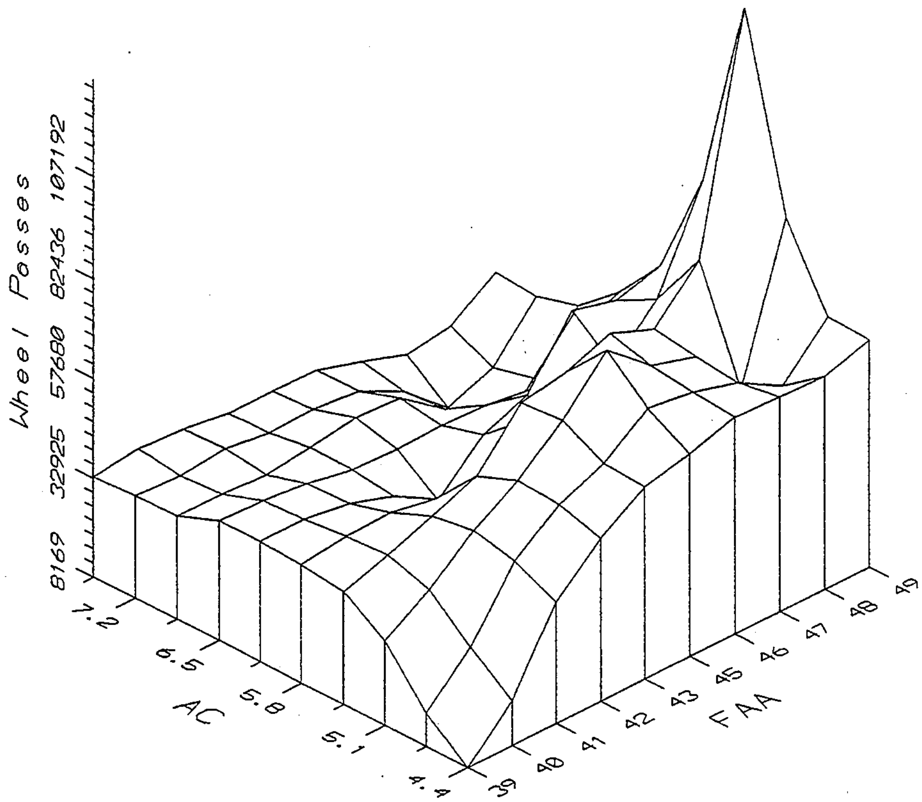

Figure 6.5 Three Dimensional Plot of Wheel Passes versus Asphalt Content and FAA

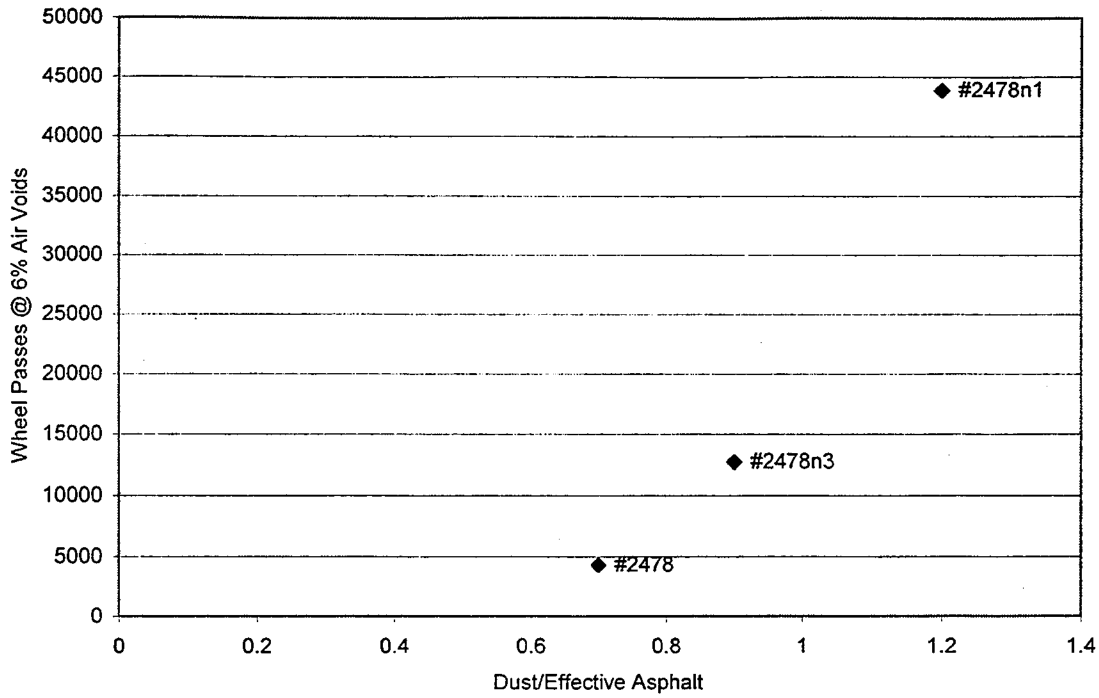

Figure 6.6 Dust Proportion vs. Wheel Passes at 6% Air Voids for Slag Mixtures

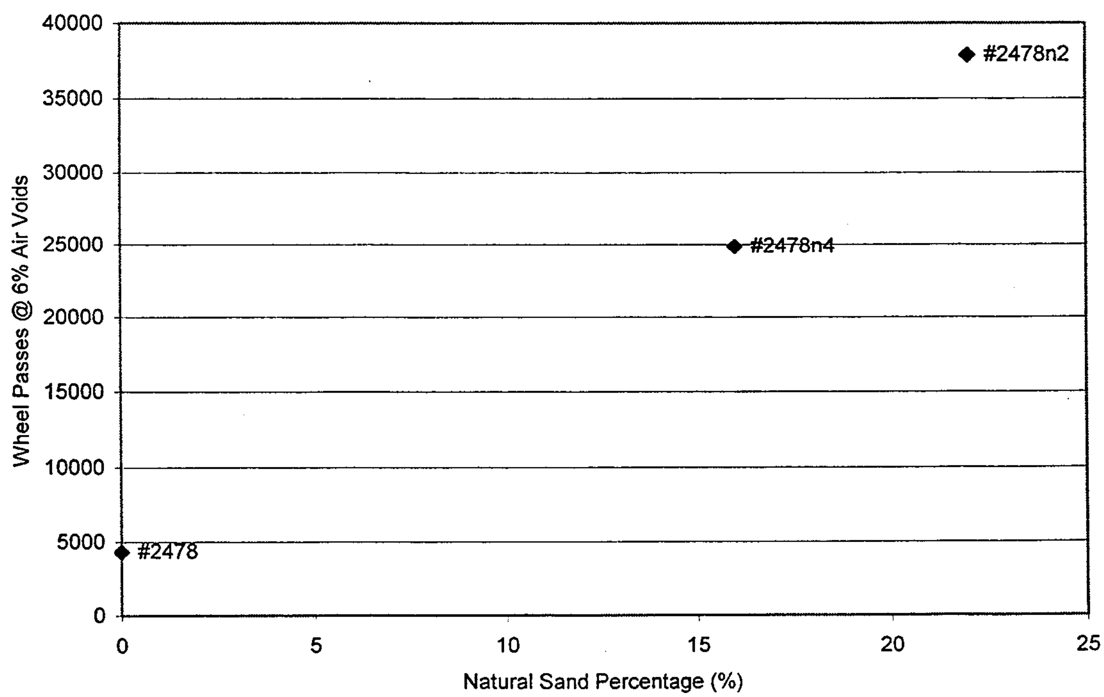

Figure 6.7 Natural Sand Percentage vs. Wheel Passes at 6% Air Voids for Slag Mixtures

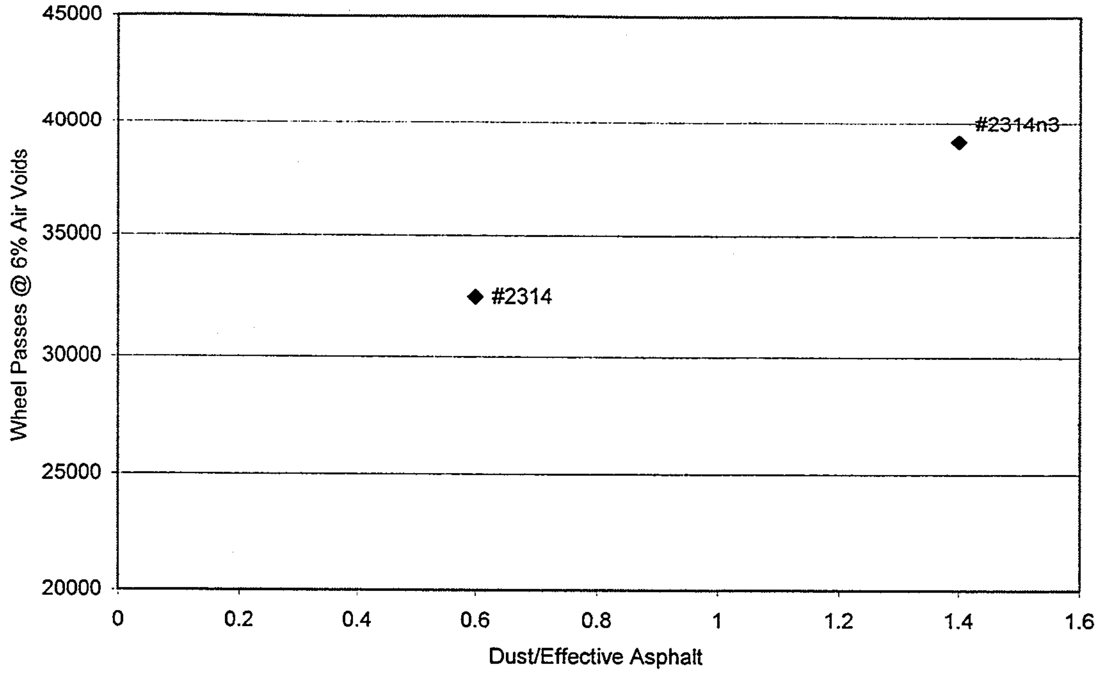

Figure 6.8 Dust Proportion vs. Wheel Passes at 6% Air Voids for Limestone Sand (#2314) Mixtures

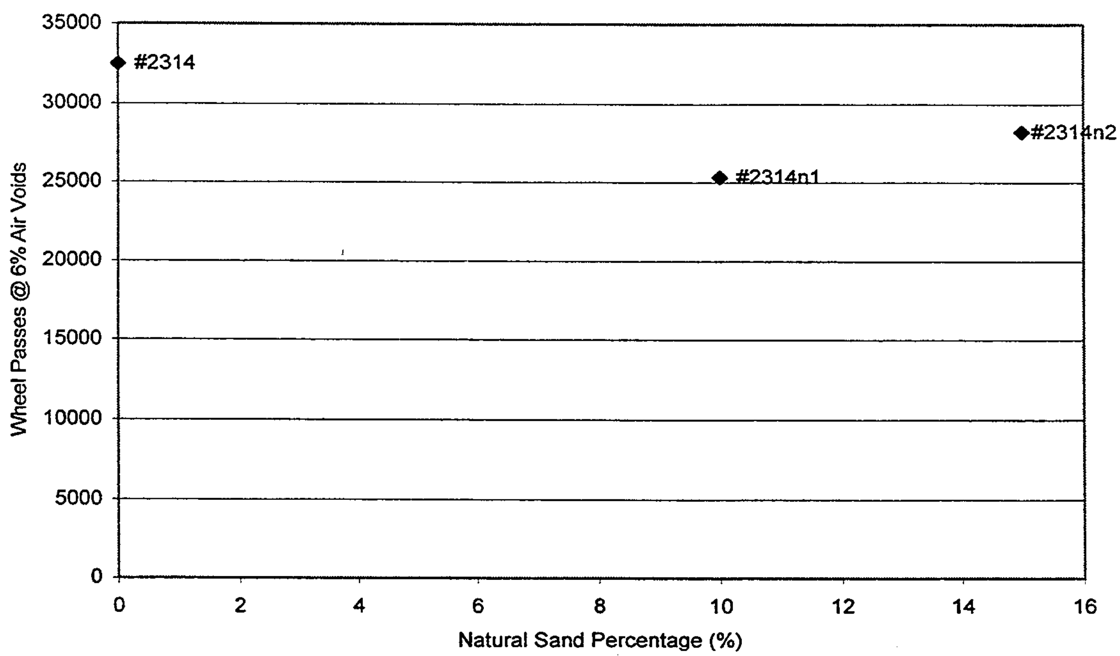

Figure 6.9 Natural Sand Percentage vs. Wheel Passes at 6% Air Voids for Limestone Sand (#2314) Mixtures

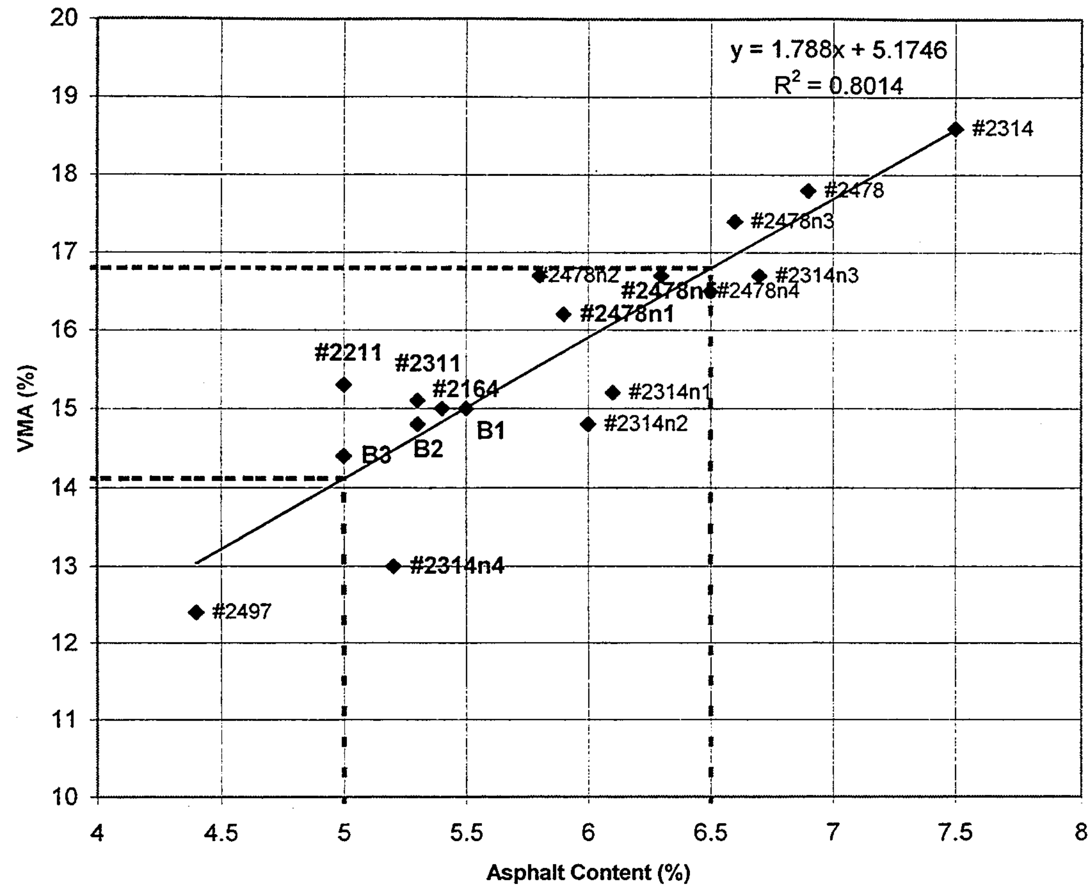

Figure 6.10 Relationship for VMA and Asphalt Content

Table 6.4 Summary of the Regression Analysis for All Mixtures

Source of Variation	df	SS	MS	F	Pr>F
Model	6	36.3052	6.0509	18.59	0.0001
Error	65	21.1514	0.3254		
Total	71	57.4566			
R-square = 0.6319					

Table 6.5 Summary of Stepwise Procedure for Dependent Variable Log (Y)

Variable Entered	Number In	Partial R^2	Model R^2	F	Prob. > F
GRAD	1	0.0875	0.0875	6.7159	0.0116
AV	2	0.1319	0.2195	11.6625	0.0011
AC	3	0.0911	0.3106	8.9871	0.0038
FAA	4	0.0869	0.3975	9.6656	0.0028
FAA*AC	5	0.2148	0.6123	36.5768	0.0001
SST	6	0.0195	0.6319	3.4485	0.0678

Table 6.6 Parameter Estimate from Regression Analysis for All Mixtures

Variable	Parameter Estimate	Standard Error	SS	F	Pr>F
Intercept	-44.2759	8.9951	7.884	24.23	0.0001
FAA	1.3080	0.2043	13.342	41.00	0.0001
AC	9.6084	1.7018	10.373	31.88	0.0001
AV	-0.2971	0.0507	11.160	34.29	0.0001
FAA*AC	-0.2256	0.0382	11.315	34.77	0.0001
SST	0.0001	0.00007	1.122	3.45	0.0678
GRAD	0.1157	0.0256	6.670	20.50	0.0001

Table 6.7 Parameters for Stepwise Regression with SST as the Dependent Variable

Mix ID	SST	FAA	AC	AV	DA	GRAD
#2311	958	45	5.3	6.6	0.6	5.5
#2497	565	39	4.4	5.2	1.1	6.5
#2211	540	48	5.0	4.8	0.7	8.0
#2164	793	49	5.4	5.1	1.0	9.0
#2478	430	47	6.9	6.0	1.0	6.0
#2314	1005	44	7.5	5.4	0.6	10.0
B1	849	46	5.5	4.4	0.9	8.0
B2	1254	45	5.3	5.2	0.9	8.0
B3	422	43	5.0	5.6	0.8	7.1
#2478n1	1643	47	5.9	7.0	1.2	5.7
#2478n2	2420	45.7	5.8	7.0	0.9	4.0
#2478n3	714	47	6.6	6.8	0.9	3.5
#2478n4	1041	46.5	6.5	5.4	0.9	4.0
#2478n5	1591	47	6.3	4.4	1.6	14.0
#2314n1	788	43.6	6.1	7.0	1.4	2.0
#2314n2	629	43	6.0	6.2	1.4	3.7
#2314n3	539	44	6.7	5.3	1.4	7.5
#2314n4	5000	44	5.2	7.1	1.1	5.0

Table 6.8 ANOVA Results for Slag Sand Mixtures with Varying D/A Ratio

Source of Variation	df	SS	MS	F	Pr>F
TRT	2	9.1677	4.5839	160.67	0.0001
AV	1	1.9531	1.9531	68.46	0.0001
Error	8	0.2282	0.0285		
R-square = 0.9799					

Table 6.9 ANOVA Results for Slag Sand Mixtures with Varying Natural Sand Percentage

Source of Variation	df	SS	MS	F	Pr>F
TRT	2	6.7926	3.3963	12.32	0.0036
AV	1	1.7077	1.7077	6.19	0.0376
Error	8	2.2055	0.2757		
R-square = 0.7940					

Table 6.10 ANOVA Results for Slag Sand Mixtures with Gradation Change

Source of Variation	Df	SS	MS	F	Pr>F
TRT	1	13.2085	13.2085	400.91	0.0001
AV	1	0.6561	0.6561	19.91	0.0066
Error	5	0.1647	0.1647		
R-square = 0.9883					

Table 6.11 ANOVA Results for Limestone Sand Mixtures with Varying D/A Ratio

Source of Variation	df	SS	MS	F	Pr>F
TRT	1	0.0202	0.0202	0.06	0.8138
AV	1	2.0598	2.0598	6.3	0.0538
Error	5	1.6351	0.3270		
R-square = 0.5599					

Table 6.12 ANOVA Results for Limestone Sand Mixtures with Varying Natural Sand Percentage

Source of Variation	df	SS	MS	F	Pr>F
TRT	2	0.0527	0.0264	0.18	0.8402
AV	1	1.7441	1.7441	11.77	0.0089
Error	8	1.1855	0.1482		
R-square = 0.6025					

Table 6.13 ANOVA Results for Limestone Sand Mixtures with Gradation Change

Source of Variation	Df	SS	MS	F	Pr>F
TRT	1	1.4730	1.4730	8.56	0.0328
AV	1	1.8243	1.8243	10.60	0.0226
Error	5	0.8607	0.1721		
R-square = 0.7930					

Table 6.14 Parameters in Correlation Analysis

	FAA	CAR[1]	Florida[2]	SST(RSCH)[3]	Wheel Pass[4]
#2311	45	3100	28.8	958	53063
#2497	39	560	4.3	565	8169
#2211	49	2210	25.2	793	43709
#2164	48	3025	19.3	540	131539
#2478	47	3800	27.2	430	4327
#2314	44	2525	28.8	1005	32493
B1	46	2400	16.9	849	73366
B2	45	1580	15.7	1007	69115
B3	43	1090	12.1	422	51228
#2478n1	47	3800	27.2	1643	43867
#2478n2	45.7	1605	21.4	2420	37901
#2478n3	47	3800	27.2	714	12719
#2478n4	46.5	2180	23.5	1041	24872
#2478n5	47	3800	27.2	1591	84339
#2314n1	43.6	1620	27.4	788	25341
#2314n2	43	1730	21.4	629	28230
#2314n3	44	2525	28.8	539	39155
#2314n4	44	2970	29.2	5,000	84776

[1] Results for CAR test are the peak load values for each fine aggregate (see Chap. 3).
[2] Results for Florida Bearing Value are in the unit of Mpa (see Chap. 3)
[3] Results for SST (RSCH) are numbers of load cycles to two percent shear strain in Repeated Shear Test at Constant Height (see Section 6.3.1).
[4] Wheel Pass is the normalized number of wheel passes in the PURWheel test (see Chap. 5).

Table 6.15 Correlation Matrix of Different Tests

Correlation Coefficients / Prob > | R | under H_0: Rh_o=0

	FAA	CAR	Florida	SST	Wheel Pass
FAA	1.000 p=0.0	0.69560 p=0.0013	0.48312 p=0.0423	0.00218 p=0.9931	0.39810 p=0.1018
CAR	0.69560 p=0.0013	1.000 p=0.0	0.71988 p=0.0008	0.18322 p=0.4668	0.19716 p=0.4329
Florida	0.48312 p=0.0423	0.71988 p=0.0008	1.000 p=0.0	0.28600 p=0.2499	-0.01691 p=0.9469
SST	0.00218 p=0.9931	0.18322 p=0.4668	0.28600 p=0.2499	1.000 p=0.0	0.34083 p=0.1663
Wheel Pass	0.39810 p=0.1018	0.19716 p=0.4329	-0.01691 p=0.9469	0.34083 p=0.1663	1.000 p=0.0

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

The objectives of this research were to address effects of fine aggregate angularity (FAA) on asphalt mixture rutting performance. Six fine aggregates were selected for this study and eighteen mixtures were designed using the Superpave volumetric mix design criteria. Phase I of the study included nine asphalt mixtures, six of them included a single sand and the remaining three mixtures included blends of different percentages of crushed gravel sand (#2164) and natural sand (#2497). In Phase II of the study, five mixtures were designed and tested for the slag sand (#2478) and four mixtures were designed and tested with an S-shaped gradation produced from a limestone sand (#2314). Mixtures in Phase II were evaluated for the effects on rutting of varying dust/asphalt ratio, gradation and natural sand. All of the mixtures were tested in the PURWheel and in the Superpave Simple Shear Tester (SST).

A separate design was conducted for each mixture in the study. The asphalt contents from these mix designs reflect the effect of FAA as well as particle shape and texture and gradation on the VMA. Asphalt content tends to increase with FAA. This reflects increased resistance to compaction and associated higher VMA. Very high FAA values, FAA of 48 or higher, may reflect particle shape (slivered) such as the crushed gravel or texture such as the slag. When compacted, the slivered particles will break or turn flat. The result is that the

VMA and associated asphalt demand are reduced. This is not the case with slag aggregate. The slag mixture VMA and asphalt demand remains high. Type of gradation such as the S-shaped gradation of mixture #2314 can also have high VMA and associated high asphalt content.

The variations of dust/asphalt ratio, gradation, and natural sand percentage incorporated in Phase II mixtures were used to increase the mastic stiffness, change the VMA and decrease the resistance to compaction, respectively. All three means successfully decreased the asphalt demand and associated VMA for slag mixture. However, adding natural sand and mineral filler did not improve the rutting performance of the S-shaped limestone sand mixture. The reason is that the gradation remained S-shaped after adding either natural sand or mineral filler. The only means to improve the rutting performance was to change the gradation. By straightening the S-shaped gradation curve, the VMA and associated asphalt demand were greatly reduced. With lower asphalt content and denser mineral aggregate structure, the rutting performance was also improved.

The Purwheel test results were statistically analyzed with the aid of the Statistical Analysis Software (SAS) [SAS Institute, Inc. 1991]. The statistical analyses were performed to correlate rutting in the PURWheel to measurements of mixture physical properties. The dependent variable is the number of wheel passes to a rut depth of 6.35mm (Y). The independent variables included in the analysis were fine aggregate angularity (FAA), asphalt content (AC), air void (AV), dust/asphalt ratio (DA), gradation (GRAD), and the interaction between fine aggregate angularity and asphalt content

(FAA*AC). Results from repeated shear, constant height test were also included as an independent variable (SST) in the statistical model. A stepwise regression analysis was performed.

Results of the statistical analysis showed that fine aggregate angularity (FAA), asphalt content (AC), air void (AV), gradation (GRAD), number of load cycles to two percent shear strain in the repeated shear test at constant height (SST), and the interaction between fine aggregate angularity and asphalt content (FAA*AC), are all significant. Among these factors, SST has the lowest significance level. Although the repeated shear, constant height test seems to vary in a reasonable way compared to PURWheel tests, the correlation is not very good. A possible reason might be the variation induced during sample preparation.

The most significant factor is FAA. But there is negative effect of the interaction of FAA and AC. This effect might be associated with the fact that higher FAA sands produce greater resistance to compaction. For a given compactive effort the result is higher VMA. With a fixed AV (four percent) requirement in the Superpave criteria the asphalt content will be high and rutting performance lowered. This effect is accentuated for more open graded mixtures (below the restricted zone).

Another stepwise regression analysis was conducted with SST as the dependent variable. Independent variables in the model included fine aggregate angularity (FAA), asphalt content (AC), air void (AV), dust/asphalt ratio (DA), and gradation (GRAD). With the default significance level of 0.15, none of the factors is significant enough to enter the statistical model.

Rutting performance appears to be sensitive to the design asphalt content. This result is mirrored in the VMA. Probably VMA is critical because it is determined by fine aggregate shape and texture and mixture gradation. Fine aggregate angularity becomes less critical if an upper limit is adopted for VMA.

As part of the analysis film thickness was determined for all mixtures. The average film thickness for the three best performing mixtures was 8.2 microns. Film thickness needs to be examined in more detail for possible use in evaluating design asphalt contents for mixtures.

Results of mix designs and performance tests indicate that the lower VMA limit for 9.5mm mixtures may need to be adjusted. In addition, an upper limit on VMA would help to eliminate mixture designs with unacceptably high asphalt contents.

Mixture #2478n5, #2314n1, #2314n2 and #2314n3 violated the current criteria for dust/asphalt ratio. The dust/asphalt ratio of mixture #2478n5 is 1.6 and that of mixtures #2314n1 to #2314n3 is 1.4. Rutting Performance in the PURWheel for these mixtures was good. However, for some mixtures an increase in dust may contribute to overfilling the voids. Also, the dust, by reducing asphalt content can reduce durability.

FAA alone may not be adequate to evaluate the contribution of fine aggregate to the mixture performance. From this study, we know that fine aggregate angularity has correlation with the (rutting) performance of a mixture but the mixture performance is based on many other factors. Different mixtures with the same fine aggregate can either perform well or poorly.

In general, results of the study indicate there is improved rutting performance with increasing FAA. However, the results also indicate that a mixture with fine aggregate having an FAA value of 43 performed as well as a mixture with fine aggregate having an FAA value of 48. This result is possible because of confounding effects such as gradation and compactability. The key is to have a performance test such as the PURWheel to compliment the Superpave volumetric design procedures. Results of the study show that the SST test does not explain the effects of aggregate and mixture variables based on the level of performance exhibited by mixtures satisfying Superpave volumetric criteria.

The PURWheel laboratory wheel test device was effective in showing the relative performance of the mixtures tested in this study. This type of equipment can be utilized to test a large number of material and mixture variables in a relatively short period of time.

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APPENDIX A TEST PROCEDURE FOR COMPACTED AGGREGATE RESISTANCE (CAR) TEST

COMPACTED AGGREGATE RESISTANCE (CAR) TEST

A test for evaluating the shear resistance of compacted fine aggregate materials in their "as received" condition.

This procedure is intended for use on the combined fine aggregate materials to be used in the paving mixture. The performance of individual components can be judged provided engineering judgement is used. For example a high fine component will give a high stability value but could not represent 100% of the fine aggregate material in the mix.

Equipment Needed

Marshall mold with base-plate attached (welded or secured in a permanent manner), Marshall mold collar, Marshall compaction hammer, Mixing bowl and utensils, riffle splitter, screen shaker, 2.36mm (No. 8) sieve, drying oven, balance (at least 8,000 gram capacity accurate to 0.1 gram), Marshall stability and flow machine, graph recorder with 5,000lb. graph paper, 1.5 inch diameter X 1.5 inch high steel round stock (top and bottom are flat).

Procedure

Secure a representative 5,000-6,000 gram sample by riffle splitting. Splitting should be performed at or near SSD (Saturated-Surface Dry) condition to prevent loss of fines.

Sieve this portion to refusal over a 2.36mm (No.8) screen, again, at or near SSD to prevent the loss of fines. A Gilson 2' X 3' screen shaker is recommended. Discard the material retained on the 2.36mm (No. 8) sieve.

Oven dry the material finer than the No.8 sieve to a constant weight at 110 ± 5°C, remove from oven and cool the material to ambient temperature. Weigh the material to the nearest 0.1-gram.

Add 1.75% of water by dry weight of the sample and mix thoroughly.

Reduce material by riffle splitting or quartering to approximately 1,100 grams as quickly as possible to reduce moisture loss. Record the weight. Remaining prepared material may be used within one hour if kept in a sealed container. Secondary absorption after a period of time may require that the drying procedure be repeated.

Cover the Marshall hammer striking face with cellophane (saran wrap held in place with a rubber band) or aluminum foil. This will prevent particles from adhering to the striking face surface and will produce a smooth bearing surface on the compacted specimen.

Place material in 4-inch diameter Marshall mold meeting the requirements of ASTM D 1559. Spade the material with a spatula 15 times around the perimeter and 10 times over the interior. Remove the collar and smooth the surface with the spatula to a slightly rounded shape.

Replace collar and place mold assembly with specimen on the compaction pedestal. Compact specimen using 50 blows from the Marshall hammer. Unlike the Marshall method only one surface of the specimen is to be compacted.

After compaction, carefully remove mold assembly from compaction pedestal. Remove collar and measure distance from top of mold to top of specimen. Calculate specimen height. The specimen should be 6.35 ± 0.318-cm (2.5 ± 0.125 inches) in height. If specimen does not meet height requirements, discard compacted specimen. Compact a new specimen using remaining prepared material adjusting the amount required to achieve a specimen height of 6.35-cm (2.5 inches) using the following formula:

Adjusted weight of aggregate = (2.5 X weight of aggregate used)
÷(actual specimen height obtained in inches).

Place compacted sample, with base plate and mold still in the upright, vertical position (compacted face up) along with appropriate spacers on the Marshall Stability and Flow machine. Place 1.5-in. diameter X 1.5-in. high steel round stock (flat top and bottom) on the center of the compacted specimen and align vertically under the load cell.

Operate Stability and Flow apparatus at 2 inches per minute travel using 5,000-lb load range and plot the graph on 5,000lb Marshall graph paper.

Suggestion: The stability value at a flow of 20 or highest value achieved prior to 20 should be the reported value. Some fine aggregate materials exceed 6,000-lb. stability values and may damage load cells. The test could be terminated before this point.

APPENDIX B TEST PROCEDURE FOR FLORIDA BEARING VALUE

INDIANA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS DIVISION

DETERMINING FLORIDA BEARING VLAUE OF FINE AGGREGATE
Indiana Test Method or Procedure No. 201-89

1.0 SCOPE

1.1 This method of test covers the determination of the Florida Bearing Value of Fine Aggregate.

2.0 APPARATUS

2.1 Oven, capable of maintaining the temperature at 110° ± 5°C (230° ± 9°F).

2.2 Sieve, a 4.75-mm (No. 4), conforming to the requirements of the Standard Specification for Sieves for Testing Purposes (AASHTO M-92).

2.3 Mortar and Pestle, a mortar and rubber covered pestle.

2.4 Balances, a Class D-Type 1 or 2 and Class E-Type 1 or 2, conforming to the requirements for the Standard Specifications for Weights and Balances used in the Testing of Highway Materials (AASHTO M-231).

2.5 Pans and containers, as needed.

2.6 Soil Bearing Cup, a cylindrical brass cup 3-3/16" in height with an outside diameter of 3-1/16" (inside diameter of 3").

2.7 Bearing Plates, a large brass circular bearing plate 3" in diameter and a small brass circular bearing plate 1.128" in diameter (1 sq. inch in area).

2.8 Graduate or Pipette, minimum capacity of 15 mL, readable to 0.5 mL.

2.9 Mixing Spoon, 12" long made of stainless steel.

2.10 Straight Edge, 12" long made of stainless steel.

2.11 Spring Tester, Rimac Spring Tester or equivalent capable of applying a total load of 100 pounds uniformly at the rate of 20 pounds per second.

2.12 Compression Testing Machine, capable of applying a total load of 1500 pounds at a rate of 2.4 inches per minute.

2.13 Bearing Value Machine.

3.0 SAMPLING

3.1 Sampling shall be conducted conforming to the requirements of the Standard Specifications for Sampling Stone, Slag, Gravel, Sand, and Stone Block for Use as Highway Materials (AASHTO T-2), INDOT Standard Specifications, and Division of Materials and Tests, Manual for Aggregate Inspectors.

4.0 PROCEDURE

4.1 Thoroughly mix the sample of fine aggregate. Select a representative portion of the sample by the use of a sample splitter or by the method of quartering. The sample shall be in a moist condition at the time of splitting or quartering. The representative portion shall have a mass from 650 to 700 grams and shall be the end result of the splitting or quartering. The selections of an exact predetermined mass shall not be attempted.

4.2 The sample shall be dried in the oven at 110° ± 5°C (230° ± 9°F) to constant mass and cooled. The dry, cool sample shall be sieved through the 4.75-mm (No. 4) sieve. The material retained on the 4.75-mm (No. 4) sieve shall be ground in the mortar with the rubber-covered pestle and such a manner as to avoid breaking individual particles. This material shall then be sieved through the 4.75-mm (No. 4) sieve. Thoroughly mix all of the material passing the 4.75-mm (No. 4) sieve, weigh to the nearest 0.1 gram and transfer to a round bottom pan. Add 1.75% water (based on the oven dry mass of sample) and thoroughly mix into the material in the round bottom pan with the mixing spoon. Mixing shall be accomplished within 15 seconds to minimize loss of evaporation.

4.3 Fill the soil bearing cup with the mixed material with a continuos pouring action and pile it conically above the cup. Place the 3" diameter bearing plate on top of the coned material. Place the soil bearing cup in the Spring Tester and apply a load of 100 pounds at a rate of 20 pounds per second, hold load for 5 seconds and release the load. The bearing plate shall then be removed and additional material added and piled conically above the cup, and the plate again placed on the material. A load of 100 pounds is again applied as previously described and released. Remove the soil bearing cup from the Spring Tester, remove the bearing plate, and then remove the excess material by means of the straight edge with a simple, one pass movement.

4.4 The 3" diameter bearing plate is again placed on the material and the bearing cup is placed in the compression testing machine. Apply a load at a rate of 2.4 inches per minute, to a total load of 1500 pounds and release the load. Remove the bearing cup from the compression testing machine. Remove the bearing plate and place the small bearing plate on 1 square inch in the center of the upper surface of the compressed sample. The cup, material and bearing plate shall then be placed on the adjustable platen of the Bearing Value Machine. Raise the bearing cup by means of the screw adjustment until the ball bearing on the lever arm is in contact with the spherical indentation on the stem of the bearing plate. Position the stem of the micrometer dial gauge on the lever arm, above the center of the bearing plate, and get an initial reading.

Note: The lever arm with the bucket attached shall have been previously leveled by means of the counterweight and the funnel filled with shot.

4.5 Apply a constant increasing load to the specimen by opening the valve on the funnel and allowing the shot to enter the bucket at the rate of 454 grams in 7.5 seconds. Stop until the pressure on the bearing plate is great enough to cause a deformation of 0.01" in 5 seconds. When this rate of deformation is reached, immediately close the valve on the funnel. Weigh the shot in the bucket to the nearest gram and record the mass. Some materials do not noticeably compress, nor is there any noticeable penetration of the bearing plate until failure, which occurs abruptly. In this case, immediately close the valve on the funnel, weigh the shot in the bucket to the nearest gram, and record the mass.

5.0 CALCULATION

5.1 The Florida Bearing Value in pounds per square inch shall be calculated by the following formula:

$$\text{Florida Bearing Value} = \frac{W}{454} \times L$$

in which:

W = mass of shot in grams
L = lever arm ratio

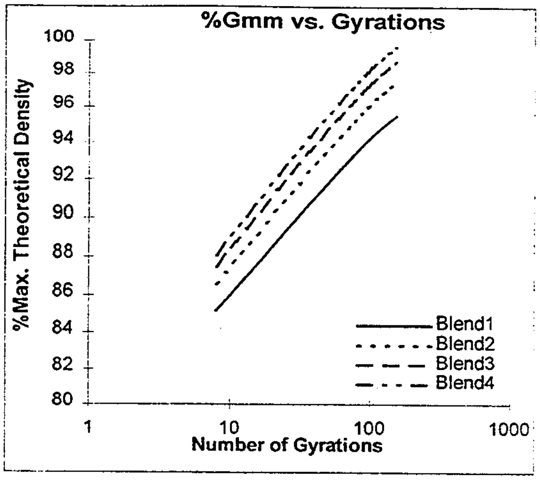
APPENDIX C SUPERPAVE MIX DESIGN DATA

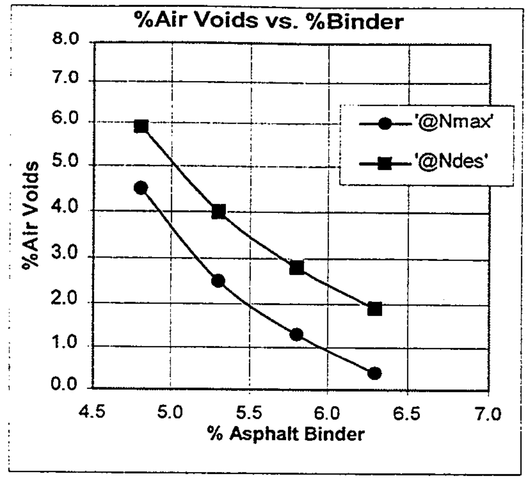
Mix Design Summary for Mixture #2311

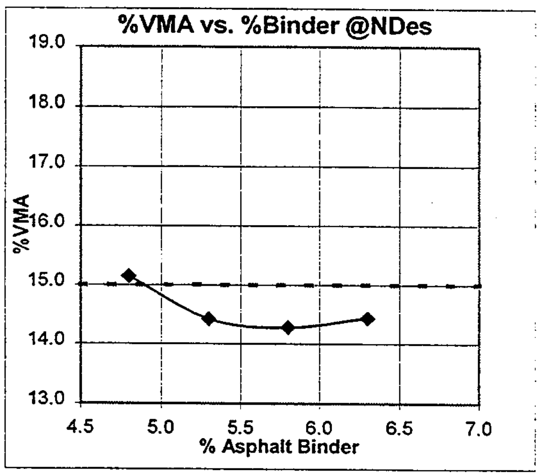
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2311	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

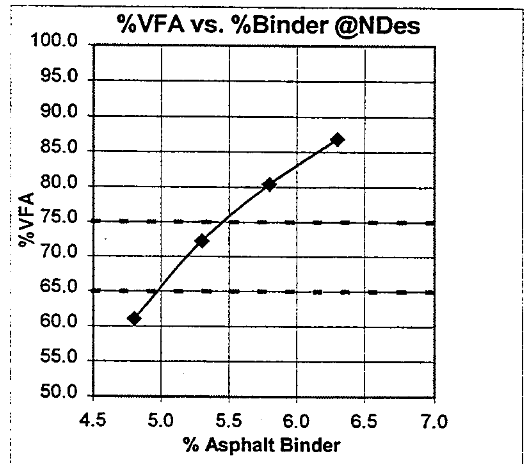
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	4.8	85.2	94.1	95.5	5.9	15.1
Blend 2	5.3	86.6	96.0	97.5	4.0	14.4
Blend 3	5.8	87.5	97.2	98.7	2.8	14.3
Blend 4	6.3	88.1	98.1	99.6	1.9	14.4

	Blend 1	Blend 2	Blend 3	Blend 4	*Design AC*
Agg. Bulk Specific Gravity (G_{sb}):	2.626	2.626	2.626	2.626	***2.626***
Percent Binder by wt. of mix (P_b):	4.8	5.3	5.8	6.3	***5.3***
Percent Aggregate (P_s):	95.2	94.7	94.2	93.7	***94.7***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	3.3	3.3	3.3	3.3	***3.3***
Rice Specific Gravity (G_{mm}):	2.487	2.472	2.458	2.444	***2.472***
Effective Specific Gravity (G_{se}):	2.6780	2.6822	2.6874	2.6925	***2.6822***
Effective % Binder (P_{be}):	4.0	4.5	4.9	5.3	***4.5***
% Binder Absorption (P_{ba}):	0.8	0.8	0.9	1.0	***0.8***
Dust Proportion (0.6-1.2%):	0.8	0.7	0.7	0.6	***0.7***
Surface Area(m^2):	1.914	1.914	1.914	1.914	***1.914***
Film Thickness(micron):					***11.0***

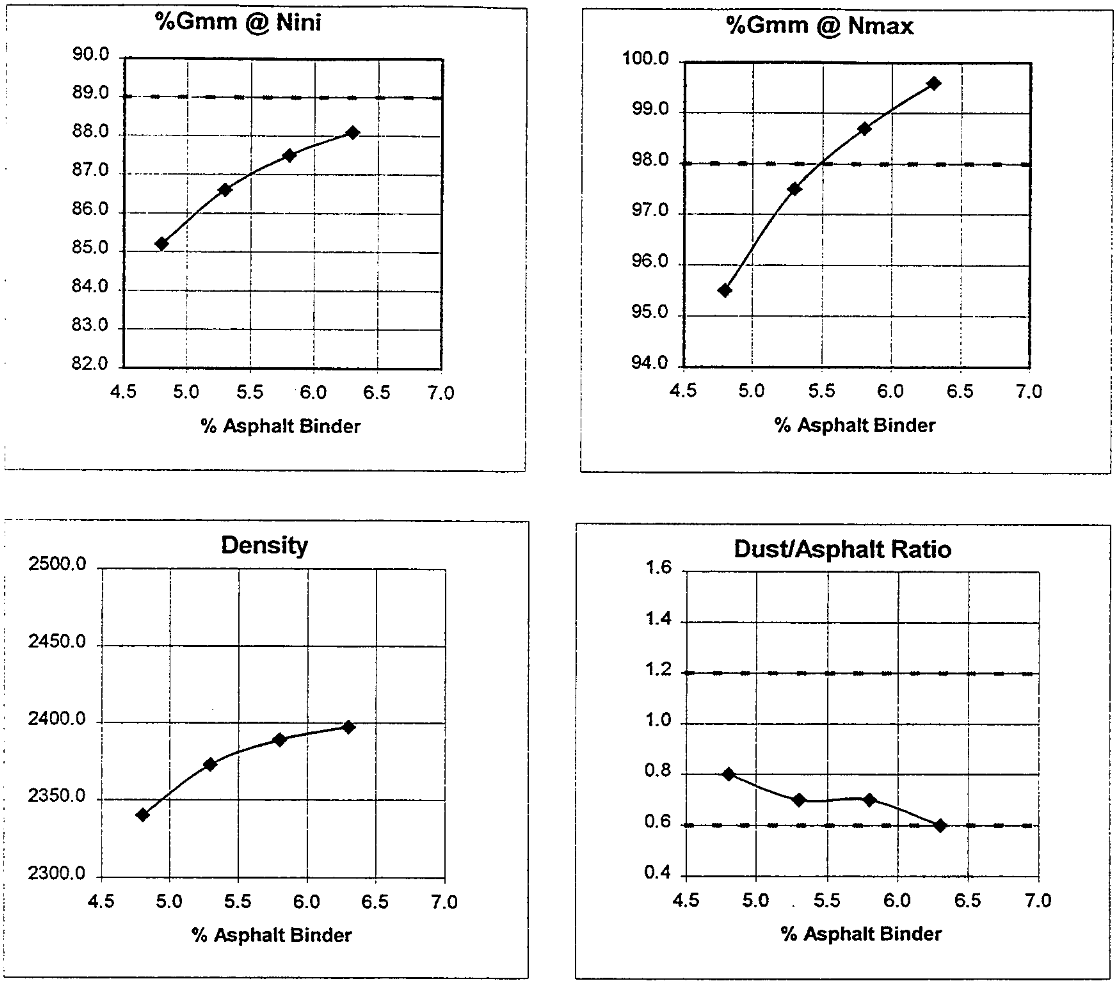








Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	4.8	4.5	5.9	15.1	61.0
Blend2	5.3	2.5	4.0	14.4	72.3
Blend3	5.8	1.3	2.8	14.3	80.4
Blend4	6.3	0.4	1.9	14.4	86.8



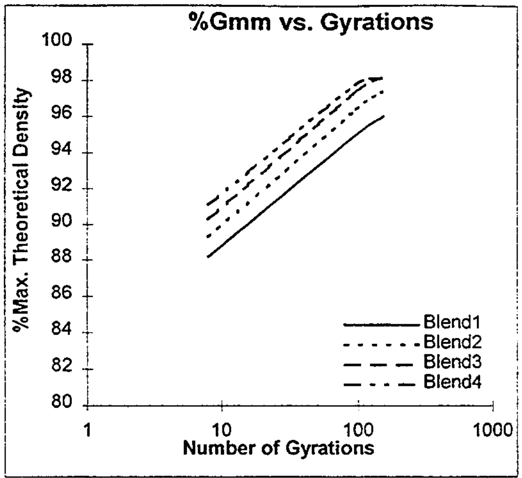
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	4.8	85.2	95.5	2340.3	0.8
Blend2	5.3	86.6	97.5	2373.1	0.7
Blend3	5.8	87.5	98.7	2389.2	0.7
Blend4	6.3	88.1	99.6	2397.6	0.6

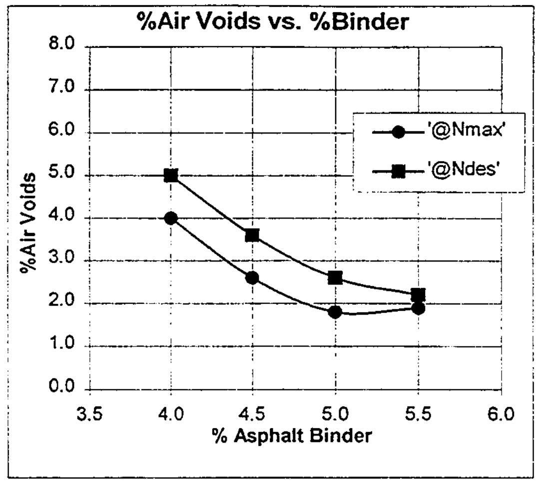
Mix Design Summary for Mixture #2497

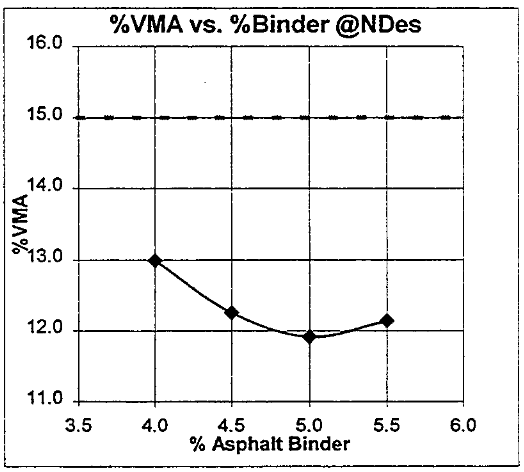
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2497	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

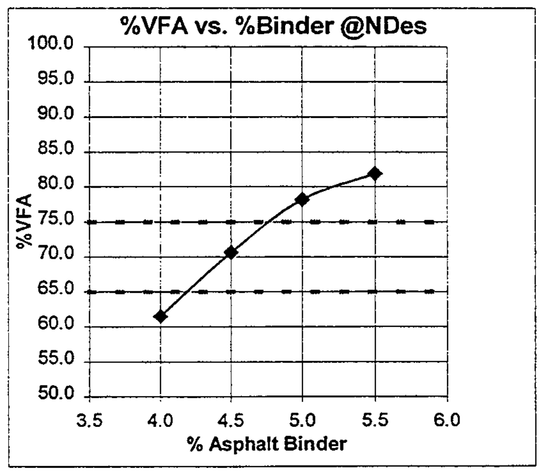
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	4.0	88.2	95.0	96.0	5.0	13.0
Blend 2	4.5	89.3	96.4	97.4	3.6	12.3
Blend 3	5.0	90.3	97.4	98.2	2.6	11.9
Blend 4	5.5	91.1	97.8	98.1	2.2	12.1

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.607	2.607	2.607	2.607	***2.607***
Percent Binder by wt. of mix (P_b):	4.0	4.5	5.0	5.5	***4.4***
Percent Aggregate (P_s):	96.0	95.5	95.0	94.5	***95.6***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.2	4.2	4.2	4.2	***4.2***
Rice Specific Gravity (G_{mm}):	2.490	2.488	2.485	2.482	***2.488***
Effective Specific Gravity (G_{se}):	2.6468	2.6656	2.6845	2.7032	***2.6614***
Effective % Binder (P_{be}):	3.4	3.6	3.9	4.1	***3.6***
% Binder Absorption (P_{ba}):	0.6	0.9	1.1	1.4	***0.8***
Dust Proportion (0.6-1.2%):	1.2	1.2	1.1	1.0	***1.2***
Surface Area(m^2):	2.248	2.248	2.248	2.248	***2.248***
Film Thickness(micron):					***7.4***

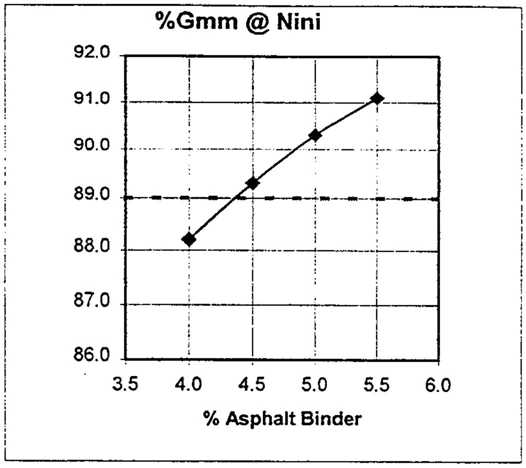


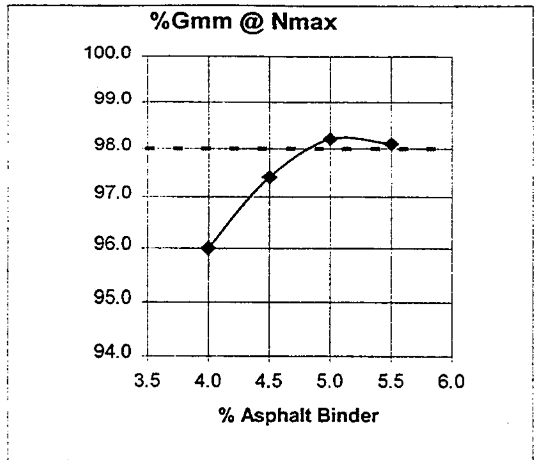


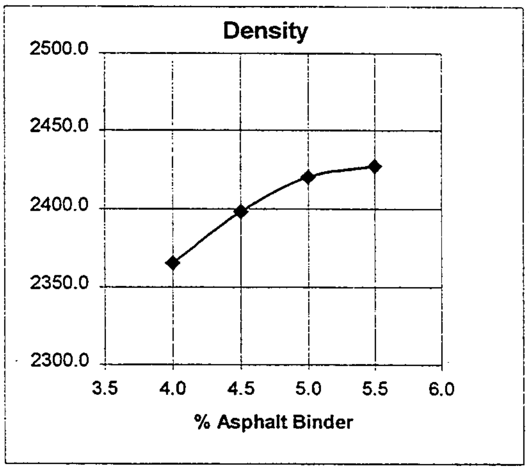


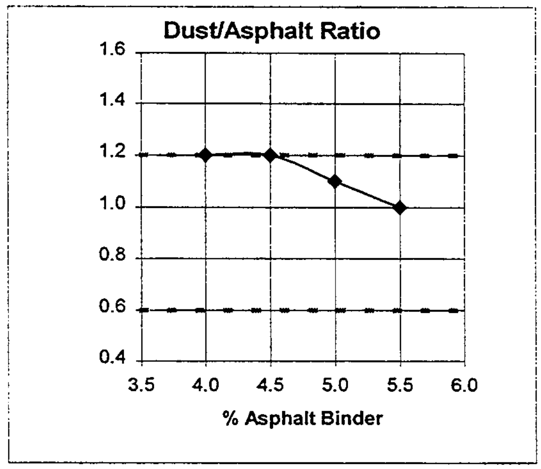


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	4.0	4.0	5.0	13.0	61.5
Blend2	4.5	2.6	3.6	12.3	70.6
Blend3	5.0	1.8	2.6	11.9	78.2
Blend4	5.5	1.9	2.2	12.1	81.9









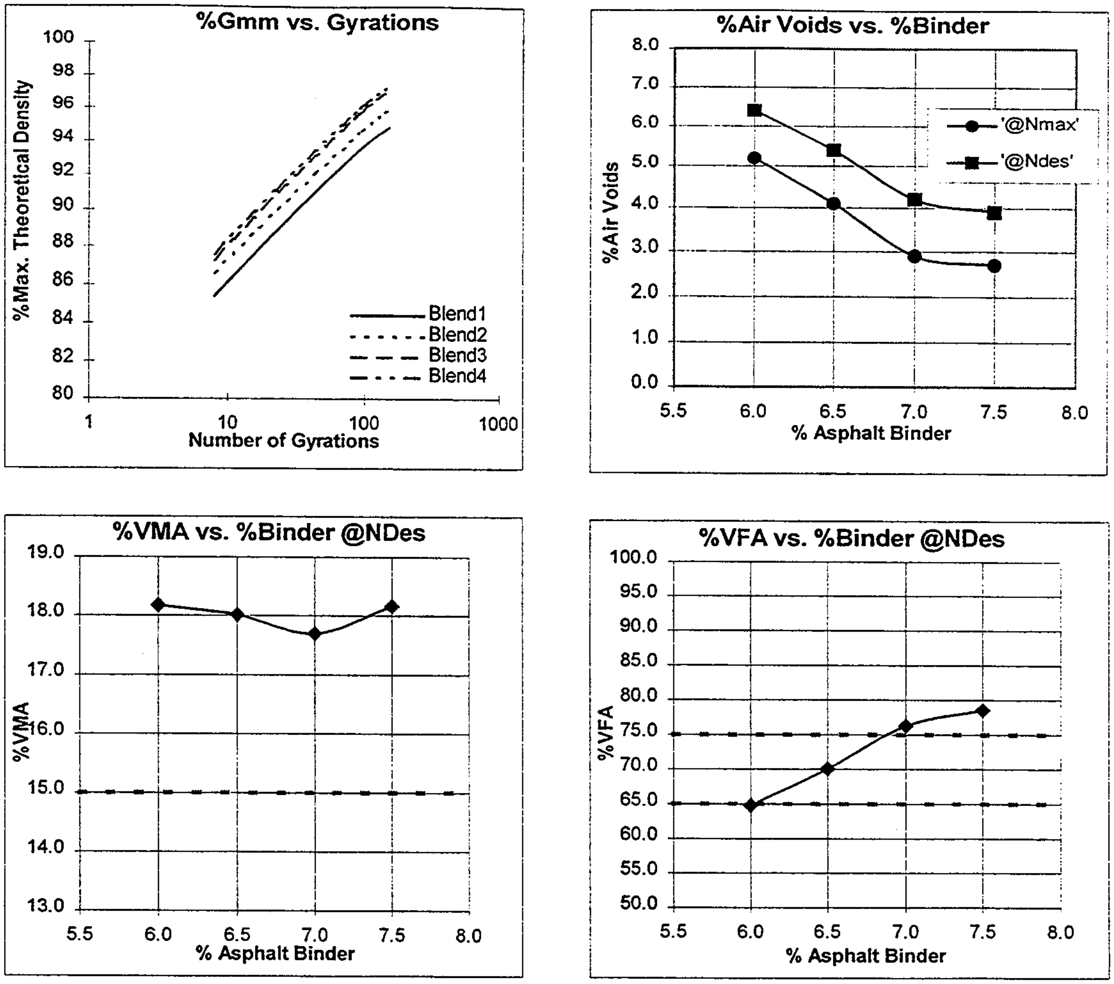
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	4.0	88.2	96.0	2365.5	1.2
Blend2	4.5	89.3	97.4	2398.4	1.2
Blend3	5.0	90.3	98.2	2420.4	1.1
Blend4	5.5	91.1	98.1	2427.4	1.0

Mix Design Summary for Mixture #2478

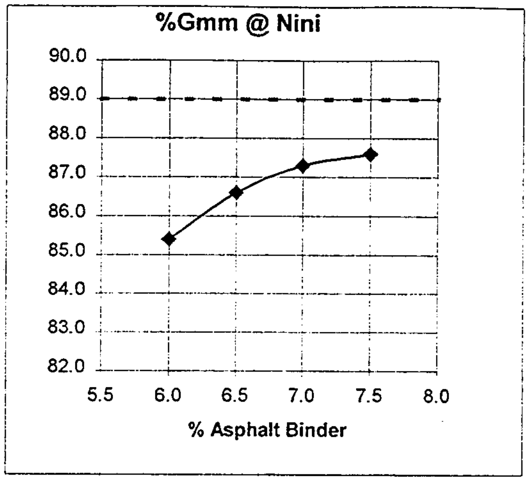
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2478	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

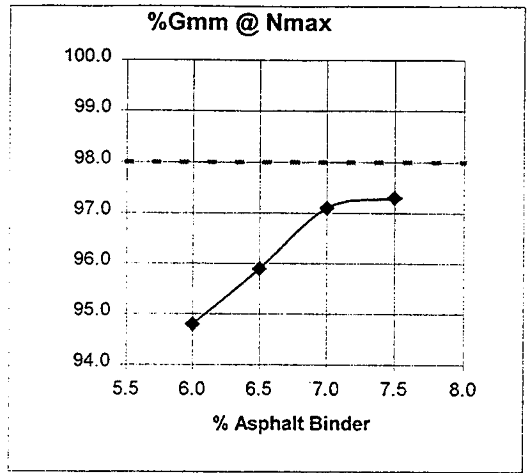
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	6.0	85.4	93.6	94.8	6.4	18.2
Blend 2	6.5	86.6	94.6	95.9	5.4	18.0
Blend 3	7.0	87.3	95.8	97.1	4.2	17.7
Blend 4	7.5	87.6	96.1	97.3	3.9	18.2

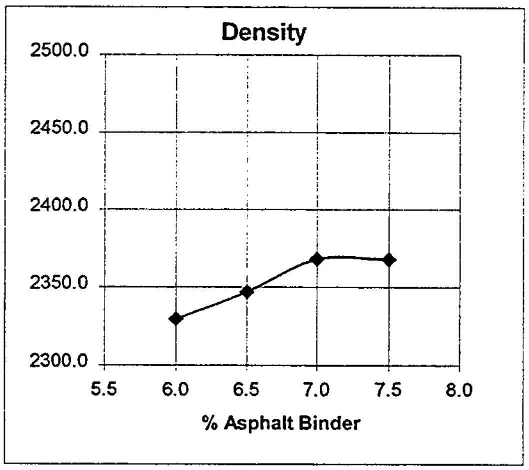
	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.676	2.676	2.676	2.676	***2.676***
Percent Binder by wt. of mix (P_b):	6.0	6.5	7.0	7.5	***6.9***
Percent Aggregate (P_s):	94.0	93.5	93.0	92.5	***93.1***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	3.7	3.7	3.7	3.7	***3.7***
Rice Specific Gravity (G_{mm}):	2.489	2.481	2.472	2.464	***2.474***
Effective Specific Gravity (G_{se}):	2.7364	2.7504	2.7632	2.7775	***2.7609***
Effective % Binder (P_{be}):	5.2	5.5	5.8	6.1	***5.7***
% Binder Absorption (P_{ba}):	0.8	1.0	1.2	1.4	***1.2***
Dust Proportion (0.6-1.2%):	0.7	0.7	0.6	0.6	***0.6***
Surface Area(m^2):	2.007	2.007	2.007	2.007	***2.007***
Film Thickness(micron):					***13.7***

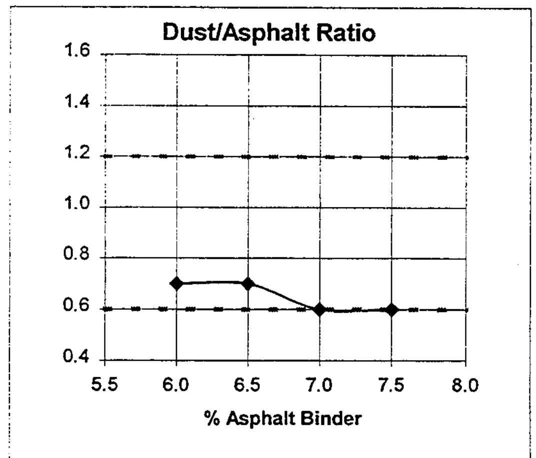


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	6.0	5.2	6.4	18.2	64.8
Blend2	6.5	4.1	5.4	18.0	70.0
Blend3	7.0	2.9	4.2	17.7	76.3
Blend4	7.5	2.7	3.9	18.2	78.5









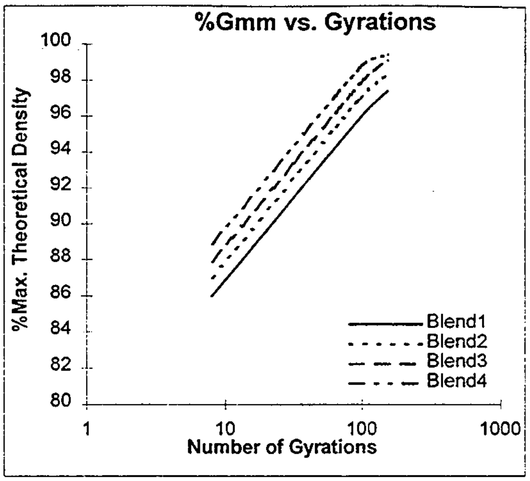
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	6.0	85.4	94.8	2329.7	0.7
Blend2	6.5	86.6	95.9	2347.0	0.7
Blend3	7.0	87.3	97.1	2368.2	0.6
Blend4	7.5	87.6	97.3	2367.9	0.6

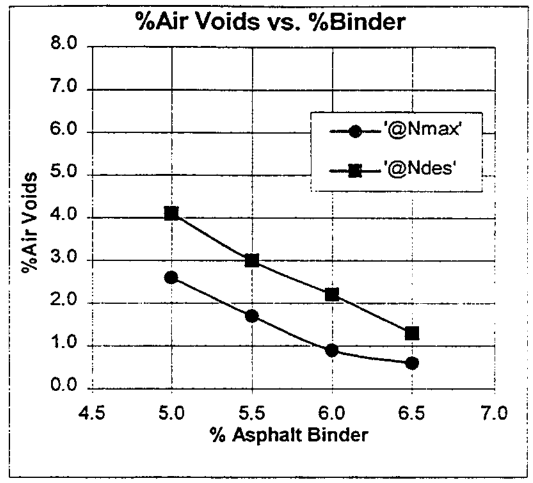
Mix Design Summary for Mixture #2211

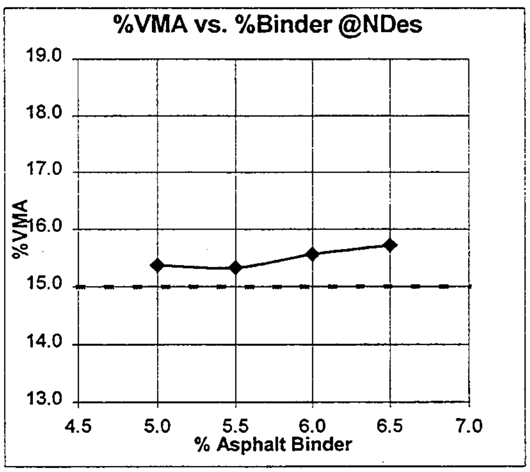
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2211	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

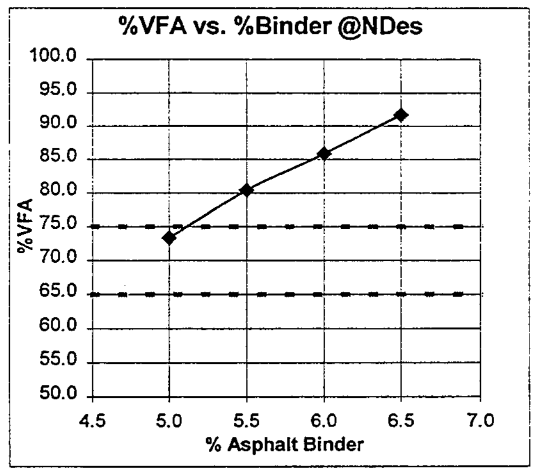
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.0	86.0	95.9	97.4	4.1	15.4
Blend 2	5.5	87.0	97.0	98.3	3.0	15.3
Blend 3	6.0	87.9	97.8	99.1	2.2	15.6
Blend 4	6.5	88.9	98.7	99.4	1.3	15.7

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.671	2.671	2.671	2.671	***2.671***
Percent Binder by wt. of mix (P_b):	5.0	5.5	6.0	6.5	***5.0***
Percent Aggregate (P_s):	95.0	94.5	94.0	93.5	***95.0***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.8	4.8	4.8	4.8	***4.8***
Rice Specific Gravity (G_{mm}):	2.481	2.467	2.453	2.439	***2.481***
Effective Specific Gravity (G_{se}):	2.6797	2.6850	2.6902	2.6953	***2.6797***
Effective % Binder (P_{be}):	4.9	5.3	5.7	6.2	***4.9***
% Binder Absorption (P_{ba}):	0.1	0.2	0.3	0.3	***0.1***
Dust Proportion (0.6-1.2%):	1.0	0.9	0.8	0.8	***1.0***
Surface Area(m^2):	2.267	2.267	2.267	2.267	***2.267***
Film Thickness(micron):					***10***

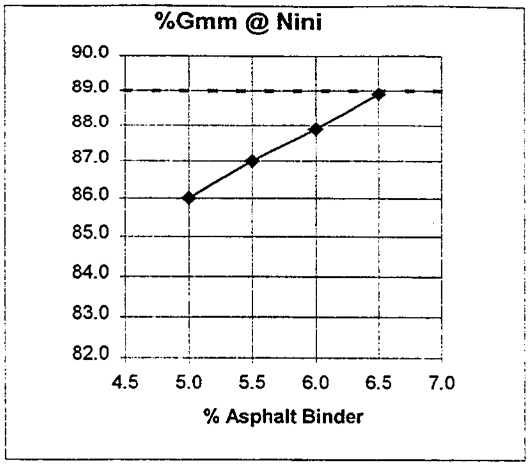


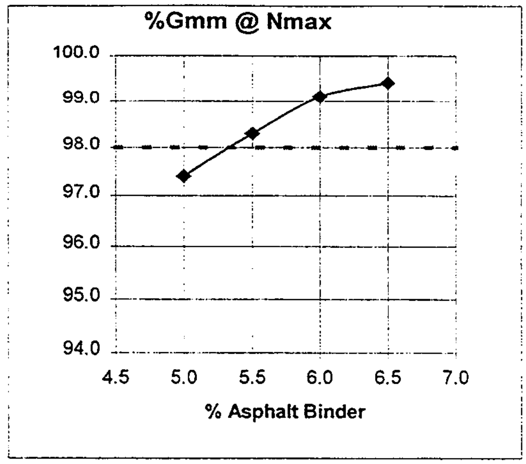


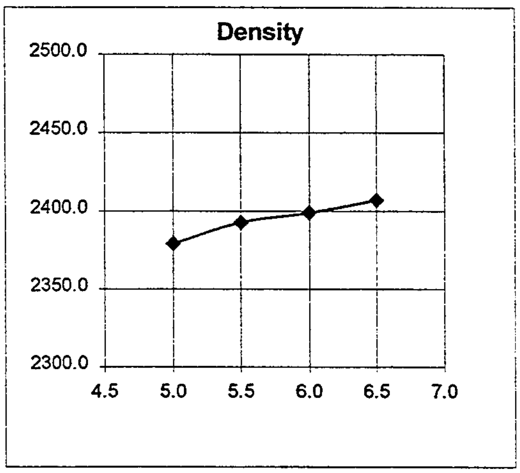


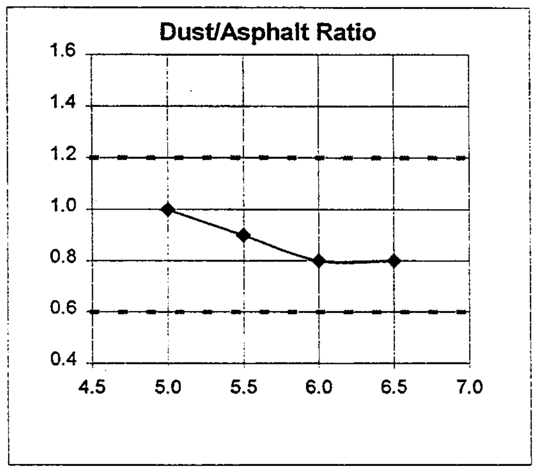


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.0	2.6	4.1	15.4	73.3
Blend2	5.5	1.7	3.0	15.3	80.4
Blend3	6.0	0.9	2.2	15.6	85.9
Blend4	6.5	0.6	1.3	15.7	91.7









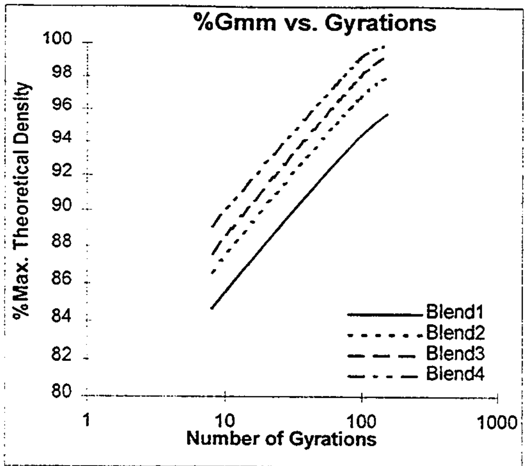
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.0	86.0	97.4	2379.3	1.0
Blend2	5.5	87.0	98.3	2393.0	0.9
Blend3	6.0	87.9	99.1	2399.0	0.8
Blend4	6.5	88.9	99.4	2407.3	0.8

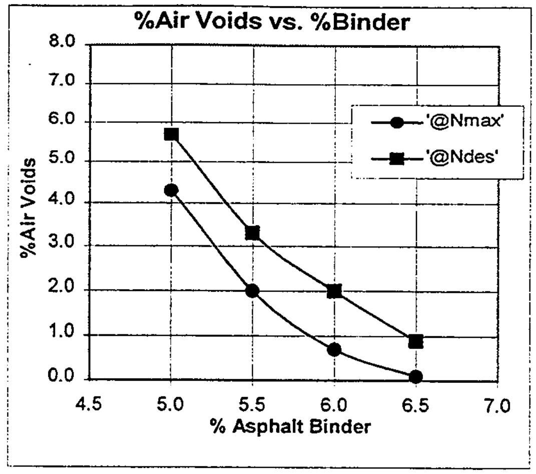
Mix Design Summary for Mixture #2164

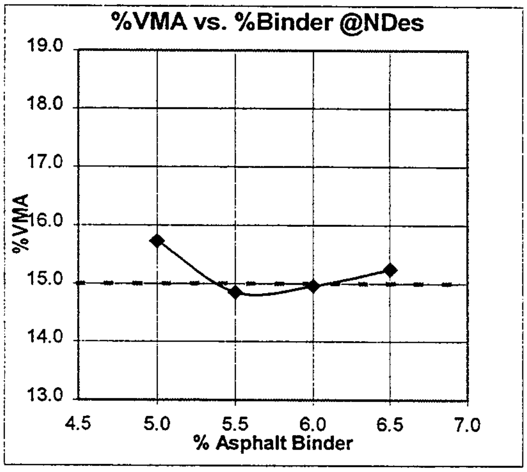
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2164	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

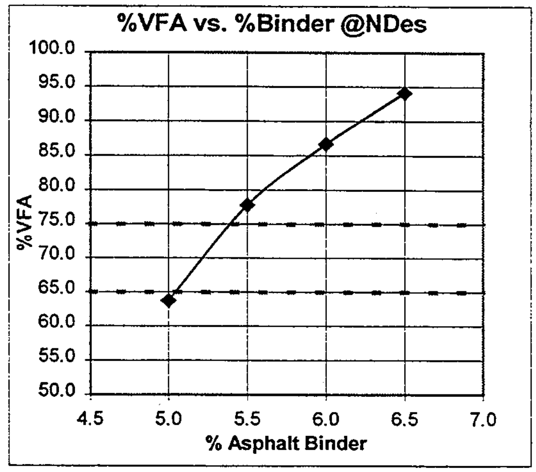
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.0	84.7	94.3	95.7	5.7	15.7
Blend 2	5.5	86.6	96.7	98.0	3.3	14.9
Blend 3	6.0	87.6	98.0	99.3	2.0	15.0
Blend 4	6.5	89.1	99.1	99.9	0.9	15.2

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.623	2.623	2.623	2.623	***2.623***
Percent Binder by wt. of mix (P_b):	5.0	5.5	6.0	6.5	***5.4***
Percent Aggregate (P_s):	95.0	94.5	94.0	93.5	***94.6***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.9	4.9	4.9	4.9	***4.9***
Rice Specific Gravity (G_{mm}):	2.470	2.447	2.424	2.402	***2.455***
Effective Specific Gravity (G_{se}):	2.6662	2.6600	2.6532	2.6471	***2.6655***
Effective % Binder (P_{be}):	4.4	5.0	5.6	6.1	***4.8***
% Binder Absorption (P_{ba}):	0.6	0.5	0.4	0.4	***0.6***
Dust Proportion (0.6-1.2%):	1.1	1.0	0.9	0.8	***1.0***
Surface Area(m^2):	2.388	2.388	2.388	2.388	***2.388***
Film Thickness(micron):					***9.4***

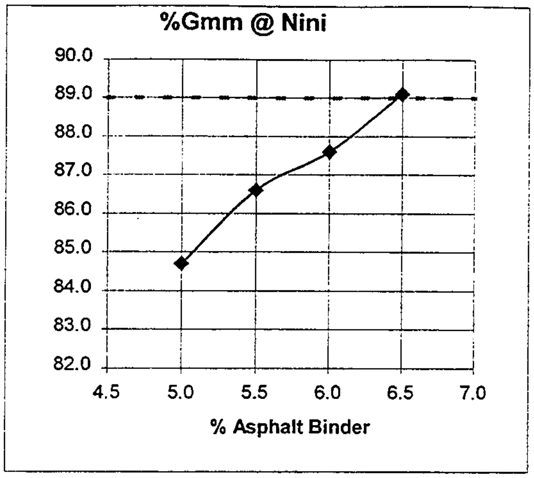


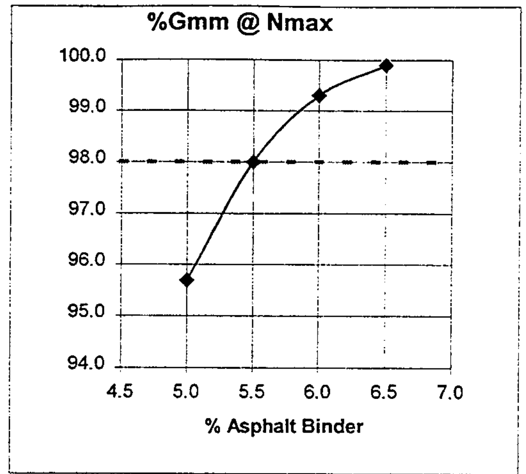


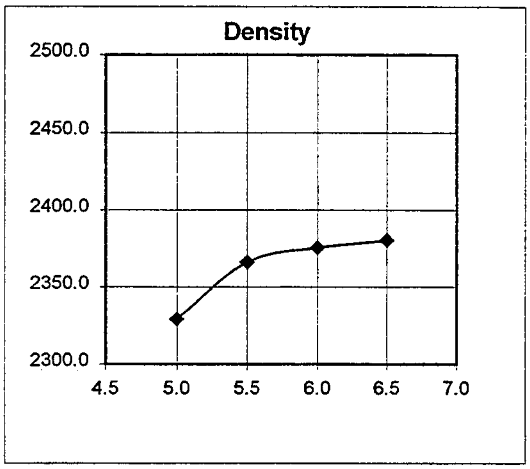


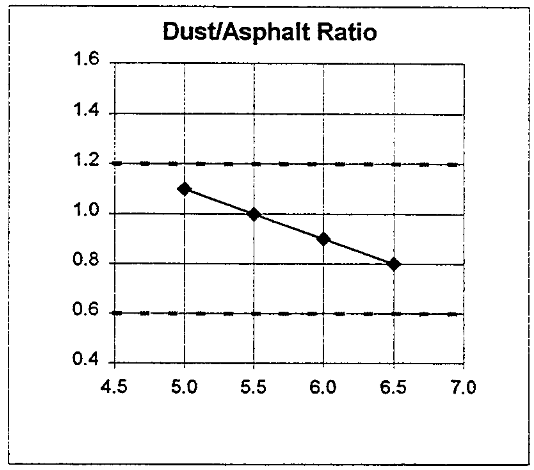


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.0	4.3	5.7	15.7	63.8
Blend2	5.5	2.0	3.3	14.9	77.8
Blend3	6.0	0.7	2.0	15.0	86.6
Blend4	6.5	0.1	0.9	15.2	94.1









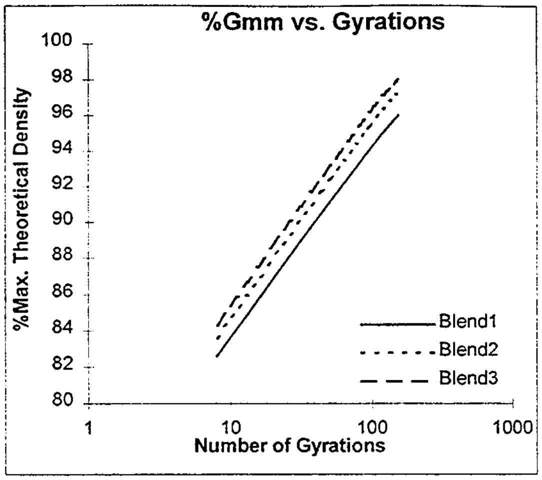
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.0	84.7	95.7	2329.2	1.1
Blend2	5.5	86.6	98.0	2366.2	1.0
Blend3	6.0	87.6	99.3	2375.5	0.9
Blend4	6.5	89.1	99.9	2380.4	0.8

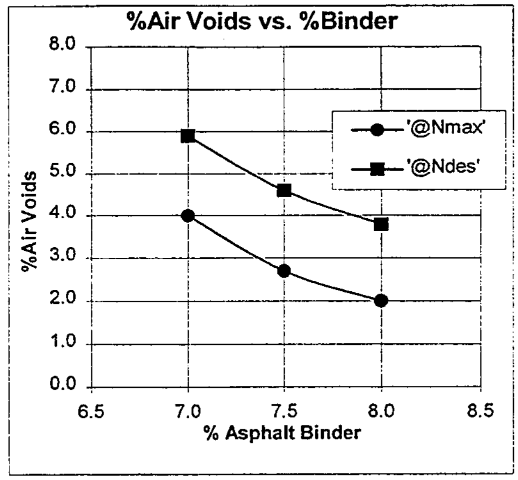
Mix Design Summary for Mixture #2314

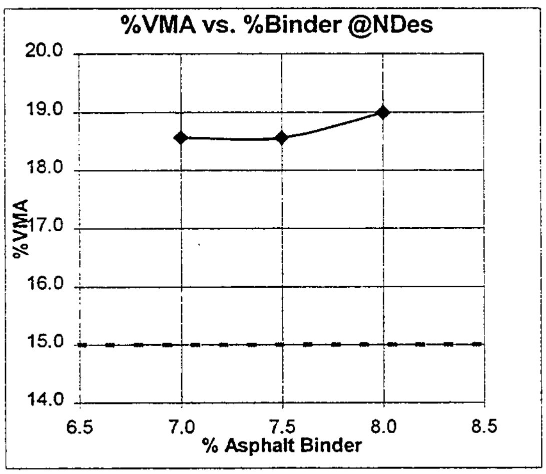
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2314	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

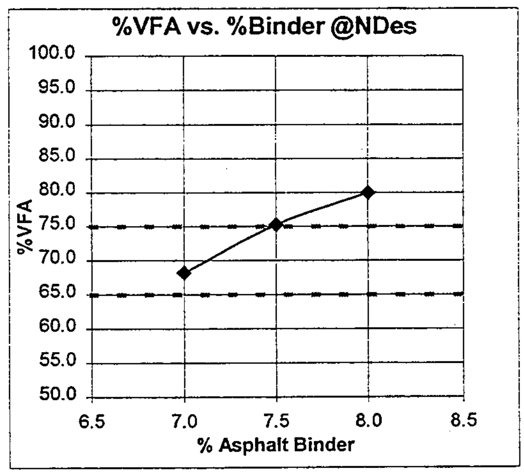
Blend	%AC	$\%G_{mm}$ @ N = 8	$\%G_{mm}$ @ N = 96	$\%G_{mm}$ @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	7.0	82.6	94.1	96.0	5.9	18.6
Blend 2	7.5	83.6	95.4	97.3	4.6	18.6
Blend 3	8.0	84.3	96.2	98.0	3.8	19.0

	Blend 1	Blend 2	Blend 3	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.601	2.601	2.601	***2.601***
Percent Binder by wt. of mix (P_b):	7.0	7.5	8.0	***7.5***
Percent Aggregate (P_s):	93.0	92.5	92.0	***92.5***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	3.9	3.9	3.9	***3.9***
Rice Specific Gravity (G_{mm}):	2.422	2.402	2.383	***2.402***
Effective Specific Gravity (G_{se}):	2.6963	2.6928	2.6903	***2.6928***
Effective % Binder (P_{be}):	5.6	6.1	6.7	***6.1***
% Binder Absorption (P_{ba}):	1.4	1.4	1.3	***1.4***
Dust Proportion (0.6-1.2%):	0.7	0.6	0.6	***0.6***
Surface Area(m^2):	1.83	1.83	1.83	***1.83***
Film Thickness(micron):				***16.3***

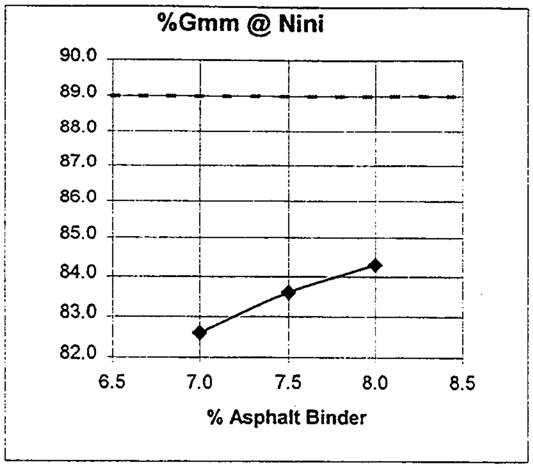


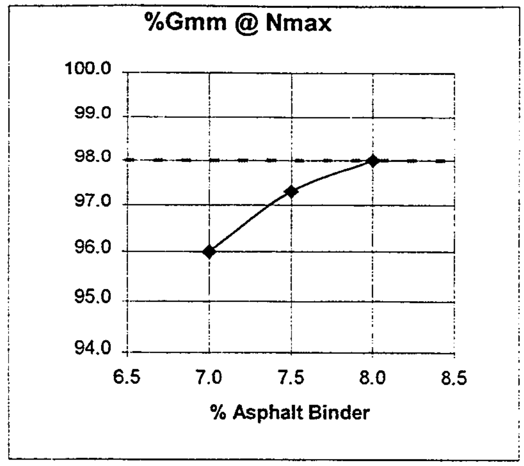


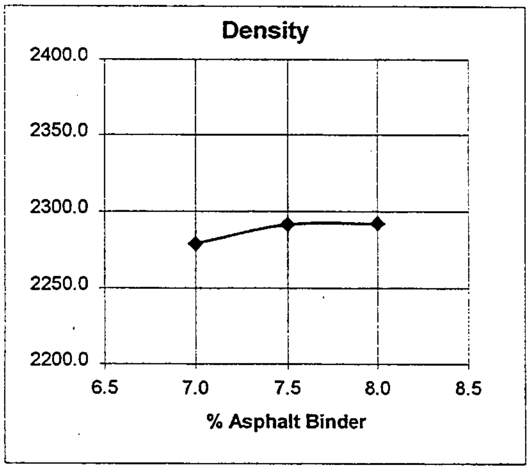


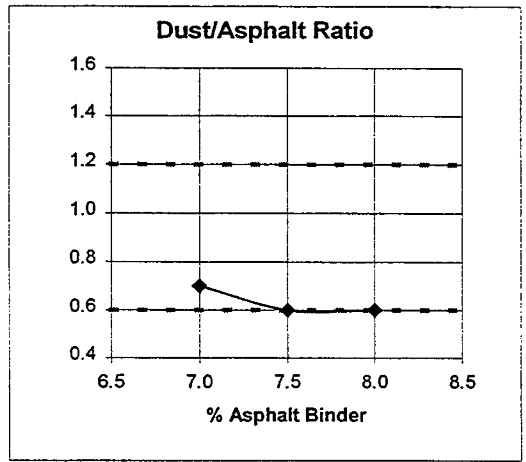


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	7.0	4.0	5.9	18.6	68.2
Blend2	7.5	2.7	4.6	18.6	75.2
Blend3	8.0	2.0	3.8	19.0	80.0









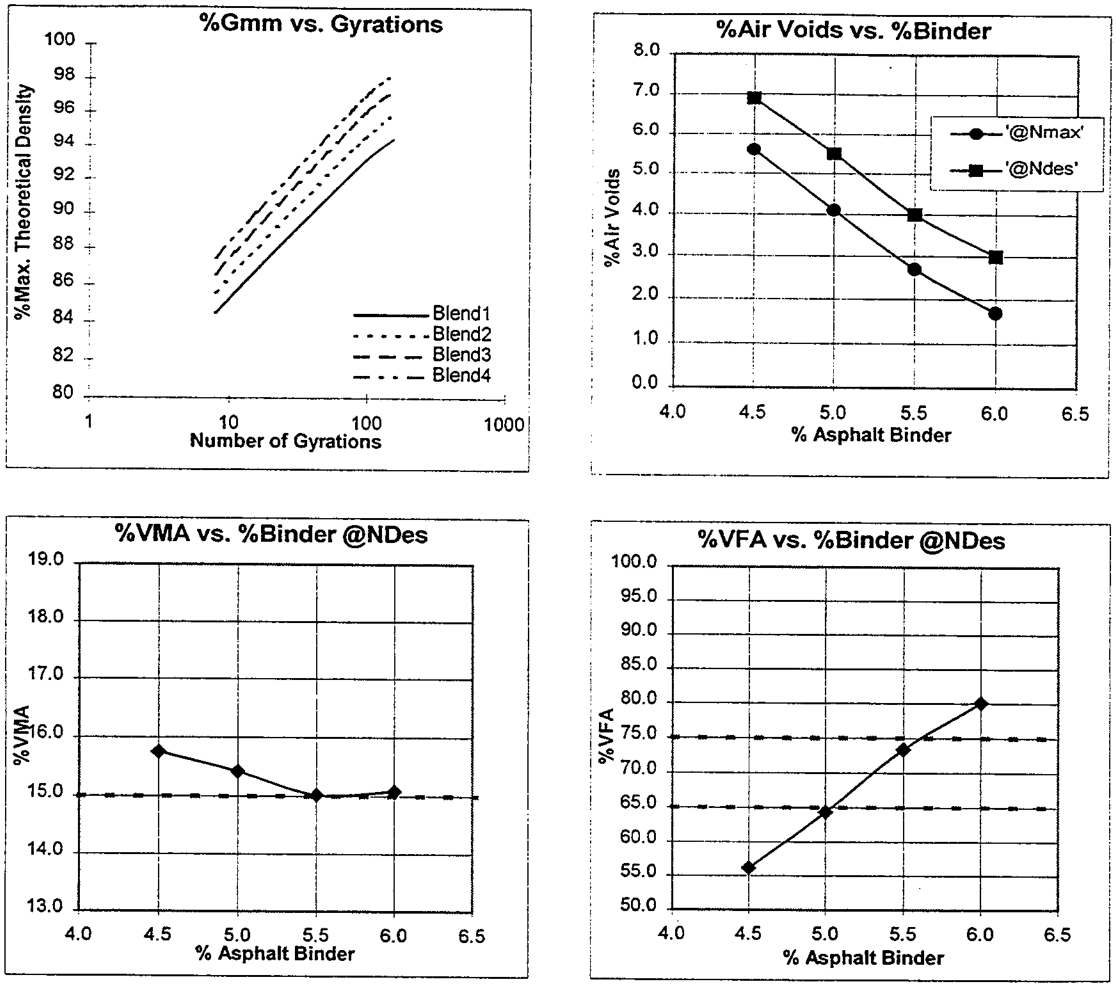
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	7.0	82.6	96.0	2279.1	0.7
Blend2	7.5	83.6	97.3	2291.5	0.6
Blend3	8.0	84.3	98.0	2292.4	0.6

Mix Design Summary for Mixture B1

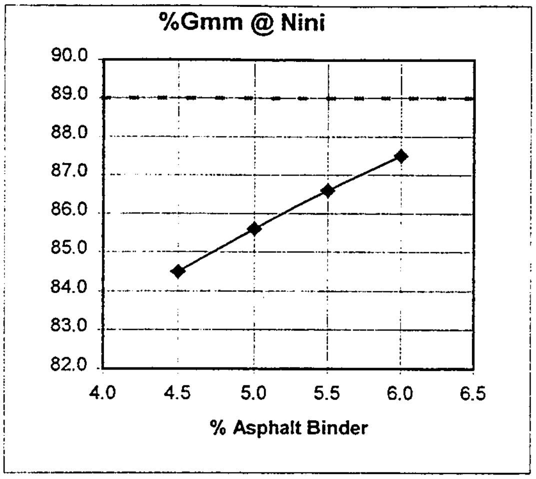
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	B1	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

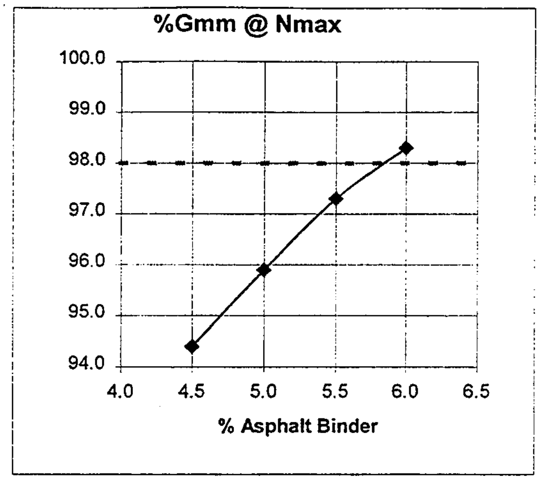
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	4.5	84.5	93.1	94.4	6.9	15.8
Blend 2	5.0	85.6	94.5	95.9	5.5	15.4
Blend 3	5.5	86.6	96.0	97.3	4.0	15.0
Blend 4	6.0	87.5	97.0	98.3	3.0	15.1

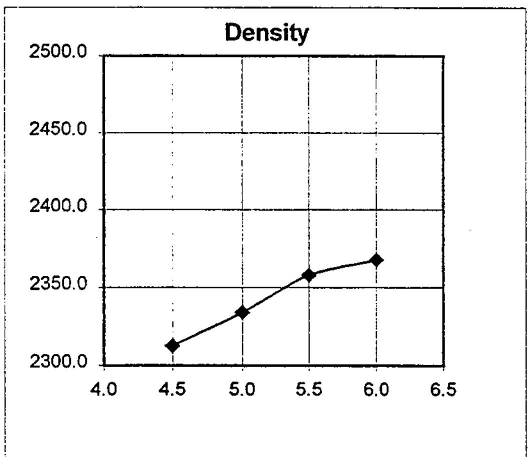
	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.622	2.622	2.622	2.622	***2.622***
Percent Binder by wt. of mix (P_b):	4.5	5.0	5.5	6.0	***5.5***
Percent Aggregate (P_s):	95.5	95.0	94.5	94.0	***94.5***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.2	4.2	4.2	4.2	***4.2***
Rice Specific Gravity (G_{mm}):	2.484	2.470	2.456	2.441	***2.456***
Effective Specific Gravity (G_{se}):	2.6610	2.6662	2.6712	2.6749	***2.6712***
Effective % Binder (P_{be}):	3.9	4.3	4.8	5.2	***4.8***
% Binder Absorption (P_{ba}):	0.6	0.7	0.7	0.8	***0.7***
Dust Proportion (0.6-1.2%):	1.1	1.0	0.9	0.8	***0.9***
Surface Area(m^2):	2.211	2.211	2.211	2.211	***2.211***
Film Thickness(micron):					***10.2***

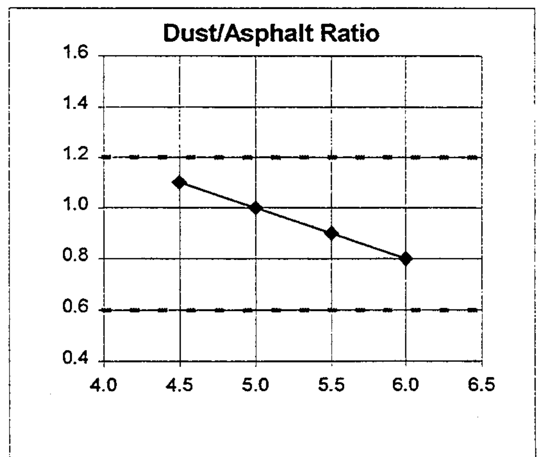


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	4.5	5.6	6.9	15.8	56.2
Blend2	5.0	4.1	5.5	15.4	64.3
Blend3	5.5	2.7	4.0	15.0	73.4
Blend4	6.0	1.7	3.0	15.1	80.1









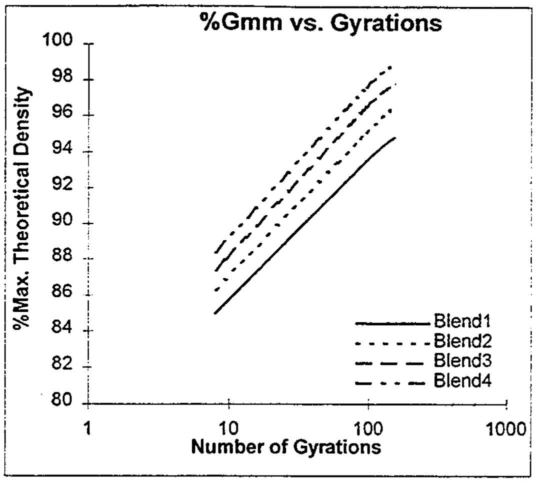
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	4.5	84.5	94.4	2312.6	1.1
Blend2	5.0	85.6	95.9	2334.2	1.0
Blend3	5.5	86.6	97.3	2357.8	0.9
Blend4	6	87.5	98.3	2367.8	0.8

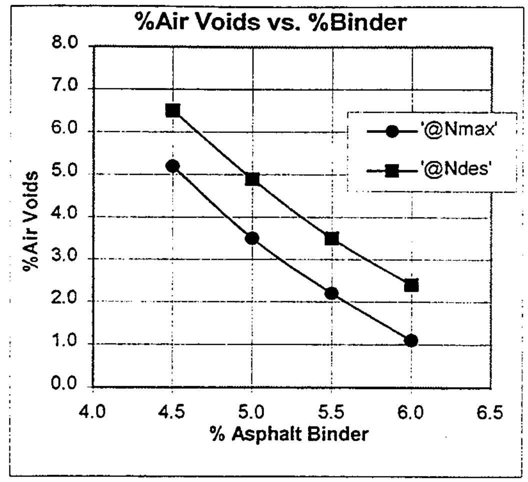
Mix Design Summary for Mixture B2

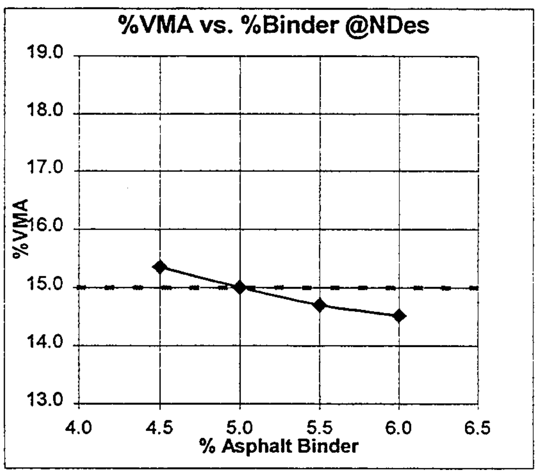
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	B2	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

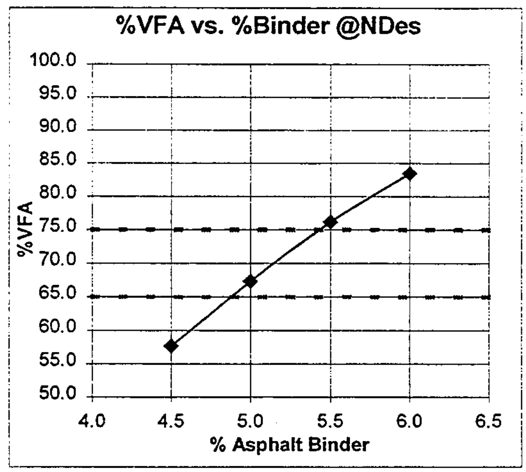
Blend	%AC	$\%G_{mm}$ @ N = 8	$\%G_{mm}$ @ N = 96	$\%G_{mm}$ @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	4.5	85.0	93.5	94.8	6.5	15.4
Blend 2	5.0	86.3	95.1	96.5	4.9	15.0
Blend 3	5.5	87.4	96.5	97.8	3.5	14.7
Blend 4	6.0	88.4	97.6	98.9	2.4	14.5

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.620	2.620	2.620	2.620	***2.620***
Percent Binder by wt. of mix (P_b):	4.5	5.0	5.5	6.0	***5.3***
Percent Aggregate (P_s):	95.5	95.0	94.5	94.0	***94.7***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.2	4.2	4.2	4.2	***4.2***
Rice Specific Gravity (G_{mm}):	2.484	2.465	2.451	2.441	***2.453***
Effective Specific Gravity (G_{se}):	2.6604	2.6598	2.6645	2.6748	***2.6586***
Effective % Binder (P_{be}):	3.9	4.4	4.8	5.2	***4.7***
% Binder Absorption (P_{ba}):	0.6	0.6	0.7	0.8	***0.6***
Dust Proportion (0.6-1.2%):	1.1	1.0	0.9	0.8	***0.9***
Surface Area(m^2):	2.202	2.202	2.202	2.202	***2.202***
Film Thickness(micron):					***10***

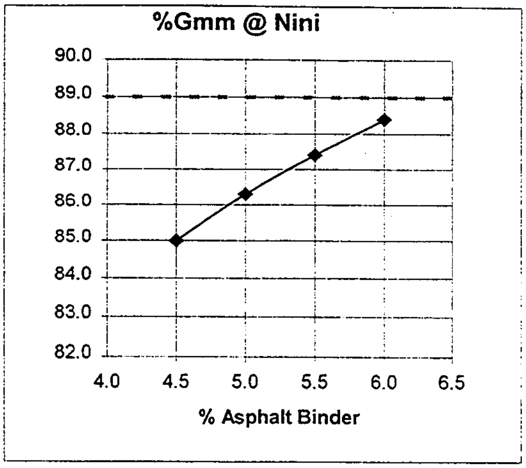


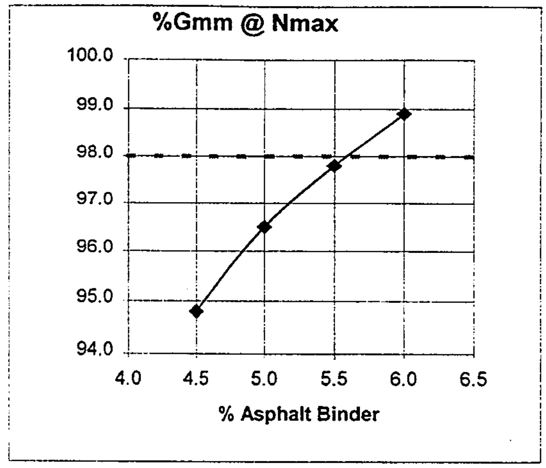


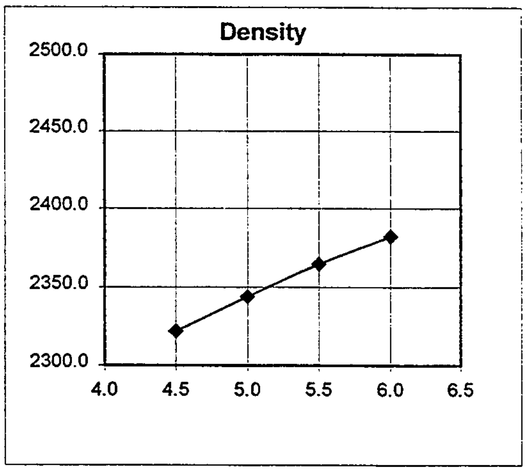


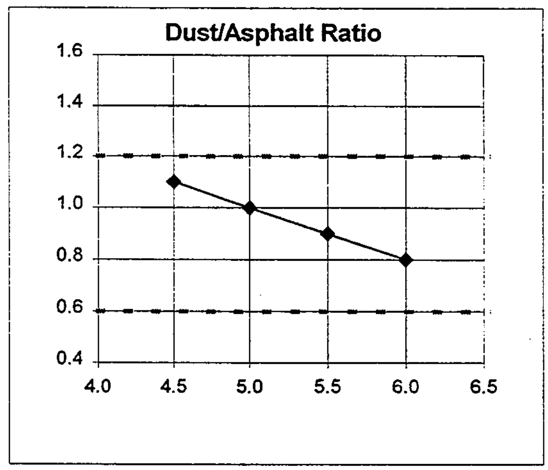


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	4.5	5.2	6.5	15.4	57.7
Blend2	5.0	3.5	4.9	15.0	67.3
Blend3	5.5	2.2	3.5	14.7	76.2
Blend4	6.0	1.1	2.4	14.5	83.5









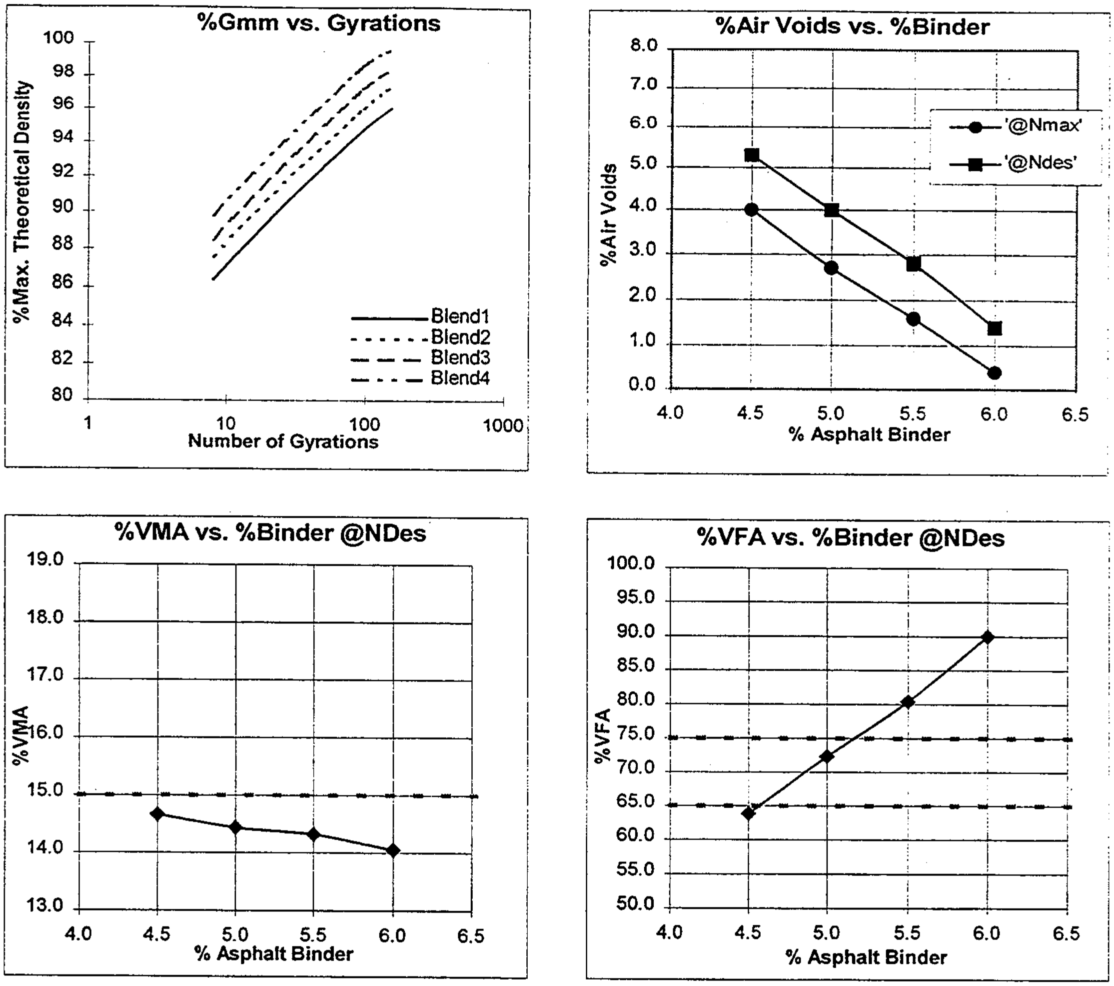
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	4.5	85.0	94.8	2322.1	1.1
Blend2	5.0	86.3	96.5	2344.0	1.0
Blend3	5.5	87.4	97.8	2364.8	0.9
Blend4	6	88.4	98.9	2382.3	0.8

Mix Design Summary for Mixture B3

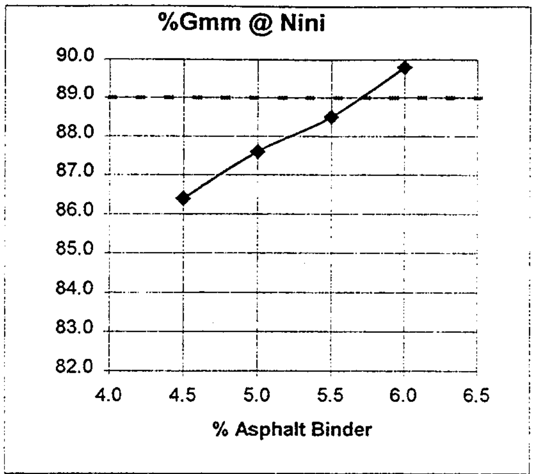
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	B3	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

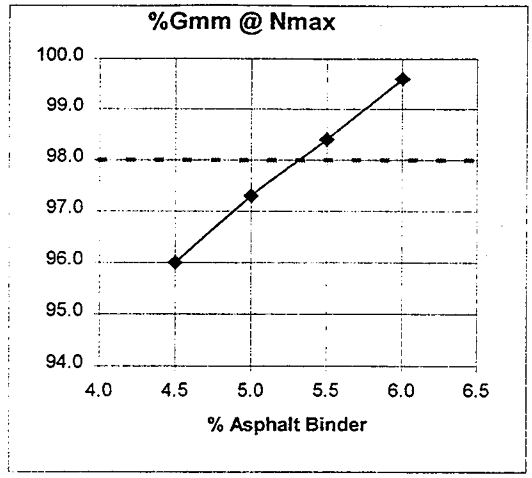
Blend	%AC	$\%G_{mm}$ @ N = 8	$\%G_{mm}$ @ N = 96	$\%G_{mm}$ @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	4.5	86.4	94.7	96.0	5.3	14.7
Blend 2	5.0	87.6	96.0	97.3	4.0	14.4
Blend 3	5.5	88.5	97.2	98.4	2.8	14.3
Blend 4	6.0	89.8	98.6	99.6	1.4	14.0

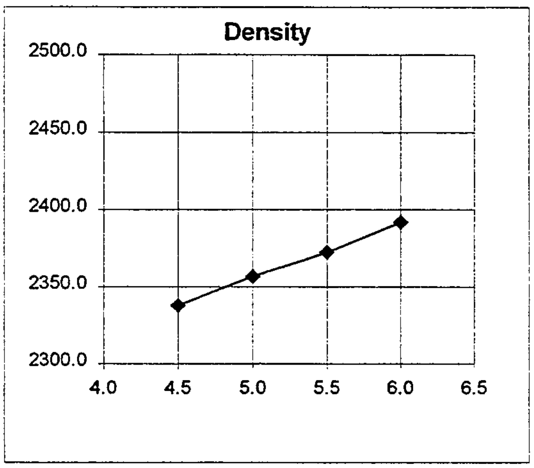
	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.616	2.616	2.616	2.616	***2.616***
Percent Binder by wt. of mix (P_b):	4.5	5.0	5.5	6.0	***5.5***
Percent Aggregate (P_s):	95.5	95.0	94.5	94.0	***94.5***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.0	4.0	4.0	4.0	***4.0***
Rice Specific Gravity (G_{mm}):	2.469	2.455	2.441	2.426	***2.441***
Effective Specific Gravity (G_{se}):	2.6430	2.6478	2.6525	2.6558	***2.6525***
Effective % Binder (P_{be}):	4.1	4.5	5.0	5.4	***5.0***
% Binder Absorption (P_{ba}):	0.4	0.5	0.5	0.6	***0.5***
Dust Proportion (0.6-1.2%):	1.0	0.9	0.8	0.7	***0.8***
Surface Area(m^2):	2.174	2.174	2.174	2.174	***2.174***
Film Thickness(micron):					***10.2***

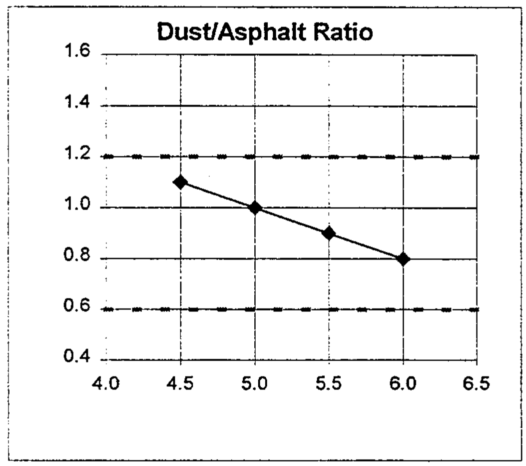


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	4.5	4.0	5.3	14.7	63.8
Blend2	5.0	2.7	4.0	14.4	72.3
Blend3	5.5	1.6	2.8	14.3	80.4
Blend4	6.0	0.4	1.4	14.0	90.0









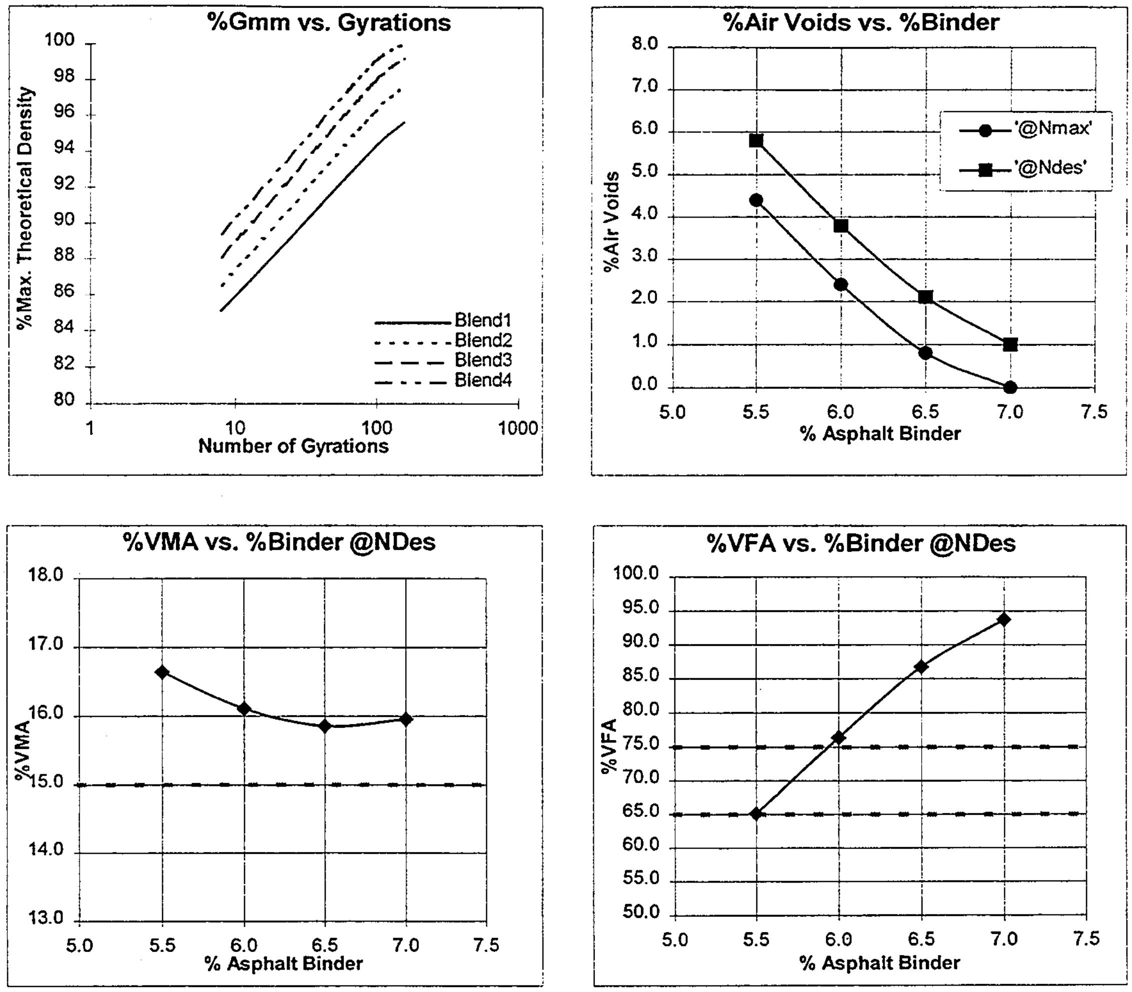
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	4.5	86.4	96.0	2338.1	1.1
Blend2	5.0	87.6	97.3	2356.8	1.0
Blend3	5.5	88.5	98.4	2372.7	0.9
Blend4	6	89.8	99.6	2392.0	0.8

Mix Design Summary for Mixture #2478n1

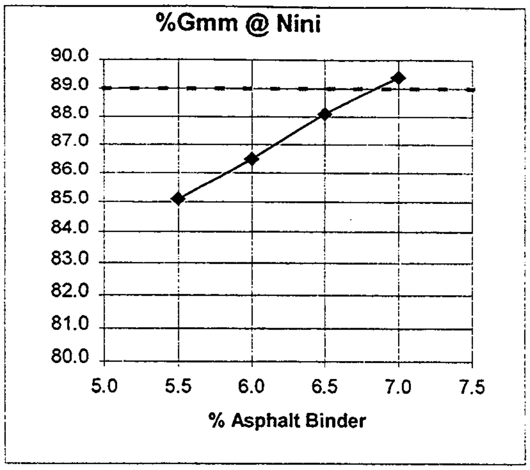
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2478n1	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

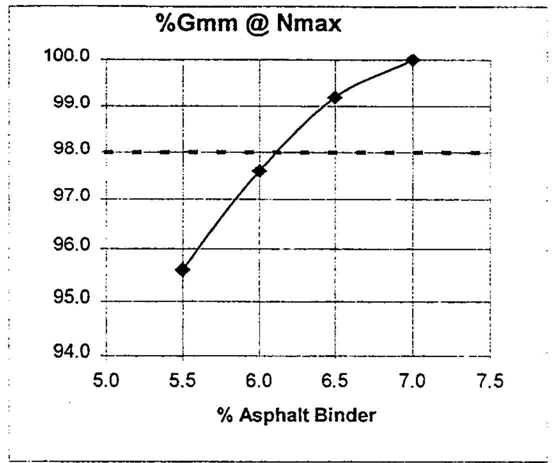
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.5	85.1	94.2	95.6	5.8	16.6
Blend 2	6.0	86.5	96.2	97.6	3.8	16.1
Blend 3	6.5	88.1	97.9	99.2	2.1	15.9
Blend 4	7.0	89.4	99.0	100.0	1.0	16.0

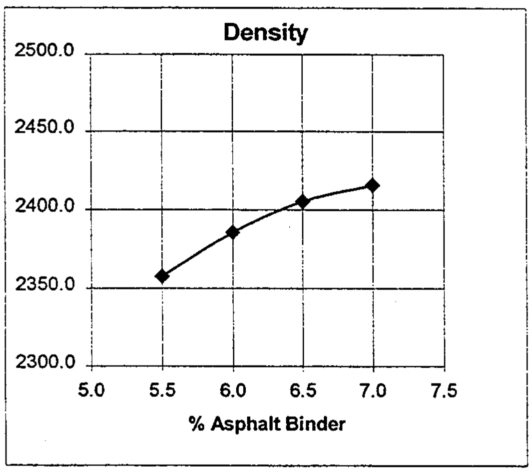
	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.673	2.673	2.673	2.673	***2.673***
Percent Binder by wt. of mix (P_b):	5.5	6.0	6.5	7.0	***5.9***
Percent Aggregate (P_s):	94.5	94.0	93.5	93.0	***94.1***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	6.2	6.2	6.2	6.2	***6.2***
Rice Specific Gravity (G_{mm}):	2.503	2.480	2.457	2.440	***2.484***
Effective Specific Gravity (G_{se}):	2.7302	2.7248	2.7189	2.7203	***2.7252***
Effective % Binder (P_{be}):	4.7	5.3	5.8	6.3	***5.2***
% Binder Absorption (P_{ba}):	0.8	0.7	0.7	0.7	***0.7***
Dust Proportion (0.6-1.2%):	1.3	1.2	1.1	1.0	***1.2***
Surface Area(m^2):	2.759	2.759	2.759	2.759	***2.759***
Film Thickness(micron):					***8.8***

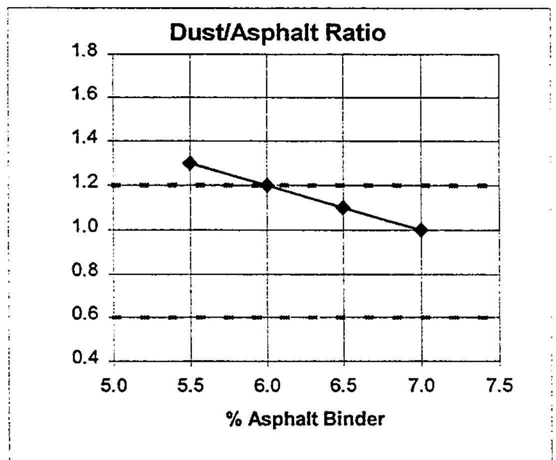


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.5	4.4	5.8	16.6	65.1
Blend2	6.0	2.4	3.8	16.1	76.4
Blend3	6.5	0.8	2.1	15.9	86.8
Blend4	7.0	0.0	1.0	16.0	93.7









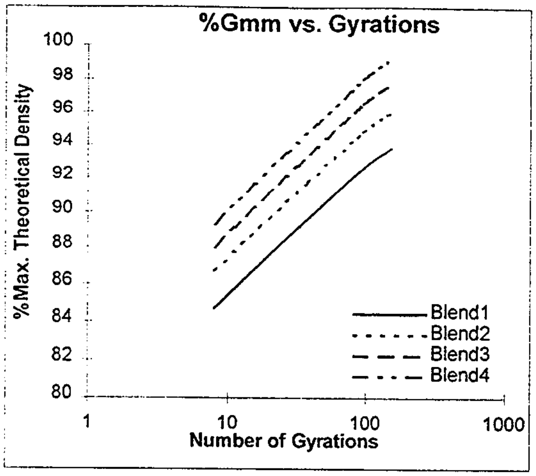
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.5	85.1	95.6	2357.8	1.3
Blend2	6.0	86.5	97.6	2385.8	1.2
Blend3	6.5	88.1	99.2	2405.4	1.1
Blend4	7	89.4	100.0	2415.6	1.0

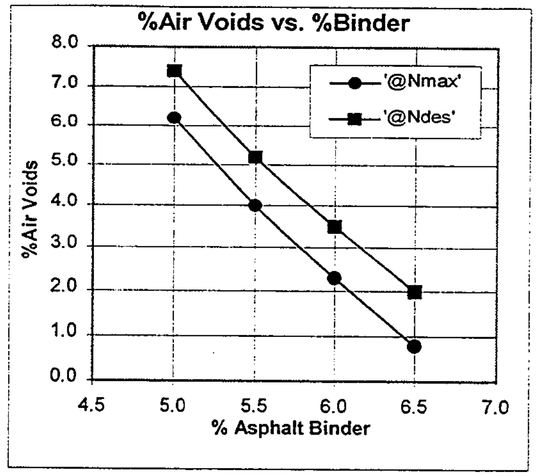
Mix Design Summary for Mixture #2478n2

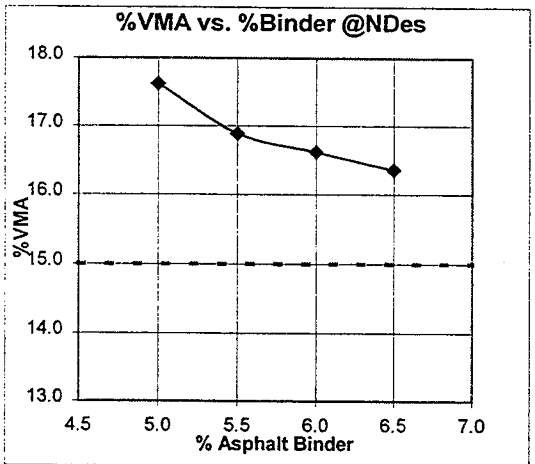
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2478n2	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

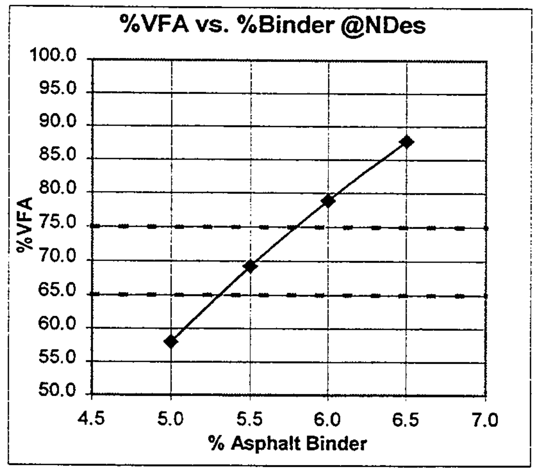
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.0	84.7	92.6	93.8	7.4	17.6
Blend 2	5.5	86.7	94.8	96.0	5.2	16.9
Blend 3	6.0	88.0	96.5	97.7	3.5	16.6
Blend 4	6.5	89.3	98.0	99.2	2.0	16.4

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.643	2.643	2.643	2.643	***2.643***
Percent Binder by wt. of mix (P_b):	5.0	5.5	6.0	6.5	***5.8***
Percent Aggregate (P_s):	95.0	94.5	94.0	93.5	***94.2***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.3	4.3	4.3	4.3	***4.3***
Rice Specific Gravity (G_{mm}):	2.516	2.488	2.461	2.434	***2.466***
Effective Specific Gravity (G_{se}):	2.7227	2.7114	2.7005	2.6888	***2.6976***
Effective % Binder (P_{be}):	3.9	4.5	5.2	5.8	***5.0***
% Binder Absorption (P_{ba}):	1.1	1.0	0.8	0.7	***0.8***
Dust Proportion (0.6-1.2%):	1.1	1.0	0.8	0.7	***0.9***
Surface Area(m^2):	2.258	2.258	2.258	2.258	***2.258***
Film Thickness(micron):					***10.5***

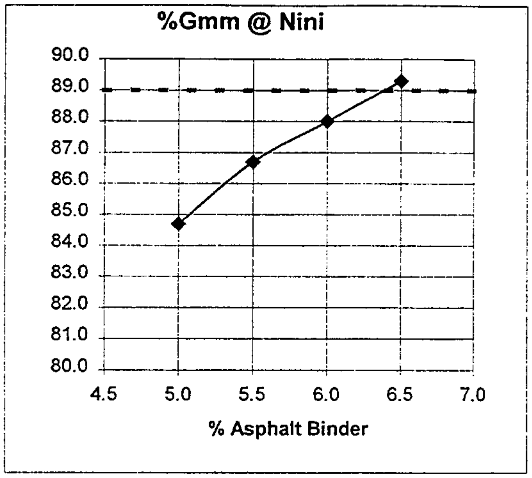


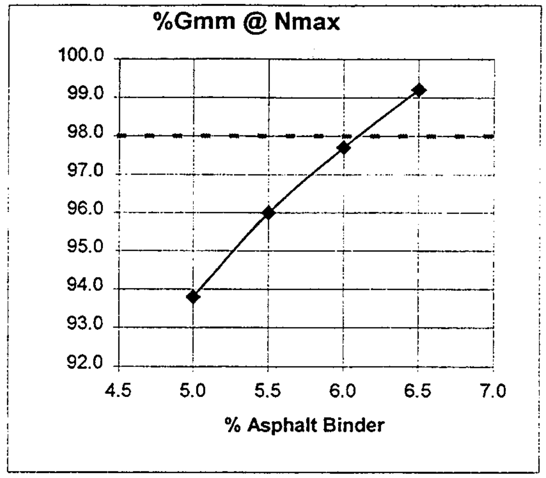


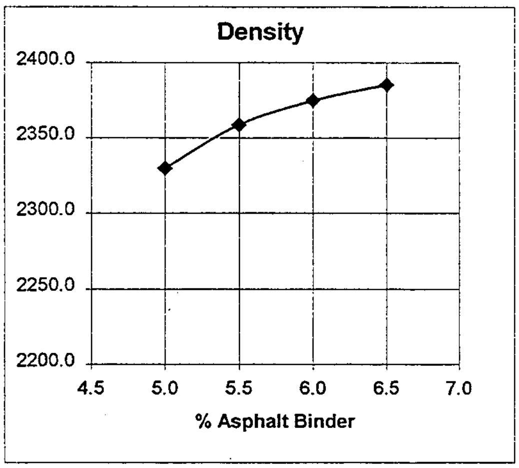


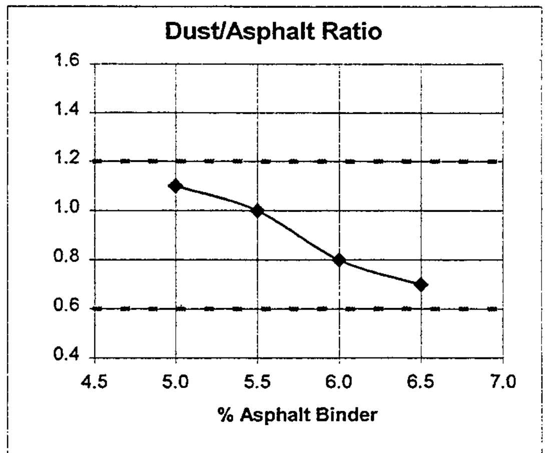


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.0	6.2	7.4	17.6	58.0
Blend2	5.5	4.0	5.2	16.9	69.2
Blend3	6.0	2.3	3.5	16.6	78.9
Blend4	6.5	0.8	2.0	16.4	87.8









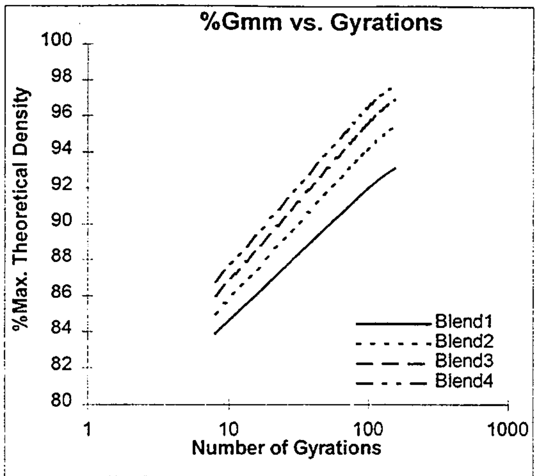
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.0	84.7	93.8	2329.8	1.1
Blend2	5.5	86.7	96.0	2358.6	1.0
Blend3	6.0	88.0	97.7	2374.9	0.8
Blend4	6.5	89.3	99.2	2385.3	0.7

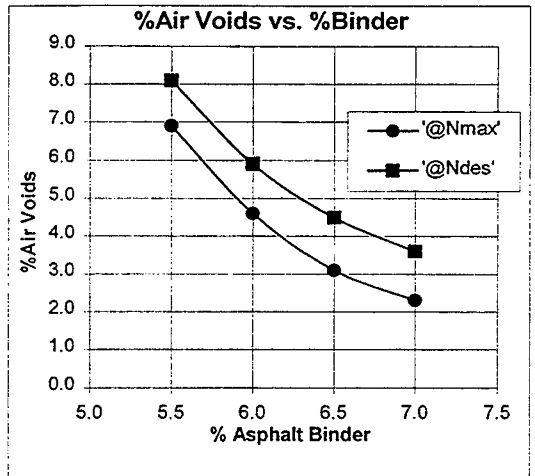
Mix Design Summary for Mixture #2478n3

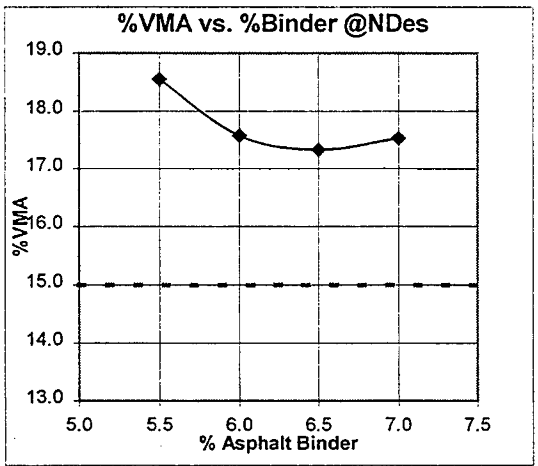
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2478n3	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

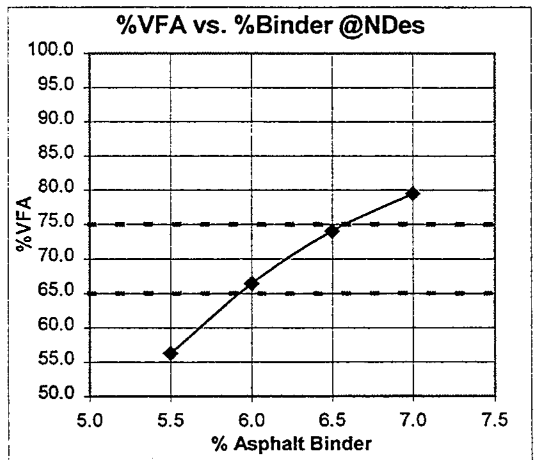
Blend	%AC	$\%G_{mm}$ @ N = 8	$\%G_{mm}$ @ N = 96	$\%G_{mm}$ @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.5	83.9	91.9	93.1	8.1	18.6
Blend 2	6.0	85.0	94.1	95.4	5.9	17.6
Blend 3	6.5	86.0	95.5	96.9	4.5	17.3
Blend 4	7.0	86.8	96.4	97.7	3.6	17.5

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.671	2.671	2.671	2.671	***2.671***
Percent Binder by wt. of mix (P_b):	5.5	6.0	6.5	7.0	***6.6***
Percent Aggregate (P_s):	94.5	94.0	93.5	93.0	***93.4***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	5.1	5.1	5.1	5.1	***5.1***
Rice Specific Gravity (G_{mm}):	2.505	2.489	2.473	2.457	***2.470***
Effective Specific Gravity (G_{se}):	2.7328	2.7364	2.7398	2.7430	***2.7408***
Effective % Binder (P_{be}):	4.6	5.1	5.5	6.0	***5.6***
% Binder Absorption (P_{ba}):	0.9	0.9	1.0	1.0	***1.0***
Dust Proportion (0.6-1.2%):	1.1	1.0	0.9	0.9	***0.9***
Surface Area(m^2):	2.555	2.555	2.555	2.555	***2.555***
Film Thickness(micron):					***10.5***

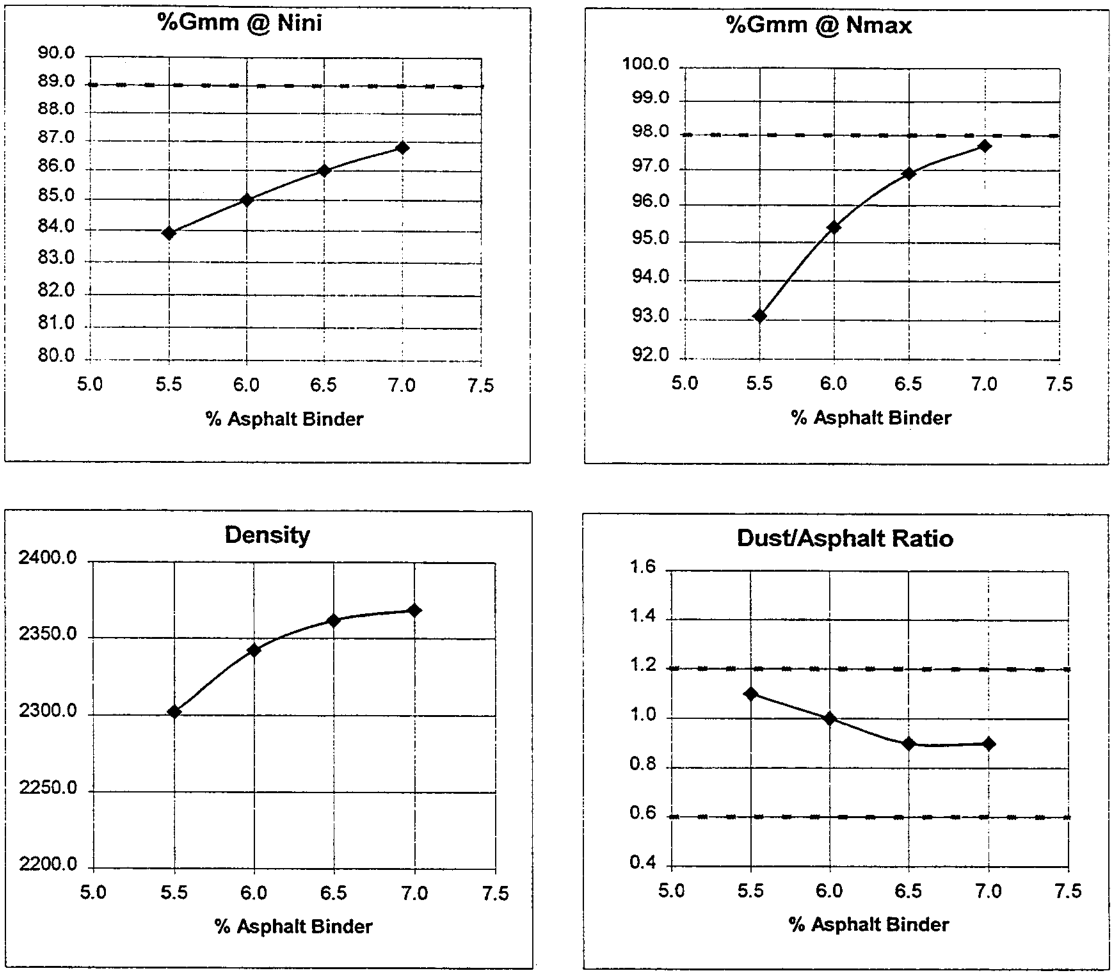








Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.5	6.9	8.1	18.6	56.3
Blend2	6.0	4.6	5.9	17.6	66.4
Blend3	6.5	3.1	4.5	17.3	74.0
Blend4	7.0	2.3	3.6	17.5	79.5



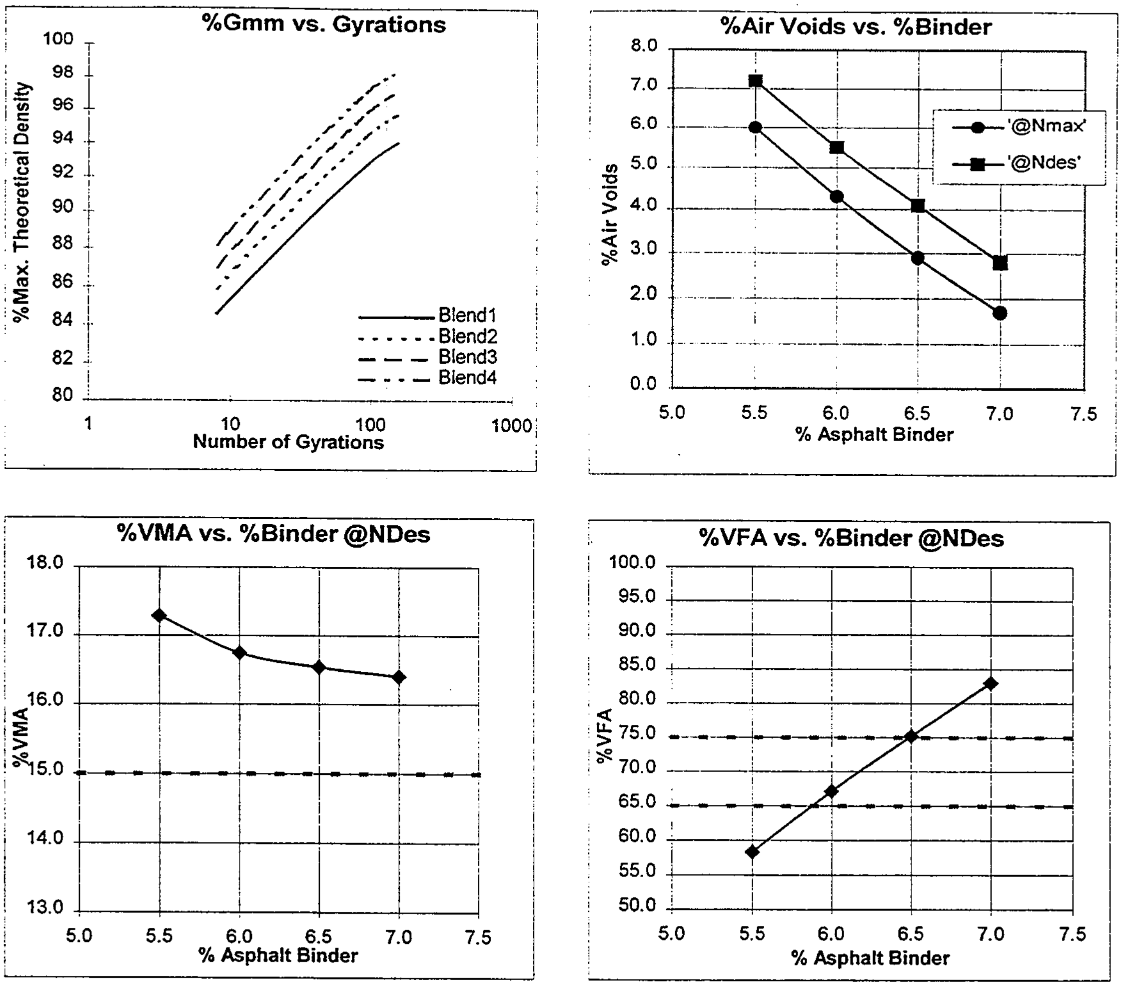
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.5	83.9	93.1	2302.1	1.1
Blend2	6.0	85.0	95.4	2342.1	1.0
Blend3	6.5	86.0	96.9	2361.7	0.9
Blend4	7	86.8	97.7	2368.5	0.9

Mix Design Summary for Mixture #2478n4

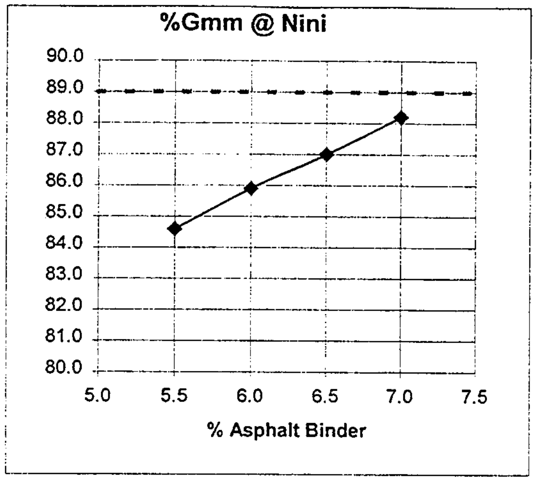
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2478n4	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

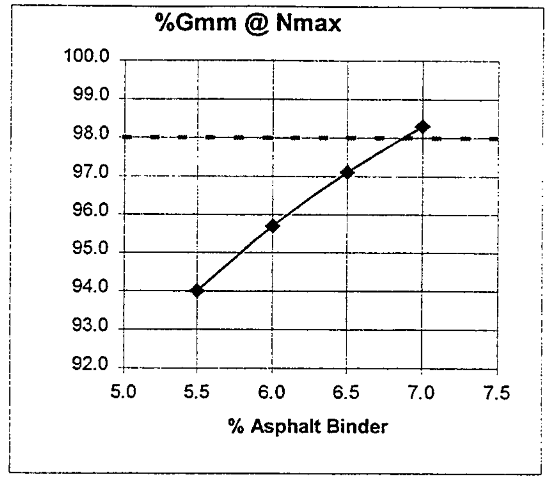
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.5	84.6	92.8	94.0	7.2	17.3
Blend 2	6.0	85.9	94.5	95.7	5.5	16.7
Blend 3	6.5	87.0	95.9	97.1	4.1	16.5
Blend 4	7.0	88.2	97.2	98.3	2.8	16.4

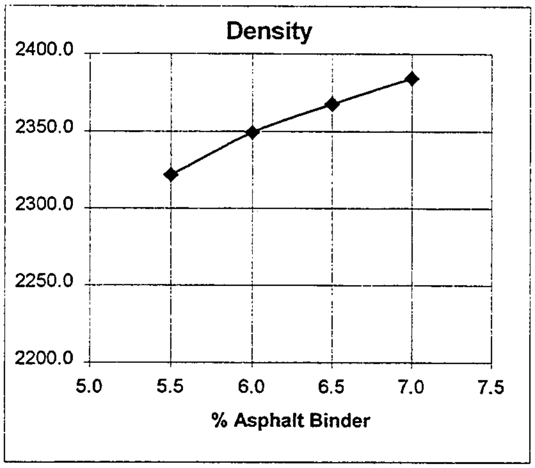
	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.653	2.653	2.653	2.653	***2.653***
Percent Binder by wt. of mix (P_b):	5.5	6.0	6.5	7.0	***6.5***
Percent Aggregate (P_s):	94.5	94.0	93.5	93.0	***93.5***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.6	4.6	4.6	4.6	***4.6***
Rice Specific Gravity (G_{mm}):	2.502	2.486	2.469	2.453	***2.469***
Effective Specific Gravity (G_{se}):	2.7290	2.7326	2.7346	2.7377	***2.7346***
Effective % Binder (P_{be}):	4.4	4.9	5.3	5.8	***5.3***
% Binder Absorption (P_{ba}):	1.1	1.1	1.2	1.2	***1.2***
Dust Proportion (0.6-1.2%):	1.0	0.9	0.9	0.8	***0.9***
Surface Area(m^2):	2.332	2.332	2.332	2.332	***2.332***
Film Thickness(micron):					***10.9***

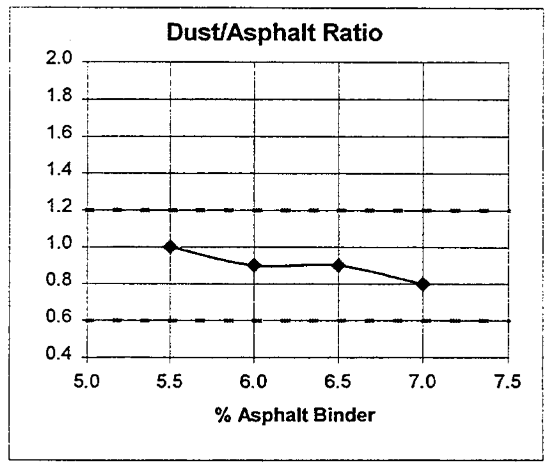


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.5	6.0	7.2	17.3	58.3
Blend2	6.0	4.3	5.5	16.7	67.2
Blend3	6.5	2.9	4.1	16.5	75.2
Blend4	7.0	1.7	2.8	16.4	82.9









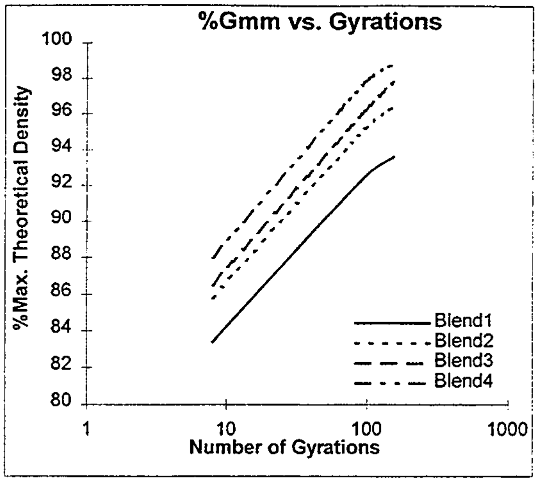
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.5	84.6	94.0	2321.9	1.0
Blend2	6.0	85.9	95.7	2349.3	0.9
Blend3	6.5	87.0	97.1	2367.8	0.9
Blend4	7	88.2	98.3	2384.3	0.8

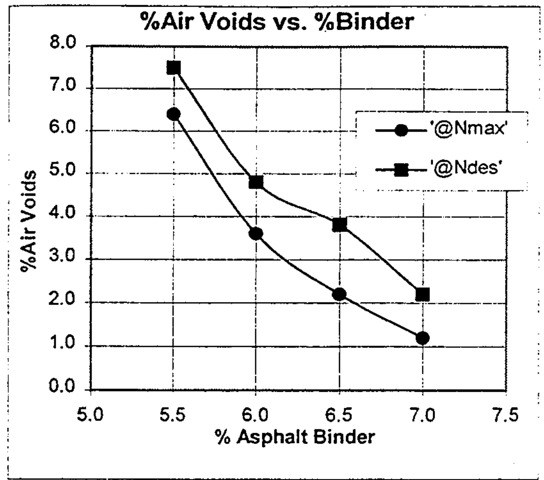
Mix Design Summary for Mixture #2478n5

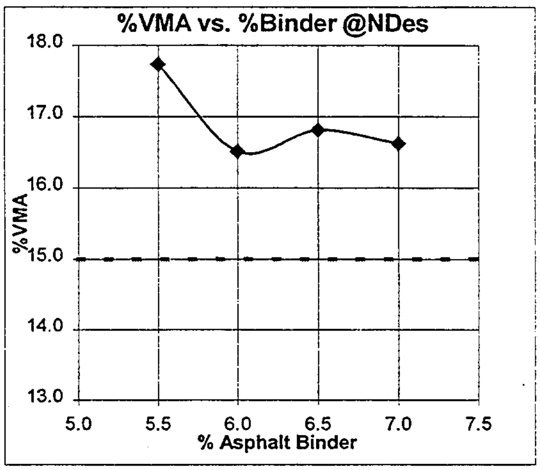
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2478n5	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

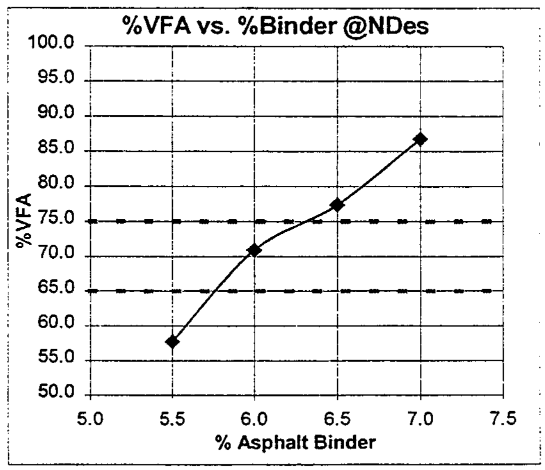
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.5	83.4	92.5	93.6	7.5	17.7
Blend 2	6.0	85.8	95.2	96.4	4.8	16.5
Blend 3	6.5	86.5	96.2	97.8	3.8	16.8
Blend 4	7.0	88.0	97.8	98.8	2.2	16.6

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.707	2.707	2.707	2.707	***2.707***
Percent Binder by wt. of mix (P_b):	5.5	6.0	6.5	7.0	***6.3***
Percent Aggregate (P_s):	94.5	94.0	93.5	93.0	***93.7***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	8.6	8.6	8.6	8.6	***8.6***
Rice Specific Gravity (G_{mm}):	2.548	2.526	2.504	2.482	***2.513***
Effective Specific Gravity (G_{se}):	2.7871	2.7841	2.7806	2.7766	***2.7823***
Effective % Binder (P_{be}):	4.4	5.0	5.5	6.1	***5.3***
% Binder Absorption (P_{ba}):	1.1	1.0	1.0	0.9	***1.0***
Dust Proportion (0.6-1.2%):	1.9	1.7	1.6	1.4	***1.6***
Surface Area(m^2):	3.79	3.79	3.79	3.79	***3.79***
Film Thickness(micron):					***6.6***

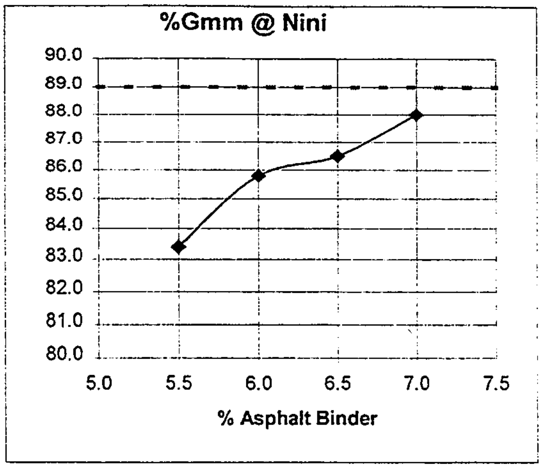


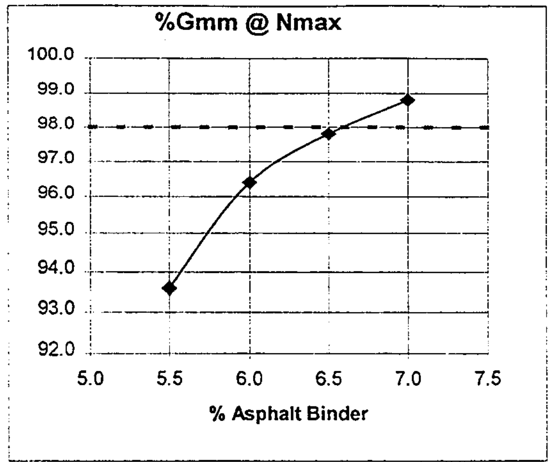


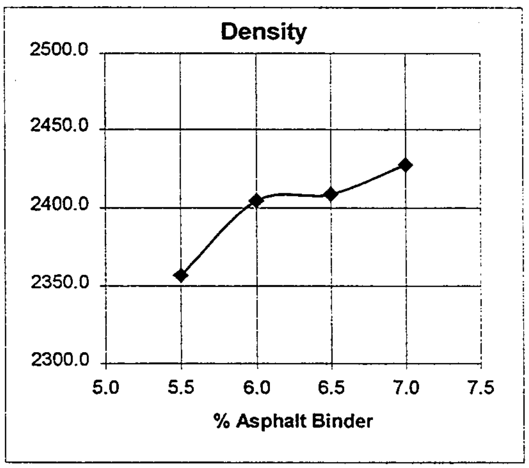


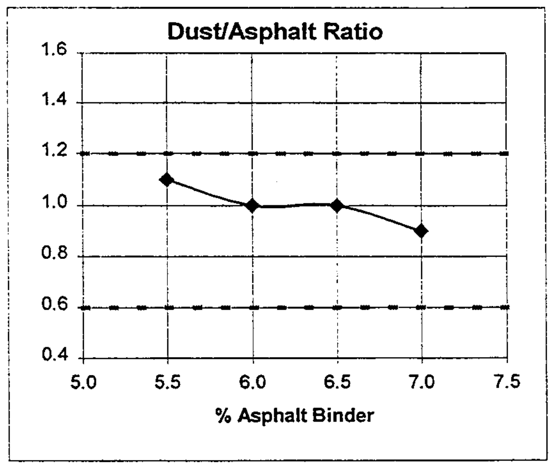


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.5	6.4	7.5	17.7	57.7
Blend2	6.0	3.6	4.8	16.5	70.9
Blend3	6.5	2.2	3.8	16.8	77.4
Blend4	7.0	1.2	2.2	16.6	86.8









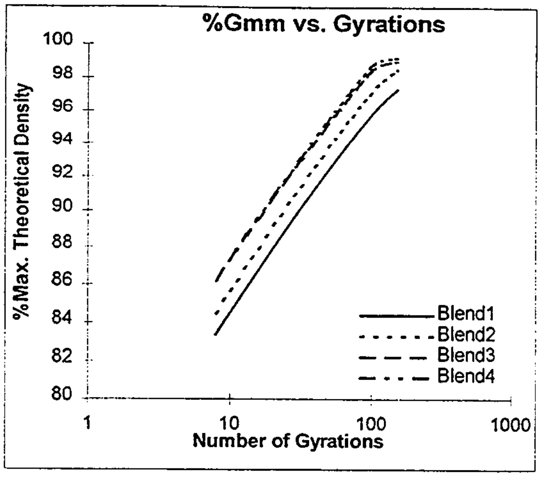
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.5	83.4	93.6	2356.9	1.1
Blend2	6.0	85.8	96.4	2404.8	1.0
Blend3	6.5	86.5	97.8	2408.8	1.0
Blend4	7	88.0	98.8	2427.4	0.9

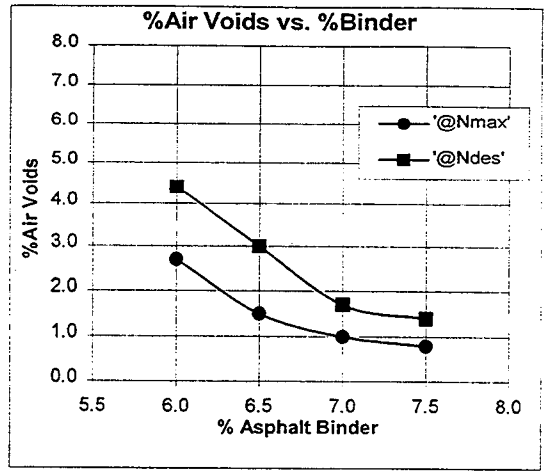
Mix Design Summary for Mixture #2314n1

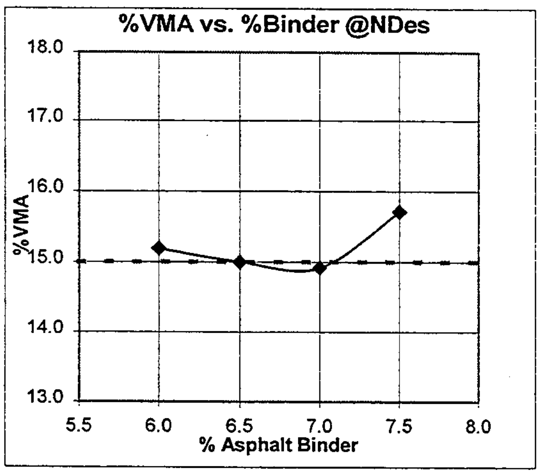
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2314n1	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

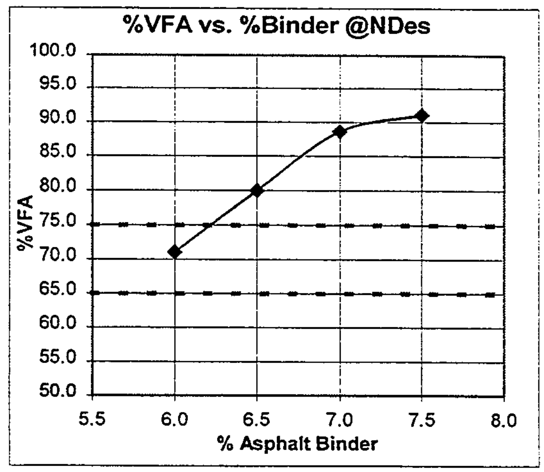
Blend	%AC	$\%G_{mm}$ @ N = 8	$\%G_{mm}$ @ N = 96	$\%G_{mm}$ @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	6.0	83.4	95.6	97.3	4.4	15.2
Blend 2	6.5	84.5	97.0	98.5	3.0	15.0
Blend 3	7.0	86.2	98.3	99.0	1.7	14.9
Blend 4	7.5	86.2	98.6	99.2	1.4	15.7

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.612	2.612	2.612	2.612	***2.612***
Percent Binder by wt. of mix (P_b):	6.0	6.5	7.0	7.5	***6.1***
Percent Aggregate (P_s):	94.0	93.5	93.0	92.5	***93.9***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	6.7	6.7	6.7	6.7	***6.7***
Rice Specific Gravity (G_{mm}):	2.460	2.443	2.426	2.409	***2.456***
Effective Specific Gravity (G_{se}):	2.6992	2.7005	2.7016	2.7024	***2.6992***
Effective % Binder (P_{be}):	4.7	5.2	5.7	6.2	***4.8***
% Binder Absorption (P_{ba}):	1.3	1.3	1.3	1.3	***1.3***
Dust Proportion (0.6-1.2%):	1.4	1.3	1.2	1.1	***1.4***
Surface Area(m^2):	2.902	2.902	2.902	2.902	***2.902***
Film Thickness(micron):					***7.94***

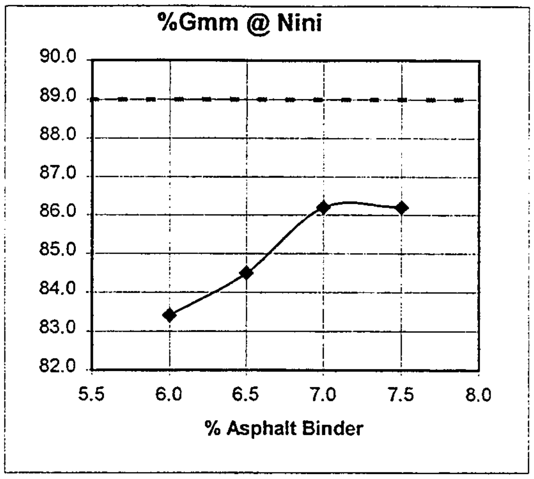


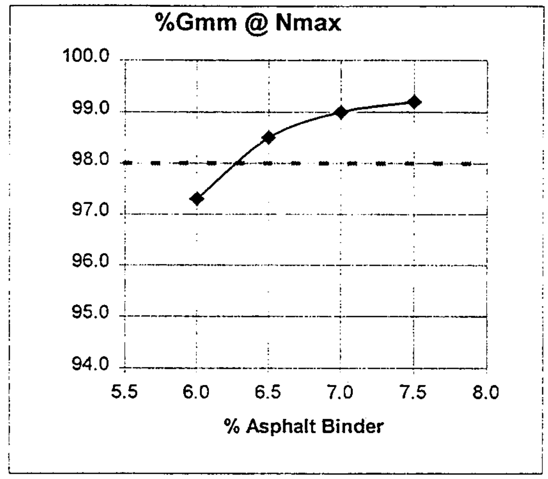


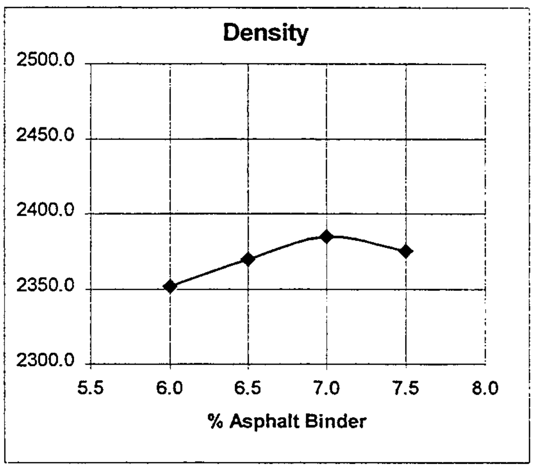


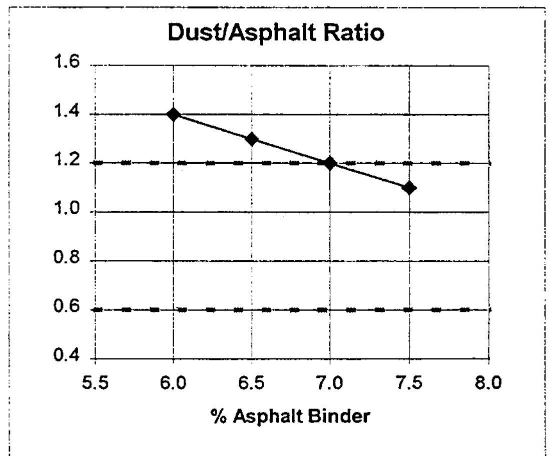


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	6.0	2.7	4.4	15.2	71.0
Blend2	6.5	1.5	3.0	15.0	80.0
Blend3	7.0	1.0	1.7	14.9	88.6
Blend4	7.5	0.8	1.4	15.7	91.1









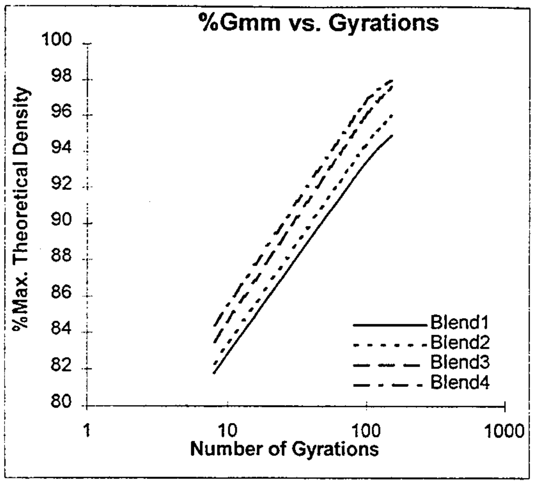
Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	6.0	83.4	97.3	2351.8	1.4
Blend2	6.5	84.5	98.5	2369.7	1.3
Blend3	7.0	86.2	99.0	2384.8	1.2
Blend4	7.5	86.2	99.2	2375.3	1.1

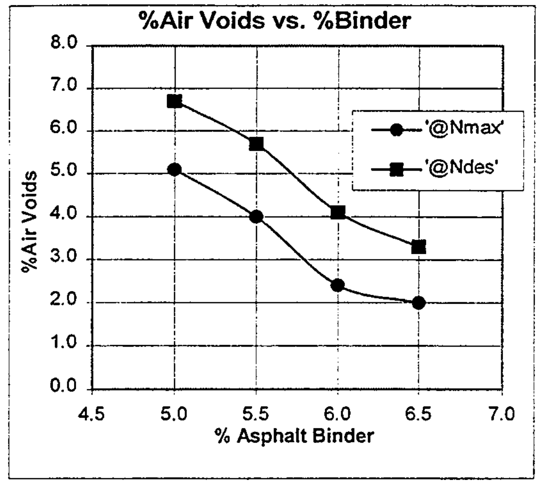
Mix Design Summary for Mixture #2314n2

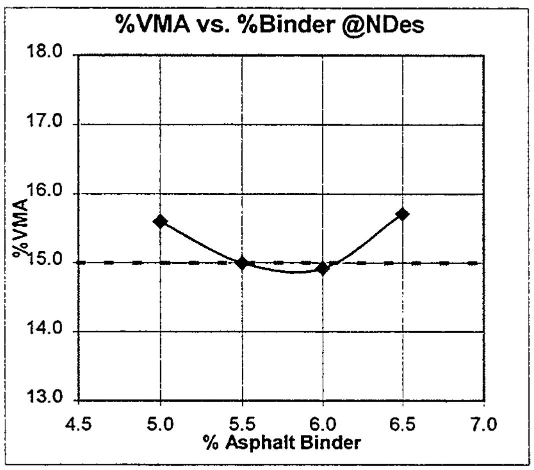
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2314n2	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

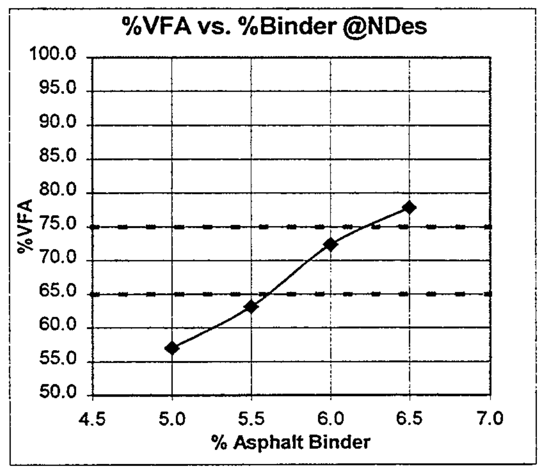
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.0	81.8	93.3	94.9	6.7	15.6
Blend 2	5.5	82.3	94.3	96.0	5.7	15.5
Blend 3	6.0	83.5	95.9	97.6	4.1	14.8
Blend 4	6.5	84.4	96.7	98.0	3.3	14.9

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.607	2.607	2.607	2.607	***2.607***
Percent Binder by wt. of mix (P_b):	5.0	5.5	6.0	6.5	***6.0***
Percent Aggregate (P_s):	95.0	94.5	94.0	93.5	***94.0***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	6.7	6.7	6.7	6.7	***6.7***
Rice Specific Gravity (G_{mm}):	2.483	2.473	2.463	2.453	***2.463***
Effective Specific Gravity (G_{se}):	2.6821	2.6925	2.7030	2.7136	***2.7030***
Effective % Binder (P_{be}):	3.9	4.2	4.6	4.9	***4.60***
% Binder Absorption (P_{ba}):	1.1	1.3	1.4	1.6	***1.4***
Dust Proportion (0.6-1.2%):	1.7	1.6	1.5	1.4	***1.5***
Surface Area(m^2):	2.954	2.954	2.954	2.954	***2.954***
Film Thickness(micron):					***7.4***

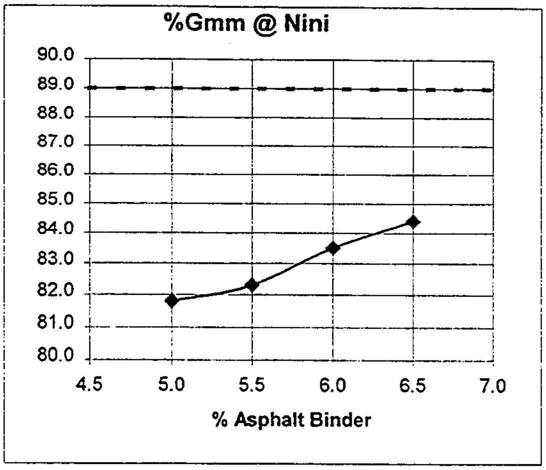


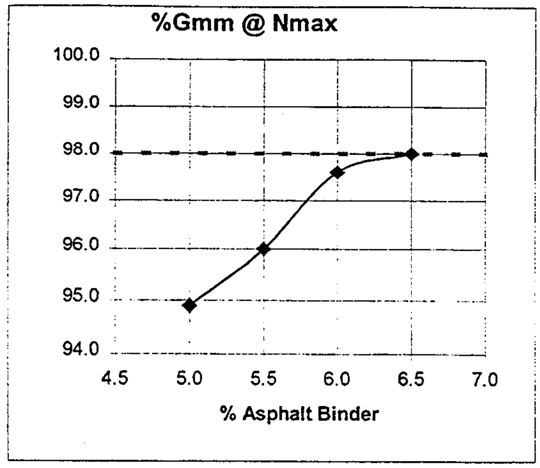


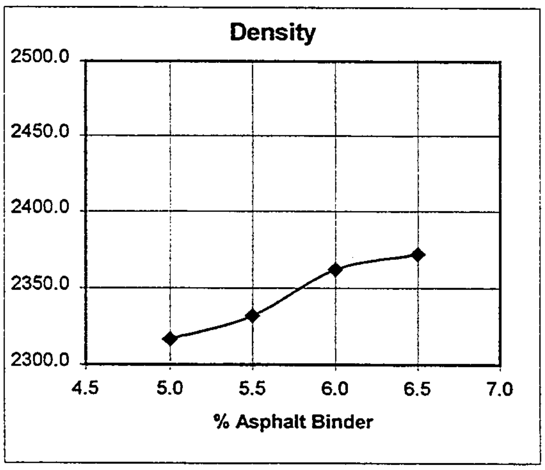


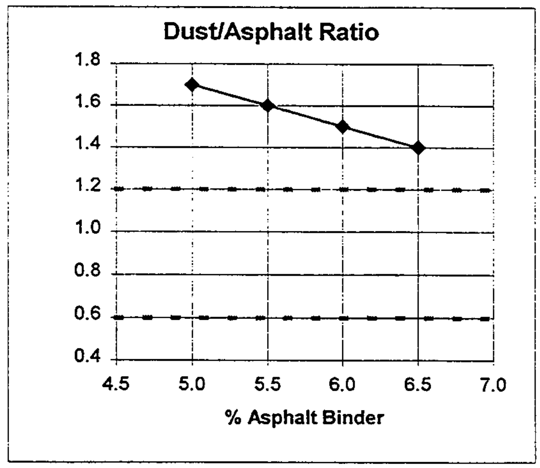


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.0	5.1	6.7	15.6	57.1
Blend2	5.5	4.0	5.7	15.0	63.2
Blend3	6.0	2.4	4.1	14.9	72.4
Blend4	6.5	2.0	3.3	15.7	77.9









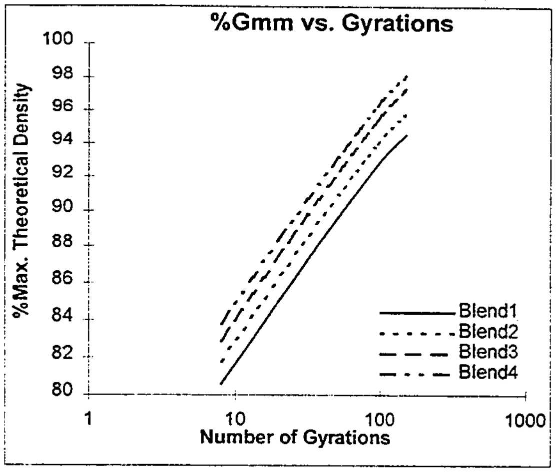
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.0	81.8	94.9	2316.6	1.7
Blend2	5.5	82.3	96.0	2332.0	1.6
Blend3	6.0	83.5	97.6	2362.0	1.5
Blend4	6.5	84.4	98.0	2372.1	1.4

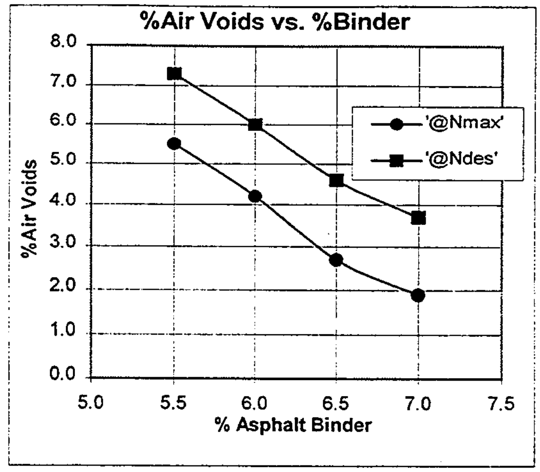
Mix Design Summary for Mixture #2314n3

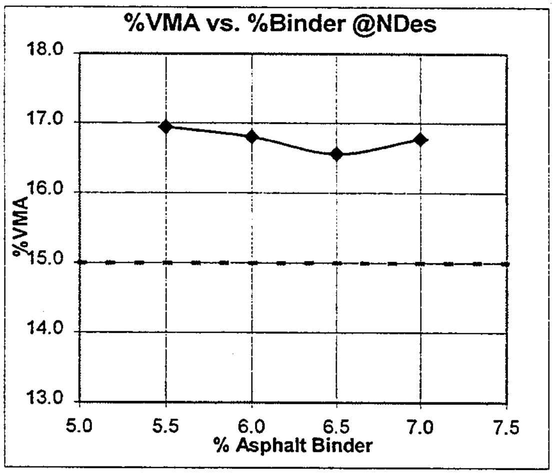
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2314n3	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

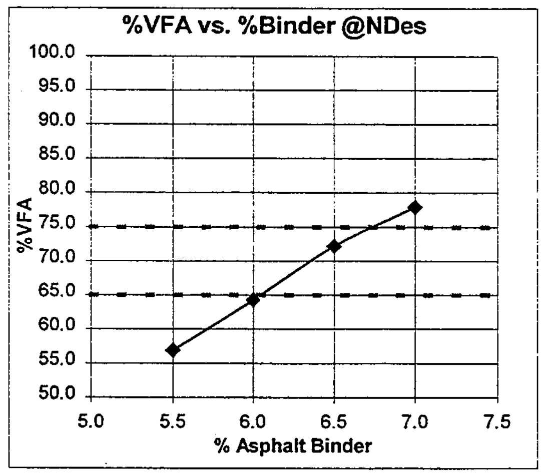
Blend	%AC	$\%G_{mm}$ @ N = 8	$\%G_{mm}$ @ N = 96	$\%G_{mm}$ @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	5.5	80.6	92.7	94.5	7.3	16.9
Blend 2	6.0	81.8	94.0	95.8	6.0	16.8
Blend 3	6.5	82.9	95.4	97.3	4.6	16.6
Blend 4	7.0	83.8	96.3	98.1	3.7	16.8

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.608	2.608	2.608	2.608	***2.608***
Percent Binder by wt. of mix (P_b):	5.5	6.0	6.5	7.0	***6.7***
Percent Aggregate (P_s):	94.5	94.0	93.5	93.0	***93.3***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	7.8	7.8	7.8	7.8	***7.8***
Rice Specific Gravity (G_{mm}):	2.473	2.456	2.440	2.424	***2.434***
Effective Specific Gravity (G_{se}):	2.6925	2.6941	2.6966	2.6989	***2.6981***
Effective % Binder (P_{be}):	4.3	4.7	5.2	5.7	***5.4***
% Binder Absorption (P_{ba}):	1.2	1.3	1.3	1.3	***1.3***
Dust Proportion (0.6-1.2%):	1.8	1.6	1.5	1.4	***1.4***
Surface Area(m^2):	2.685	2.685	2.685	2.685	***2.685***
Film Thickness(micron):					***9.6***

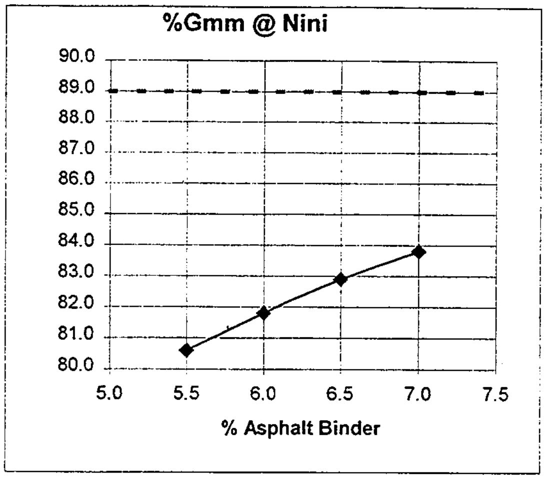


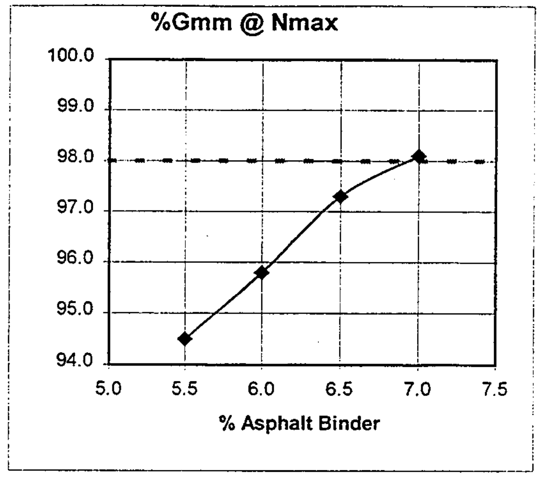


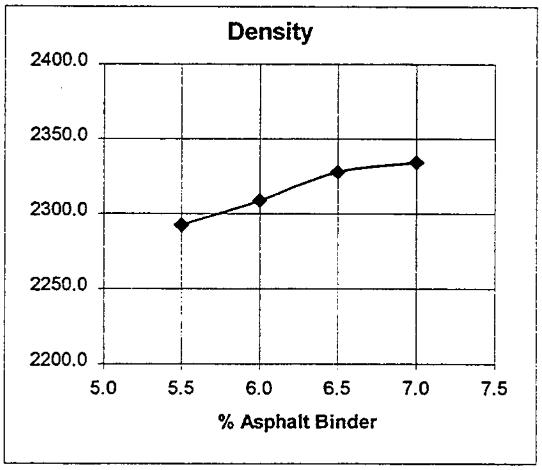


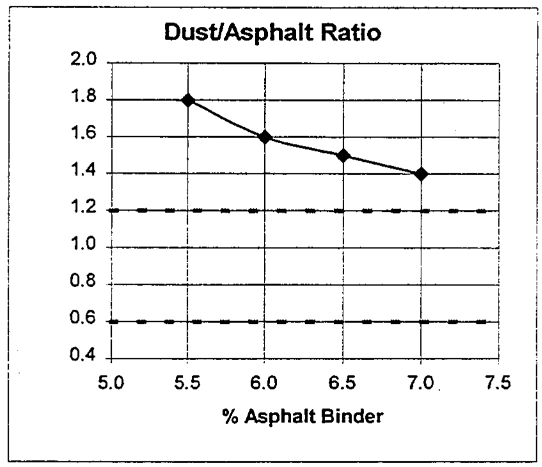


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	5.5	5.5	7.3	16.9	56.9
Blend2	6.0	4.2	6.0	16.8	64.3
Blend3	6.5	2.7	4.6	16.6	72.2
Blend4	7.0	1.9	3.7	16.8	77.9









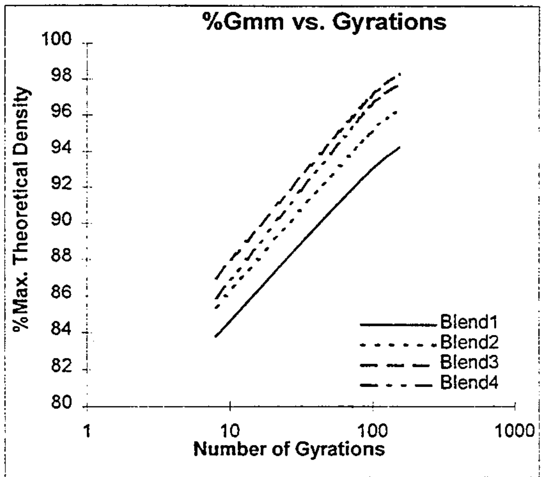
Blend	%AC	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	5.5	80.6	94.5	2292.5	1.8
Blend2	6.0	81.8	95.8	2308.6	1.6
Blend3	6.5	82.9	97.3	2327.8	1.5
Blend4	7	83.8	98.1	2334.3	1.4

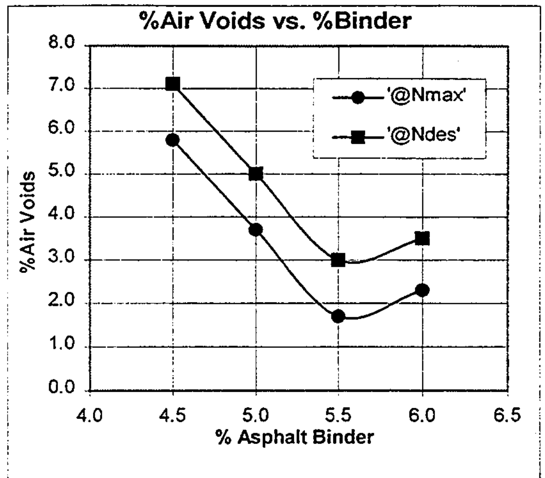
Mix Design Summary for Mixture #2314n4

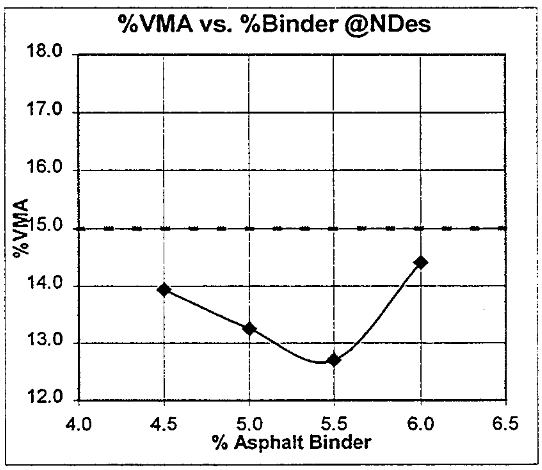
Project Name:	FAA	$N_{Initial}$:	8
Workbook Name:	#2314n4	N_{Design}:	96
Nominal Sieve Size:	9.5mm	N_{Max}:	152
Asphalt Grade:	PG 64-22	Design Temperature:	38°C
Compaction Temp:	150°C	Design ESAL's (millions):	4

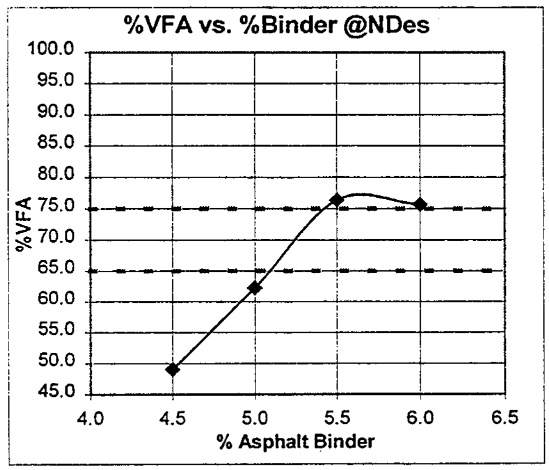
Blend	%AC	%G_{mm} @ N = 8	%G_{mm} @ N = 96	%G_{mm} @ N = 152	%Air Voids @ N_{Design}	%VMA @ N_{Design}
Blend 1	4.5	83.8	92.9	94.2	7.1	13.9
Blend 2	5.0	85.4	95.0	96.3	5.0	13.3
Blend 3	5.5	87.0	97.0	98.3	3.0	12.7
Blend 4	6.0	85.9	96.5	97.7	3.5	14.4

	Blend 1	Blend 2	Blend 3	Blend 4	***Design AC***
Agg. Bulk Specific Gravity (G_{sb}):	2.602	2.602	2.602	2.602	***2.602***
Percent Binder by wt. of mix (P_b):	4.5	5.0	5.5	6.0	***5.2***
Percent Aggregate (P_s):	95.5	95.0	94.5	94.0	***94.8***
Specific Gravity of Binder (G_b):	1.030	1.030	1.030	1.030	***1.030***
Fines (%Passing 0.075mm Sieve):	4.3	4.3	4.3	4.3	***4.3***
Rice Specific Gravity (G_{mm}):	2.526	2.503	2.480	2.457	***2.494***
Effective Specific Gravity (G_{se}):	2.7116	2.7067	2.7013	2.6954	***2.7049***
Effective % Binder (P_{be}):	2.9	3.5	4.0	4.6	***3.7***
% Binder Absorption (P_{ba}):	1.6	1.5	1.5	1.4	***1.5***
Dust Proportion (0.6-1.2%):	1.5	1.2	1.1	0.9	***1.2***
Surface Area(m^2):	2.22	2.22	2.22	2.22	***2.22***
Film Thickness(micron):					***7.9***

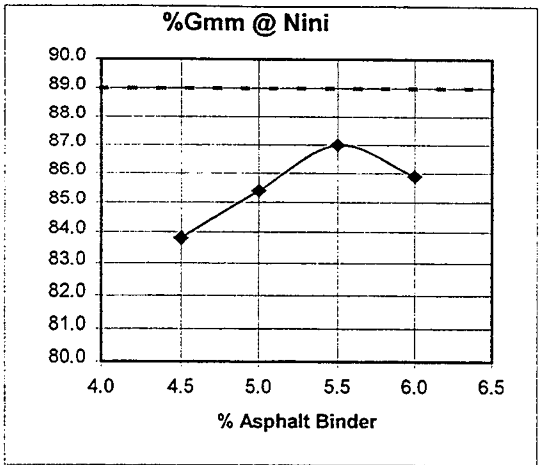


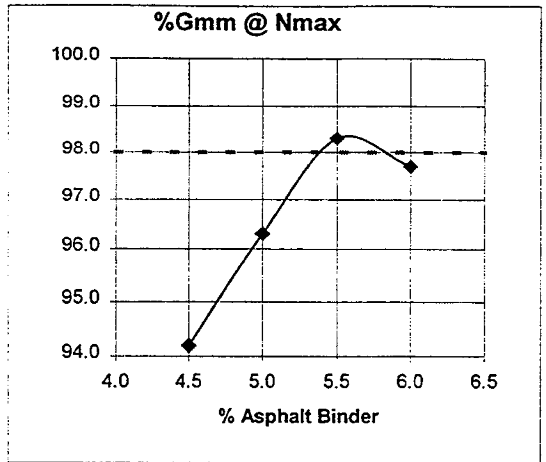


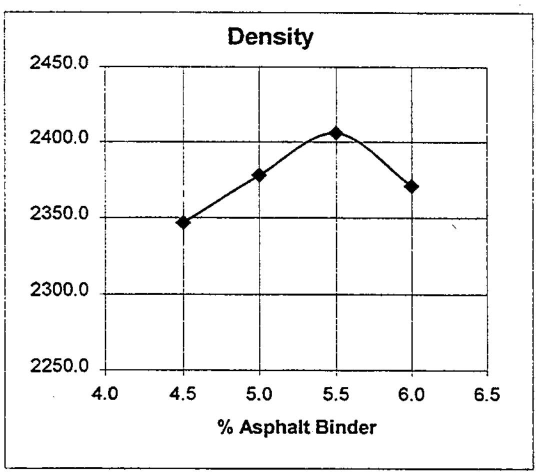


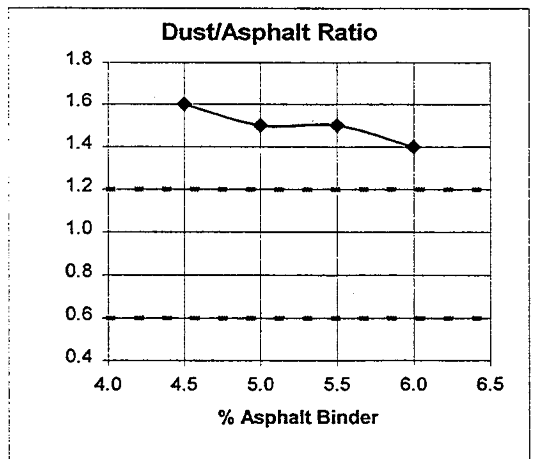


Blend	%AC	Air Voids @ N_{Max}	Air Voids @ N_{Design}	%VMA N_{Design}	%VFA @ N_{Design}
Blend1	4.5	5.8	7.1	13.9	49.1
Blend2	5.0	3.7	5.0	13.3	62.3
Blend3	5.5	1.7	3.0	12.7	76.4
Blend4	6.0	2.3	3.5	14.4	75.7









Blend	%AC	$\%G_{mm}$ @ N_{ini}	$\%G_{mm}$ @ N_{max}	Density(kg/m^3)	D/A ratio
Blend1	4.5	83.8	94.2	2346.7	1.6
Blend2	5.0	85.4	96.3	2377.9	1.5
Blend3	5.5	87.0	98.3	2405.6	1.5
Blend4	6	85.9	97.7	2371.0	1.4

APPENDIX D PURWHEEL TEST RESULTS FOR DRY/45°C AND WET/45°C

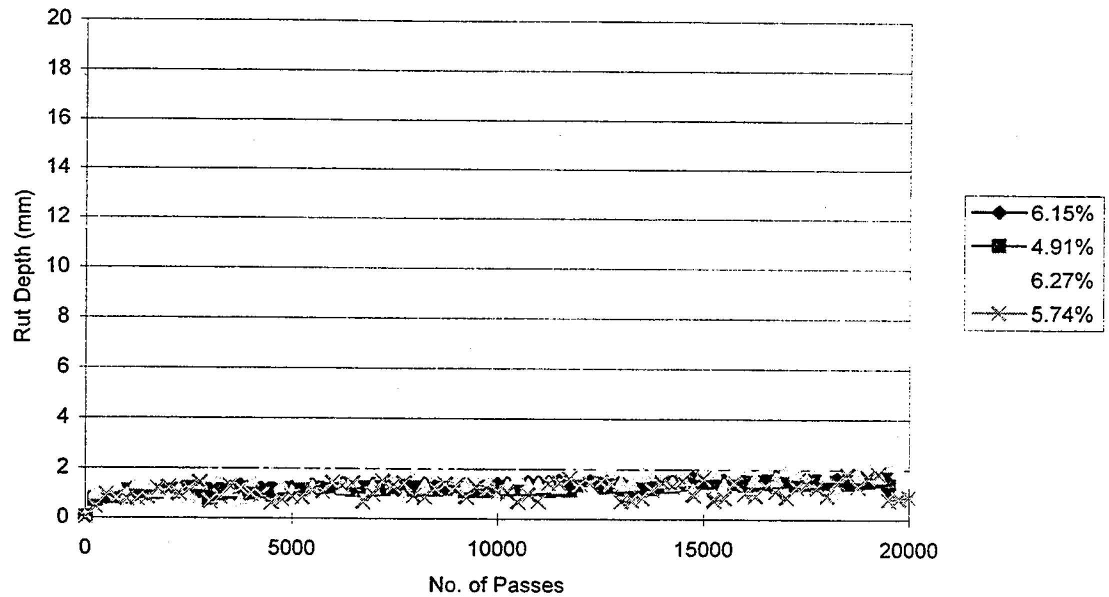


Figure D.1 PURWheel Dry/45°C Test Result for #2311

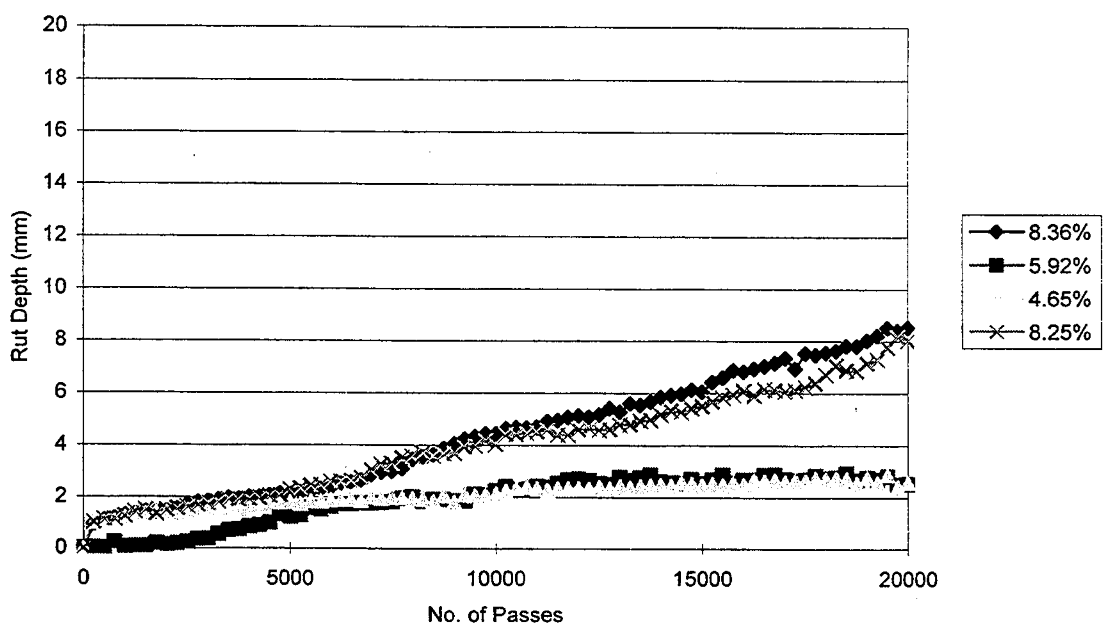


Figure D.2 PURWheel Wet/45°C Test Result for #2311

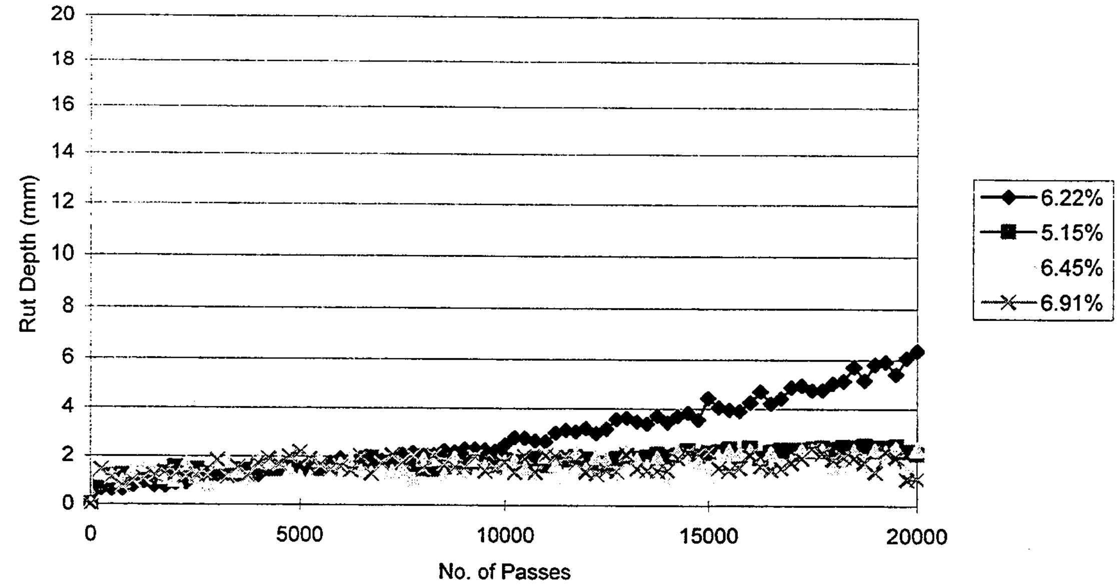


Figure D.3 PURWheel Dry/45°C Test Result for #2497

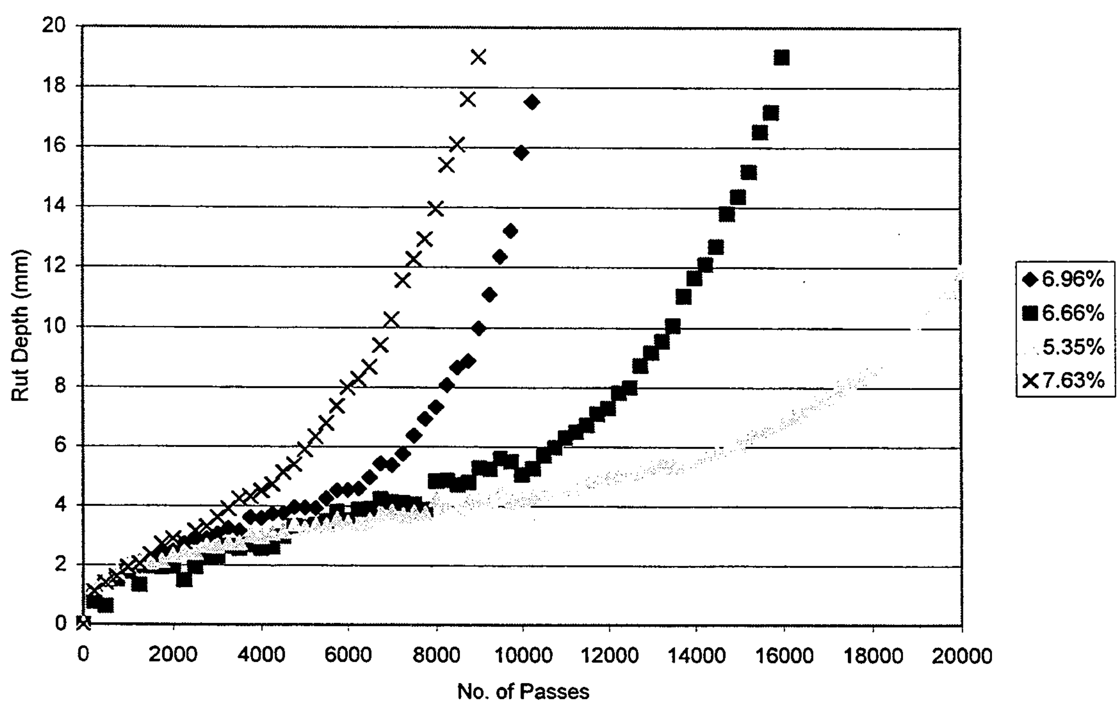


Figure D.4 PURWheel Wet/45°C Test Result for #2497

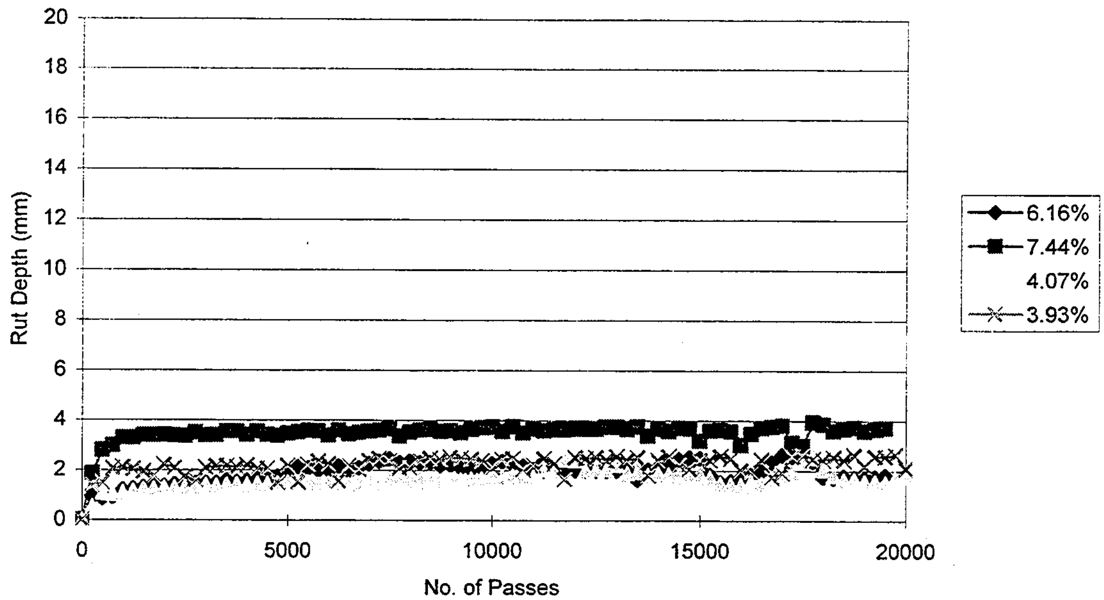


Figure D.5 PURWheel Dry/45°C Test Result for #2211

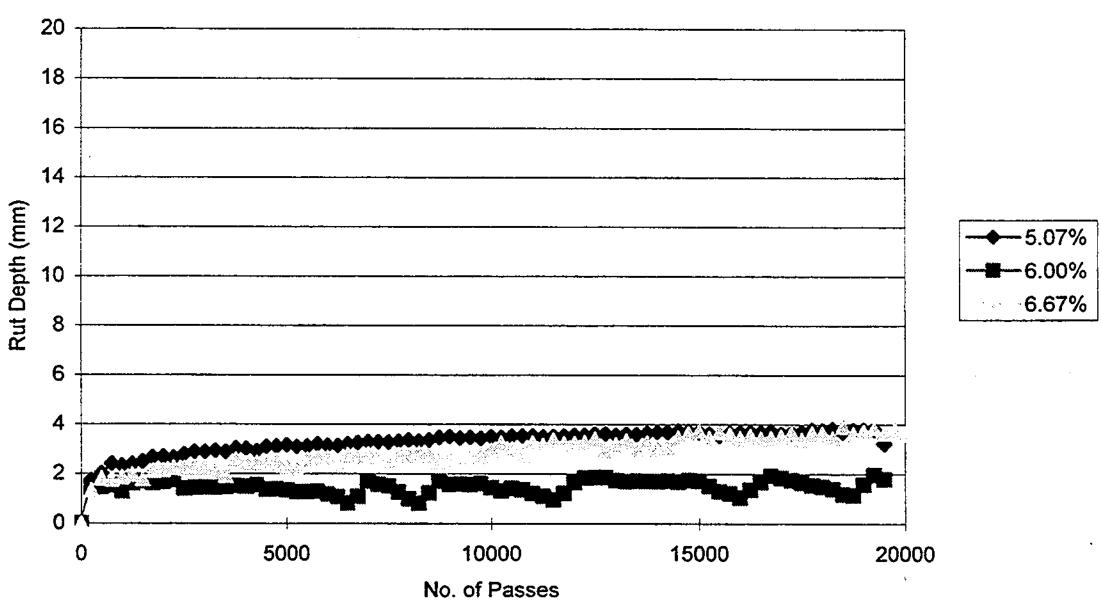


Figure D.6 PURWheel Wet/45°C Test Result for #2211

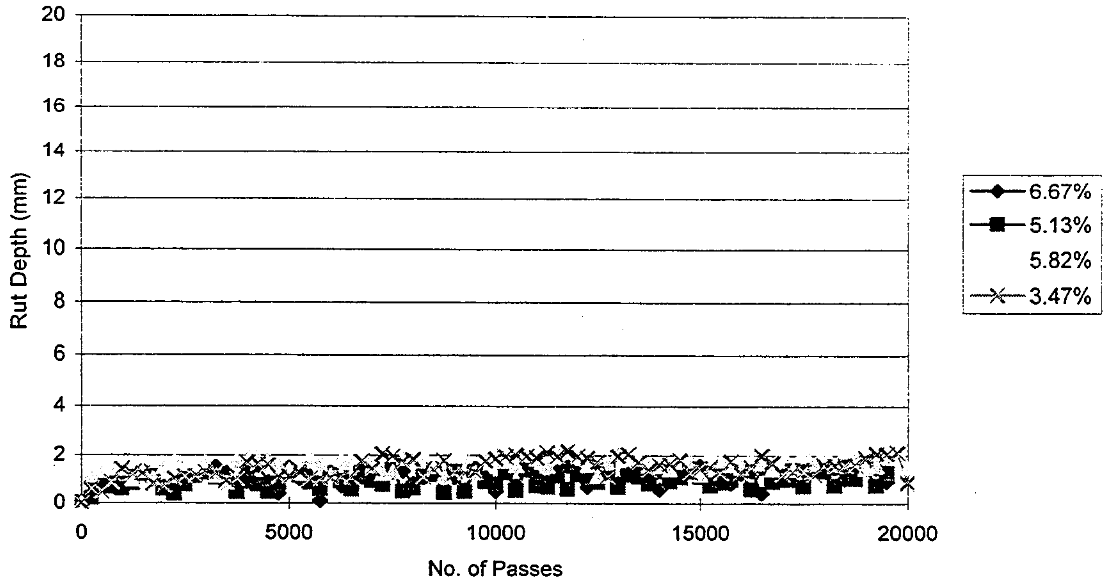


Figure D.7 PURWheel Dry/45°C Test Result for #2164

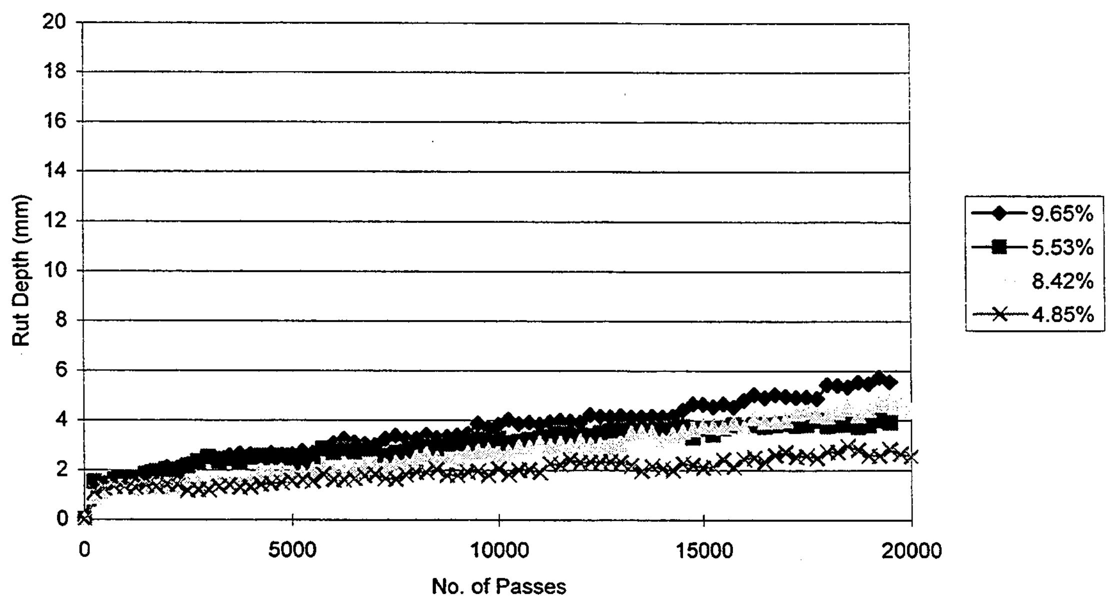


Figure D.8 PURWheel Wet/45°C Test Result for #2164

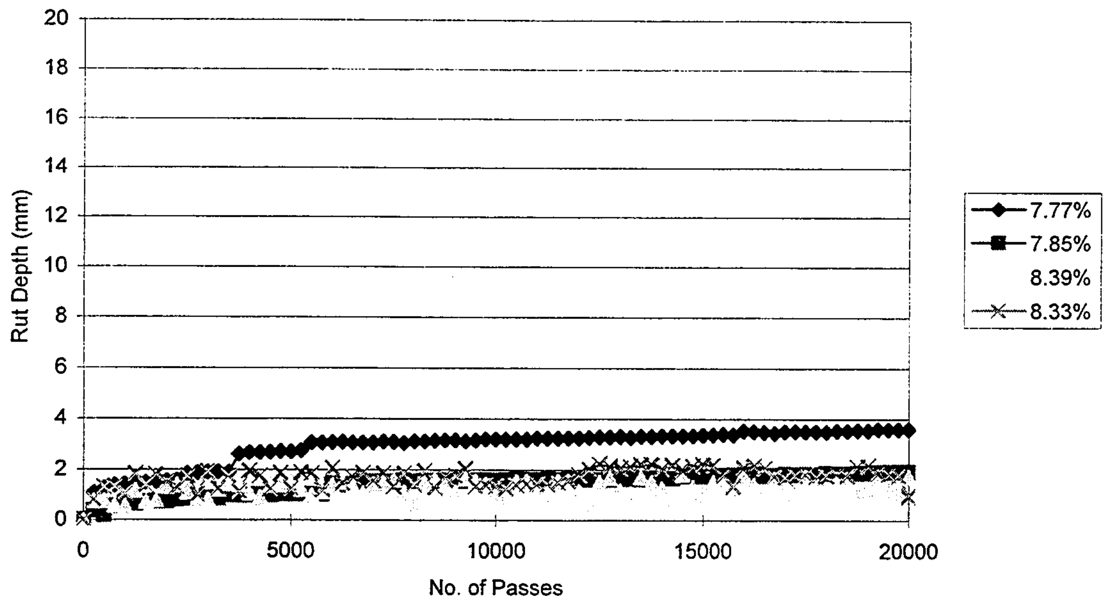


Figure D.9 PURWheel Dry/45°C Test Result for #2478

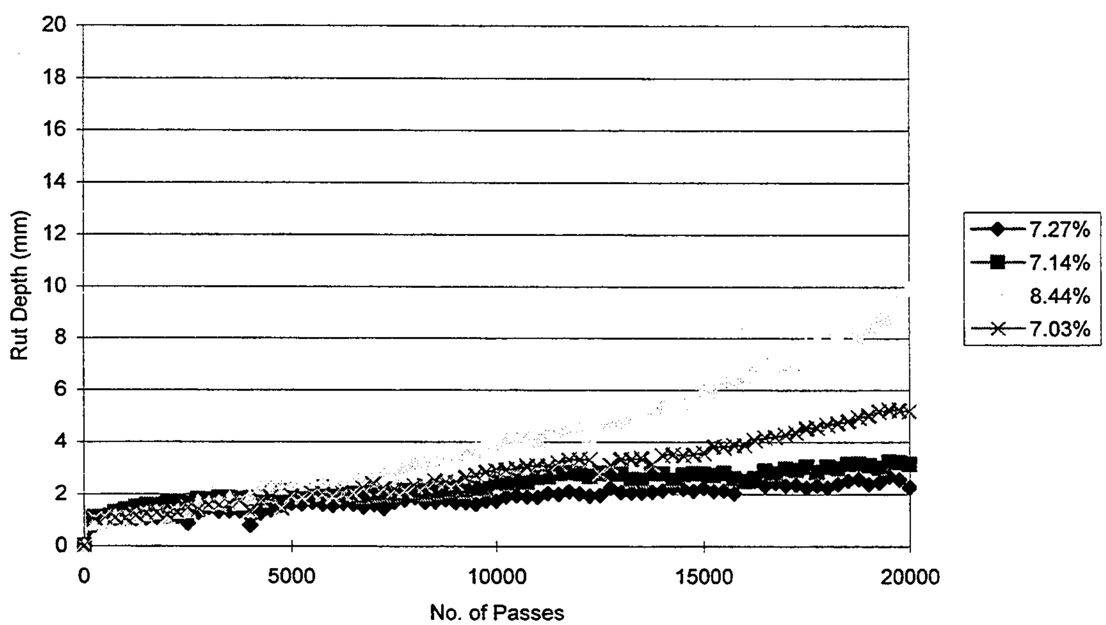


Figure D.10 PURWheel Wet/45°C Test Result for #2478

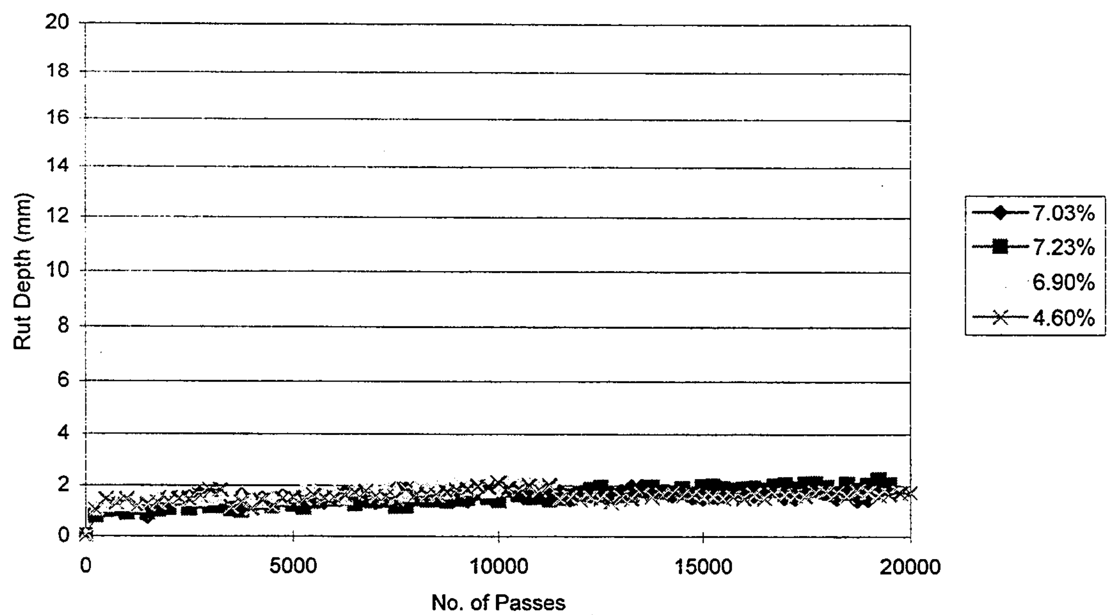


Figure D.11 PURWheel Dry/45°C Test Result for #2314

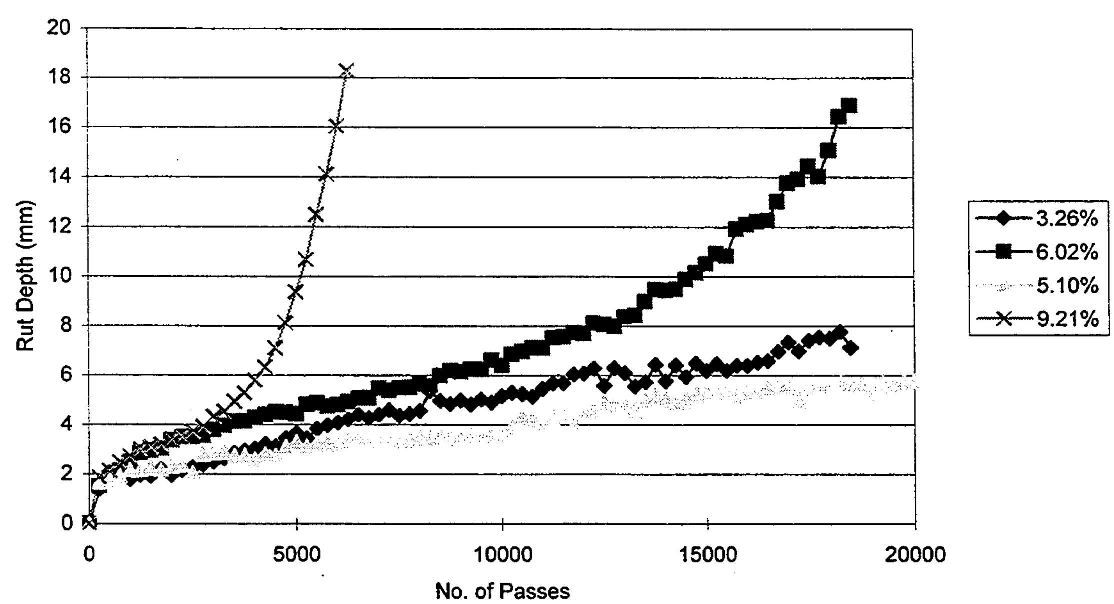


Figure D.12 PURWheel Wet/45°C Test Result for #2314

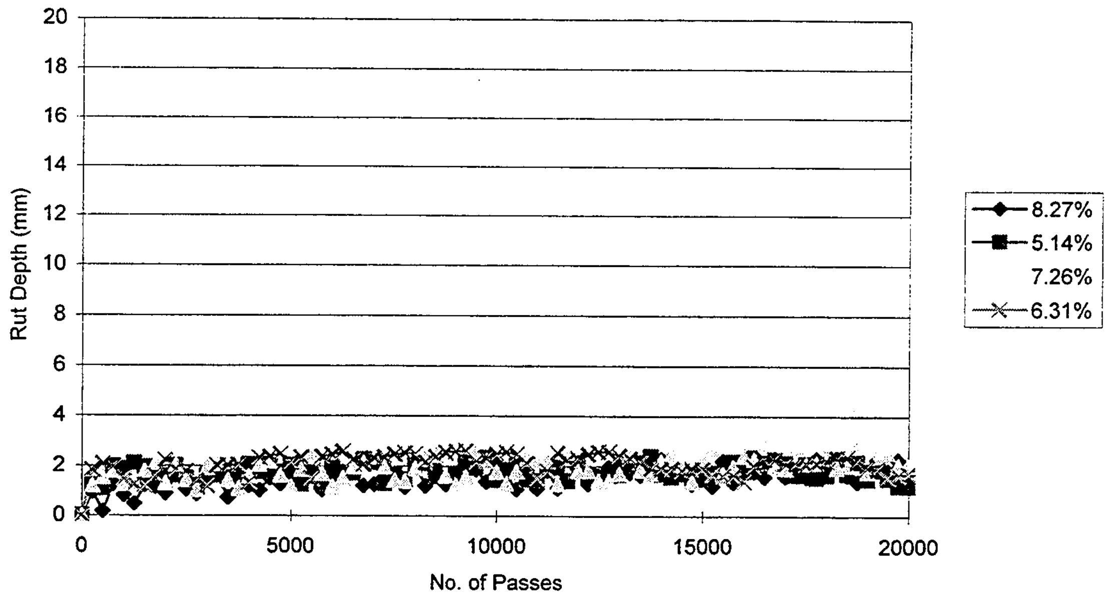


Figure D.13 PURWheel Dry/45°C Test Result for B1

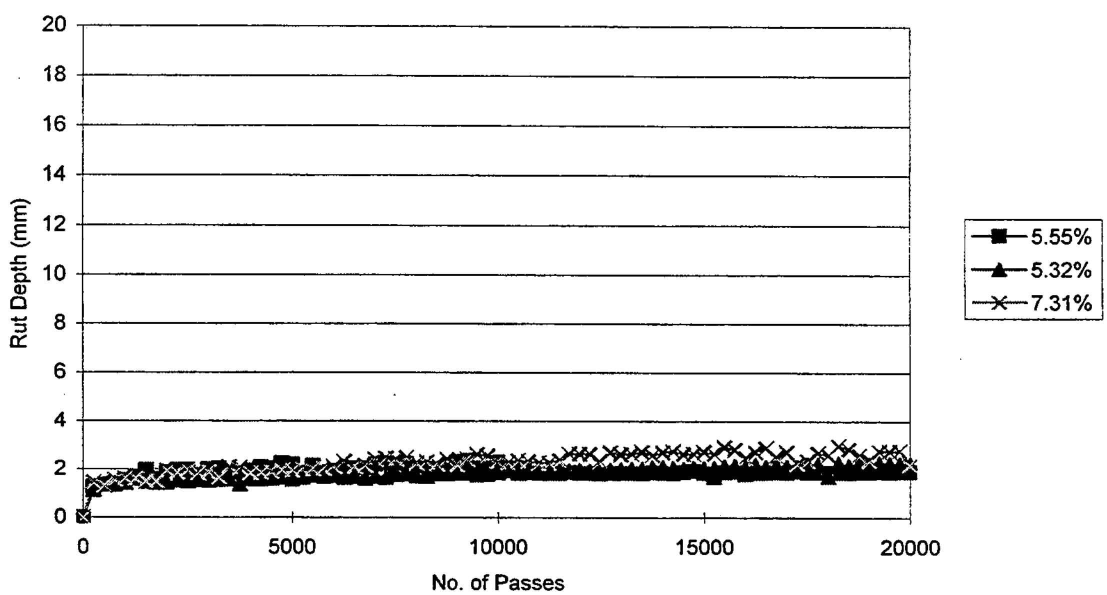


Figure D.14 PURWheel Wet/45°C Test Result for B1

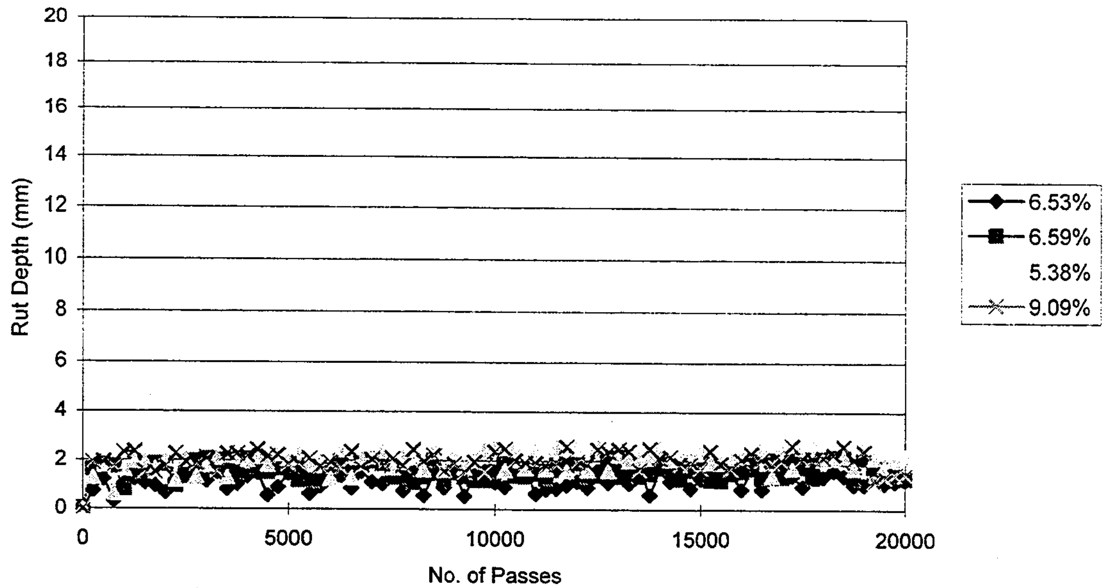


Figure D.15 PURWheel Dry/45°C Test Result for B2

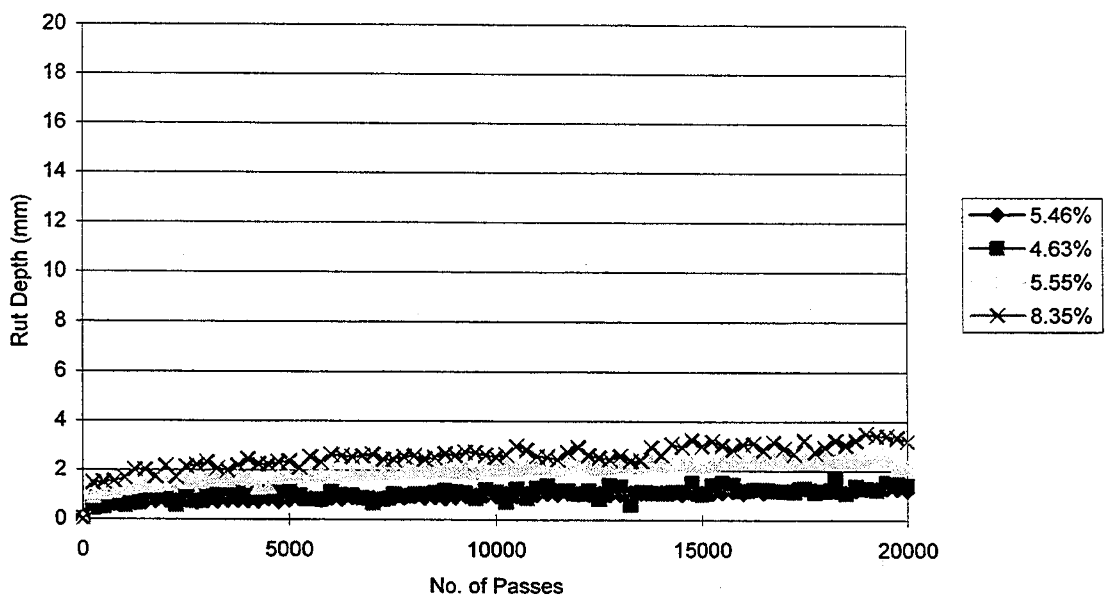


Figure D.16 PURWheel Wet/45°C Test Result for B2

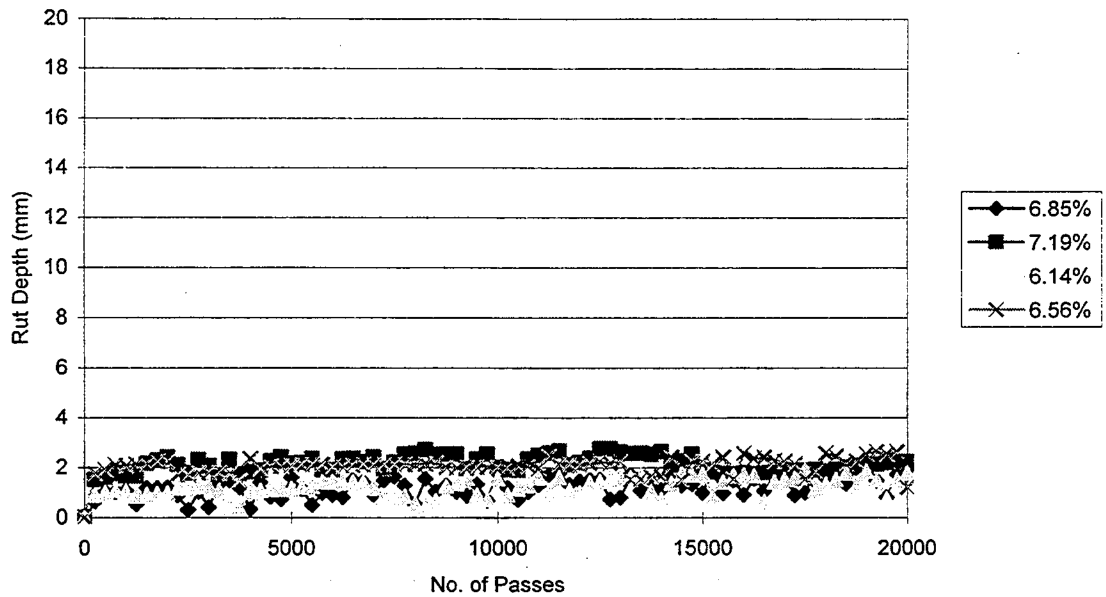


Figure D.17 PURWheel Dry/45°C Test Result for B3

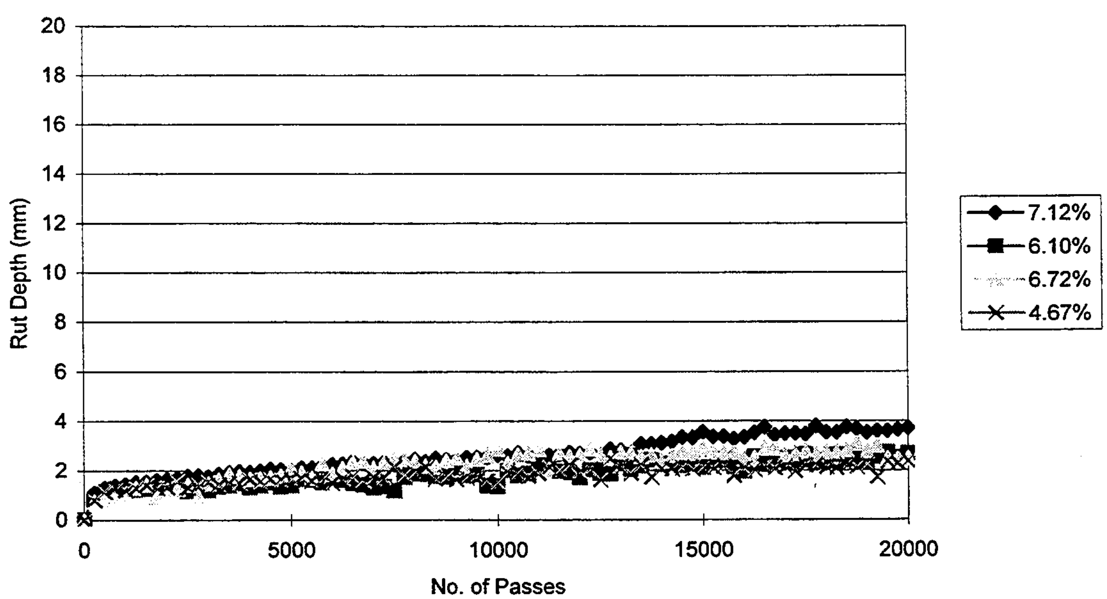


Figure D.18 PURWheel Wet/45°C Test Result for B3