NCAT Report No. 05-xx

DETERMINING N_{DESIGN} FOR SMA MIXTURES IN ALABAMA

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Sponsored by

The Alabama Department of Transportation

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TABLE OF CONTENTS

ABSTRACT

Stone Matrix Asphalt (SMA) mixtures have performed well in Alabama and many other states and countries. The mix design procedure used in Alabama has been based on the 50 blow Marshall hammer compactive effort. This design method was adapted from the practices of several European countries that are credited with development of SMA. Earlier research at NCAT attempted to correlate the 50 blow Marshall hammer compactive effort to compaction in the Superpave Gyratory Compactor (SGC). The finding of that study was the 78 gyrations, on average, would provide the same density as the Marshall hammer. However, there was a significant amount of scatter in the correlation. Later, when the SMA mix design procedure was balloted by AASHTO, the experience of one state was influential in setting the standard design gyrations at 100 gyrations. A footnote in the AASHTO procedure permits the use of 75 gyrations for aggregates having Los Angeles Abrasion values greater than 30. According to several mix designers in Alabama and other states, 100 gyrations significantly over compacts their SMA mixes even with high quality aggregates. The mix designers generally find that meeting the VMA requirement is not possible because the gyratory compactor continues to grind the aggregates past the point of stone-on-stone contact.

The objective of this study was to determine an equivalent compactive effort with the SGC to match the 50 blow Marshall hammer using aggregates and mix designs common in Alabama. To accomplish this objective, SMA mix designs were prepared with four aggregate types and two maximum aggregate size (MAS) gradations. Optimum asphalt contents and Voids in the Mineral Aggregate (VMA) from the Marshall mix designs were compared to the mix designs performed using 50, 75, and 100 gyrations in the SGC. To evaluate the potential of over compaction in the SGC, comparisons of aggregate breakdown from each of the compactive efforts were analyzed. To assure that the mixtures achieved good stone-on-stone contact, laboratory rutting tests were conducted on each of the mix designs and the Locking Point concept was examined. The results indicate for the small MAS gradation, 88 gyrations in the SGC generally provided the same optimum asphalt content and VMA as the Marshall procedure. For the larger MAS gradation, 58 gyrations, on average, matched the Marshall procedure. Considering all of the data together, 70 gyrations would, on average, match the Marshall hammer compaction. Aggregate breakdown was slightly less with the SGC compared to the Marshall hammer. The laboratory rut tests in the APA indicated that some 50 gyration mixtures may have a problem. Locking Point analysis indicated that stone-on-stone interlock generally occurred around 63 gyrations. Further testing and analysis with several plant produced SMA mixtures provided results which indicated slightly lower gyrations. On average, the field mixtures required 63 gyrations to match the density from the Marshall hammer. Locking Point for the field mixes averaged 57 gyrations. Analysis of the aggregate breakdown for the plant produced mixtures showed that compaction in the SGC caused less breakdown than compaction with the Marshall hammer. As with the laboratory prepared mix designs, slightly more breakdown was evident with increasing gyrations. All of the samples made with the field mixtures performed well in the APA tests. Based on the results and the lab and field mixes, 70 gyrations with the SGC are recommended to replace the 50 blow Marshall hammer for SMA mix design in Alabama.

Determining N_{design} for SMA Mixtures in Alabama

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INTRODUCTION

Background

Stone Matrix Asphalt (SMA) has been used for over a decade in the United States as a premium asphalt mixture to resist rutting and cracking on many heavy traffic roadways. SMA was originally developed in Germany in the 1960's to combat studded tires (*1*). A 1990 study tour of European paving practices found many countries using the SMA mix technology. SMA mixtures were introduced in the United States in 1991 when Georgia, Indiana, Michigan, Missouri, and Wisconsin constructed SMA projects. By 1997, over 100 SMA projects had been placed in the United States representing over three million tons of mix (*2*).

The technical basis for SMA is a stone skeleton with stone-on-stone contact unlike traditional dense graded mixes where aggregates tend to "float" in the mix with little contact between the larger aggregate particles. The coarse aggregate must be hard, durable, and roughly cubical in shape when crushed. The stone-on-stone contact between the high quality aggregate resists the shear forces created by the applied loads creating a very rut resistant pavement. SMA also typically utilizes a modified binder and some type of fiber to prevent the binder from draining off of the aggregate especially during handling and construction. High percentages of mineral filler and binder create a glue-like mastic to hold the stone together and fill in the spaces between the coarse aggregate skeleton. This mastic filled skeleton prevents water intrusion and provide excellent durability.

SMA has been increasing in popularity in the United States and 28 states now utilize SMA, which has been reported to provide a 20 to 30 percent increase in pavement life over conventional pavements (*3*). Alabama began using SMA on experimental projects in 1998. In 2001, the Alabama Department of Transportation (ALDOT) initiated a policy to use SMA on all projects with a history of rutting problems and projects with greater than 30,000 Equivalent Single Axle Loads (ESALs) over a twenty-year design period.

In Alabama, SMA mixtures are currently designed with the Marshall hammer. There is interest in changing the SMA design procedure to a procedure using the Superpave gyratory compactor. The key to this transition is identifying the appropriate number of design gyrations for SMA's in the gyratory compactor. That is the goal of this study. Two other NCAT research studies are also underway to address this issue on a national level and for the State of Georgia. These studies should be completed within the next year.

Purpose

The purpose of this project was to assist the Alabama Department of Transportation in refining their current Stone Matrix Asphalt design method. The new method will utilize the Superpave gyratory compactor (SGC) for the design of SMA mixtures. ALDOT and HMA contractors in the state have experience designing SMA pavements using the Alabama SMA design procedure ALDOT-395, which is based on compacting mix design samples with the Marshall hammer (*4*). Asphalt mix designers and quality control technicians in the state are also very comfortable with the use of the Superpave gyratory compactor.

Previous research has indicated various SGC design gyrations for SMA mixtures. Recommendations of 70, 73, 75, 78, 100 and 103 gyrations have been made in various studies (*5, 6, 7, 8*). The goal of this project was to identify a gyration level for Alabama SMA mixtures.

Scope

A literature review was conducted to investigate the state of the practice for Stone Matrix Asphalt design. Laboratory testing was then performed to determine the appropriate gyration level for Alabama SMA's. The emphasis was to determine the number of gyrations in an SGC that would provide similar volumetric properties to SMA mixtures designed with the 50 blow Marshall hammer. The effects of laboratory compactive effort on aggregate breakdown and rutting potential were also examined.

Literature Review

SMA technology was developed in Europe. Several tours by U.S. pavement engineers observed the excellent performance of SMA in several European countries and returned to this country with many of the mix design concepts necessary to adapt the European practices to the states (*1*). However, many European SMA specifications were vague and mix design practices varied from country to country in Europe. In German specifications, for example, it was known that the Marshall hammer was used in the design SMA mixtures; however, asphalt content was commonly selected based on recipes from experience (*7*). As SMA began to be used in the U.S, most highway agencies specified 50 blows from a Marshall hammer for SMA mix designs.

However, several problems are recognized with the Marshall hammer. The Marshall mix design procedure suffers from poor repeatability from one laboratory to another. The four-inch Marshall mold also limits the maximum size aggregate to one inch. This can cause excessive aggregate breakdown and does not simulate field compaction (*9*). In comparison with the Corps of Engineer's gyratory compactor, the Marshall procedure showed a higher variability with regard to air void content (*6*). In addition, with the implementation of Superpave in the U.S., the SGC has become the compactor of choice for the majority of HMA laboratories. Marshall hammers are being used less which inevitably leads to lack of maintenance for this equipment.

The Marshall test procedure requires that the mold be 4 inches in diameter and 2.5 inches in height (AASHTO T 245)(*10*). The compaction procedure for Marshall mixes recommends that the aggregate be no larger than ¾ inch (19 mm). Even though this maximum size encompasses most mixes, this can be a disadvantage if an agency desires to use a larger aggregate than ¾ inch. Kandhal worked on the development of a six inch Marshall mold and procedure to alleviate this problem (*11*), but use of the six inch Marshall procedure has not been widely accepted. An advantage of the Superpave Gyratory Compactor is the use of a standard 150 mm (≈six inches) mold. The six-inch mold allows larger maximum aggregate sizes, up to two inch (50 mm) maximum size aggregate (*12*).

Aggregate breakdown in Marshall mixes has also been an issue. The Marshall hammer applies direct vertical blows without any kneading action (and therefore no particle reorientation). The concern is that impact compaction can crush the aggregate more than field roller compaction. In *Evaluation of Laboratory Properties of SMA Mixtures*, Brown and Manglorkar discuss 12 states that placed SMA mix in 1993. All of the states used 50 blows with a Marshall hammer. It was reasoned that 75 blows tends to break down the aggregate more and does not result in a significant increase in density compared to 50 blows (*13*). Brown reported that as Marshall blow count increases, breakdown significantly increases; but as gyrations increase, breakdown increases only slightly. The study also compared aggregate breakdown from 50 blow Marshall to 100 gyrations with the SGC. The SGC resulted in less aggregate breakdown (*14*). Some laboratory aggregate breakdown is acceptable if it is comparable with the aggregate breakdown found during construction. When the aggregate breakdown becomes excessive, a mixture may not be able to meet minimum VMA requirements (*9*). In Virginia, Prowell found that density increases, beyond the point where stone-on-stone contact was achieved, were most likely due to aggregate breakdown. (*8*).

The aggregate durability test, Los Angeles Abrasion (L.A. Abrasion), is an important aggregate characteristic for good SMA performance. This test provides an indication of the toughness and degradation resistance of an aggregate. Some studies show a fairly good correlation between L.A. Abrasion and aggregate breakdown during lab compaction. An increase in L.A. Abrasion generally corresponds to an increase in aggregate breakdown for both Marshall and Superpave gyratory compactors (*14*). Brown recommends a maximum L.A. Abrasion value of 30 percent to minimize aggregate breakdown. *Designing and Constructing SMA Mixtures* suggests that L.A. Abrasion values less than 30 percent should receive 100 gyrations for design and L.A. Abrasion values between 30 and 45 percent should be designed at 75 gyrations. The manual also states that aggregates with L.A. Abrasion values greater than 30 percent should not be used in the wearing course (*5*). Georgia and Wisconsin allow a maximum L.A. Abrasion value of 45 percent (*15*). Maryland's SMA specification requires a maximum L.A. Abrasion of 30 percent. (*16*). Alabama allows aggregates with L.A. Abrasion values up to 48 percent (ALDOT 423) (*17*).

Volumetric properties of SMA mixtures are influenced by the compaction type and effort. Most agencies require a minimum VMA of 17.0 percent for SMA mixtures, regardless of the compactor type and effort.

The voids in coarse aggregate ratio, VCA ratio, were developed to ensure stone-on-stone contact of the coarse aggregate in an SMA mixture. This parameter can also be affected by aggregate breakdown. If the coarse aggregate degrades, the calculated VCA ratio will decrease due to the smaller particles of aggregate filling in the voids. If the compacted mixture has excessive breakdown, the VCA ratio may appear to be acceptable, when in fact the mixture has only achieved the acceptable VCA ratio because of aggregate breakdown.

The Locking Point concept is a relatively new idea for establishing SGC compactive effort that was originated to reduce breakdown of aggregate in SGC specimens due to over-compaction (*18*). The rationale of limiting the gyrations to the point where the aggregate has "locked" together is to reduce aggregate breakdown. Very little additional compaction of specimens occurs beyond the Locking Point. In effect, the Locking Point concept reduces the number of gyrations for mix design and results in higher binder contents for asphalt mixtures.

Alabama DOT has defined the Locking Point as the second of two consecutive gyrations, which have the same recorded sample height (*17*). The specimen heights in the SGC are recorded to the nearest 0.1 mm as required by AASHTO T-312 (*10*). Georgia DOT defines Locking Point differently. Georgia defines the first Locking Point, used for lower volume roads, as the "number of gyrations at which, in the first occurrence, the same height has been recorded for the third time." In other words, the first time the gyratory compactor displays a single height three times in a row, the locking point is the first gyration in which that height occurs. The second Locking Point, for higher volume roadways, is "the number of gyrations at which, in the first occurrence, the same height has been recorded for the fourth time" (*19*). Pine's original recommendation was that the Locking Point be the first gyration in which three gyrations are at the same recorded height preceded by two sets of two gyrations at the same recorded height. For example, if the heights in order for a sample are 116.2, 116.2, 116.1, 116.0, 116.0, 115.9, 115.9, 115.9 mm, the Locking Point would be the gyration which corresponds with the first occurrence of the 115.9 mm. The Locking Point is the first of those three consecutive height gyrations. The Alabama definition for Locking Point will yield the lowest compactive effort followed by the Georgia method and the Pine method. One concern with the Locking Point concept is the possibility that different makes and models of SGC's may yield significantly different compactive efforts.

One of the tasks in NCHRP 9-8, *Designing Stone Matrix Asphalt Mixtures*, was to correlate the 50 blow Marshall hammer compaction to compaction in the SGC. For this task, SMA mixtures from eleven field projects across the U.S. were sampled and compacted with the Marshall hammer to 50 blows and with the SGC to 100 gyrations. From the gyratory data, the bulk specific gravity of the mixture, G_{mb}, was back-calculated to 50, 60, 70, 80, and 90 gyrations. This data was used to develop the correlation shown in Figure 1. Although there was significant variability in the data from the field project mixtures, it was estimated that on average 78 gyrations in the SGC would provide the same density as 50 blows of the Marshall hammer (*7*). Some error is known to exist in the back-calculation of G_{mb} for coarse-graded and SMA mixtures. This error would tend to over predict the G_{mb} at lower numbers of gyrations. Correcting this error would be expected to result in fewer gyrations to match the Marshall hammer.

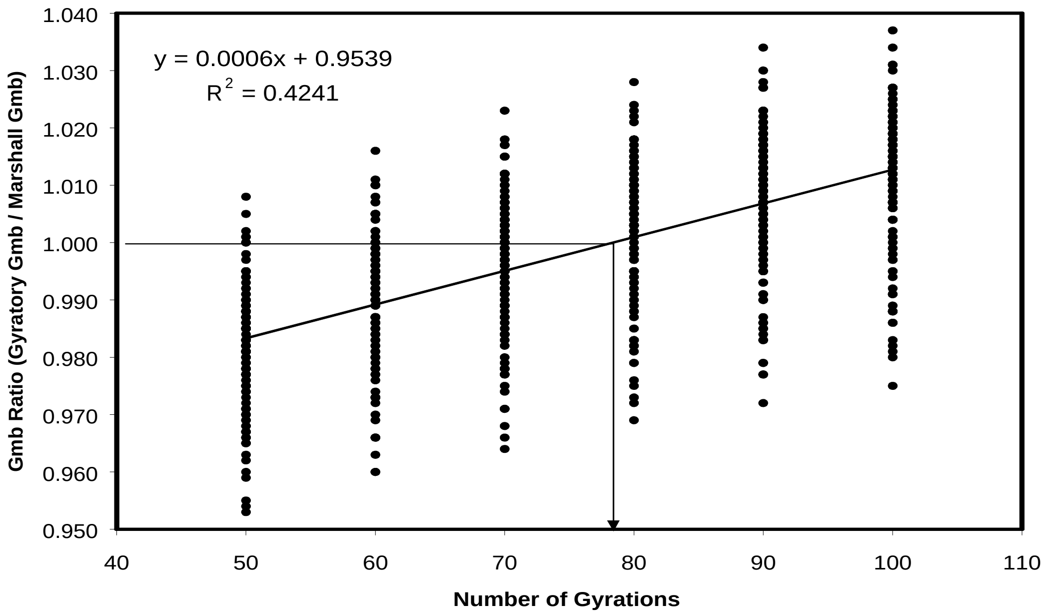

Figure 1. Comparison of Densities Compacted with 50=Blows of the Marshall Hammer and 100 Gyrations of the SGC- All Data. (*7*)

Several U.S. highway agencies now use the SGC for laboratory compaction for SMA. Two states that have been at the forefront of SMA usage in the U.S. are Maryland and Georgia. Maryland requires 100 gyrations for its SMA (*16*). Georgia currently uses 75 gyrations for their 9.5 mm nominal maximum size aggregate (NMAS) mixes. Prowell's paper on 9.5mm NMAS SMA mixes in Virginia recommended 75 gyrations (*8*). Colorado allows either a 50 blow Marshall hammer or 100 gyrations from a Superpave Gyratory Compactor (*20*). The American Association of State and Highway Transportation Officials (AASHTO) allow 100 gyrations in its federal provisional standard AASHTO PP28-29, but MP8-04 states that it may be desirable to design to 75 gyrations if L.A. Abrasion values are higher than 30 percent (*21*). NCHRP 9-9 recommends 100 gyrations except for cases of softer aggregate, then the N_{design} gyration level should be 70 gyrations, but the decision should be made from the experience of the user agency (*22*).

The possible benefits of using the Superpave gyratory compactor include reduced variability, reduced aggregate breakdown, and larger allowable aggregate size mix designs. Given the increased familiarity with the SGC, and other possible benefits, it is anticipated that SMA mixtures can be designed with the same or better success than with the Marshall hammer.

EXPERIMENTAL PLAN

The project was divided into 4 tasks described in the following sections. Figure 2 illustrates the testing plan.

Task 1-Material Selection

Materials commonly used in SMA mixtures for Alabama were used in the laboratory work for this study. The aggregate types used were granite, sandstone and limestone. The properties of the selected aggregates are shown in Table 1. They represent a range of Los Angeles Abrasion values and meet Alabama Standard Specification Section 423. Cellulose fiber from Interfibe was used to minimize draindown. A performance graded 76-22 binder modified with styrene-butadiene-styrene (SBS) was used as the asphalt binder.

Table 1. Properties of Aggregates Used for Laboratory Designed SMA Mixes

Aggregate	G_{sca}[1]	G_{sfa}[2]	LA Abrasion, %	FAA[3], %	F&E[4], 3:1,%	F&E[4], 5:1,%	F&E[5], 3:1,%	F&E[5], 5:1,%
Granite	2.671	2.669	36.1	48.3	17.2	0.7	8.9	0.1
Sandstone	2.598	2.572	25.8	47.9	14.9	1.0	6.7	0.6
Limestone	2.719	2.686	27.2	45.3	9.6	0.4	11.6	1.2

[1]Bulk Specific Gravity of Coarse Aggregate
[2]Bulk Specific Gravity of Fine Aggregate
[3]Fine Aggregate Angularity
[4]Flat and Elongated, by count, 9.5 mm Mixtures
[5]Flat and Elongated, by count, 19.0 mm Mixtures

Task 2- Mix Designs

The selected materials were combined to produce mix designs compacted with the Marshall hammer and with the SGC at three N_{design} levels. Two maximum aggregate size (MAS) gradations, 19.0 mm and 9.5 mm, were designed for each aggregate type. Table 2 shows the gradations for these mixes and the gradation limits from ALDOT Specification Section 423 Special Provision 02-0359 (*17*).

The 9.5 mm MAS limestone mixture gradation met the requirements except for the percent dust. For this mixture, it was not possible to achieve the minimum VMA of 17 percent with the minimum dust content of 12 percent. Cellulose fiber was added at 0.3 percent by weight of mixture to prevent draindown. A flat-faced, static Marshall hammer was used to compact samples with 50 blows per side. A Pine Instrument Co. model AFG1A Superpave Gyratory Compactor was used to compact the SMA samples to 50, 75 and 100 gyrations.

SMA mix designs were conducted in accordance with Alabama DOT method ALDOT-395. In addition to acquiring the typical volumetric data from the samples, the ALDOT defined Locking Point was also examined.

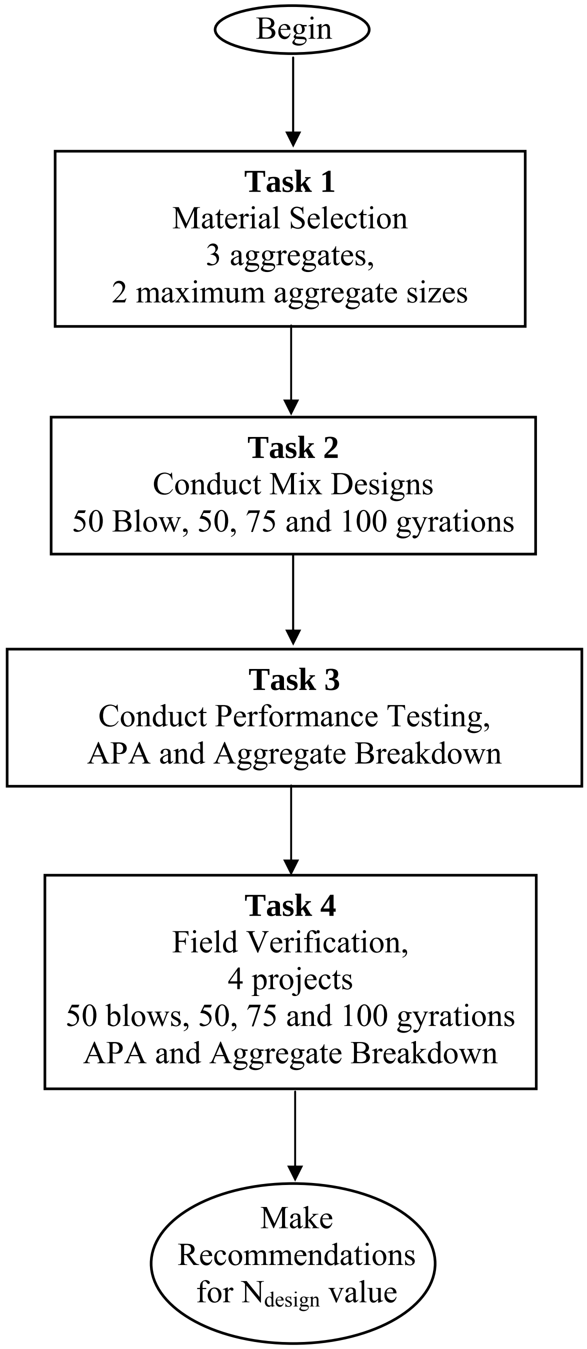

Figure 2. Experimental Plan for the Project

Table 2. Recommended 19.0 mm and 9.5 mm SMA Gradation Bands

Sieve Size		19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	75 µm
		Percent Passing By Volume								
9.5 mm Maximum Aggregate Size	Lower Limit	100	100	100	90	28	22	18	15	12
	Upper Limit	100	100	100	100	65	36	28	22	15
19.0 mm Maximum Aggregate Size	Lower Limit	100	90	26	20	16	13	12	12	8
	Upper Limit	100	100	78	28	24	21	18	15	10

Table 3. Gradations Used in Laboratory Mix Designs

		Percent Passing by Volume		
Gradation and Aggregate		9.5mm Sandstone	9.5mm Granite	9.5mm Limestone
3/8"	9.5mm	100.0	100.0	100.0
#4	4.75mm	90.2	88.8	96.3
#8	2.36mm	32.4	29.4	26.8
#16	1.18mm	25.4	23.2	20.4
#30	0.600mm	22.1	20.3	16.2
#50	0.300mm	19.9	16.1	12.7
#100	0.150mm	17.2	14.2	10.7
#200	0.075mm	12.8	11.2	7.9
Gradation and Aggregate		19.0mm Sandstone	19.0mm Granite	19.0mm Limestone
3/4"	19.0mm	100.0	100.0	100.0
1/2"	12.5mm	94.0	91.3	96.9
3/8"	9.5mm	32.6	30.1	29.0
#4	4.75mm	24.4	20.5	20.1
#8	2.36mm	21.1	16.7	16.3
#16	1.18mm	18.7	14.9	13.3
#30	0.600mm	17.1	14.0	12.3
#50	0.300mm	16.3	13.2	12.0
#100	0.150mm	14.4	11.6	10.3
#200	0.075mm	10.5	8.5	7.8

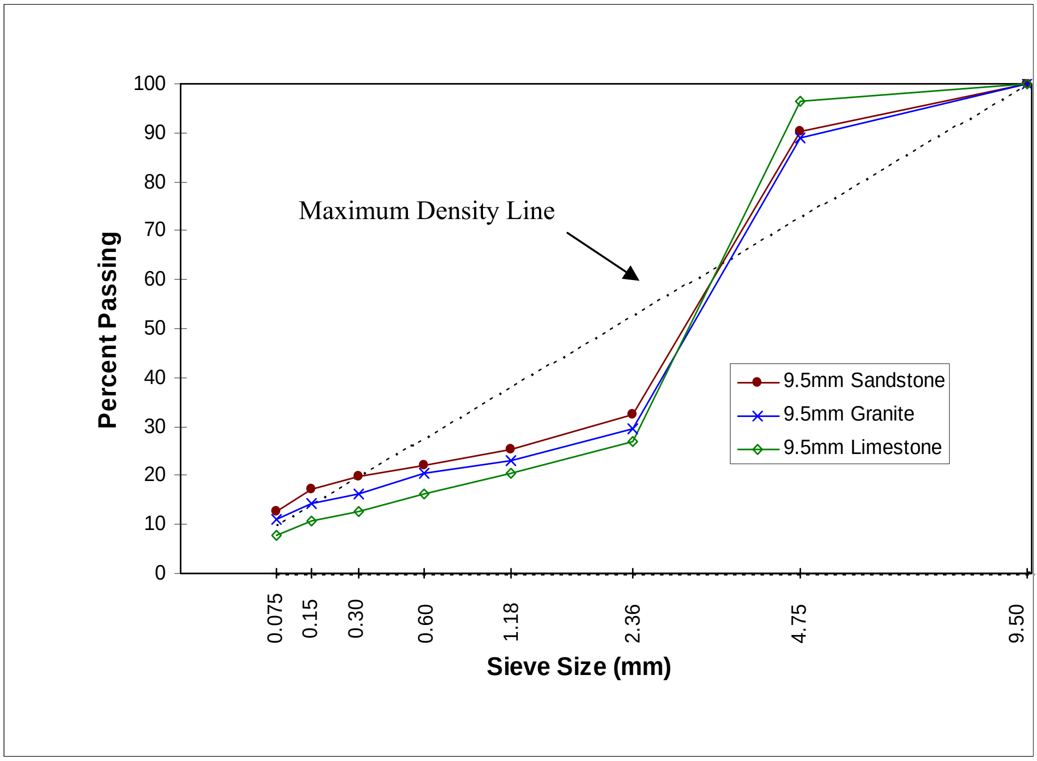

Figure 3. 9.5 mm MAS Gradation Plot

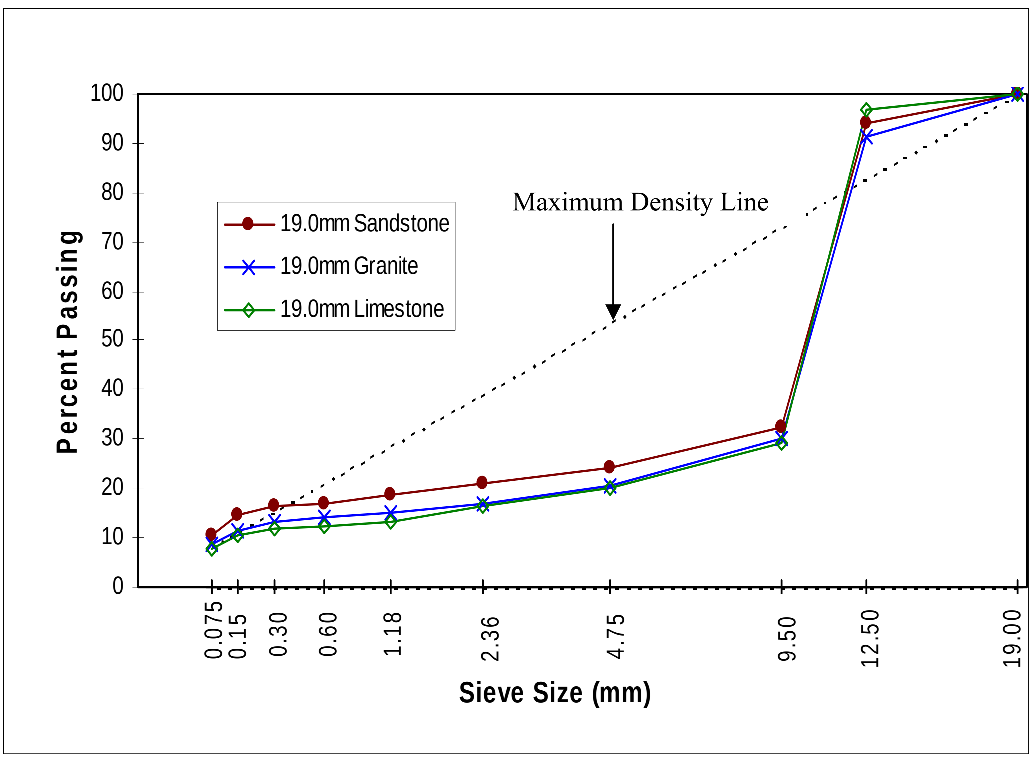

Figure 4. 19.0 mm MAS Gradation Plot

Task 3 – Performance Testing

After the mix designs were complete, samples were compacted at optimum binder contents corresponding to each N_{design} level to test for rutting potential with the Asphalt Pavement Analyzer (APA). These samples were tested according to AASHTO T-166 to insure that they met the criteria of 4±0.5 percent air voids. Full height samples were used as allowed by ALDOT-401. For each test, six samples were prepared and tested on the APA.

The APA tests were conducted to 8,000 cycles at 64°C, 120 psi hose pressure, and wheel loads of 120 lbs. These hose pressure and wheel load conditions are different than the ALDOT-401 test conditions. The ALDOT-401 test conditions are 100 psi hose pressure and wheel loads of 100 lbs. At the time this study was initiated, it was thought that the conditions of the APA test would be changing to the higher pressure and higher load. At the time of publication, ALDOT was still considering the new specifications.

The current ALDOT SMA specification requires a maximum rut depth in the APA of 4.5 mm using ALDOT 401. Moore performed a mini-experiment where asphalt mixtures were tested using both the 100 psi/100 lbs and 120 psi/120 lbs conditions (*23*). Figure 5 shows the graph of the relationship between the two methods. Using the relationship developed from this graph, the 4.5 mm criteria for the 100 psi, 100 lbs conditions would be equivalent to 5.9 mm using 120 psi hose pressure and 120 lbs. wheel load.

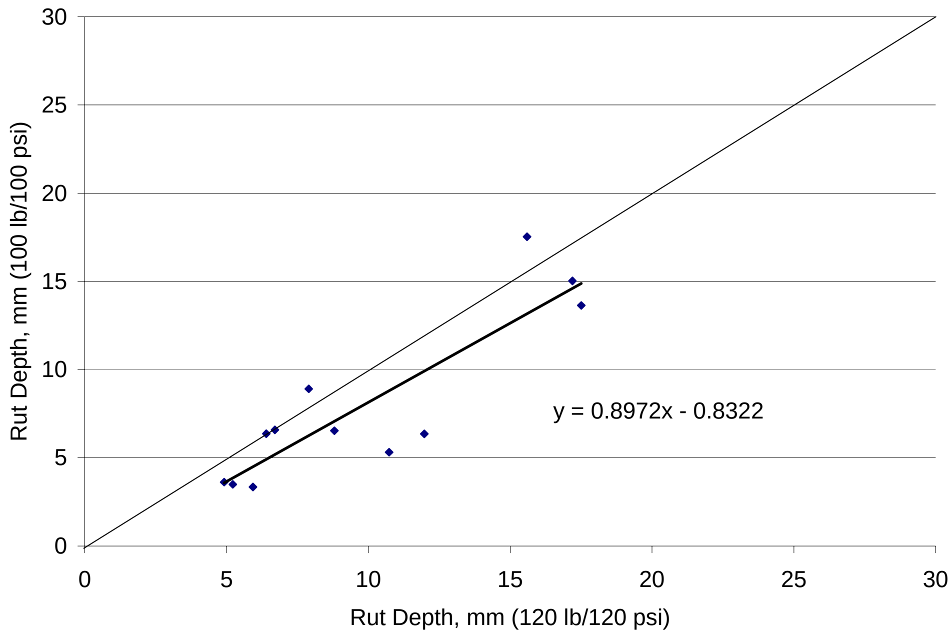

Figure 5. Comparison Between 100psi/100lbs and 120psi/120lbs APA Conditions (*23*)

Aggregate breakdown was also examined. Samples compacted at each N_{design} level and with the Marshall hammer were heated and broken down. The asphalt was then burned from the aggregate using the NCAT Ignition Oven and a sieve analysis was performed on the aggregate. Gradations were also performed on aggregate from samples of uncompacted mix after solvent extraction and the NCAT Ignition Oven to verify that there was no breakdown of the aggregate due to the ignition oven test.

Task 4 – Field Verification of N_{design} Level

For this task, four current SMA projects in Alabama were selected. For each project, four consecutive lots were sampled to include typical variation in mix characteristics. Samples were taken at the same time that a quality control sample was taken. Four cores corresponding to each sampled lot were also taken after the mix was placed and compacted on the roadway. The job mix formulas and quality control data for the samples were provided by the contractor (job mix formulas are shown in the appendix).

For each project, the uncompacted plant mix from each of the four lots was compacted to 50 blows with the Marshall hammer and 50, 75 and 100 gyrations with the SGC. The bulk specific gravity of compacted samples was determined using AASHTO T-166. The maximum theoretical specific gravity for each sample was determined using AASHTO T-209. The two sets of gyratory compacted samples representing the greatest range in characteristics were chosen for testing in the APA. This was determined by examining the contractor's quality control data, the core densities, and the bulk specific gravities of the lab compacted samples. The samples were tested in the APA using the same test conditions used for the laboratory designed mixtures. Loose mix samples, cores, and the other lab compacted samples were used to evaluate aggregate breakdown.

ANALYSIS OF RESULTS

Laboratory Mix Designs

Mix designs were prepared for each aggregate type. Since ALDOT currently specifies SMA mix designs to use the Marshall 50 blow compactive effort, these mix designs were completed first to assure that they met the ALDOT SMA mix design requirements. The Marshall mix designs then served as baseline mix designs to compare the same aggregate blends designed at various gyrations in the SGC. The mix design results are shown in Table 4. The table shows each aggregate, maximum aggregate size, compaction procedure and level of compaction. For example, "LMS 9.5 mm, 50 Gyr" means that the 9.5 mm maximum aggregate size (MAS) gradation of limestone was compacted to 50 gyrations on the SGC. The table also shows the percent asphalt cement required by the design (Design AC) and voids in mineral aggregate (VMA).

Table 4. Laboratory Designed Mixes Results

Aggregate/MAS/Compaction Level	Design AC,%	VMA, %
Granite 9.5 mm, 50 Blows	6.6	17.9
Granite 9.5 mm, 50 Gyr	7.5	19.6
Granite 9.5 mm, 75 Gyr	6.9	18.3
Granite 9.5 mm, 100 Gyr	6.4	17.5
Granite 19 mm, 50 Blows	6.5	17.8
Granite 19 mm, 50 Gyr	6.6	18.0
Granite 19 mm, 75 Gyr	6.2	17.2
Granite 19 mm, 100 Gyr	5.9	16.5
Sandstone 9.5 mm, 50 Blows	7.2	17.2
Sandstone 9.5 mm, 50 Gyr	8.6	20.2
Sandstone 9.5 mm, 75 Gyr	7.4	18.1
Sandstone 9.5 mm, 100 Gyr	7.1	17.1
Sandstone19 mm, 50 Blows	6.9	17.6
Sandstone 19 mm, 50 Gyr	6.9	17.6
Sandstone 19 mm, 75 Gyr	6.1	15.9
Sandstone 19 mm, 100 Gyr	5.8	15.2
LMS 9.5 mm, 50 Blows	6.7	18.2
LMS 9.5 mm, 50 Gyr	7.3	19.6
LMS 9.5 mm, 75 Gyr	6.7	18.4
LMS 9.5 mm, 100 Gyr	6.4	17.9
LMS 19 mm, 50 Blows	6.7	18.9
LMS 19 mm, 50 Gyr	7.8	21.2
LMS 19 mm, 75 Gyr	6.3	18.1
LMS 19 mm, 100 Gyr	6.0	17.4

The asphalt contents of the mix designs are based on a target air void content of four percent. A bar graph of the design asphalt contents is shown in Figure 6. The ALDOT minimum binder content for 19.0 mm MAS mixes is 5.7 percent, and for 9.5 mm MAS mixtures the minimum binder content is 6.1 percent. Each of the mixtures met these respective minimum binder contents. As expected, the design asphalt content decreases as the gyratory compactive effort increases. On average, the design asphalt content of the SMA mixtures decreased about 0.85 percent from 50 to 75 gyrations, and decreased by 0.33 percent from 75 to 100 gyrations.

The optimum asphalt contents for the Marshall mixes were either the same or lower than the 50 gyration samples. Compared to the design asphalt contents for the 75 gyration samples, the design asphalt content for the Marshall samples were higher in three cases, lower in two cases, and the same in one case. All of the 100 gyration samples required less asphalt than the 50-blow Marshall designs. Based on this data, it is apparent that no single gyratory compactive effort will match each 50 blow Marshall mix. However, for the majority of these laboratory designed SMA mixtures, the SGC compactive effort that provides the same optimum binder content appears to be between 50 and 75 gyrations.

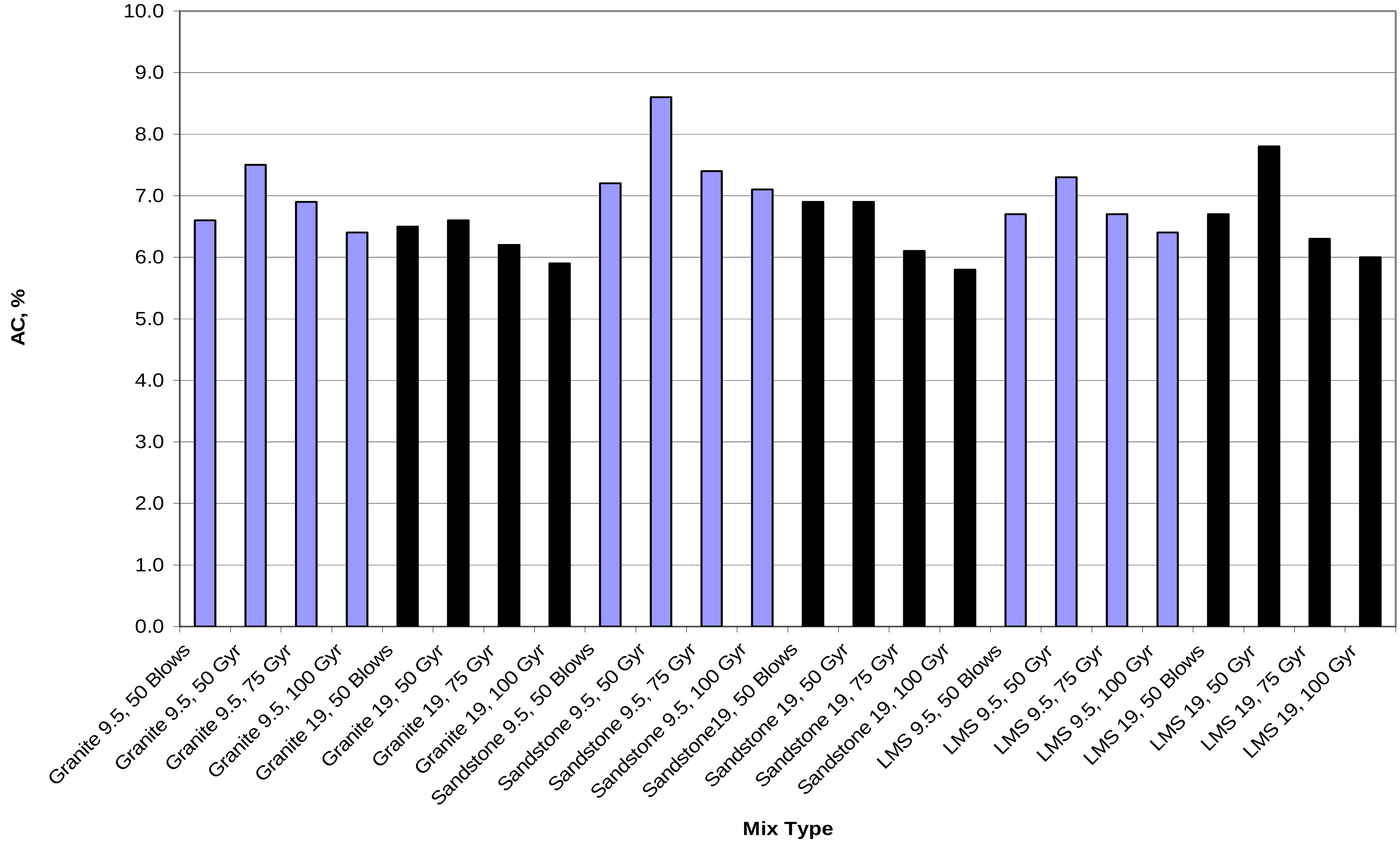

Figure 6. Design Asphalt Content of Laboratory Prepared Samples

The VMA results for the laboratory mix designs are shown in Figure 7. Three of the mix designs had VMA below the minimum of 17 percent: granite 19.0 mm at 100 gyrations, and the sandstone 19.0 mm at 75 and 100 gyrations. Although there is no upper limit specification for VMA, several mix designs had VMA results over 19 percent. Each of these high VMA mix designs was based on 50 gyrations in the SGC.

To compare mix designs between the Marshall hammer and the Superpave gyratory compactor, plots were made of VMA ratio versus gyrations. For each aggregate type/MAS blend, VMA ratio was calculated by dividing the average VMA of gyratory samples by the average VMA of the Marshall samples. Therefore, if the Marshall and the Gyratory samples have equal VMA then the VMA ratio would be one. This ratio was calculated for each gyration level. Figure 8 shows the VMA ratio for all of the laboratory designed mixes. On average, 70 gyrations in the SGC yield the same VMA as 50 blows with a Marshall hammer. This value of 70 is reasonably close to the value of 78 gyrations recommended by NCHRP 9-8. This plot also shows the 95 percent confidence interval for the relationship between VMA ratio and gyrations. From this confidence interval, the range of gyrations to provide a VMA ratio of 1.0 goes from a low 60 to a high of 87 gyrations. Further examination of this data indicates that the results appear to be grouped by maximum aggregate size. An analysis of variance was conducted on VMA ratio with respect to the aggregate type and the maximum aggregate size with a level of significance of 95 percent. The results are shown in Table 5. While not particularly robust because of the low degrees of freedom, the P-value shows that there is a significant difference between the maximum aggregate sizes, but not between the aggregate types.

Table 5. ANOVA on VMA Ratio

Source	Degrees of Freedom	Adjusted Sum of Squares	F	P
Aggregate Type	2	21.33	0.17	0.853
Maximum Aggregate Size	1	2053.5	33.12	0.029
Error	2	124		
Total	5			

To further examine the influence of maximum aggregate size on the relationship between VMA ratio and gyrations, separate plots were made for each maximum aggregate size. Figures 9 and 10 show the VMA ratio plots for the 9.5 mm MAS mixes and for the 19.0 mm MAS mixes respectively. From Figure 8, it is evident that, on average, 88 gyrations provide the same VMA as the 9.5 mm MAS Marshall mix designs. And for 19.0 mm MAS mixes, Figure 9 shows that, on average, 58 gyrations provide equivalent VMA as Marshall mix designs.

Plots of VMA ratio for the different aggregate types are shown in Figures 11, 12 and 13. The difference between the 19.0 mm and the 9.5 mm mixtures as is also evident in these plots. The cause of the difference between 9.5 mm MAS and 19.0 mm MAS is believed to be due to the boundary effect of compacting the SMA mixtures in the four-inch Marshall molds. Hypothetically, the mold size would have a greater effect on mixtures with larger aggregate particles (e.g. 19.0 mm) than mixtures with smaller maximum aggregate sizes (e.g. 9.5 mm). Because of the mold boundary interference, the coarse aggregates for larger size MAS mixtures are not able to be reoriented near the specimen surfaces, and the total VMA is higher than expected. This effect is more pronounced in the smaller Marshall molds compared to the SGC molds. Thus, the VMA ratio (SGC VMA/Marshall VMA) would be lower for the 19.0 mm MAS than for the 9.5 mm MAS.

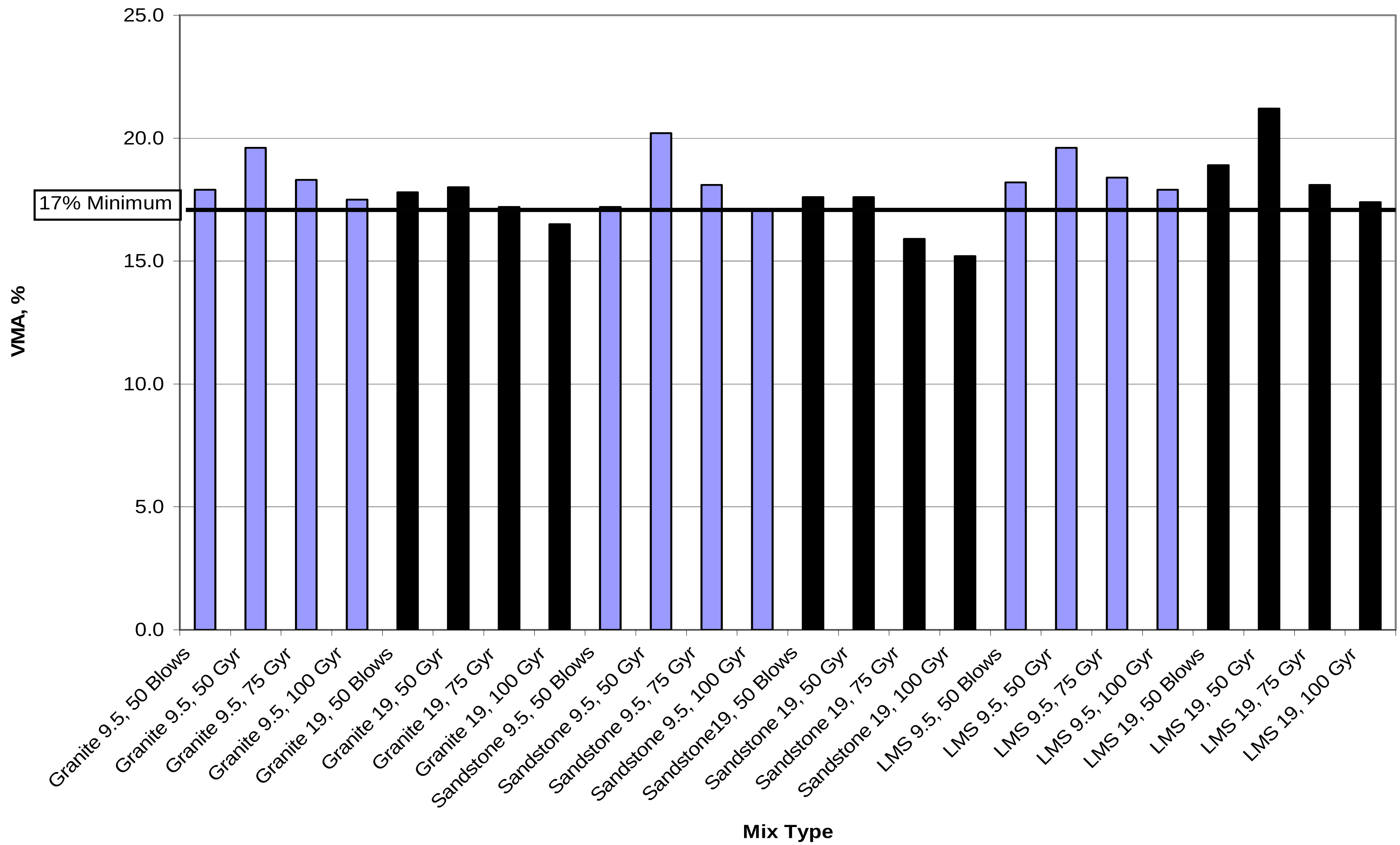

Figure 7. VMA of Laboratory Prepared Samples

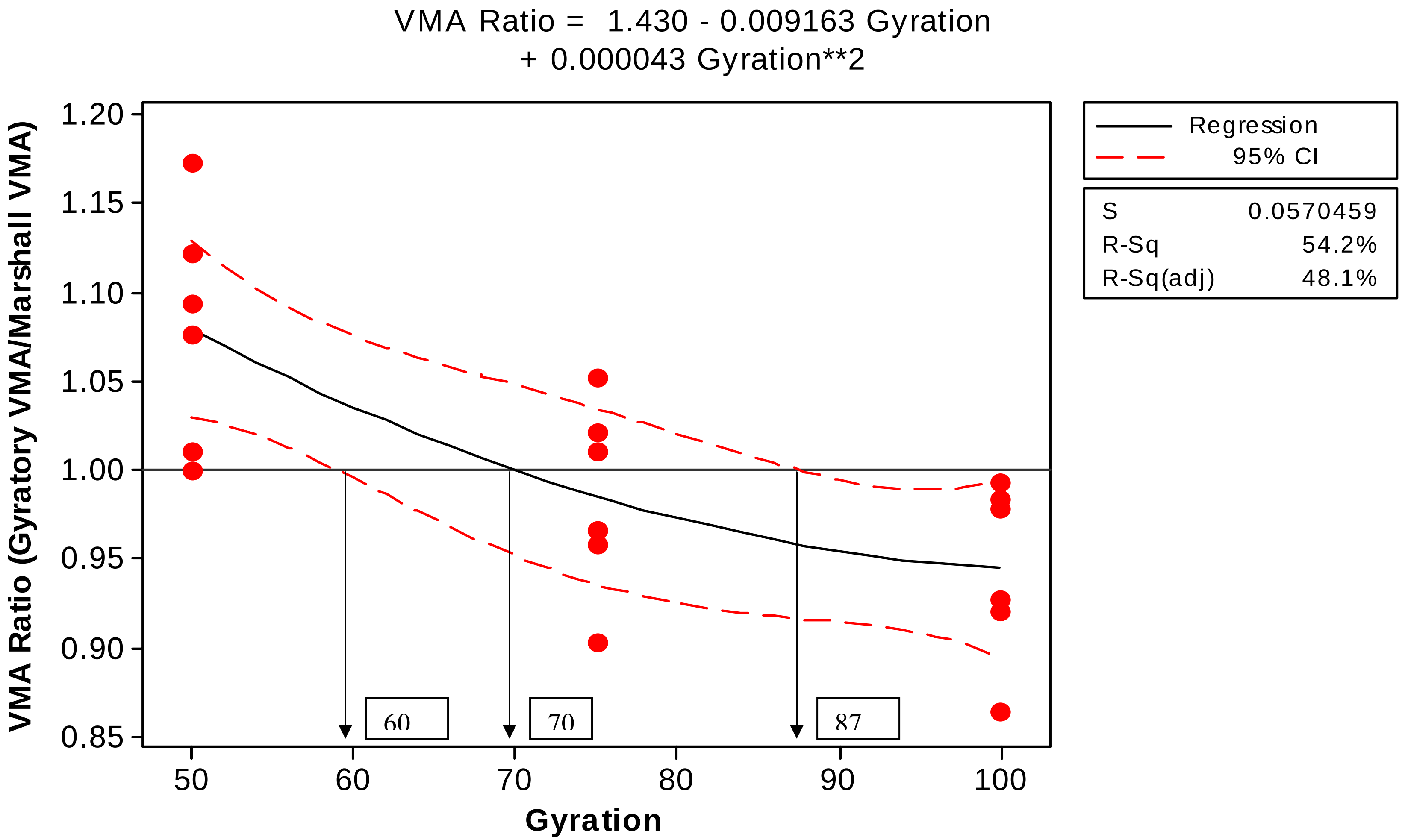

Figure 8. SGC/Marshall VMA Ratio, All Mixes

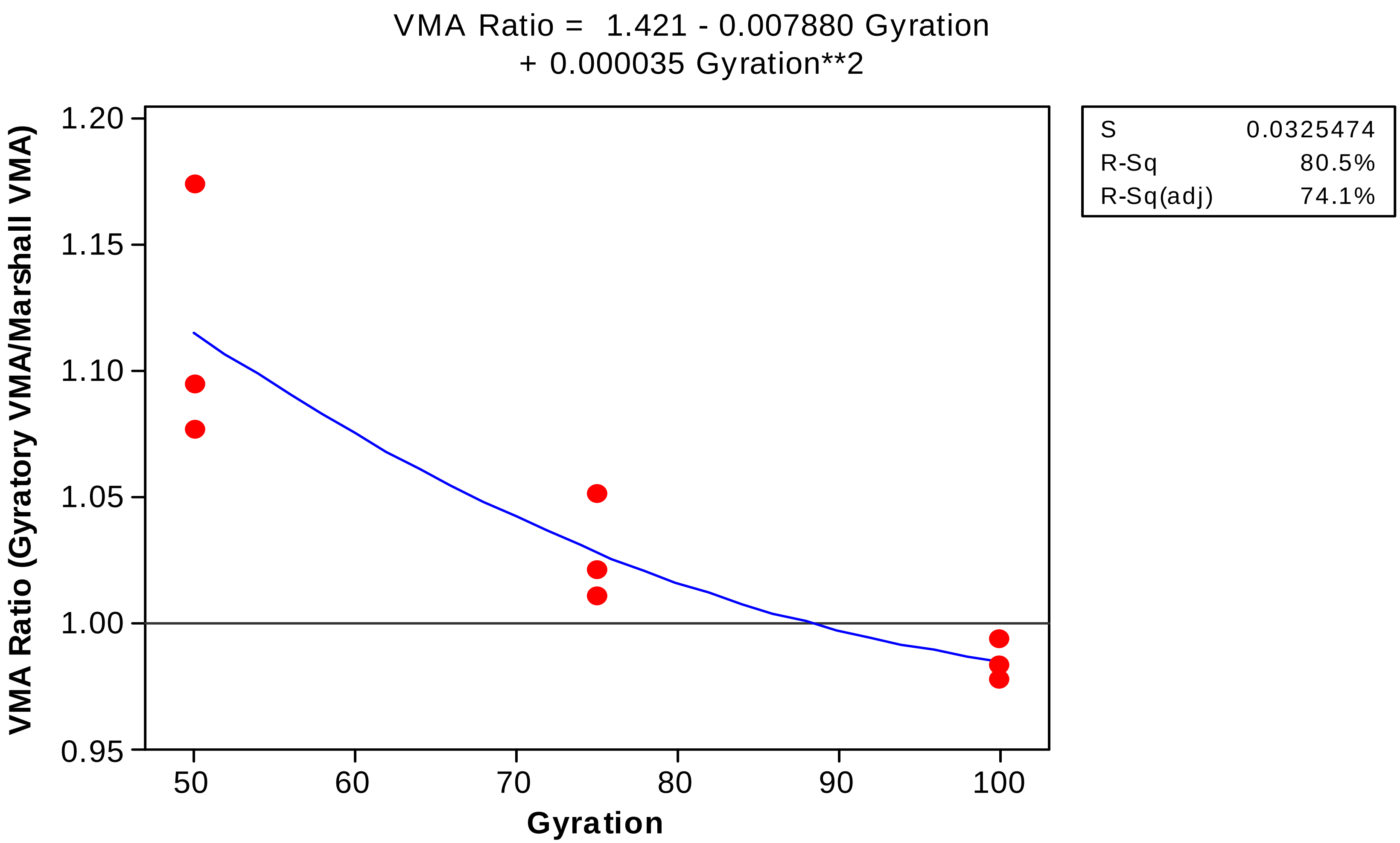

Figure 9. SGC/Marshall VMA Ratio, 9.5 mm MAS Mixes

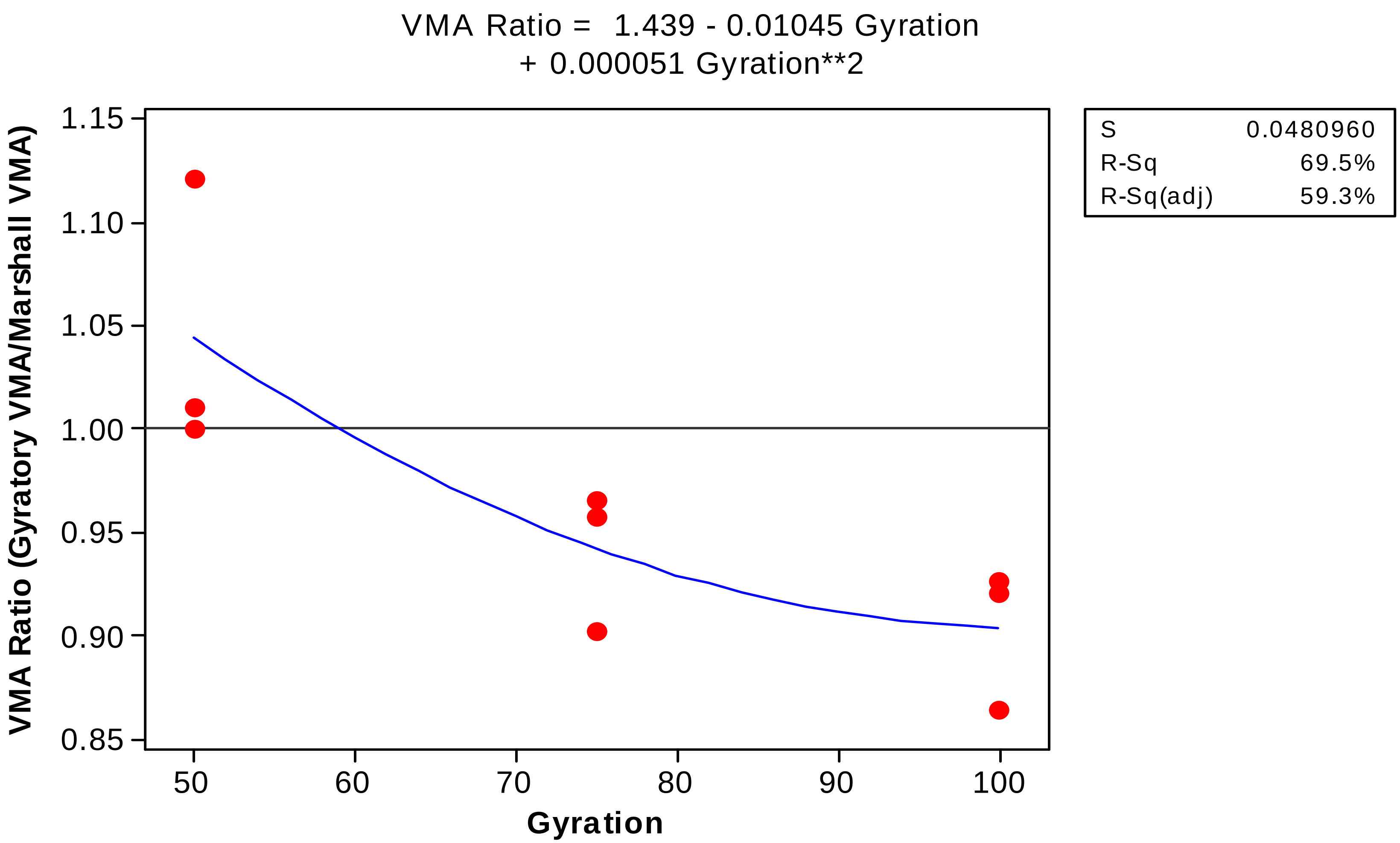

Figure 10. SGC/Marshall VMA Ratio, 19.0 mm MAS Mixes

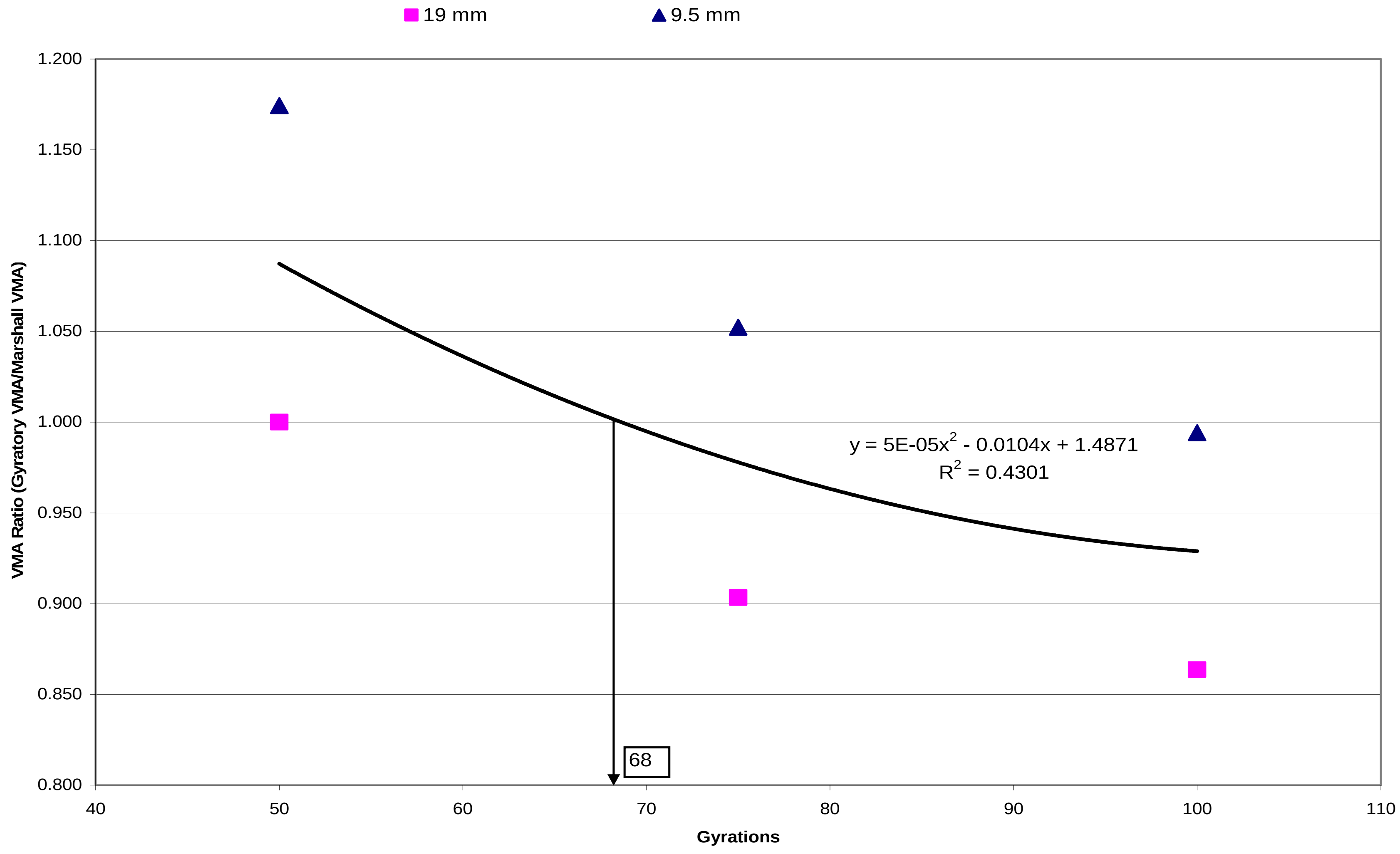

Figure 11. SGC/Marshall VMA Ratio, Sandstone Mixes

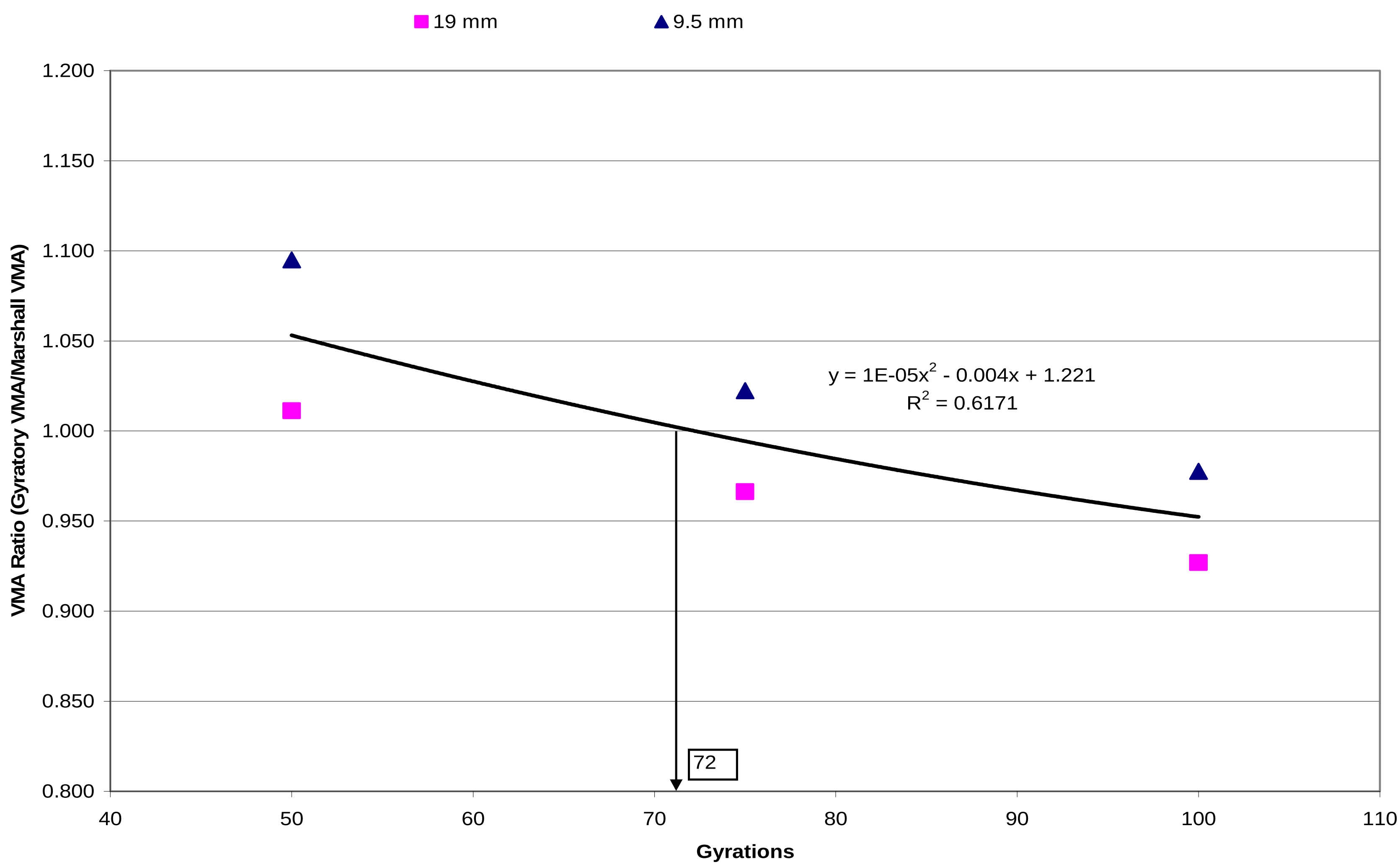

Figure 12. SGC/Marshall VMA Ratio, Granite Mixes

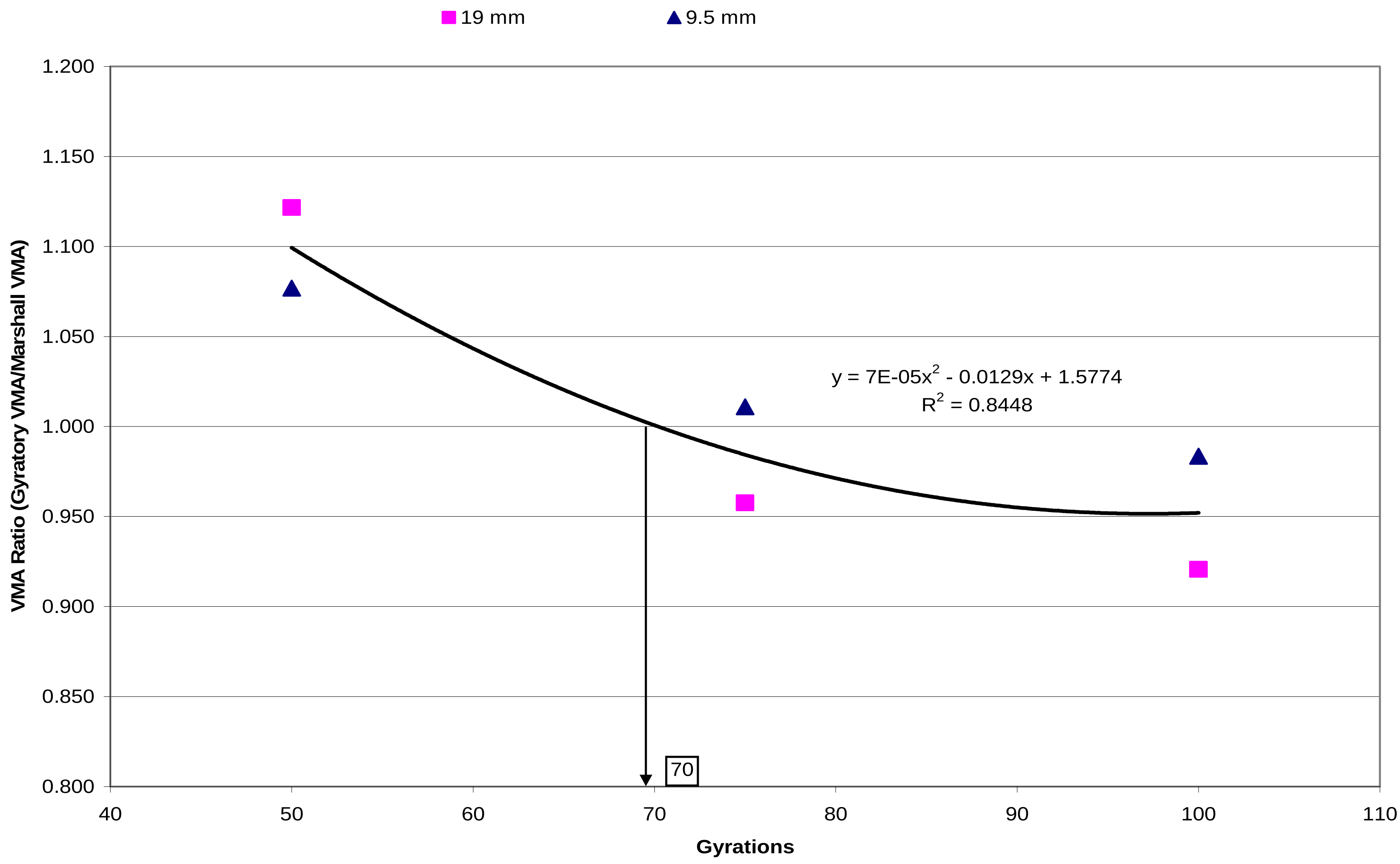

Figure 13. SGC/Marshall VMA Ratio, Limestone Mixes

APA Testing on Laboratory Mix Designs

Each of the SGC mix designs was tested in the APA to examine their rutting susceptibility. This test is intended to provide an indication of how the mixtures would perform with regard to rutting under traffic loading. Results of the APA testing are shown in Table 6.

Table 6. Rut Depths (mm) from APA Tests

	Sample Number						
	1	2	3	4	5	6	Average
Granite 9.5, 50 Gyr	4.5	4.0	4.0	3.8	3.6	2.4	3.7
Granite 9.5, 75 Gyr	5.7	5.3	4.5	3.4	2.9	*	4.3
Granite 9.5, 100 Gyr	3.1	3.0	2.3	1.9	1.8	1.8	2.3
Granite 19, 50 Gyr	6.1	5.5	4.2	3.9	2.3	*	4.4
Granite 19, 75 Gyr	5.4	4.7	4.5	3.6	2.8	2.6	4.0
Granite 19, 100 Gyr	3.8	3.0	2.8	2.6	2.4	1.4	2.7
Sandstone 9.5, 50 Gyr	5.3	5.2	4.4	3.7	2.5	2.3	3.9
Sandstone 9.5, 75 Gyr	3.4	2.8	2.7	2.2	1.7	1.4	2.4
Sandstone 9.5, 100 Gyr	4.6	4.3	3.2	2.7	2.4	*	3.5
Sandstone 19, 50 Gyr	7.6	7.0	5.4	5.3	4.7	4.1	5.7
Sandstone 19, 75 Gyr	6.7	6.6	3.7	3.5	3.4	3.3	4.5
Sandstone 19, 100 Gyr	3.1	2.8	2.7	2.6	2.3	2.2	2.6
LMS 9.5, 50 Gyr	7.7	7.2	7.0	6.3	3.9	3.6	5.9
LMS 9.5, 75 Gyr	5.7	5.0	5.0	4.9	4.2	3.5	4.7
LMS 9.5, 100 Gyr	5.1	5.0	4.8	4.3	3.9	3.4	4.4
LMS 19, 50 Gyr	7.3	6.3	**	**	6.2	5.5	6.3
LMS 19, 75 Gyr	4.4	4.3	3.3	2.4	1.9	1.3	2.9
LMS 19, 100 Gyr	5.6	5.6	3.8	3.5	2.4	1.0	3.7

* Outlier (2 mm from average rule)
**The center wheel malfunctioned on these tests

Box plots of the APA results are shown in Figure 14. Box plots allow for visual comparison of results by showing averages and variations for each test. The average for each test is shown as a circle with cross-hairs. The box represents the center 50 percent of the distribution estimated from the data. The "whiskers" represent the actual range of the data. For each aggregate type/MAS, the expected trend for these results is to have greater rut depths for mix designs with fewer gyrations since these mixes have higher asphalt contents. Most of the mixes follow this trend, but some do not.

ALDOT's specification requires APA rut depths of 4.5 mm or less using the test conditions of 100 lbs wheel load and 100 lbs of hose pressure. Utilizing the relationship shown in Section 3, a rut depth of 4.5 mm for 100 lbs/100 psi is equal to 5.9 mm for 120 lbs/120 psi. Only two of the eighteen mix designs tested failed to meet the 5.9 mm rutting criteria. These two mix designs were both 50 gyration limestone mixtures. Both of the mixtures that failed the rut depth criteria also had very high VMA, above 19.5

percent. However, high VMA by itself is not a clear indicator of rutting potential. Two other mix designs with the other aggregate types also had high VMA (greater than 19.5 percent) but had good result in the APA rutting test. Another mixture near the 5.9 mm limit for the APA test was the sandstone 19.0 mm mix design at 50 gyrations. Since three of the six aggregate/MAS combinations had high rut depths when designed using 50 gyrations, it raises concern about using 50 gyrations for SMA mix design.

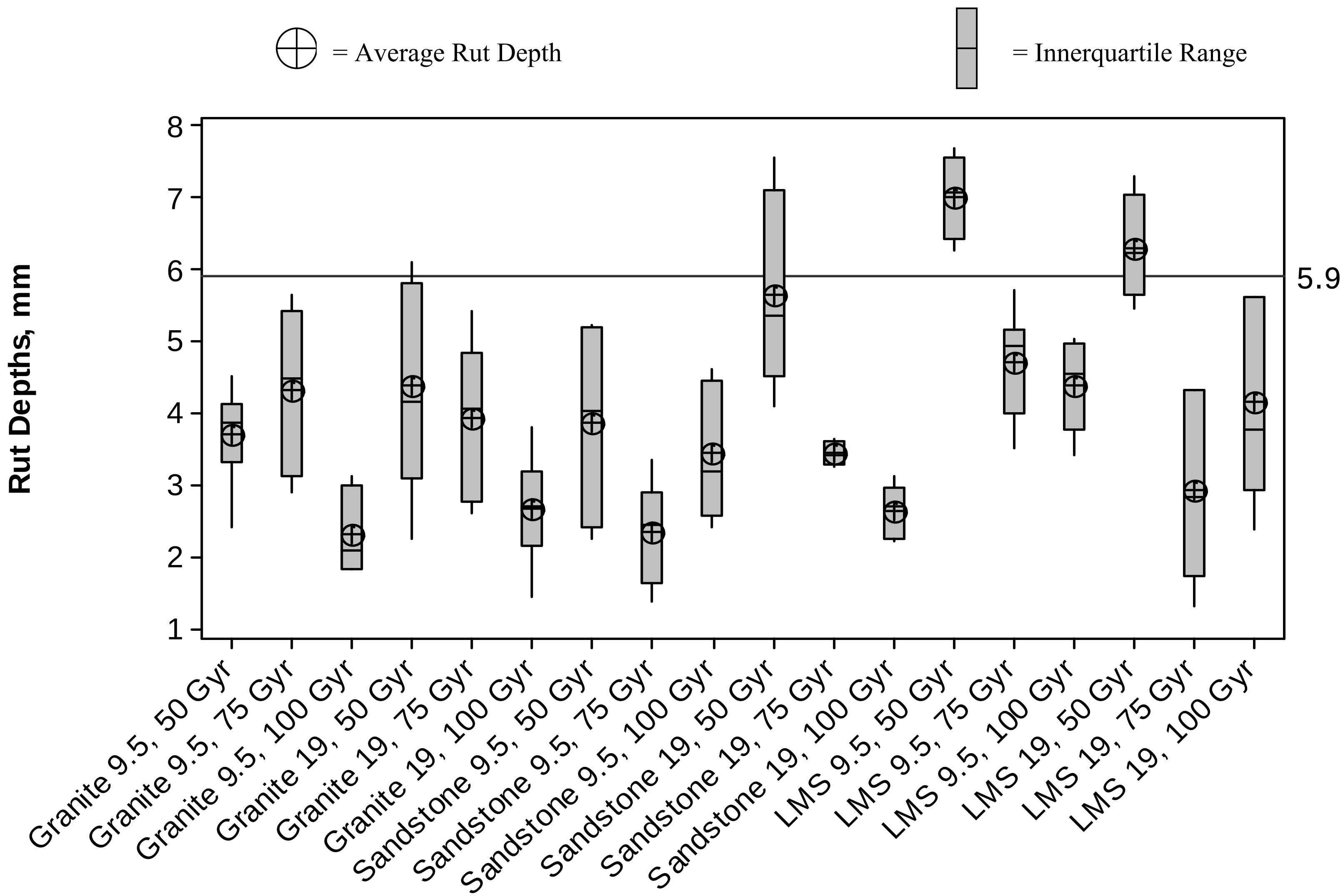

Figure 14. Boxplot of Rut Depths from Laboratory Designed Samples

Aggregate Breakdown for Laboratory Mix Designs

Aggregate breakdown during laboratory compaction was also evaluated to determine the number of gyrations that would provide similar results to the Marshall hammer. For this analysis, aggregate breakdown was calculated as the change in percent passing on two sieves: the breakpoint sieve and the 0.075 mm sieve. The breakpoint sieve is the sieve size that defines a break in the aggregate gradation between the fine aggregate and the coarse aggregate. The breakpoint sieve is dependent on the maximum aggregate size of the SMA. For SMA mixes in Alabama, the breakpoint sieves are specified by ALDOT-395 and are shown in Table 7. It is important for SMA mix designs that the percentage of aggregate passing the breakpoint sieve be limited to assure stone-on-stone contact between coarse aggregate particles.

Table 7. Breakpoint Sieve Designations per ALDOT 395

Maximum Aggregate Size	Nominal Aggregate Size	Break Point Sieve
1 1/2" (37.5mm)	1" (25mm)	#4 (4.75mm)
1" (25mm)	3/4" (19mm)	#4 (4.75mm)
3/4" (19mm)	1/2" (12.5mm)	#4 (4.75mm)
1/2" (12.5mm)	3/8" (9.5mm)	#8 (2.36mm)
3/8" (9.5mm)	#4 (4.75mm)	#16 (1.18mm)

Results of the aggregate breakdown for the laboratory designed mixes are shown in Table 8. The aggregate breakdown on the breakpoint sieve ranged from 1.7 to 8.9 percent. The change in percent passing the 0.075 mm (No. 200) sieve for the compacted samples ranged from -0.6 to 2.0 percent.

Aggregate breakdown for the 50, 75, and 100 gyration mix designs was similar with a trend of slightly more breakdown as gyrations increase. The percent passing the break point sieve for the 50 blow Marshall mix designs was similar to but slightly more than the gyratory compacted samples for each of the 9.5mm MAS mixes and for the 19.0 mm MAS granite mixture. However, for the 19.0 mm MAS limestone, the 50 blow Marshall samples have substantially more material passing the break point sieve than do the gyratory samples. This increased degradation could indicate that larger MAS mixes are more likely to experience excessive aggregate breakdown by the Marshall method than are finer MAS mixes. This is consistent with the observation by Brown and Haddock that the Marshall hammer tends to excessively degrade the coarse aggregate fraction (*24*).

Some aggregate breakdown is expected. "Excessive" breakdown during laboratory compaction is considered to be breakdown that significantly exceeds the breakdown which occurs during placement and compaction on the roadway. Since these mixes were not placed in the field, it is not known which compaction method would give similar breakdown as that seen in the field.

The change in percent passing the 0.075 mm sieve is also shown in Table 8. The maximum difference can be seen in the limestone 19.0 mm samples. The 50 blow

Marshall and the 100 gyration sample experience similar change with 1.9 and 2.0 percent respectively. Several of the results appear as a negative number which indicates the percent passing the 0.075 mm sieve for the compacted samples was less than the percent passing the 0.075 mm sieve for the uncompacted samples. This occurrence is due to the inherent variability of the gradation test. The test method AASHTO T 27, *Sieve Analysis of Fine and Coarse Aggregates,* allows a range between two results of 1.1 percent for a single operator with between two and ten percent of the fine aggregate material passing any given sieve, and a range of 1.0 percent for a single operator with between 10 and 15 percent of the fine aggregate material passing any given sieve (*10*). The 19.0 mm MAS mixtures have between two and ten percent passing the 0.075 mm sieve and the 9.5 mm MAS mixtures have between ten and fifteen percent passing the 0.075 mm sieve. Therefore, variation on the 0.075 mm sieve of 1.0 to 1.1 percent is considered within testing precision by AASHTO T 27. While the percent passing the 0.075 mm sieve is critical, the differences shown here are within reasonable tolerances. There are no apparent consistent trends regarding breakdown on the 0.075 sieve for the Marshall mix designs compared to the SGC mix designs.

Table 8. Breakdown Analysis Test Results for Laboratory Samples

Aggregate/MAS/ Compaction	Sample 1 % Passing Breakpoint Sieve	Sample 1 % Passing #200	Sample 2 % Passing Breakpoint Sieve	Sample 2 % Passing #200	Average % Passing Breakpoint Sieve	Average % Passing #200	Breakdown on Breakpoint Sieve	Breakdown on %Passing #200
Granite 9.5, 50 Blows	28.6	10.8	30.7	13.2	29.7	12.0	6.5	0.8
Granite 9.5, 50	27.8	12.0	27.5	11.2	27.7	11.6	4.5	0.4
Granite 9.5, 75	28.0	12.4	28.7	12.5	28.4	12.5	5.2	1.2
Granite 9.5, 100	29.1	12.5	28.9	12.5	29.0	12.5	5.8	1.3
Actual Gradation	23.2	11.3	23.2	11.2	23.2	11.3	N/A	N/A
Granite 19, 50 Blows	28.9	8.5	29.9	10.3	29.4	9.4	8.9	0.9
Granite 19, 50	27.6	10.0	28.5	9.6	28.1	9.8	7.6	1.3
Granite 19, 75	28.4	9.6	27.1	9.4	27.8	9.5	7.3	1.0
Granite 19, 100	29.1	10.2	27.7	9.7	28.4	10.0	7.9	1.5
Actual Gradation	20.4	8.5	20.5	8.5	20.5	8.5	N/A	N/A
Sandstone 9.5, 50 Blows	29.4	12.8	30.0	13.3	29.7	13.1	4.3	0.3
Sandstone 9.5, 50	28.0	12.4	28.2	12.4	28.1	12.4	2.7	-0.4
Sandstone 9.5, 75	28.6	12.1	28.5	12.5	28.6	12.3	3.2	-0.4
Sandstone 9.5, 100	28.7	12.3	28.1	12.0	28.4	12.2	3.0	-0.6
Actual Gradation	25.4	12.7	25.4	12.8	25.4	12.8	N/A	N/A
LMS 9.5, 50 Blows	24.3	9.7	23.2	8.5	23.8	9.1	3.4	1.3
LMS 9.5, 50	22.1	8.2	22.0	8.2	22.1	8.2	1.7	0.4
LMS 9.5, 75	23.2	9.0	22.7	8.5	23.0	8.8	2.6	0.9
LMS 9.5, 100	22.7	8.5	23.0	8.8	22.9	8.7	2.5	0.8
Actual Gradation	20.4	7.8	20.4	7.9	20.4	7.9	N/A	N/A
LMS 19, 50 Blows	27.9	10.3	27.5	9.0	27.7	9.7	7.6	1.9
LMS 19, 50	23.5	8.8	20.6	7.6	22.1	8.2	1.9	0.4
LMS 19, 75	23.6	9.7	23.0	8.6	23.3	9.2	3.2	1.4
LMS 19, 100	23.8	10.0	23.8	9.5	23.8	9.8	3.7	2.0
Actual Gradation	20.1	7.5	20.2	8.1	20.2	7.8	N/A	N/A

*Sandstone 19.0 mm samples were not tested.

An analysis of variance was conducted for the relationship between aggregate breakdown, compactor type (Marshall and SGC), and mix type with a level of significance of 95 percent. For this analysis, all of the gyratory compaction levels were grouped together as one type, SGC. The results are shown in Table 9. The P-Value indicates that there is a significant difference between the breakdown of the aggregate between the Marshall and the SGC and within the aggregate types. The F-value indicates that the aggregate type influences the aggregate breakdown more than the compactor type. This is because softer aggregates will breakdown more readily than harder aggregates no matter what the compaction type.

Table 9. ANOVA of Breakdown on Breakpoint Sieve for Laboratory Designed Samples

Source	Degrees of Freedom	Adjusted Sum of Squares	F	P
Compaction	1	27.705	29.84	0.000
Aggregate	4	240.253	64.70	0.000
Error	30	27.852		
Total	35			

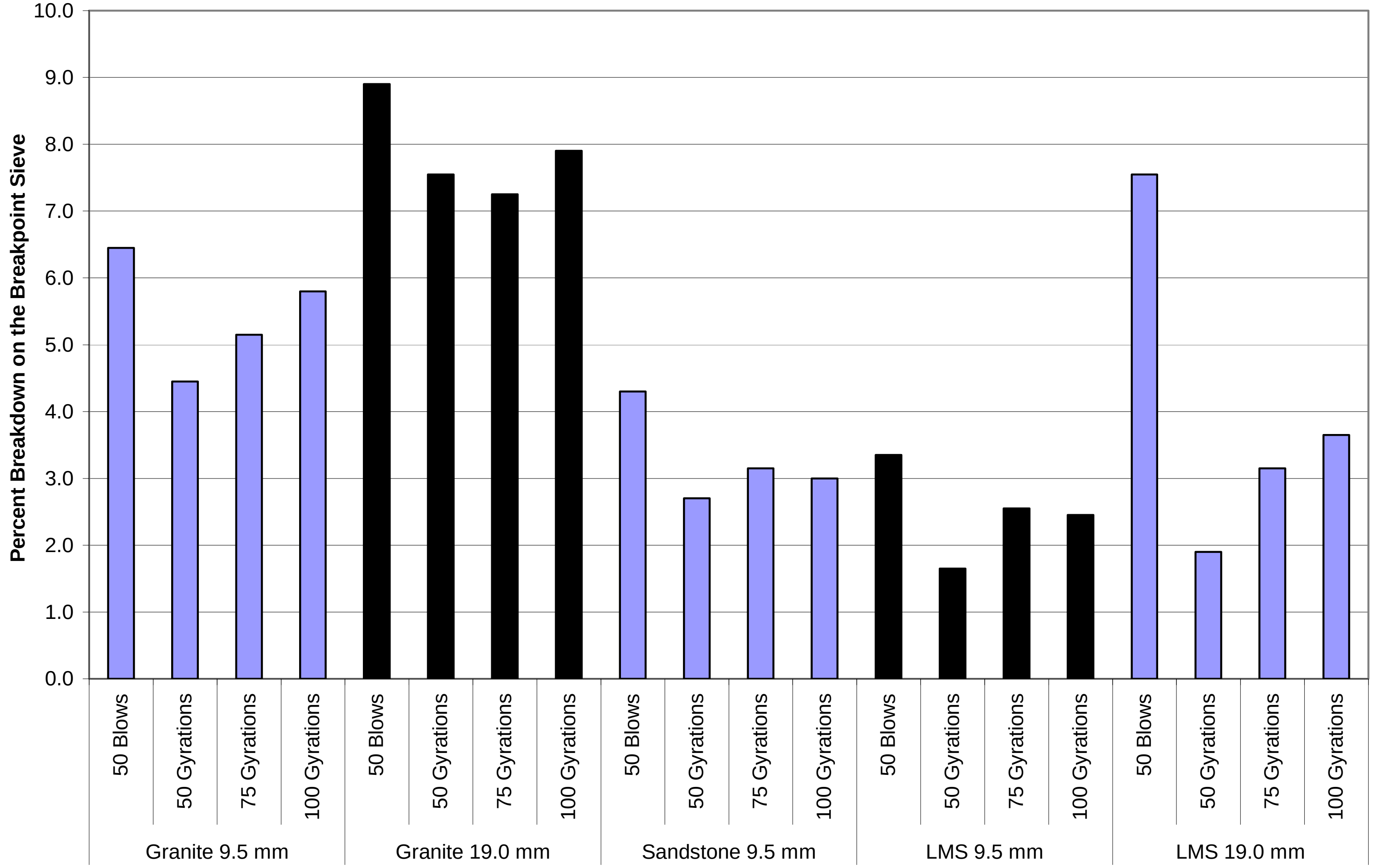

Figure 15. Aggregate Breakdown on the Breakpoint Sieve for Laboratory Designed Mixes

Locking Point for Laboratory Mix Designs

The Locking Point analysis for the laboratory mix designs is based on the data from the 75 and 100 gyration samples. The 50 gyration samples were not used because the ALDOT specification does not allow for adjusting the design gyrations below 60. Although the ALDOT Locking Point specification does not permit the Locking Point gyrations to be reduced below 60, for this analysis, all Locking Point data was included in the analysis to better understand the distribution of the results.

Table 10 shows the Locking Point for each combination of aggregate, MAS, and gyration level for the laboratory prepared samples using the ALDOT definition. Figure 16 shows a histogram of the Locking Point gyrations. The Locking Point data appears normally distributed. The range of the Locking Point for the laboratory compacted samples is 45 to 78 gyrations with an average of 63 gyrations. This is reasonably close to the 70 gyrations needed to provide a VMA equivalent to that of a 50 blow Marshall design. Based on the hypothesis that Locking Point indicates the number of gyrations when good stone-on-stone contact has been achieved and that further gyrations may only degrade the aggregate, the value of 70 gyrations for SMA mix design would seem appropriate.

Table 10. Locking Point for Laboratory Designed Samples

	Locking Point						
Aggregate/MAS/ Compaction Level	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
Granite 9.5 mm, 75	59*	53*	45*	46*	51*	55*	**52***
Granite 9.5 mm, 100	57*	52*	59*	56*	55*	57*	**56***
Granite 19 mm, 75	67	75	71	67	66	71	**70**
Granite 19 mm, 100	64	71	72	65	68	71	**69**
Sandstone 9.5 mm, 75	62	62	63	58	67	62	**62**
Sandstone 9.5 mm, 100	64	56	60	63	68	61	**62**
Sandstone 19 mm, 75	60	57*	61	59*	58*	48*	**57***
Sandstone 19 mm, 100	68	66	65	63	61	54*	**63**
LMS 9.5 mm, 75	56*	64	65	56*	66	56*	**61**
LMS 9.5 mm, 100	61	65	63	55	62	63	**62**
LMS 19 mm, 75	56*	75	68	61	62	64	**64**
LMS 19 mm, 100	78	76	71	76	69	75	**74**
						Average All	**63**

*According to ALDOT-413, the lowest allowable compactive effort that can be used with the Locking Point procedure is 60 gyrations.

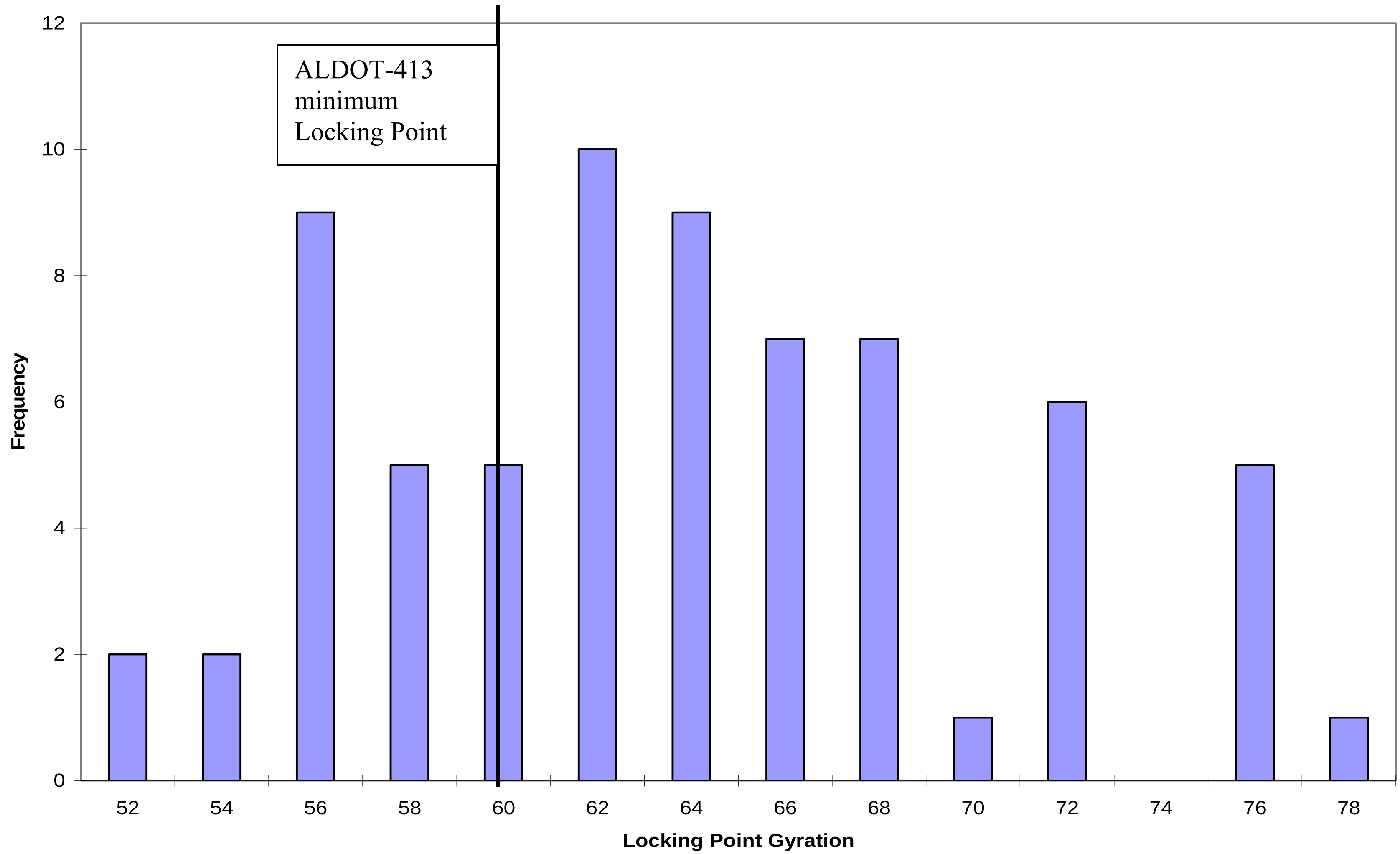

Figure 16. Histogram of Locking Points for Laboratory Designed Mixes

Field Verification of N_{design} Level

Four SMA projects in Alabama were selected for the field validation phase. The mix design sheets for each of these projects are provided in the appendix. Table 11 shows the maximum aggregate sizes and the component materials for each of the projects. Table 12 shows selected coarse aggregate data from the ALDOT approved materials source list. The first two projects had the same contractor and were from the same part of the state and therefore used the same aggregates.

Table 11. Mix Components for the Field Projects

	MAS	Component	Percentage
Project 1	19.0	Limestone	63
		Slag	21
		Fly Ash	6
		RAP	10
Project 2	12.5	Limestone	64
		Slag	21
		Fly Ash	5
		RAP	10
Project 3	12.5	Quartzite	44
		Limestone	31
		Granite Screenings	8
		Fly Ash	7
		RAP	10
Project 4	12.5	Limestone	72
		Granite	21
		Baghouse Fines	1
		Fly Ash	6

Table 12. Coarse Aggregate Properties for the Field Sampled SMA*

	Aggregate	Bulk Specific Gravity	LA Abrasion, %
Project 1	Steel Slag	3.625	14
	Limestone	2.708	26
Project 2	Steel Slag	3.625	14
	Limestone	2.708	26
Project 3	Limestone	2.744	22
	Quartzite	2.519	21
Project 4	Limestone	2.809	30
	Granite	2.681	34

* data from ALDOT approved materials source list (*25*)

Samples of the plant produced SMA from each project were taken from four consecutive lots in order to include typical material variability in the field phase. The collected samples from each lot were compacted to 50 blows with the Marshall hammer and 50, 75, and 100 gyrations with the SGC. The test results for the field samples are shown in Tables 13 to 16.

The densities achieved in the Marshall compacted samples were compared to the gyratory compacted samples. The bulk specific gravity of the mix (G_{mb}) ratio was examined for this comparison. The G_{mb} ratio was calculated by taking the average G_{mb} value for the gyratory samples and dividing it by the average G_{mb} value for the corresponding 50-blow Marshall samples. This was calculated for each of the gyration levels. Figure 17 shows the relationship of G_{mb} ratio for all of the field mixes compared to the number of gyrations.

In this graph, the first sample of Project 1 appears to be a possible outlier. Comparing this sample to the rest of the Alabama Project 1 samples, it can be seen that the air voids are 4 to 5 percent over the rest of the samples. A review of the quality control data provided by the contractor, found that the mix tested during that day had about 6 percent less passing the 0.075 mm sieve than was required by the job mix formula. Since this dust fills some of the available voids in the SMA mixture, the high air voids is attributed to the low dust content. The one-sided T-test indicates that there is a strong probability that they are outliers (ASTM E 178-94). Since there is a physical explanation for these outliers, it was decided to eliminate them from the analysis.

Another possible outlier was sample 4 from Project 3. However, the one-sided T test was not able to exclude this sample from the statistical population (ASTM E 178-94). In other words, there is little statistical evidence that this is an outlier.

Excluding the outliers from the analysis, the regression indicates that, on average, 63 gyrations will result in a G_{mb} ratio of one. In other words, 63 gyrations in the SGC will provide the same lab compacted density as the 50 blow Marshall hammer. Figure 18 examines the influence that each project has on the corresponding gyrations. Project 1 gave a corresponding gyration level of 69 gyrations, with the outliers removed from the calculations; Project 2 gave a corresponding gyration level of 60 gyrations; Project 3 gave a corresponding gyration level of 56 gyrations and Project 4 gave a corresponding gyration level of 66. Based on these four field projects, the number of equivalent gyrations ranges from 56 to 69. The differences in gyrations could be due to differences in aggregate type, gradation, maximum aggregate size, or asphalt contents of the mixtures.

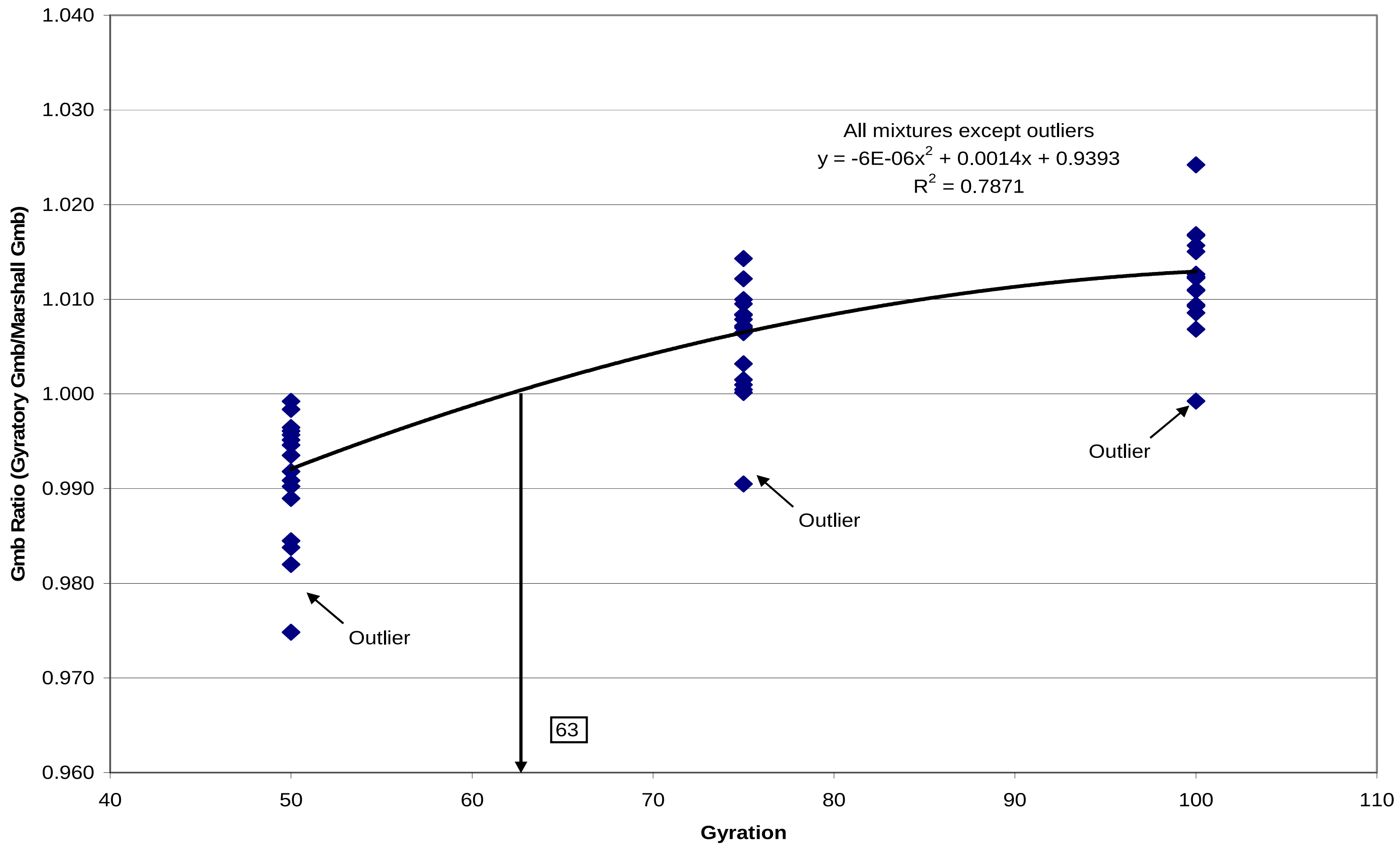

Figure 17. G_{mb} Ratio– 50 Blow Marshall Equivalent Gyrations, All Projects

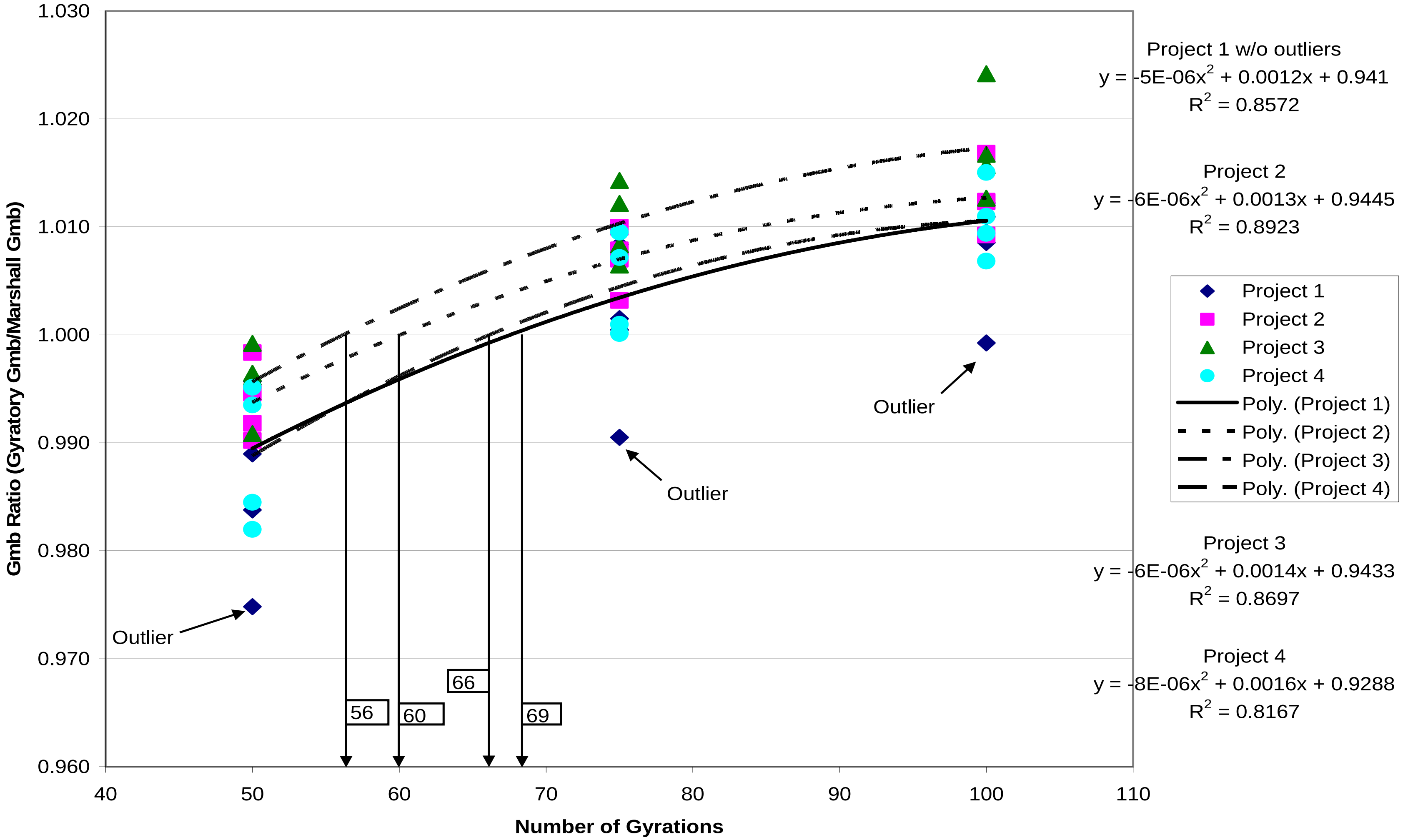

Figure 18. G_{mb} Ratio- 50 Blow Marshall Equivalent Gyrations, Individual Project

Table 13. Specific Gravity and Air Void Data for Field Project 1

Project 1, Sample 1					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.434	2.449	2.400	2.430	2.463
2	2.428	2.454	2.389	2.436	2.446
3	2.412	2.466	**	**	**
4	2.412	*	**	**	**
Average	2.422	2.456	2.395	2.433	2.455
G_{mm}	2.648	2.648	2.648	2.648	2.648
VTM	8.6	7.2	9.6	8.1	7.3
Project 1, Sample 2					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.513	2.538	2.536	2.573	2.572
2	2.508	2.545	2.535	2.563	2.577
3	2.511	2.557	**	**	**
4	2.510	*	**	**	**
Average	2.511	2.547	2.536	2.568	2.575
G_{mm}	2.636	2.636	2.636	2.636	2.636
VTM	4.8	3.4	3.8	2.6	2.3
Project 1, Sample 3					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.525	2.562	2.509	2.552	2.580
2	2.484	2.553	2.509	2.551	2.583
3	2.468	2.536	**	**	**
4	2.457	*	**	**	**
Average	2.484	2.550	2.509	2.552	2.582
G_{mm}	2.631	2.631	2.631	2.631	2.631
VTM	5.6	3.1	4.6	3.0	1.9
Project 1, Sample 4					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.438	2.562	2.515	2.552	2.571
2	2.434	2.561	2.536	2.563	2.580
3	2.429	2.538	**	**	**
4	2.439	*	**	**	**
Average	2.435	2.554	2.526	2.558	2.576
G_{mm}	2.624	2.624	2.624	2.624	2.624
VTM	7.2	2.7	3.8	2.5	1.8

* Three samples were compacted with the Marshall hammer for each Project.

** Two samples each were compacted for the 50, 75 and 100 gyration SGC samples.

Table 14. Specific Gravity and Air Void Data for Field Project 2

Project 2, Sample 1					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.465	2.535	2.492	2.541	2.553
2	2.468	2.522	2.508	2.540	2.535
3	2.430	2.505	**	**	**
4	2.442	*	**	**	**
Average	2.451	2.521	2.500	2.541	2.544
G_{mm}	2.616	2.616	2.616	2.616	2.616
VTM	6.3	3.6	4.4	2.9	2.8
Project 2, Sample 2					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.432	2.504	2.478	2.518	2.532
2	2.445	2.499	2.483	2.508	2.540
3	2.440	2.512	**	**	**
4	2.458	*	**	**	**
Average	2.444	2.505	2.481	2.513	2.536
G_{mm}	2.625	2.625	2.625	2.625	2.625
VTM	6.9	4.6	5.5	4.3	3.4
Project 2, Sample 3					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.429	2.494	2.487	2.503	2.538
2	2.463	2.497	2.480	2.526	2.540
3	2.459	2.500	**	**	**
4	2.428	*	**	**	**
Average	2.445	2.497	2.484	2.515	2.539
G_{mm}	2.618	2.618	2.618	2.618	2.618
VTM	6.6	4.6	5.1	4.0	3.0
Project 2, Sample 4					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.373	2.539	2.535	2.572	2.568
2	2.300	2.550	2.544	2.566	2.582
3	2.402	2.542	**	**	**
4	2.345	*	**	**	**
Average	2.355	2.544	2.540	2.569	2.575
G_{mm}	2.613	2.613	2.613	2.613	2.613
VTM	9.9	2.7	2.8	1.7	1.5

* Three samples were compacted with the Marshall hammer for each Project.
** Two samples each were compacted for the 50, 75 and 100 gyration SGC samples.

Table 15. Specific Gravity and Air Void Data for Field Project 3

Project 3, Sample 1					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.273	2.347	2.341	2.361	2.374
2	2.270	2.346	2.339	2.360	2.376
3	2.275	2.343	2.331	**	**
4	2.275	*	**	**	**
Average	2.273	2.345	2.337	2.361	2.375
G_{mm}	2.404	2.404	2.404	2.404	2.404
VTM	5.4	2.4	2.8	1.8	1.2
Project 3, Sample 2					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.189	2.293	2.285	2.332	2.332
2	2.204	2.310	2.301	2.328	2.349
3	2.200	2.303	**	**	**
4	2.192	*	**	**	**
Average	2.196	2.302	2.293	2.330	2.341
G_{mm}	2.413	2.413	2.413	2.413	2.413
VTM	9.0	4.6	5.0	3.4	3.0
Project 3, Sample 3					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.261	2.317	2.296	2.336	2.348
2	2.253	2.324	2.293	2.334	2.356
3	2.270	2.306	**	**	**
4	2.271	*	**	**	**
Average	2.264	2.316	2.295	2.335	2.352
G_{mm}	2.414	2.414	2.414	2.414	2.414
VTM	6.2	4.1	5.0	3.3	2.6
Project 3, Sample 4					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.240	2.319	2.321	2.354	2.375
2	2.221	2.328	2.318	2.355	2.380
3	2.236	2.317	**	**	**
4	2.240	*	**	**	**
Average	2.234	2.321	2.320	2.355	2.378
G_{mm}	2.415	2.415	2.415	2.415	2.415
VTM	7.5	3.9	4.0	2.5	1.6

* Three samples were compacted with the Marshall hammer for each Project.
** Two samples each were compacted for the 50, 75 and 100 gyration SGC samples.

Table 16. Specific Gravity and Air Void Data for Field Project 4

Project 4, Sample 1					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.393	2.416	2.398	2.434	2.456
2	2.41	2.421	2.404	2.434	2.450
3	2.398	2.413	**	**	**
4	2.392	*	**	**	**
Average	2.398	2.417	2.401	2.434	2.453
G_{mm}	2.535	2.535	2.535	2.535	2.535
VTM	5.4	4.7	5.3	4.0	3.2
Project 4, Sample 2					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.341	2.437	2.431	2.462	2.453
2	2.359	2.446	2.422	2.461	2.457
3	2.368	2.432	**	**	**
4	2.341	*	**	**	**
Average	2.352	2.438	2.4265	2.4615	2.455
G_{mm}	2.527	2.527	2.527	2.527	2.527
VTM	6.9	3.5	4.0	2.6	2.8
Project 4, Sample 3					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.321	2.433	2.386	2.421	2.452
2	2.307	2.417	2.396	2.437	2.451
3	2.353	2.436	**	**	**
4	2.345	*	**	**	**
Average	2.332	2.429	2.391	2.429	2.4515
G_{mm}	2.510	2.510	2.510	2.510	2.510
VTM	7.1	3.2	4.7	3.2	2.3
Project 4, Sample 4					
Sample	Core	50 Blow	50 Gyrations	75 Gyrations	100 Gyrations
1	2.286	2.395	2.352	2.392	2.419
2	2.305	2.391	2.355	2.406	2.427
3	2.305	2.404	**	**	**
4	2.315	*	**	**	**
Average	2.303	2.397	2.3535	2.399	2.423
G_{mm}	2.526	2.526	2.526	2.526	2.526
VTM	8.8	5.1	6.8	5.0	4.1

* Three samples were compacted with the Marshall hammer for each Project.
** Two samples each were compacted for the 50, 75 and 100 gyration SGC samples.

Table 17 shows a summary of air void data from all the field projects. The averages for all the 50 blow Marshall compacted mixes are 4.0 percent VTM with a range of 2.7 to 5.1 percent VTM. Of the sixteen samples obtained from the field projects, five of the Marshall compacted samples had air void contents outside of the 4.0 ± 1 percent tolerance for air voids during production. The average air voids for the 50, 75 and 100 gyration samples were 4.8, 3.4, and 2.8 percent, respectively. Also shown in the table are the predicted air voids for 63 and 70 gyrations. Sixty-three is the number of gyrations where the G_{mb} ratio is equal to one. Seventy gyrations is the number of gyrations where the VMA ratio is equal to one for the laboratory designed samples. The predicted air void content at 70 gyrations is 3.6 percent.

Table 17. Average and Range of Air Voids from Field Projects*

Description	Average VTM	Range
Field Cores	7.0	4.8 to 9.9
50 Blow Marshall Samples	4.0	2.7 to 5.1
50 Gyration Samples	4.8	2.8 to 6.8
75 Gyration Samples	3.4	1.7 to 5.0
100 Gyration Samples	2.8	1.2 to 4.1
Predicted Air Voids at 63 Gyrations	4.0	
Predicted Air Voids at 70 Gyrations	3.6	

* Excludes sample 1 from Project 1

Locking Point for Field SMA Mixtures

The Locking Point results for the field samples are shown in Table 18. This data is based on the ALDOT definition of Locking Point. The Locking Point for the field produced SMA samples ranges from 47 to 66 gyrations with an average of 57 gyrations.

Table 18. Field Sample Locking Point – ALDOT Definition

Project, Sample, Gyration	1	2	Avg.
AL 1-1,75 gyr	58*	49*	56
AL 1-1,100 gyr	56*	61	
AL 1-2,75 gyr	57*	54*	
AL 1-2,100 gyr	53*	56*	
AL 1-3, 75 gyr	56*	62	
AL 1-3, 100 gyr	47*	47*	
AL 1-4, 75 gyr	50*	65	
AL 1-4, 100 gyr	50*	61	
AL 2-1,75 gyr	47*	54*	57
AL 2-1,100 gyr	53*	61	
AL 2-2,75 gyr	57*	64	
AL 2-2,100 gyr	61	55*	
AL 2-3, 75 gyr	60	57*	
AL 2-3, 100 gyr	62	61	
AL 2-4, 75 gyr	57*	49*	
AL 2-4, 100 gyr	55*	54*	
AL 3-1,75 gyr	51*	56*	55
AL 3-1,100 gyr	49*	54*	
AL 3-2,75 gyr	52*	56*	
AL 3-2,100 gyr	57*	57*	
AL 3-3, 75 gyr	58*	58*	
AL 3-3, 100 gyr	59*	56*	
AL 3-4, 75 gyr	54*	49*	
AL 3-4, 100 gyr	55*	51*	
AL 4-1,75 gyr	61	61	60
AL 4-1,100 gyr	54*	63	
AL 4-2,75 gyr	55*	56*	
AL 4-2,100 gyr	63	56*	
AL 4-3, 75 gyr	62	54*	
AL 4-3, 100 gyr	64	62	
AL 4-4, 75 gyr	66	59*	
AL 4-4, 100 gyr	58*	58*	
	Average		57

*ALDOT-413 currently requires a minimum of 60 gyrations to adjust the gyration level using locking point criteria.

Aggregate Breakdown for Field SMA Mixtures

The change in percent passing (breakdown) on the breakpoint sieve and the 0.075 mm sieve for the field project samples is shown in Table 19. The breakpoint sieve for Projects 1 and 3 is the 4.75 mm (#4) sieve and for Projects 2 and 4 it is the 2.36 mm (#8) sieve. Two samples each of the Marshall, SGC and loose mix samples were tested. The field cores were also tested. The field cores were heated in an oven, cut aggregate was removed, and the remaining material was combined to yield enough material to conduct the ignition test and a washed gradation.

Aggregate breakdown is evident for each type of compacted sample: Marshall hammer samples, SGC samples, and roadway compacted samples (cores). The breakdown results are also shown in a bar chart in Figure 19.

A comparison the amount of aggregate breakdown in the cores from each of the projects shows that there is a wide range in breakdown among these projects. Project 1 had the greatest amount of breakdown (7.8 percent on the breakpoint sieve and 1.2% on the 0.075 mm sieve), and Project 3 had the least amount of breakdown (0.6% on the breakpoint sieve and no breakdown on the 0.075 mm sieve). The differences in breakdown observed for the field projects are likely due to differences in rollers and compaction techniques.

Except for Project 3, the aggregate breakdown on the breakpoint sieve for the Marshall hammer samples was similar to the breakdown in the field cores. As with the laboratory prepared mixtures, the samples compacted in the SGC had slightly less breakdown than the Marshall hammer samples. Due to the variations in aggregate breakdown observed from the roadway samples, it is not possible to determine the gyratory compaction level that best simulates compaction by rollers. However, it can be stated that samples compacted to 70 gyrations would not be expected to have more aggregate breakdown than samples compacted with 50 blows with the Marshall hammer.

Table 18. Breakdown Analysis Test Results for Field Samples

		Sample 1		Sample 2		Average			
		% Passing Breakpoint Sieve	% Passing .075 mm Sieve	% Passing Breakpoint Sieve	% Passing .075 mm Sieve	% Passing Breakpoint Sieve	% Passing .075 mm Sieve	Breakdown on Breakpoint Sieve	Breakdown on .075 mm Sieve
Project 1	50 Blow	38.9	10.3	40.5	10.9	39.7	10.6	6.8	0.1
	50 Gyrations	35.5	10.1	36.6	10.5	36.1	10.3	3.1	-0.2
	75 Gyrations	37.2	11.3	36.9	10.9	37.1	11.1	4.1	0.6
	100 Gyrations	37.9	11.4	37.0	11.1	37.5	11.3	4.5	0.8
	Cores	40.8	11.7	*	*	40.8	11.7	7.8	1.2
	Loose Sample	33.5	10.6	32.4	10.4	33.0	10.5	N/A	N/A
Project 2	50 Blow	26.4	11.0	26.9	11.1	26.7	11.1	3.2	-0.4
	50 Gyrations	25.6	11.3	25.1	10.9	25.4	11.1	1.9	-0.3
	75 Gyrations	25.5	11.1	25.5	10.9	25.5	11.0	2.0	-0.4
	100 Gyrations	25.6	10.9	26.1	11.0	25.9	11.0	2.4	-0.5
	Cores	26.0	11.2	*	*	26.0	11.2	2.5	-0.2
	Loose Sample	23.3	11.4	23.7	11.4	23.5	11.4	N/A	N/A
Project 3	50 Blow	42.7	9.6	39.2	9.5	41.0	9.6	6.4	0.5
	50 Gyrations	34.8	9.4	36.3	9.4	35.6	9.4	1.0	0.4
	75 Gyrations	38.7	10.1	35.7	8.4	37.2	9.3	2.6	0.2
	100 Gyrations	39.5	9.5	38.7	9.9	39.1	9.7	4.5	0.6
	Cores	35.2	9.1	*	*	35.2	9.1	0.6	0.0
	Loose Sample	32.9	8.9	36.3	9.2	34.6	9.1	N/A	N/A
Project 4	50 Blow	27.6	8.8	27.3	8.9	27.5	8.9	5.5	0.7
	50 Gyrations	25.9	9.2	25.6	8.7	25.8	9.0	3.8	0.8
	75 Gyrations	26.2	8.4	27.5	9.3	26.9	8.7	4.9	0.5
	100 Gyrations	27.9	8.7	27.1	9.1	27.5	8.7	5.5	0.5
	Cores	26.2	8.8	26.7	9.5	26.5	9.2	4.5	1.0
	Loose Sample	22.6	8.7	21.3	7.6	22.0	8.2	N/A	N/A

*Due to the small size of the cores only enough material for one test was recovered

An analysis of variance (ANOVA) was conducted on the aggregate breakdown of the field samples to examine the influence of Project (Project 1, Project 2, Project 3 and Project 4) and Compaction Type, just as it was on the laboratory designed samples. The results are shown in Table 19 with a level of significance of 95 percent. The outcome is basically the same as those shown in Table 9, the ANOVA results for the laboratory sample breakdown. The low p-values show there is a significant difference between the breakdown of the aggregate between the compaction types and between the project. The F-value indicates that the compaction type influences the aggregate breakdown more than the project.

Table 19. ANOVA of Field Sample Breakdown

Source	Degrees of Freedom	Adjusted Sum of Squares	F	P
Project	3	15.9075	6.84	0.011
Compaction	3	19.7525	8.49	0.005
Error	9	6.9775		
Total	15			

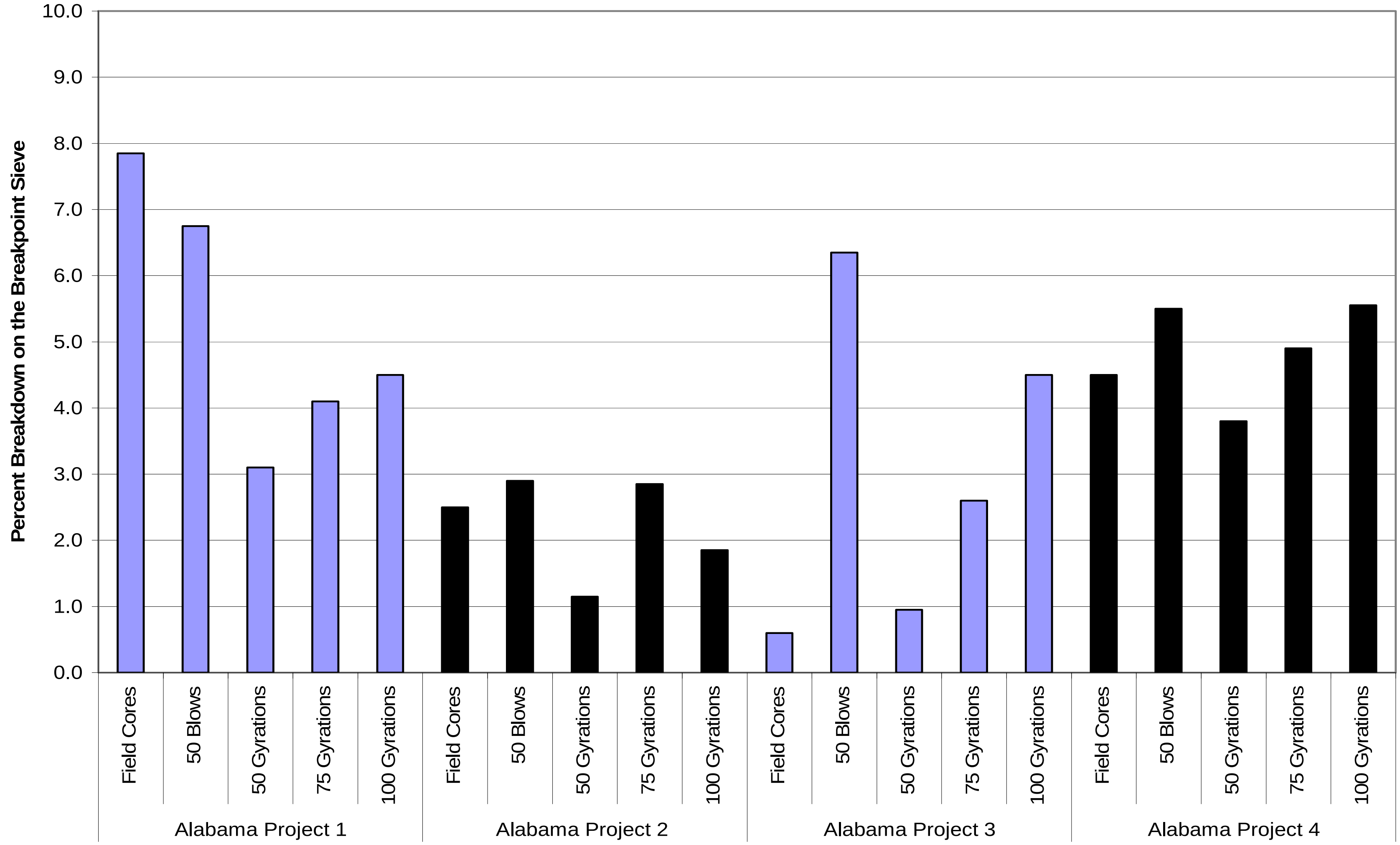

Figure 19. Percent Passing the Breakpoint Sieve for the Field Samples

APA Testing on Field SMA Mixtures

The results of the APA testing on the field samples are shown in Table 20 and Figure 20. APA tests were only performed on samples from two lots for each project. The two lots were selected to give the greatest range in quality control results. APA tests were conducted using the same testing conditions as the laboratory designed samples. All of the rut depths are low. None of the results exceeded the 5.9 mm requirement. The results show that SMA mixtures are generally very rut resistant, despite the significant quality control variations in the mixtures. The low APA rut depths measured for the field mixtures may be due partly to the fact that the mixtures had to be reheated to make the samples, which would likely have caused an increase in binder stiffness for these samples.

Tukey's statistical analysis was used to compare rut depths from the three gyration levels. In essence, the comparison is between the air void levels in the APA samples. For each project, the mixture is the same regardless of the level of compaction. Results of Tukey's analysis are shown in Table 21. The high p-values indicate that there is no statistical difference between rut depths for any of the air void levels. This is not surprising since the dependent variable, rut depth, has such a limited range.

Table 20. Field Sample Rut Depths

	Gyration Level	Rut Depth, mm	Average VTM, %
Field Project 1, Test 1 (Sample 1)	50 Gyrations	3.01	9.9
	75 Gyrations	3.09	8.1
	100 Gyrations	1.89	7.4
Field Project 1, Test 2 (Sample 2)	50 Gyrations	2.18	3.8
	75 Gyrations	1.09	2.6
	100 Gyrations	0.59	2.3
Field Project 2, Test 1 (Sample 2)	50 Gyrations	1.54	5.5
	75 Gyrations	2.09	4.3
	100 Gyrations	1.20	3.4
Field Project 2, Test 2 (Sample 4)	50 Gyrations	2.27	2.8
	75 Gyrations	1.34	1.7
	100 Gyrations	1.52	1.5
Field Project 3, Test 1 (Sample 1)	50 Gyrations	1.52	2.8
	75 Gyrations	1.29	1.8
	100 Gyrations	1.95	1.2
Field Project 3, Test 2 (Sample 2)	50 Gyrations	2.21	5.0
	75 Gyrations	2.22	3.4
	100 Gyrations	1.54	3.0
Field Project 4, Test 1 (Sample 3)	50 Gyrations	2.32	4.7
	75 Gyrations	1.74	3.2
	100 Gyrations	1.14	2.3
Field Project 4, Test 2 (Sample 4)	50 Gyrations	3.02	6.8
	75 Gyrations	2.21	5.0
	100 Gyrations	3.04	4.1

Table 21. Tukey's Simultaneous Tests Between Levels of Gyration

50 Gyrations Subtracted from 75 and 100				
Gyration	Difference of Means	SE of Means	T-Value	Adjusted P-Value
75	-0.2683	0.3548	-0.756	0.7346
100	-0.6733	0.3548	-1.898	0.1736

75 Gyrations Subtracted from 100				
Gyration	Difference of Means	SE of Means	T-Value	Adjusted P-Value
100	-0.405	0.3548	-1.141	0.5045

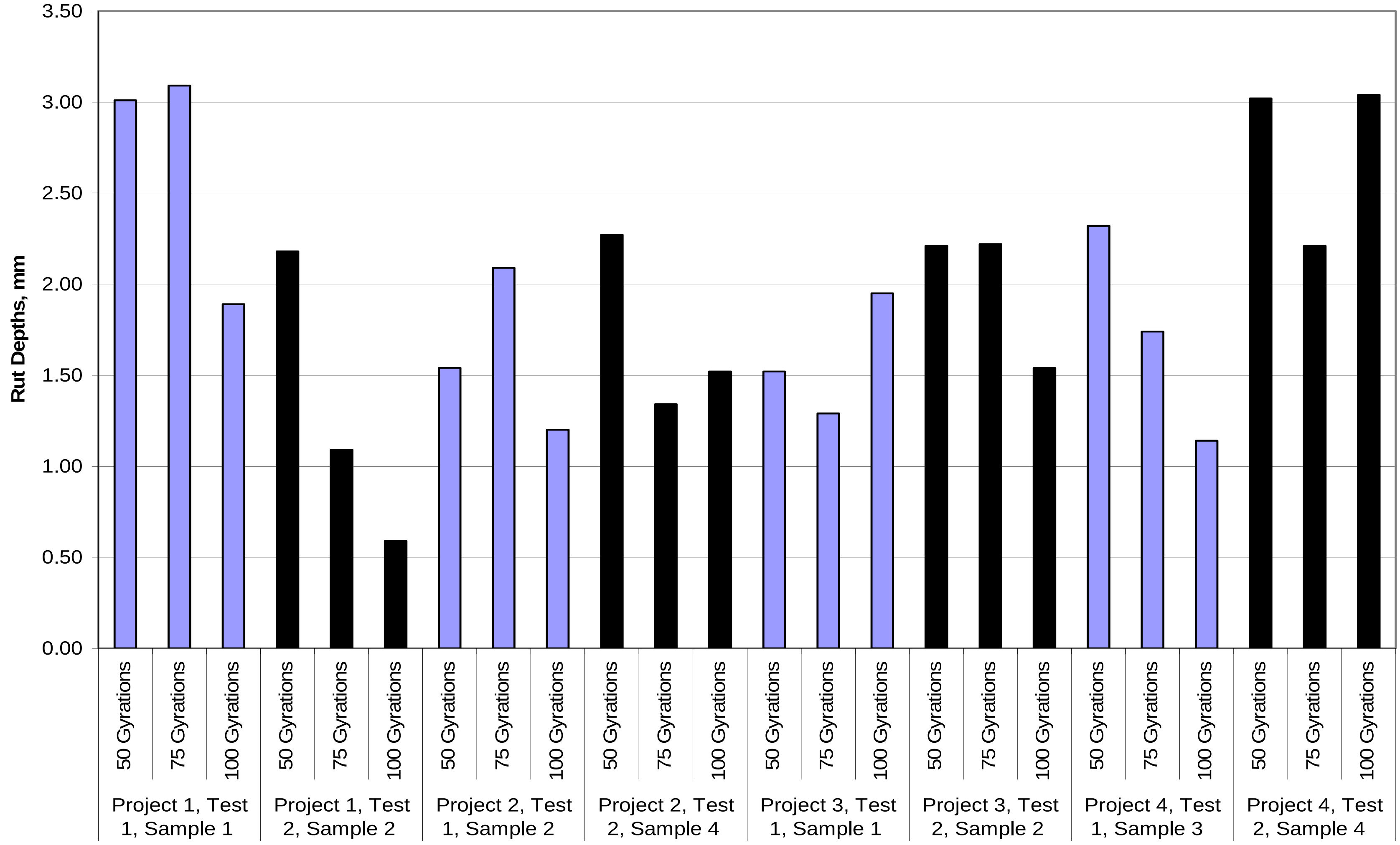

Figure 20. Field Sample Rut Depths

Discussion of Results

The first phase of this project examined how to determine the number of gyrations with the SGC (N_{design}) to give the same results as SMA mix designs conducted with the Marshall hammer. SMA mix designs were first completed with the 50-blow Marshall procedure described in ALDOT-395. SMA mixtures were designed using thee types of aggregate commonly used in SMA in Alabama. Two maximum aggregate size gradations were evaluated. All of the Marshall designed SMA mixtures met the ALDOT specifications for SMA. The same gradations were then used to determine the asphalt content to achieve 4.0% air voids using three gyration levels (50, 75 and 100 gyrations) in the SGC.

It was observed that, on average, the design asphalt content of the SMA mixtures decreased about 0.85 percent from 50 to 75 gyrations, and decreased by 0.33 percent from 75 to 100 gyrations. Of the 18 SGC mix designs, three did not meet the minimum VMA requirement of 17 percent. The three SGC mixes that failed VMA were 19.0 mm maximum aggregate size mixtures. Two of these failing mix designs were 100 gyration mixtures and the other was a 75 gyration mixture.

The primary technique for comparing the SGC mix designs to the Marshall mix designs was to determine the number of gyrations that provided the same VMA as the 50 blow Marshall mix designs. Based on a regression through the combined data set using the three aggregate types and two maximum aggregate sizes, 70 gyrations was found to give the best match to the VMA from the Marshall compaction. However, a difference was evident between data from two MAS gradations. Separate regressions showed that for the 19.0 mm MAS mixes, an average of 58 gyrations provided the best match to the Marshall VMA; and for the 9.5 mm MAS mixes, an average of 88 gyrations provided the best match to Marshall VMA. It is not clear why the two MAS gradations would have different relationships between Marshall VMA and SGC VMA. Perhaps the larger MAS mixtures are influenced more by the 4-inch Marshall mold compared to small MAS mixtures. The difference between MAS gradations may also point to the need to have VMA criteria based on MAS as with Superpave mixtures.

The Locking Point concept was also explored for the SGC mix designs. Since ALDOT allows some high L.A. Abrasion aggregates to be used in SMA, the Locking Point may be helpful in avoiding excessive aggregate degradation. Using the ALDOT definition of Locking Point, the laboratory designed SMA mixtures had an average of 63 gyrations for the Locking Point. The possible effect of using the Locking Point concept to set the number of design gyrations can be estimated by calculating the change in asphalt content that would occur between 70 gyrations and 63 gyrations. As stated above, the data from this study indicates that the design asphalt content changes by an average of 0.85% between 50 and 75 gyrations. Therefore, we could expect that from 70 to 63 gyrations, the asphalt content would increase by approximately 0.85% * 7/25 = 0.24%.

APA tests on the laboratory phase mix designs were conducted to evaluate the rutting potential of the SGC mix designs. Two mixtures had APA results that failed the criteria of 5.9 mm. Both of the mixtures that failed were designed to 50 gyrations indicating that 50 gyrations may be too few gyrations for the design of SMA mixtures.

Aggregate breakdown is a key concern for SMA mix design given the critical nature of the stone on stone contact. An ANOVA test run on the breakdown in the laboratory samples used in this study showed that there is a significant difference between compaction types (when considering 50-blow Marshall versus the SGC compacted samples). The SGC samples generally had less aggregate breakdown than the Marshall samples. When less aggregate breakdown occurs in mix design samples, it will be easier to achieve VMA for any SMA gradation.

For Phase 2 of the study, which used four plant produced SMA mixtures in the evaluation of Marshall versus SGC compaction, the primary parameter used for the analysis was the ratio of compacted sample bulk specific gravities. The G_{mb} Ratio was calculated as the G_{mb} of the SGC samples divided by the G_{mb} of the Marshall samples. Regressions were performed on the G_{mb} Ratio versus the number of gyrations. This analysis yielded 63 gyrations as the average number of gyrations needed to produce an equivalent bulk density value to the Marshall hammer sample. Regressions on the individual project data yielded a range of equivalent gyrations from 56 to 69.

The Locking Point for the compacted field samples ranged from 56 to 60 gyrations with an average of 57 gyrations. However, the ALDOT Locking Point procedure does not allow the design number of gyrations to be less than 60.

Analysis of the aggregate breakdown for the plant produced mixtures showed that compaction in the SGC caused less breakdown than compaction with the Marshall hammer. As with the laboratory prepared mix designs, a trend of slightly more breakdown with increasing gyrations was evident. Significant differences in aggregate breakdown were observed for the roadway samples taken from the four projects. Due to this large variation, it was not possible to find a consistent relationship for aggregate breakdown between any laboratory compaction method and field compaction.

All of the samples made with the field mixtures performed well in the APA tests. There was no significant difference in APA rut depths found between samples of the same mixture compacted to different gyrations. The low APA rut depths for the field samples shows that SMA mixtures are very rut resistant and are not sensitive to normal variations which occur during SMA production.

When evaluating compaction of asphalt mixtures in an SGC, it is critical to consider the effect of the internal angle for the compactor. All of the SMA samples compacted with an SGC in this study were compacted with one machine, Pine AFG1A Serial Number 1193, which has had a measured internal angle of 1.23 degrees as measured with the Dynamic Angle Validator. Recently, the specification for Superpave Gyratory Compactors, AASHTO T 312, was amended to allow either external angel calibration or internal angle calibration. It is believed that using internal angle calibrations will help minimize differences in density, which can occur with different SGC's. The internal angle specified by AASHTO T-312 is 1.16±0.02°.

Prowell developed a relationship between the dynamic internal angle (DIA) and G_{mb} using a 19.0 mm nominal maximum aggregate size granite mixture. The relationship stated that for every 0.01 degree change in internal angle, there was a 0.001 change in G_{mb} (*25*).

A gyration adjustment chart was developed from the above relationship and the regression between G_{mb} Ratio and gyrations from Figure 17 (page 35). The adjustment chart is shown in Figure 21. To adjust the gyrations for the NCAT AFG1A with an internal angle of 1.23º to an internal angle of 1.16º, enter the chart from the x-axis at 1.16º and go up to intersect the line, then go left to the y-axis to determine that about four gyrations should be added to the results from the AFG1A to achieve the same density at the lower angle.

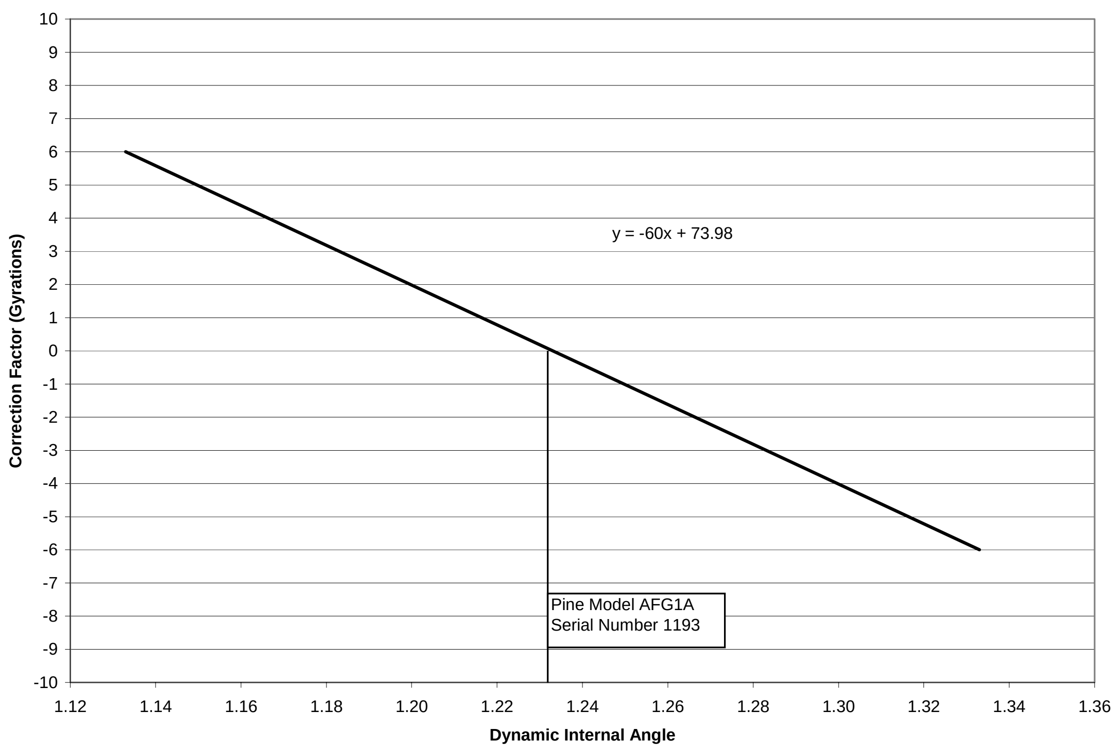

Figure 21. Dynamic Internal Angle Correction Factor Chart

Summary

The results from this study do not indicate a unique relationship between gyrations in the SGC and the 50 blow Marshall hammer. There is significant scatter in each data set and depending on which mix parameter is used for the analysis, different numbers of gyrations can be found to provide equivalency to the Marshall hammer. Key observations from this research include:

- For laboratory SMA mix designs, 70 gyrations, on average, provide the same VMA and therefore the same design asphalt content as 50 blows with the Marshall hammer.
- The relationship between specimen density and the number of gyrations is not linear, but rather a growth curve often depicted as a near linear relationship on a semi-log chart. Therefore, the change in volumetric properties is not proportional to gyrations in the range of concern.
- Locking Point analysis of the laboratory SMA mix designs indicates that the average Locking Point occurs at 63 gyrations.
- For plant produced SMA mixtures, 63 gyrations, on average, provides the same compacted density as 50 blows with the Marshall hammer.
- Less aggregate breakdown occurs with the SGC compared to 50 blows with the Marshall hammer. Slightly more aggregate breakdown occurs in the SGC compacted samples as the number of gyrations increases.
- Gyratory SMA mixtures can be successfully designed to withstand rutting at 75 gyrations. However, some SMA mix designs at 50 gyrations may have a problem with meeting the APA rutting test requirements.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

SMA mix designs using the Marshall method of specimen compaction have performed very well in Alabama. With this history of success, the purpose of this research was to change the type of compactor without changing SMA mixtures. Gyratory compaction, while not a perfect simulation to the compaction achieved in the field, has several advantages compared to the Marshall hammer. The Superpave Gyratory Compactor (SGC) has become the primary compactor type in laboratories across the state.

In the first part of this study, SMA designs were successfully performed using 50 blows from a static, flat faced, mechanical Marshall hammer. Mix designs were prepared with three aggregate types and using two maximum aggregate size gradations. These mixes were then compacted in a Pine Model AFG1A SGC with 50, 75 and 100 gyrations. The design asphalt content to yield 4.0% air voids and corresponding VMA were determined for each SGC compactive effort. These mix designs were evaluated with respect to aggregate degradation, Locking Point, and rutting in the APA test. Findings from the analysis of the laboratory mix designs are as follows:

- 70 gyrations with the SGC, on average, provided approximately the same Voids in Mineral Aggregate (VMA) as 50 blows from a Marshall hammer. Since the design air void content is fixed at 4.0%, the same VMA means that the design asphalt content is also the same.
- Using the ALDOT definition of Locking Point, the laboratory designed SMA mixtures had an average of 63 gyrations for the Locking Point.

- The SMA mix designs using 75 gyrations had good rutting resistance in the APA test. However, mix designs using 50 gyrations appears too low for SMA because of some mix failures in the APA test.
- The Superpave gyratory compactor causes less aggregate breakdown compared to 50 blows with the Marshall hammer.

In the second part of the study, testing and analysis used mixtures obtained from four SMA projects in Alabama. Each of these field mixtures had been designed with the Marshall hammer in accordance with ALDOT-395. The field SMA mixtures were compacted in the SGC at 50, 75, and 100 gyrations. Analysis was also conducted with regard to aggregate breakdown, Locking Point, and rutting resistance with the APA test. Findings from the analysis of the work with the field SMA mixtures are as follows:

- 63 gyrations with the SGC, on average, provided the same compacted density as 50 blows with the Marshall hammer.
- The Locking Point for the field mixes averaged about 57 gyrations. This is slightly below the minimum number of design gyrations allowed with the Locking Point method.
- The SGC caused less aggregate breakdown than the Marshall hammer. Significant differences were observed for the amount of aggregate breakdown from cores obtained from the four projects. Therefore, it was not possible to establish a relationship between aggregate breakdown with the laboratory compactors and aggregate breakdown due to roadway compaction.
- All of the field SMA mixtures performed well in the Asphalt Pavement Analyzer.

Considering the complete body of data, the most appropriate range of gyrations to yield the same results as with the Marshall hammer would appear to be between 63 and 70 gyrations. The center of this range is 66.5 gyrations. This range is based only on the NCAT Pine AFG1A SGC which has had the internal angle measured at 1.23 degrees. It is estimated that four additional gyrations would be required to yield the same density if the internal angle were lowered to 1.16 degrees.

Recommendation

The design number of gyrations (N_{design}) for SMA mix designs in Alabama should be 70 gyrations using a Superpave gyratory compactor calibrated to an internal angle of gyration of 1.16 ± 0.02^{o}. For SGC's calibrated to different internal angles, the design number of gyrations should be adjusted using Figure 21 on page 52.