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EFFECTS OF AGGREGATE ANGULARITY ON VMA AND RUTTING OF KDOT SUPERPAVE LEVEL 1 MIXES

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16 Abstract

With the recent introduction and acceptance of Superpave design criteria for hot mix asphalt, designers have had difficulty meeting the minimum voids in the mineral aggregate (VMA) requirements. VMA is affected by compactive effort, gradation, and aggregate angularity. This research focused on the effects of fine aggregate angularity on VMA and rutting.

Two 12.5-millimeter (mm) Superpave gradations, one coarse and one fine, were developed using 100 percent crushed limestone. Once the base line gradations were established, laboratory samples were produced with increasing natural sand percentages. The percentage of natural sand directly replaced the limestone on each sieve allowing the gradation to remain constant and the effect of fine aggregate angularity to be observed independent of gradation. The resultant VMA and fine aggregate angularity of each blend was compared.

In an effort to meet Superpave criteria, designers in Kansas have been using chat sand, a flaky fine aggregate of almost pure silica that is a byproduct of lead and zinc mining, to boost VMA. Chat sand was included in this research to further understand the effect of aggregate angularity on VMA and to investigate the effect of chat sand on rutting performance. Samples were made at various chat percentages and VMA was determined and compared to the fine aggregate angularity of the blend.

Since meeting the Superpave criteria does not ensure a stable mix, all the samples produced for VMA testing were saved and tested in an Asphalt Pavement Analyzer (APA). The effect of fine aggregate angularity of rounded and flaky fine aggregate on rutting performance was evaluated.

The results of this testing indicated that increased fine aggregate angularity results in greater VMA and decreased rutting. Chat sand was shown to be effective at increasing VMA, but increased the potential for rutting the same as the natural sand. Both mixes met Superpave gradation and voids criteria, but the rutting performance of the fine mix was superior to that of the coarse, regardless of fine aggregate angularity. Therefore, it is clear that stability testing is needed to ensure quality mixes.

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Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

With the recent introduction and acceptance of Superpave design criteria for hot mix asphalt, designers have had difficulty meeting the minimum voids in the mineral aggregate (VMA) requirements. VMA is affected by compactive effort, gradation, and aggregate angularity. This research focused on the effects of fine aggregate angularity on VMA and rutting.

Two 12.5-mm Superpave gradations, one coarse and one fine, were developed using 100% crushed limestone. Once the base line gradations were established, laboratory samples were produced with increasing natural sand percentages. The percentage of natural sand directly replaced the limestone on each sieve allowing the gradation to remain constant and the effect of fine aggregate angularity to be observed independent of gradation. The resultant VMA and fine aggregate angularity of each blend was compared.

In an effort to meet Superpave criteria, designers in Kansas have been using chat sand, a flaky fine aggregate of almost pure silica that is a byproduct of lead and zinc mining, to boost VMA. Chat sand was included in this research to further understand the effect of aggregate angularity on VMA and to investigate the effect of chat sand on rutting performance. Samples were made at various chat percentages and VMA was determined and compared to the fine aggregate angularity of the blend.

Since meeting the Superpave criteria does not ensure a stable mix, all the samples produced for VMA testing were saved and tested in an Asphalt Pavement Analyzer (APA). The effect of fine aggregate angularity of rounded and flaky fine aggregate on rutting performance was evaluated.

The results of this testing indicated that increased fine aggregate angularity results in greater VMA and decreased rutting. Chat sand was shown to be effective at increasing VMA, but increased the potential for rutting the same as the natural sand. Both mixes met Superpave gradation and voids criteria, but the rutting performance of the fine mix was superior to that of the coarse, regardless of fine aggregate angularity. Therefore, it is clear that stability testing is needed to ensure quality mixes.

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INTRODUCTION

BACKGROUND

Since the introduction and subsequent acceptance of Superpave mix design criteria, there has been growing concern over meeting the design volumetric requirements. Some mixes that have met previous design requirements and performed satisfactorily in service have failed the Superpave design volumetric criteria, most notably, voids in the mineral aggregate (VMA). Past Kansas Department of Transportation (KDOT) mix design criteria, based on the Marshall mix design method, did not include a minimum VMA requirement. With the adoption of Superpave, these old Marshall mixes are failing to meet the volumetric design requirements.

The lack of VMA requirement in the previous mix design method is not the only reason that current mixes are failing Superpave VMA requirements. The compactive effort of the Superpave gyratory compactor has been shown to be greater than the 50 or 75-blow compaction of the Marshall hammer (1). When Marshall mixes with VMA that meet the new Superpave standards are converted to Superpave mixes, they can fail VMA due to the increased compactive effort. The combination of changing to a mix design method that requires a minimum VMA and increasing the compactive effort has lead designers, suppliers, and contractors to look for ways to increase VMA, including importing aggregates.

VMA is a function of compactive effort, aggregate gradation, aggregate angularity, and asphalt content (2). For a Superpave mix, the compactive effort is controlled by the predicted traffic and the asphalt content is a function of gradation.

Therefore, aggregate angularity and gradation are the variables available to designers to adjust VMA.

In areas with subangular aggregates or places where economy necessitates the use of greater percentages of natural sand and gravel, designers have had trouble meeting the VMA requirements with gradation adjustments alone. In an effort to boost the angularity of rounded aggregate sources they have turned to sweeteners. These are typically highly angular aggregates that can compensate for the rounded nature of the local materials. Contractors in Kansas have been using chat sand, a by-product from lead and zinc mining in the tri-state area of Missouri, Oklahoma and Kansas as a way of obtaining VMA. The chat sand is a flaky fine aggregate of nearly pure chert.

A concern with KDOT mixes containing large percentages of rounded to sub angular aggregate has been the potential for permanent deformation or rutting. Superpave does not include a strength or permanent deformation test as part of the mix design criteria. A mix is only required to meet volumetric and aggregate angularity requirements. Also of interest is the effect of the use of chat sand on rutting. Chat is being used effectively to increase VMA, which allows more natural sand to be used in a mix. Since Superpave does not call for a strength test, the effect of chat sand on rutting potential is unknown. This is further compounded by the fact that the addition of chat is often used to reduce the percentage of crushed limestone fine aggregate, increasing the susceptibility to rutting.

OBJECTIVES

The objectives of this research were to observe the effect of fine aggregate angularity on VMA and rutting. More specifically how much fine aggregate angularity is required to meet minimum VMA requirements? The Superpave requirement for VMA is to provide a minimum asphalt content to ensure pavement durability. Since meeting this requirement does not ensure that the pavement will not rut, the second objective was to determine the minimum fine aggregate angularity required to maintain stability. The third objective is to observe the effect of flaky fine aggregate (chat sand) on VMA and rutting.

SCOPE

Two Superpave 12.5-mm mixes, one coarse and one fine, were evaluated for VMA at 4% voids total mix (VTM). These samples were also tested for rutting susceptibility using an Asphalt Pavement Analyzer (APA). These mix gradations were established with 100% crushed limestone, then to observe the effect of fine aggregate angularity, samples were made by blending different percentages of fine aggregate, including crushed limestone, natural sand from the Kansas River, and chat sand. The fine aggregate angularity (FAA) of each material was determined and this was used to evaluate the effect of FAA on VMA and rutting.

Chapter 2

LITERATURE REVIEW

VOLUMETRIC DESIGN AND VMA

Volumetric design using Voids in the Mineral Aggregate (VMA) was first suggested by McLeod (3) in the late fifties and early sixties. He ushered in volumetric mix design using VMA as a way to ensure adequate film thickness, which in turn created a durable pavement. Inadequate film thickness speeds asphalt aging and causes premature pavement failure (4). McLeod established a minimum VMA requirement of 15%, this allowed for 10% asphalt and 5% air by volume. This was adjusted to a minimum 14% VMA when air void recommendations were set at 4%. VMA recommendations were later scaled to represent nominal maximum size of aggregate. This allowed lower asphalt contents for larger aggregate mixes due to reduced surface area. These volumetric design concepts using VMA have been incorporated as the basis of Superpave mix design.

With the creation of Superpave, designers looked to produce a rational mix design procedure that took the principles of the past and added more control over the selection of materials, the compaction process, and more consideration to the volumetric properties of the design pavement. Where minimum VMA was a recommendation for many mix designs of the past, Superpave has made minimum VMA a requirement (5). Superpave also implemented a new compaction process that has increased compactive effort. The improved compaction of the Superpave Gyratory Compactor has lead to mix designs that fail the minimum VMA requirements. This in turn has lead designers and researchers to investigate two areas, ways to increase VMA of mixes, and the rationale behind the VMA requirements.

Rationale for VMA Requirements

McLeod (3) established 10% asphalt by volume as a minimum for durability but did not produce any supporting evidence for this assumption. In an NCAT report, Kandhal, Foo, and Mallick (6), investigated required film thickness and VMA. Film thickness was defined with the use of asphalt content and SHRP aggregate surface area equations. Kandhal et al. produced samples with a range of film thickness and subjected them to both long and short-term aging to determine a minimum film thickness. Using this established film thickness, minimum VMA was then back calculated using the surface area equations calculated for their several trial gradations. They found that some gradations that were failing the Superpave VMA requirements had sufficient VMA to meet their necessary film thickness and 4% air voids. Gradations were also found that met VMA requirements of Superpave but did not have sufficient room to develop the required film thickness.

Hinrichsen and Heggen with the Iowa Department of Transportation (7) performed a similar study. They researched Iowa DOT mixes and used the surface area equations to determined a minimum film thickness. This was then used to calculate required VMA for several mixes. Here, as in the Kandhal paper, inconsistencies were seen in the VMA required by Superpave and the VMA required to meet film thickness.

Both of these studies indicate the need to further investigate the rationale for VMA requirements. They also point to future design requirements that will take into account film thickness as a means to determine a more rational VMA requirement on a mix by mix basis. This will take further testing and field verification but for now designers are faced with the task of meeting VMA as set forth by Superpave. This has led researcher to look at the factors that effect VMA.

Factors That Effect VMA

Gradation

VMA is affected by many variables. The most recognized of these are compactive effort, gradation, aggregate angularity both coarse and fine, and asphalt content. Designers have long looked to gradation as a way to attain VMA requirements. Changes in gradation have proven to be an effective way to meet VMA and is a regular part of Superpave design. Superpave uses a 0.45 power gradation chart and a maximum density reference line to aid in the selection process of trial gradations (5). A gradation that trends away from the maximum density line tends to produce more VMA. To date the process of gradation selection is a trial and error procedure.

Research has been conducted in order to establish a formal approach to gradation selection for the purpose of producing sufficient VMA. Ashenbrener and MacKean (8) of the Colorado Department of Transportation conducted a study that looked at past Colorado mix designs and the factors that effected VMA. They looked at 101 gradations and calculated the sum of the distance from the maximum density line to gradation for each sieve size. From this they found that no strong relationship existed between the sum of distance from the maximum density line and VMA. They also went on to say that the only way to ensure a gradation would have sufficient VMA was to prepare and compact a trial sample.

While Ashenbrener and MacKean (8) were unable to find a direct means for meeting VMA, they did provide several guidelines. Ashenbrener et al. (8) found that it was most important to keep the gradation away from the maximum density line throughout the sieve sizes smaller than the 2.36 mm sieve. Also, the effect of material less than 75μm was important. Reducing the material less than 75μm results in increased VMA. They also noted that VMA was easier to obtain for the fine mixes observed.

Anderson and Bahia (9) also found that there was no correlation to the sum of distances from the maximum density line and VMA in a report where they looked at several laboratory mix designs. They concluded that the current recommendations for meeting VMA were not totally effective. They did recommend the S-shaped gradation curve that has been adopted by many designers as a way to obtain VMA and noted that factors other than gradation, such as angularity, played an important role in determining VMA.

Huber and Shuler (10) also researched the relationship between VMA and aggregate gradation. While it was their intent to determine the most useful procedure for establishing the maximum density line, in doing so they also concluded that it is only possible to compare gradation to the maximum density line for the same aggregates. Aggregate properties affect VMA such that the influence of gradation on VMA for different aggregates could not be distinguished. They went on to say that in order to study the effect of aggregate properties on VMA, it would be necessary to hold gradation constant.

Angularity

Since the adoption of volumetric mix design researchers have been looking into the effect of aggregate angularity on VMA. In 1958, Field (11) looked into the effect of coarse aggregate angularity on void content and stability of a pavement. In this study Field made samples with varying amounts of gravel and crushed material. He concluded that there was little effect on VMA and air voids with increased angularity unless crushed material is below 25% at which point he noted a significant decrease in VMA and voids. Huber and Shuler (10) also researched the effect of coarse aggregate angularity and noted that there was a 1% decrease in VMA for mixes that were primarily gravel rather than crushed limestone.

Superpave uses crushed face count to classify coarse aggregate angularity. Superpave also classifies particle shape based on flat and elongated particles. Huber, Jones, Messersmith, and Jackson (12) investigated these properties as they pertained to Superpave volumetric properties. While they did not test particles that exceeded the 5:1 ratio for elongated or flat particles, they found that Superpave volumetric properties were not significantly affected by moderate coarse particle shape differences.

The angularity of fine aggregate is also a factor in VMA of hot mix asphalt. Superpave uses the FAA flow test to classify fine aggregate angularity. This test was verified in testing conducted by Kandhal, Khatri, and Motter (13). They were able to correlate the result for the FAA test to ASTM D3398 for determining particle shape and texture index. The advantages of the FAA test procedure are its simplicity and straightforward nature, unlike ASTM D3398.

Ashenbrener and MacKean (8) also looked at aggregate angularity in their research on factors effecting VMA. They looked at the FAA results for their lab mixes studied and found that fine aggregate angularity did in fact play a significant role in VMA. Natural sands or those with lower FAA values had less VMA than mixes with higher FAA values like crushed materials. The testing, however, was limited to two aggregate sources and gradation was affected by the aggregate exchange process.

VMA Summary

While recent research results indicate that a more rational means of determining VMA requirements for a mix can be used, it is accepted that the current Superpave VMA requirements need to be met and that gradation is the easiest way to meet this requirement. There seems to be little correlation between the maximum density line and VMA, but this tool is still a designer's best resource for educated gradation choices. Along with gradation, aggregate angularity, specifically fine aggregate angularity, can be increased in an effort to boost VMA. The usefulness of fine aggregate angularity has yet to be quantified due to the multiple influences of gradation and other aggregate properties such as shape and texture.

AGGREGATE ANGULARITY AND RUTTING

Coarse Aggregate Angularity

Just as having adequate asphalt thickness is important to slow the effects of aging, it is also important that a mix resist rutting, the permanent deformation of a pavement due to repeated wheel loading. The role of aggregate angularity has been a major subject of research on rutting. In Field's (11) research he also looked at the effect of coarse aggregate angularity on stability in addition to voids. He concluded that gravels or rounded material resulted in lower Marshall stability values. He also reinforced that the minimum 60% crushed material recommendation of the day be "rigidly enforced" or even be raised to ensure better pavement performance.

Superpave uses a crushed face count and flat and elongated ratio to characterize coarse aggregate angularity. Huber, Jones, Messersmith, and Jackson (12) concluded that moderate flat or elongated particles did not affect the performance of a pavement, but they did not have an aggregate source that failed to meet Superpave's recommendations.

Fine Aggregate Angularity

Just as it was understood early on that the angularity of coarse aggregate would affect the rutting potential of a pavement, researchers understood that fine aggregate angularity could affect rutting as well. Campen and Smith (14) reported on the effects of natural sand content on stability in 1948. They produced samples that had varying amounts of crushed or angular material and tested them with two of the stability tests of the day. They found that rounded materials created less stable pavements and that 20% to 40% angular materials was required to meet minimum stability values.

Campen and Smith (14) used the term natural sand but did not quantify their aggregate angularity with testing. They understood that the river sands were more rounded than the crushed materials they were using. With the advent of the FAA test designers can now quantify the angularity of their fine aggregates. In testing it was found that there was an overlap in the angularity of some natural and crushed sands. Kandhal, Khatri, and Motter (13) suggested in their study of the FAA test that a value of 45.5% be used to distinguish angular from subangular rather than the arbitrary terms of natural and manufactured sand.

With the FAA test as a reference, Huber, Jones, Messersmith, and Jackson (12) evaluated the role of fine aggregate angularity on rutting. They reported that FAA values seemed to have little effect on rutting. They did note that the coarse nature of their mixes might have de-emphasized the role of FAA on rutting susceptibility.

In looking at rutting in 14 states across the U.S., Cross and Brown (15) found that when air voids were less than 2.5%, FAA values, then the NAA flow test, did indeed correlate to rutting behavior in the field. However, in a paper by Parker and Brown (16) on rutting in Alabama, there was no correlation between FAA and rutting.

The effect of fine aggregate angularity does not seem to be completely understood. This is most likely attributed to the complexity of factors that effect rutting potential. Just as with the study of VMA (10), in order to look at the effects of a single factor on rutting the other factors need to be held constant.

Superpave currently does not require a stability test as part of standard mix design procedure. Rather they have decided that the restriction of the aggregate properties and void requirements will produce a pavement that has adequate stability and sufficient asphalt for durability. The fine aggregate angularity requirements of 40% FAA for low traffic situations and 45% FAA for high traffic have been based on the distinctions found between natural and manufactured sand. Since the FAA of the pavements, crushed face counts, and particle shape characteristics are documented as part of a Superpave design, data should soon be available to help determine which of these properties are controlling rutting and what threshold values are required to ensure better performing pavements.

Chapter 3

PLAN OF STUDY

OVERVIEW

The testing plan was developed to investigate the effect of fine aggregate angularity and flaky aggregates (chat sand) on both VMA and rutting performance. Two baseline gradations were established. These were initially made with 100% crushed limestone and designed to exceed minimum VMA requirements by 0.5% or better. To observe the effect of fine aggregate angularity, percentages of crushed limestone fine aggregate were replaced with equivalent amounts of natural river sand. To investigate the effects of flaky aggregate, samples were made with blends that included chat sand in addition to natural sand and crushed limestone. Chat sand is a flaky aggregate, or sweetener, currently used in Kansas to boost VMA. In addition to VMA testing, all samples were tested in an Asphalt Pavement Analyzer (APA) to determine their susceptibility to rutting.

MATERIALS

Asphalt Binder

Two asphalt binders of the same performance grade (PG) were used in testing. This was necessary as a single quantity of asphalt sufficient to produce samples for both gradations was unavailable at the time of testing. All samples for each gradation were completed with a single binder. The asphalt binder used for the coarse gradation samples was a PG 58-22 from Lyon refineries. A PG 58-22 binder from Ergon refineries was used for the fine gradation samples.

Aggregates

Five aggregate sources were used for the production of samples. These consisted of three crushed limestones, one coarse (plus 4.75 mm) and two fine (minus 4.75 mm), a natural river sand, and chat sand.

The coarse aggregate was obtained from the Martin Marietta Big Springs Quarry in Stull, Kansas. The aggregate was a 12.5-mm nominal sized 100% crushed limestone and met KDOT's requirements for CS-1 material (17). Two sources of crushed limestone fine aggregate were also obtained from the Martin Marietta Big Springs Quarry. Both met KDOT's requirements for CS-2 material (17). Two sources of crushed fine aggregate were required due to availability of material. The original quantity of CS-2, referred to as MM CS-2A, was intended for use in both gradations, but was not sufficient to complete the number of samples required of both gradations. This material, MM CS-2A, was used to complete all SM-1B samples. A second aggregate, MM C-S2B, was obtained to produce the SM-2A samples. The MM CS-2B material came from the same quarry as the MM CS-2A, but came from a different ledge. The natural river sand was from the Kansas River and was obtained from the Lawrence Ready Mix Company in Lawrence, Kansas and met KDOT's specification for SSG material (17). The chat sand was obtained from KDOT.

TEST PLAN

Test Gradations

Two baseline SHRP 12.5-mm gradations, one coarse and one fine, were established containing 100% crushed limestone. The mixes are based on KDOT designations SM-1B and SM-2A. The SM-2A gradation stays above the maximum density line and the SM-1B gradation is an S shaped curve that starts above and ends below the maximum density line. These two gradations were utilized to broaden the usefulness of the study as they are routinely used by KDOT. The SM-1B gradation was based on a gradation used on US 283 near Norton, Kansas. The amount of material passing the 0.150-mm sieve was adjusted from the mix design to better meet the gradation of the available aggregates. The SM-2A mix was developed for the purposes of this study.

Several trial coarse and fine gradations that met Superpave and KDOT gradation criteria were compacted with 100% limestone. One coarse and one fine gradation resulting in the greatest VMA were selected as the final gradations used for testing. The final gradations were also required to meet and exceed the minimum 14% VMA requirement of a Superpave 12.5-mm mix.

Blending

To observe the effects of fine aggregate angularity on VMA and rutting separate from the effects of gradation, it was necessary to hold the gradation constant regardless of the percentages of material blended. To achieve this, material from each aggregate source was separated by sieving over standard ASTM sieves from 12.5 mm to 0.150 mm. Samples were then batched from the sieved material to maintain the test gradations. This eliminated the original gradations of the source material, and held the mix gradation constant regardless of the percentages of each material used.

Effect of Aggregate Angularity on VMA

Rounded Fine Aggregate

To determine the effect of rounded fine aggregate angularity on VMA, samples were made with varying percentages of Kansas River sand and crushed limestone. All of the coarse aggregate, 12.5 mm to 4.75 mm, in both gradations was Martin Marietta CS-1. Both the SM-1B and the SM-2A consisted of roughly 62% material that passed the 4.75-mm sieve and was retained on the 0.150-mm sieve. The testing matrix consisted of the two gradations each made with six different percentages of natural sand. The first samples were made of 100% limestone and 0% natural sand. Then, samples with 5%, 10%, 20%, 40%, and 62% natural sand were made (percent by total weight of aggregate). The testing matrix is illustrated in Table 1. The natural sand was directly exchanged for limestone on each sieve to maintain the base gradation. Table 2 shows an example of a blend to better illustrate this replacement procedure.

Samples at each natural sand percentage were compacted at estimated asphalt contents and Voids Total Mix (VTM) and Voids in the Mineral Aggregate (VMA) were determined. Asphalt contents were adjusted for samples outside of 4% ±1% VTM and remade until VTM was within 4% ±1%. Two samples of each natural sand percentage at optimum asphalt content were then produced. The VMA values for these samples were adjusted to reflect 4.0% VTM with the use of the following SHRP equation (5).

$$\%\ VMA_{estimated} = \%\ VMA_{initial} + C * (4 - VTM) \quad [1]$$

Where: $VMA_{initial}$ = VMA from trial binder content

C = Constant = 0.1 if VTM is < 4.0%

0.2 if VTM is > 4.0%

The samples with VTM of 4% ± 1% were saved for the rut susceptibility testing in the Asphalt Pavement Analyzer.

TABLE 1 Test Matrix for Evaluation of Rounded Fine Aggregate Angularity*

% of Aggregate Used**		# of Samples	
Limestone	Natural Sand	SM-1B	SM-2A
62	0	2	2
57	5	2	2
52	10	2	2
42	20	2	2
22	40	2	2
0	62	2	2

* Percent of Total Mix

** Total % -4.75 mm to 0.150 mm material = 62%

TABLE 2 Example of Fine Aggregate Replacement/Blending, SM-1B Mix

	Percent of Total Mix				
	37.25	42.75	10	10	Blended
	Running Batch Weights For 3500 g Sample				Gradation
Sieve Size	CS-1	CS-2B	Sand	Chat	% Retained
19 mm	0.0	-	-	-	0.0
12.5 mm	140.0	-	-	-	4.0
9.5 mm	560.0	-	-	-	16.0
4.75 mm	1120.0	-	-	-	32.0
2.36 mm	-	1549.2	2900.4	3250.4	50.0
1.18 mm	-	1787.6	2956.2	3306.2	60.0
0.600 mm	-	1954.6	2995.2	3345.2	67.0
0.300 mm	-	2383.8	3095.6	3445.6	85.0
0.150 mm	-	2616.3	3150.0	3500.0	94.8
Pan	-	2800.0	3150.0	3500.0	100.0

Flaky Fine Aggregate

The effect of flaky fine aggregate (chat sand) on VMA was evaluated similarly to the rounded fine aggregate angularity testing that replaced crushed limestone with natural sand. Samples of both the SM-1B and SM-2A gradations were made with varying percentages of crushed limestone, natural sand, and chat sand. The chat sand replaced either the limestone or the natural sand. This was accomplished by holding one aggregate percentage constant and observing the effect of varying the other two.

To investigate the effect of replacing limestone with flaky fine aggregate (chat sand), samples were made holding the percentage of natural sand to 22% and 42%. For each percentage of natural sand, samples were made by replacing 0%, 5%, 10%, and 20% limestone with chat sand. This is illustrated in Table 3.

TABLE 3 Test Matrix for Evaluation of Flaky Fine Aggregate*

% of Aggregate Used**			# of Samples	
Limestone	**Natural Sand**	**Chat Sand**	**SM-1B**	**SM-2A**
42	20	0	2 #	2 #
35	22	5	2	2
30	22	10	2	2
20	22	20	2	2
22	40	0	2 #	2 #
15	42	5	2	2
10	42	10	2	2
0	42	20	2	2
42	20	0	2 #	2 #
42	15	5	2	2
42	10	10	2	2
42	5	15	2	2
42	0	20	2	2

* Total % -4.75 mm to 0.150 mm material in Mix = 62%

** Percent of Total Mix

Data used from angularity testing

The effect of replacing natural sand with chat sand was performed in the same manner as the limestone replacement samples. The percentage of limestone was held constant at 42% and the amount of natural sand was varied by replacement with chat sand. Samples were made with 20%, 15%, 10%, 5%, and 0% natural sand. This testing matrix is included in Table 3 as well.

Two samples were made for each aggregate blend using the same methods and criteria as the samples produced for the fine aggregate angularity testing. VMA values were determined, then adjusted to reflect 4% VTM with the same SHRP equation that was used for the fine aggregate angularity samples. These samples were kept for rut susceptibility testing in the Asphalt Pavement Analyzer.

Effect of Aggregate Angularity on Rutting

The samples made for observing the effect of fine aggregate angularity on VMA, both rounded and flaky, were tested in an Asphalt Pavement Analyzer to determine their susceptibility to rutting. Testing was conducted in a dry condition at 58°C. This was the upper temperature rating for both asphalt binders.

TESTING PROCEDURE

Asphalt Binder Properties

Both binders were tested in accordance with ASTM D 4402 with a Brookfield rotational viscometer to determine mixing and compaction temperatures. The test temperatures and corresponding viscosities were plotted on a log of viscosity vs. temperature plot. From this figure, mixing and compaction temperature ranges were determined as recommended by SHRP and KDOT.

Aggregate Properties

All five stockpiles of aggregate were tested in accordance with KT-6 (18) (AASHTO T 84 & T 85) to determine the specific gravity and absorption of the individual materials.

The fine aggregates were tested in accordance with KT-50 (AASHTO T 304) to determine the angularity of the fine aggregates. KT-50 (AASHTO T 304) was also conducted on blends representing each of the fine aggregate ratios tested for VMA and rutting.

Batching of Aggregates

In order to maintain the design gradation and vary the percentages of the fine aggregates used, it was necessary to first sieve the aggregates into individual sizes. The aggregates were dried in a force draft oven at 105°C then sieved over a series of ASTM standard sized sieves. The Martin Marietta (MM) CS-1 was the only source of coarse aggregate and material passing the 0.150-mm sieve. The CS-1 comprised 38% of the aggregate in each sample. The other 62% consisted of fine aggregate from MM CS-2, natural sand, chat sand, or a combination of these three. The aggregates were blended to meet the percentages called for by the testing matrix. Running batch weights were computed for each blend and from these 3500 gram aggregate batches were prepared.

Mixing of Samples

Mixing followed KDOT specification KT-58 (18). Once the aggregate samples were batched they were placed in a force draft oven overnight at 105°C. Two hours before mixing, the oven temperature was increased to the mixing temperature determined from the asphalt viscosity testing. One and one half-hours before mixing, the asphalt was placed in the same oven. Thirty minutes before mixing the asphalt was removed and placed in a self-heating kettle set to the mixing temperature. At this time the mixing bowl and whip were placed in the oven, set to the mixing temperature.

Maintaining 42% and the placing of the natural sand was varied by replacing with the desired amount. Samples were made with 20%, 15%, 10%, 5%, and 0%. Each sample was This testing matrix is included in Table 3 as well.

Two samples were made for each aggregate blend using the same methods and criteria as the samples produced for the fine aggregate angularity testing. VMA values were determined, then adjusted to 4% VTM with the same SHRP equation that was used for the fine aggregate angularity samples. These samples were kept for rut susceptibility testing in the Asphalt Pavement Analyzer.

Effect of Aggregate Angularity on Rutting

The samples made for observing the effect of fine aggregate angularity on VMA, both rounded and flaky, were tested in an Asphalt Pavement Analyzer to determine their susceptibility to rutting. Testing was conducted in a dry condition at 58°C. This was the upper temperature rating for both asphalt binders.

TESTING PROCEDURE

Asphalt Binder Properties

Both binders were tested in accordance with ASTM D 4402 with a Brookfield rotational viscometer to determine mixing and compaction temperatures. The test temperatures and corresponding viscosities were plotted on a log of viscosity vs. temperature plot. From this figure, mixing and compaction temperature ranges were determined as recommended by SHRP and KDOT.

Aggregate Properties

All stockpiles were tested in accordance with KT-6 (98) (AASHTO T to determine the individual materials.

density (Gmm). The Gmm determined from this testing was adjusted to reflect Gmm at optimum asphalt content. The Gmb, Gsb, and adjusted Gmm were used to determine the VMA and VTM of each sample in accordance with KT-58 (18).

Rutting Susceptibility Testing

The samples used to determine the effect of fine aggregate angularity on VMA, both rounded and flaky, were also tested to determine their susceptibility to rutting using an Asphalt Pavement Analyzer (APA). Testing was performed in general accordance with the method outlined in the current APA user manual (19). Samples were tested at 4% ± 1% as recommended by National Center for Asphalt Technology (NCAT) to conserve materials and reduce sample preparation time. Testing was conducted at the high temperature rating of the asphalt binders, 58°C. The wheel load was 0.44 kN and the hose pressure was 690 kPa. The samples were tested to 8,000 cycles. Rut depth measurements were obtained at 0, 500, 1000, 2000, 4000, and 8000 cycles. Rut depths greater than 10 mm are generally considered inaccurate due to support of the hose from the sample mold.

Chapter 4

RESULTS

ASPHALT PROPERTIES

Table 4 shows the mixing and compaction temperatures determined in accordance with ASTM D 4402, for the two asphalt binders used. The mixing and compaction temperatures selected were the same for both asphalt binders, 153°C and 142°C, respectively.

TABLE 4 Asphalt Mixing and Compaction Temperatures

Mix	Asphalt	Mixing Range	Compaction Range
SM-2A	Ergon PG 58-22	150°C - 155°C	139°C – 144°C
SM-1B	Lyon PG 58-22	149°C – 154°C	138°C – 143°C

AGGREGATE PROPERTIES

Table 5 contains the results of the aggregate property testing. Included are the specific gravity and absorption of the five aggregate sources and the fine aggregate angularity (FAA) results for the four sources of fine aggregate. The FAA was determined for each of the aggregates with the use of KT-50 (AASHTO T 304, Method A). Blends representing the ratios of fine aggregate used to produce samples for the VMA and rutting testing were also tested in accordance with KT-50 (AASHTO T 304, Method A). FAA values for each blend were calculated by taking a weighted average of the aggregates' individual angularity results. Table 6 shows the results of the tested and calculated FAA for the SM-1B and SM-2A blends.

TABLE 5 Aggregate Properties

Source	KDOT Classification	ID	Gsb	Absorption (%)	Fine Aggregate Angularity (%)
MM-CS1	CS-1	CS-1	2.62	2.44	N/A
MM-CS2A	CS-2	MM-CS2A	2.57	3.28	44.6
MM-CS2B	CS-2	MM-CS2B	2.55	2.5	47.7
Kansas River	SSG	Sand	2.59	0.79	37.2
Chat Screenings		Chat	2.54	1.77	46.0

N/A = Not Applicable

TABLE 6 Results of FAA Testing

	SM-1B		SM-2A	
Blend*	Measured FAA (%)	Calculated FAA (%)	Measured FAA (%)	Calculated FAA (%)
62-0-0	44.5	44.5	47.7	47.7
57-5-0	44.1	43.9	47.1	46.8
52-10-0	43.2	43.3	46.5	46.0
42-20-0	42.0	42.1	45.1	44.3
22-40-0	38.6	39.8	41.3	41.0
0-62-0	37.2	37.2	37.2	37.2
35-22-5	42.5	41.9	40.5	40.4
30-22-10	42.6	42.1	40.5	40.2
20-22-20	42.4	42.3	39.8	40.0
15-42-5	39.8	39.6	44.5	43.7
10-42-10	39.9	39.7	44.2	43.6
0-42-20	40.9	40.0	44.1	43.3
42-15-5	43.2	42.8	45.3	45.0
42-10-10	44.1	43.5	46.0	45.7
42-5-15	44.8	44.2	46.6	46.4
42-0-20	45.6	44.9	47.2	47.1

* Sample ID = Limestone % - Sand % - Chat %

Trial Gradations

Tables 7 and 8 contain the trial gradations used to determine the final gradations of the SM-1B and SM-2A mixes, respectively. These gradations are plotted on a 0.45 power gradation curve in Figures 1 and 2. All samples were made with 100% limestone and 5.0% asphalt. A voids analysis was conducted and the VMA results are included in Tables 7 and 8. The gradations were selected in an effort to achieve a VMA of 14.5% or greater, which is 0.5% above the minimum SHRP requirement for both gradations.

Final Gradations

From the trial gradations, final gradations were chosen to maximize VMA. These are shown in Tables 9 and 10. Also included in these tables are the SHRP 12.5-mm nominal mix specifications and the KDOT specifications for SM-1B and SM-2A mixes, respectively. Figure 3 is a 0.45 power gradation plot of the SM-1B mix. Included for reference are the SHRP and KDOT specification limits. Figure 4 is the 0.45 power gradation plot of the SM-2A mix with specification limits.

TABLE 7 Trial Gradations for SM-1B Samples and Resultant VMA

	Trial 1	Trial 2	Trial 3	Trial 4*	Trial 5	Trial 6
Sieve Size	% Retained					
19 mm	0.0	0.0	0.0	0.0	0.0	0.0
12.5 mm	5.0	4.0	4.0	8.0	5.0	5.0
9.5 mm	20.0	17.0	22.0	16.0	20.0	20.0
4.75 mm	48.0	48.0	52.0	34.0	48.0	48.0
2.36 mm	68.0	68.0	68.0	71.0	68.0	68.0
1.18 mm	80.0	80.0	82.0	82.0	80.0	80.0
0.600 mm	85.0	85.0	85.0	86.0	85.0	85.0
0.300 mm	90.0	90.0	90.0	91.0	90.0	90.0
0.150 mm	92.0	92.0	92.0	96.0	92.0	94.75
0.075 mm	94.0	94.0	94.0	97.0	94.0	96.0
VMA (%)	14.63	13.80	13.32	16.57	12.38	12.88

* Selected Gradation

TABLE 8 Trial Gradations for SM-2A Samples and Resultant VMA

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6*
Sieve Size	% Retained					
19 mm	0.0	0.0	0.0	0.0	0.0	0.0
12.5 mm	4.0	4.0	4.0	3.0	4.0	4.0
9.5 mm	16.0	16.0	16.0	16.0	16.0	16.0
4.75 mm	32.0	40.0	32.0	38.0	40.0	32.0
2.36 mm	55.0	56.0	50.0	46.0	56.0	50.0
1.18 mm	60.0	62.0	60.0	60.0	62.0	60.0
0.600 mm	67.0	68.0	67.0	67.0	68.0	67.0
0.300 mm	84.0	86.0	85.0	85.0	86.0	85.0
0.150 mm	87.0	92.0	92.0	92.0	94.75	94.75
0.075 mm	90.0	96.0	94.0	94.0	96.0	96.0
VMA (%)	12.92	13.84	13.72	13.79	13.45	14.56

* Selected Gradation

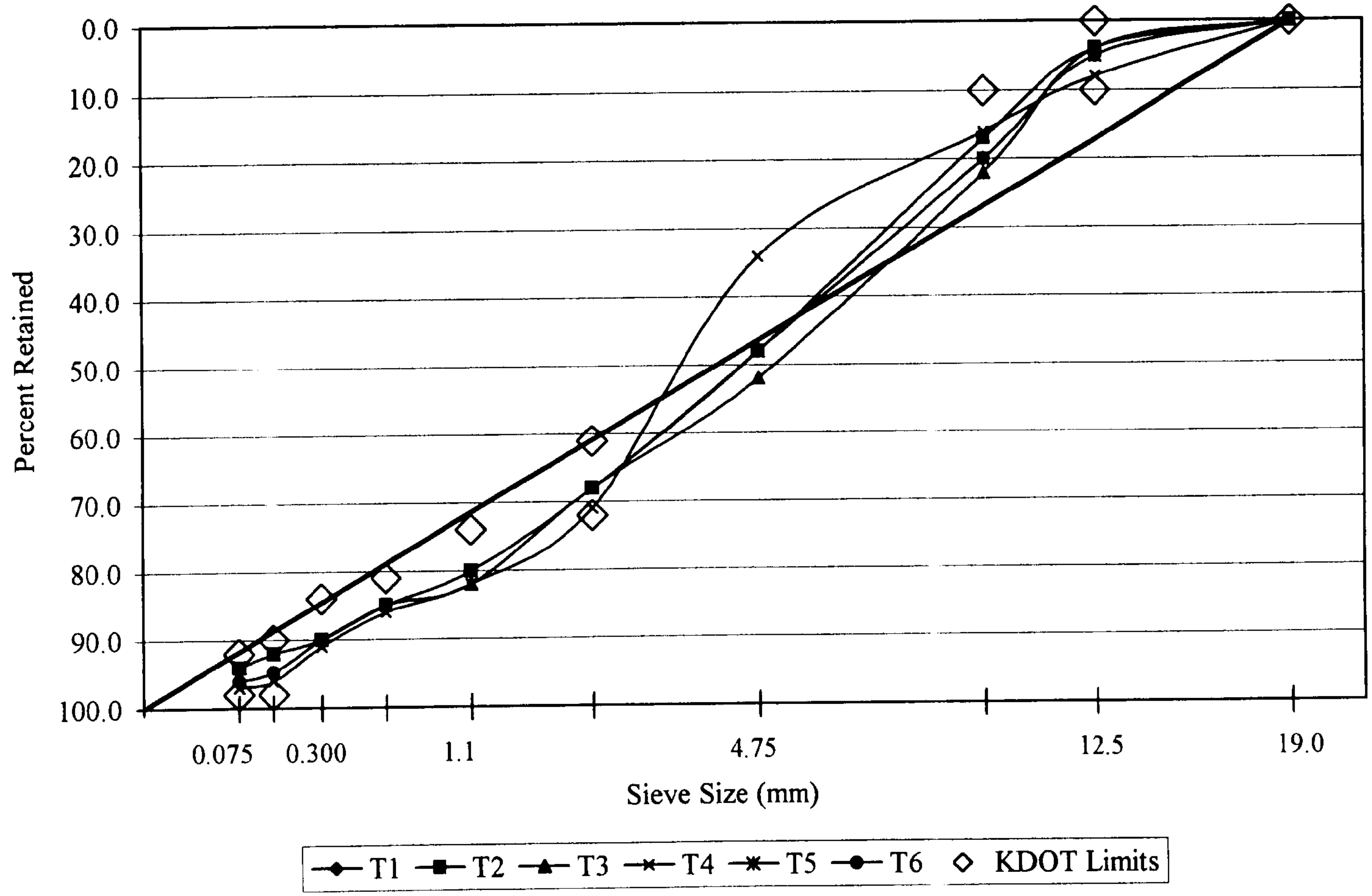

FIGURE 1 0.45 Power Gradation Plot of SM-1B Trial Gradations

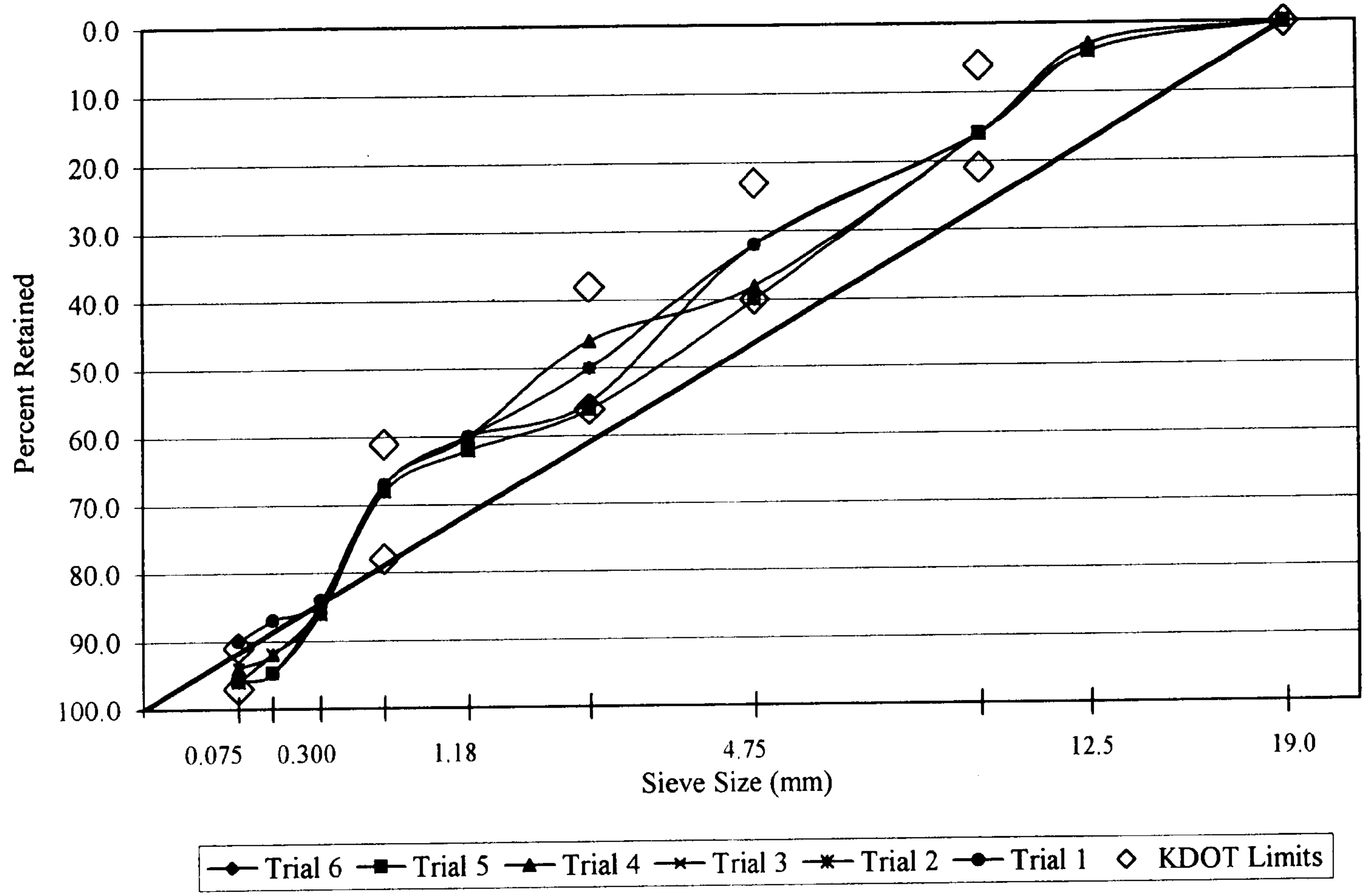

FIGURE 2 0.45 Power Gradation Plot of SM-2A Trial Gradations

TABLE 9 **Final Gradation for SM-1B Samples with SHRP and KDOT Specification Limits.**

Sieve Size	Final Gradation	SHPR 12.5 mm Limits		KDOT SM-1B Limits	
	% Retained				
19 mm	0.0		0		0
12.5 mm	8.0	10	0	10	0
9.5 mm	16.0		10		10 min
4.75 mm	34.0				
2.36 mm	71.0	72	42	72	61
1.18 mm	82.0				74 min
0.600 mm	86.0				81 min
0.300 mm	91.0				84 min
0.150 mm	96.0			98	90
0.075 mm	97.0	98	90	98	92

TABLE 10 **Final Gradation for SM-2A Samples with SHRP and KDOT Specification Limits.**

Sieve Size	Final Gradation	SHPR 12.5 mm Limits		KDOT SM-2A Limits	
	% Retained				
19 mm	0.0		0		0
12.5 mm	4.0	10	0		
9.5 mm	16.0		10	21	6
4.75 mm	32.0			40	23
2.36 mm	50.0	72	42	56	38
1.18 mm	60.0				
0.600 mm	67.0			78	61
0.300 mm	85.0				
0.150 mm	94.75				
0.075 mm	96.0	98	90	97	91

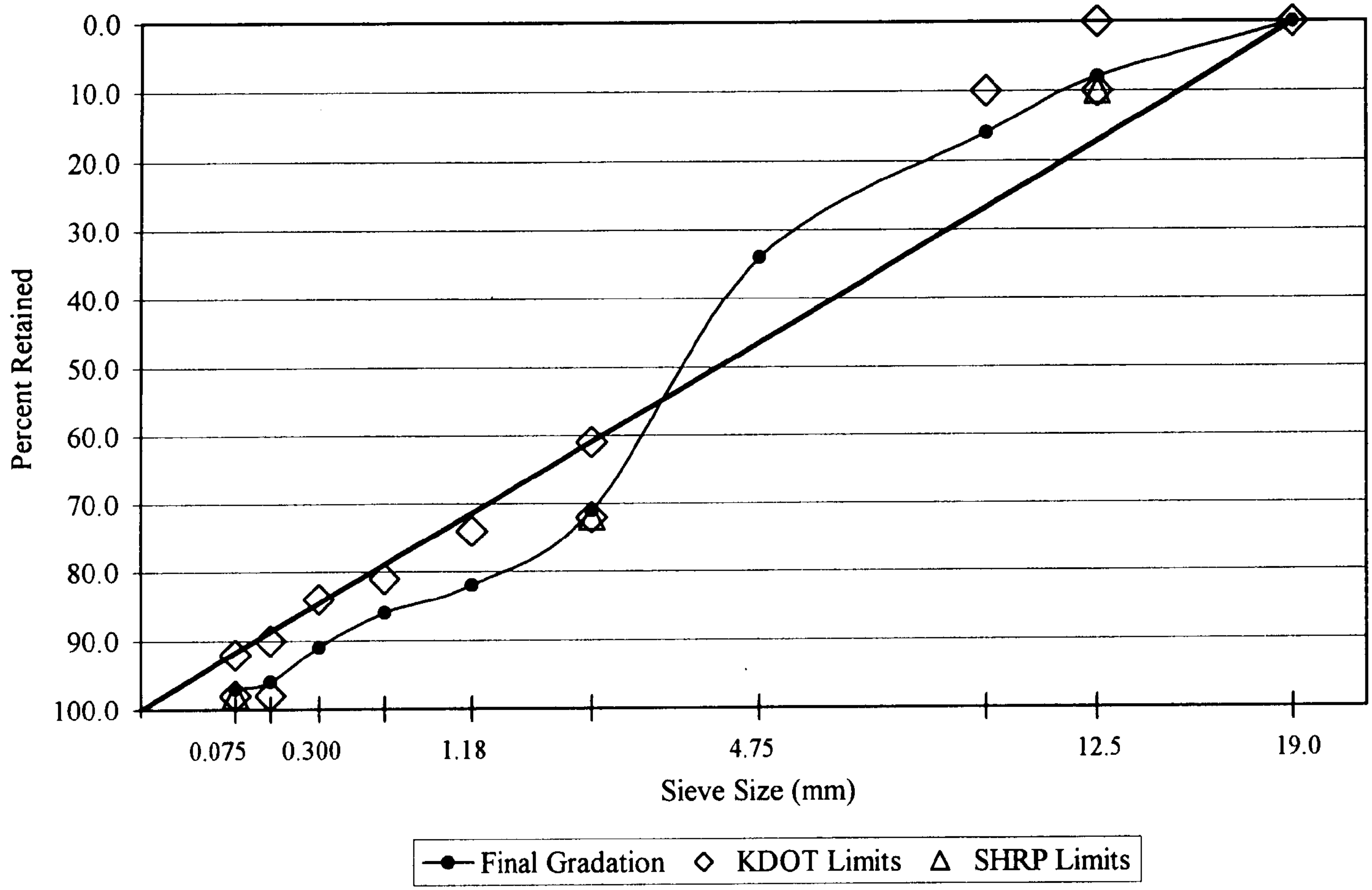

FIGURE 3 0.45 Power Gradation Plot of SM-1B Final Gradation

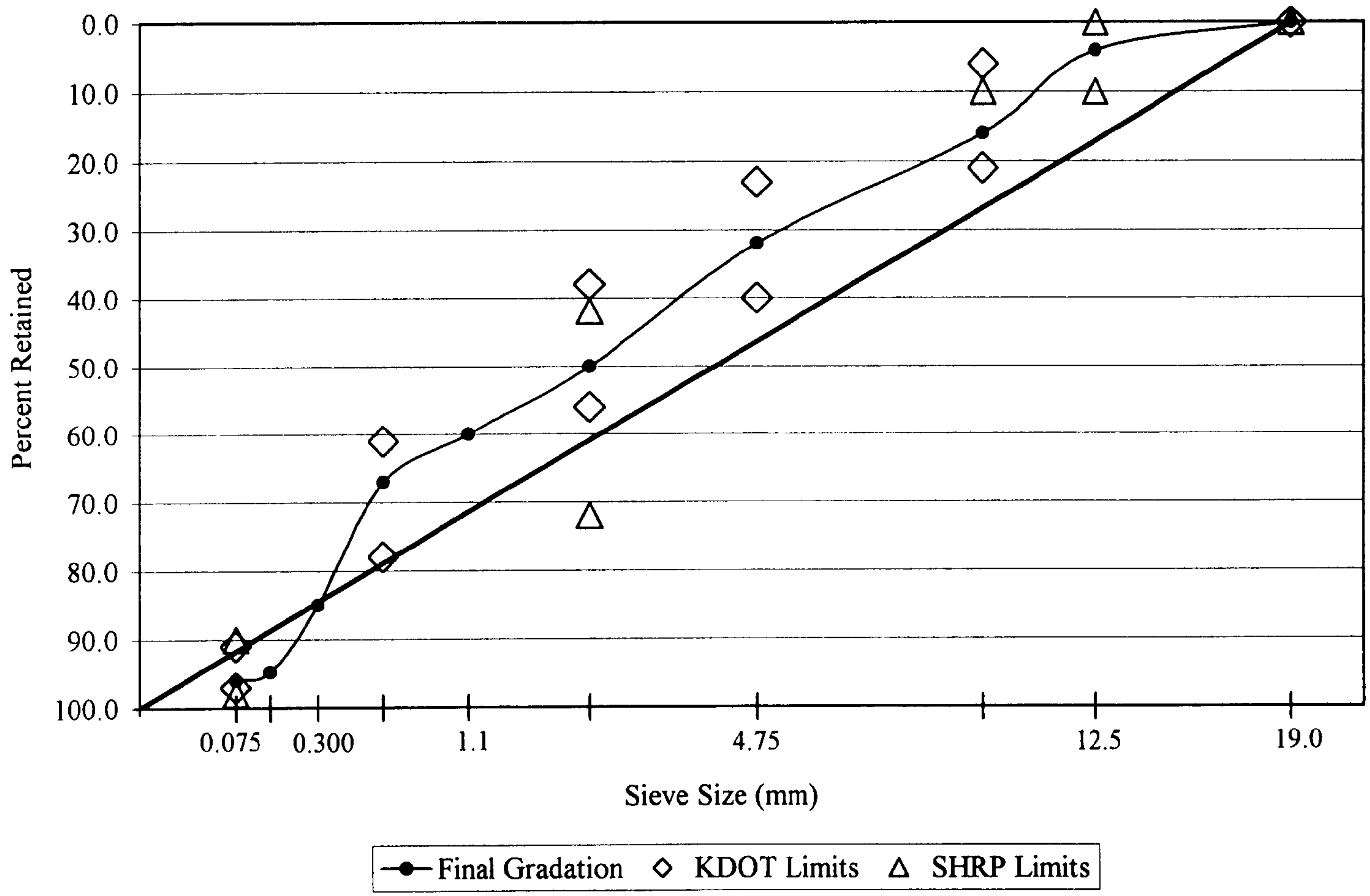

FIGURE 4 0.45 Power Gradation Plot of SM-2A Final Gradation

THE EFFECTS OF AGGREGATE ANGULARITY ON VMA AND RUTTING

Rounded Fine Aggregate

Tables 11 and 12 contain the results from the tests performed to determine the effect of rounded fine aggregate on VMA and rutting. The tables contain asphalt content, VTM, VMA, voids filled with asphalt (VFA), VMA corrected for 4% VTM, maximum rut depth at 4,000 and 8,000 cycles, and FAA flow values for each of the blends tested. Table 11 contains the data for samples made with the SM-1B gradation. Table 12 contains the data from the SM-2A samples.

Flaky Fine Aggregate

Tables 13 and 14 contain the results from the tests performed to determine the effect of flaky fine aggregate (chat sand) on VMA and rutting. The tables contain asphalt content, VTM, VMA, VFA, VMA corrected for 4% VTM, max rut depth at 4000 and 8000 cycles, and FAA values for each of the blends tested. Table 13 contains the data for samples made with the SM-1B gradation. Table 14 contains the data from the SM-2A samples.

TABLE 11 Summary of Results for SM-1B Samples Made With Natural Sand and Limestone

Blend*	AC (%)	VTM (%)	VMA (%)	VFA (%)	AVG. VMA Corrected to 4% VTM (%)	Rut Depth (mm)**		FAA Values (%)
						4000 Cycles	8000 Cycles	
62-0-0	6.5	5.6	15.1	62.9	15.44	4.6	5.6	44.5
62-0-0	6.5	5.6	15.1	62.9		4.4	5.8	
57-5-0	6.5	5.4	14.2	62.2	14.42	5.0	6.0	44.1
57-5-0	6.5	5.3	14.1	62.4		5.2	6.2	
52-10-0	6.5	5.5	14.7	62.9	14.82	5.3	6.2	43.2
52-10-0	6.5	5.1	14.4	64.8		4.6	6.0	
42-20-0	6.5	4.6	14.1	67.5	14.25	6.1	8.4	42.0
42-20-0	6.5	4.7	14.2	66.8		6.0	7.9	
22-40-0	5.8	4.3	14.1	69.6	14.22	7.5	10.0	38.6
22-40-0	5.8	4.4	14.2	68.8		11.1	12.7	
0-62-0	Samples were too unstable to produce							37.2

* Sample ID = Limestone % - Sand % - Chat %

** Rut depths greater than 10 mm considered approximate

TABLE 12 Summary of Results for SM-2A Samples Made With Natural Sand and Limestone

Blend*	AC (%)	VTM (%)	VMA (%)	VFA (%)	AVG. VMA Corrected to 4% VTM (%)	Rut Depth (mm)**		FAA Values (%)
						4000 Cycles	8000 Cycles	
62-0-0	5.53	3.71	14.60	74.60	14.54	1.4	1.6	47.7
62-0-0	5.40	3.93	14.51	72.89		1.6	2.3	
57-5-0	5.25	4.03	14.04	71.29	13.84	1.4	1.9	47.1
57-5-0	5.50	3.06	13.72	77.67		1.4	1.8	
52-10-0	5.10	4.60	13.68	66.36	14.00	1.9	2.7	46.5
52-10-0	5.10	4.97	14.01	64.55		1.8	2.1	
42-20-0	5.62	2.91	13.34	78.19	13.19	3.0	4.2	45.1
42-20-0	5.46	2.98	13.04	77.19		1.6	3.1	
22-40-0	4.91	2.78	12.92	78.45	13.11	4.4	5.6	41.3
22-40-0	4.98	3.05	13.31	77.07		3.5	4.5	
0-62-0	4.10	4.14	13.32	68.90	13.16	14.5	16.2	37.2
0-62-0	4.10	3.78	12.99	70.92		9.8	13.9	

* Sample ID = Limestone % - Sand % - Chat %

** Rut depths greater than 10 mm considered failing

TABLE 13 Summary of Results for SM-1B Samples Made With Chat Sand

Blend*	AC (%)	VTM (%)	VMA (%)	VFA (%)	AVG. VMA Corrected to 4% VTM (%)	Rut Depth (mm)**		FAA Values (%)
						4000 Cycles	8000 Cycles	
42-20-0	6.5	4.6	14.1	67.5	14.18	6.1	8.4	42.0
42-20-0	6.5	4.7	14.2	66.8		6.0	7.9	
35-22-5	7.0	4.2	15.2	72.4	15.24	9.0	14.4	42.5
35-22-5	6.8	4.8	15.1	68.4		8.6	14.0	
30-22-10	5.8	3.6	15.4	76.8	15.38	7.6	10.1	42.6
30-22-10	5.8	3.7	15.4	76.3		8.3	10.8	
20-22-20	6.8	4.8	17.8	73.0	18.17	11.5	15.7	42.4
20-22-20	6.8	5.3	18.2	71.1		9.6	13.1	
22-40-0	5.8	4.3	14.1	69.6	14.22	7.5	10.0	38.6
22-40-0	5.8	4.4	14.2	68.8		11.1	12.7	
15-42-5	5.0	6.0	15.6	61.7	15.23	7.5	10.0	39.8
15-42-5	5.0	6.6	16.1	59.4		15.8	***	
10-42-10	6.0	5.7	16.4	65.5	16.65	15.1	***	39.9
10-42-10	6.0	5.5	16.3	66.0		14.2	***	
0-42-20	6.7	4.7	18.1	74.0	18.22	13.3	***	40.9
0-42-20	6.7	4.6	18.1	74.6		19.6	21.7	
42-20-0	6.5	4.6	14.1	67.5	14.18	6.1	8.4	42.0
42-20-0	6.5	4.7	14.2	66.8		6.0	7.9	
42-15-5	6.6	5.5	15.7	65.0	15.80	4.7	6.3	43.2
42-15-5	7.2	4.0	15.6	74.2		6.1	7.6	
42-10-10	5.5	5.4	14.9	63.7	15.38	5.4	6.8	44.1
42-10-10	5.5	5.7	15.2	62.5		4.1	5.1	
42-5-15	7.5	3.9	16.5	76.2	16.42	4.9	6.1	44.8
42-5-15	7.3	4.3	16.3	73.8		5.3	7.1	
42-0-20	6.9	5.7	16.6	65.4	16.87	4.0	4.8	45.6
42-0-20	7.0	5.5	16.5	67.0		5.0	6.3	

* Sample ID = Limestone % - Sand % - Chat %

** Rut depths greater than 10 mm considered approximate

*** Samples rutted and heaved so much that an accurate reading could not be taken

TABLE 14 Summary of Results for SM-2A Samples Made With Chat Sand

Blend*	AC (%)	VTM (%)	VMA (%)	VFA (%)	AVG. VMA Corrected to 4% VTM (%)	Rut Depth (mm)** 4000 Cycles	Rut Depth (mm)** 8000 Cycles	FAA Values (%)
42-20-0	5.6	2.9	13.3	78.2	13.19	3.0	4.2	45.1
42-20-0	5.5	3.0	13.0	77.2		1.6	3.1	
35-22-5	4.8	4.0	13.8	70.7	13.75	2.2	2.9	40.5
35-22-5	4.8	3.8	13.7	72.6		3.0	3.9	
30-22-10	5.2	4.0	14.5	72.1	14.24	3.7	4.6	40.5
30-22-10	5.2	3.6	14.1	74.5		2.2	3.3	
20-22-20	5.3	3.2	14.3	77.9	14.30	3.4	4.4	39.8
20-22-20	5.0	3.8	14.4	73.4		4.4	5.4	
22-40-0	4.9	2.8	12.9	78.4	13.11	4.3	5.6	41.3
22-40-0	5.0	3.1	13.3	77.1		3.5	4.5	
15-42-5	4.5	4.1	13.5	69.7	13.35	5.5	7.5	44.5
15-42-5	4.5	3.7	13.2	71.9		4.5	6.0	
10-42-10	5.0	3.0	13.9	78.3	13.77	8.8	11.6	44.2
10-42-10	4.2	4.8	13.6	64.7		8.7	10.9	
0-42-20	4.8	4.2	15.0	71.8	15.07	10.4	14.1	44.1
0-42-20	4.8	4.2	15.0	72.1		10.0	13.7	
42-20-0	5.6	2.9	13.3	78.2	13.19	3.0	4.2	45.1
42-20-0	5.5	3.0	13.0	77.2		1.6	3.1	
42-15-5	5.3	3.7	13.5	72.9	13.76	1.0	1.6	45.3
42-15-5	5.1	4.6	13.9	66.8		1.8	2.8	
42-10-10	5.3	3.9	13.9	72.2	13.98	1.9	3.0	46.0
42-10-10	5.3	4.0	14.1	71.3		2.1	2.9	
42-5-15	5.5	4.1	14.8	72.0	14.46	1.5	1.9	46.6
42-5-15	5.6	3.4	14.2	76.4		1.9	3.1	
42-0-20	6.0	3.6	15.2	76.4	14.94	1.4	2.3	47.2
42-0-20	5.8	3.6	14.8	75.4		1.5	2.5	

* Sample ID = Limestone % - Sand % - Chat %

** Rut depths greater than 10 mm considered approximate

Chapter 5

DISCUSSION OF RESULTS

FINE AGGREGATE ANGULARITY OF THE BLENDS

Figure 5 shows the relationship between calculated and measured FAA values of the blends. Testing was performed in accordance with KT-50 (AASHTO T 304). Calculated values are based on a weighted average of the FAA values of the individual aggregates, as recommended by SHRP. The measured values are the result of FAA testing performed on samples that were blended from the aggregates. The comparison resulted in a linear relationship with a slope of 1.007, y-intercept of 0.053 and an R^2 value relating the quality of the linear fit of 0.99. This shows the near equality of the two methods. Since both methods resulted in nearly identical values either method can be used to determine the FAA of a specific blend. The results of the measured FAA are used for the purposes of this study.

ROUNDED FINE AGGREGATE

Effect of Rounded Fine Aggregate Angularity on VMA

SM-1B Samples

Figure 6 shows the relationship between FAA and VMA for the SM-1B samples made with limestone and natural sand. As shown in Figure 6, FAA values below 42.5% affect VMA very little. Each percent increase in FAA above 42.5% results in a 0.36% increase in VMA. Figure 7 depicts the VMA results as a function of natural sand percentage. It can be seen here that with increased natural sand content, VMA decreases. The exception is the 5% natural sand samples that resulted in a VMA slightly lower than the

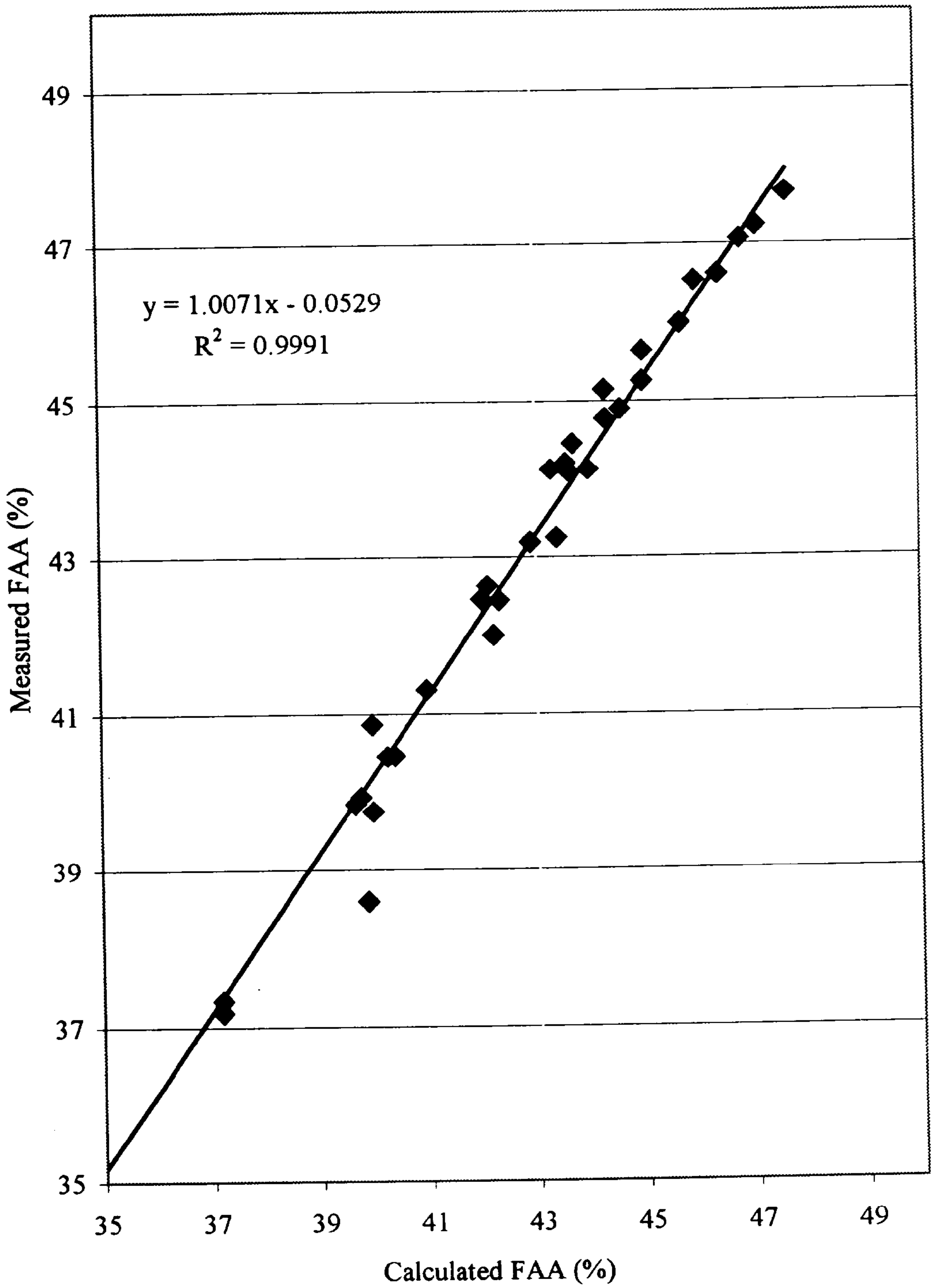

FIGURE 5 Comparison of Measured to Calculated FAA Values

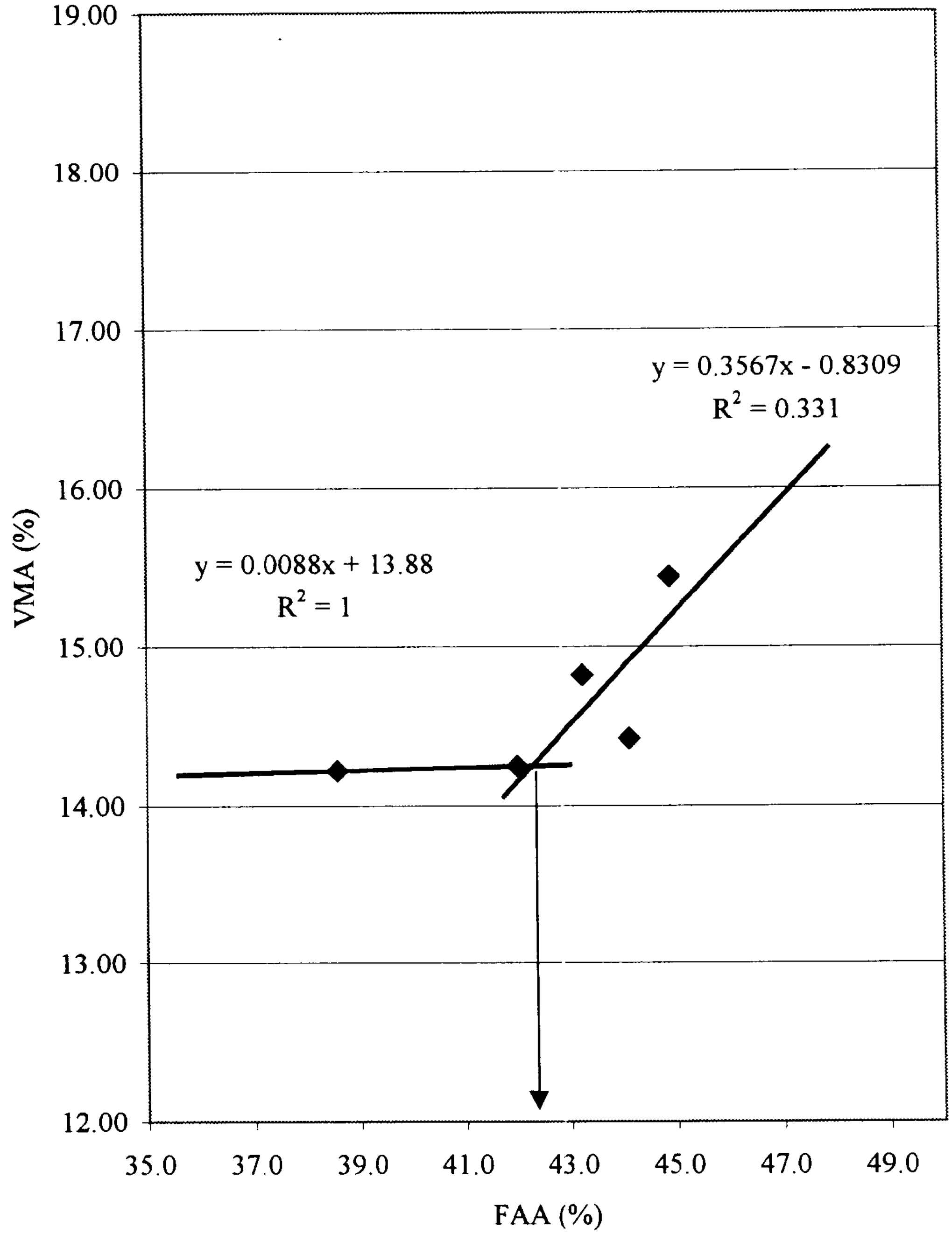

FIGURE 6 VMA vs. FAA for SM-1B Gradation

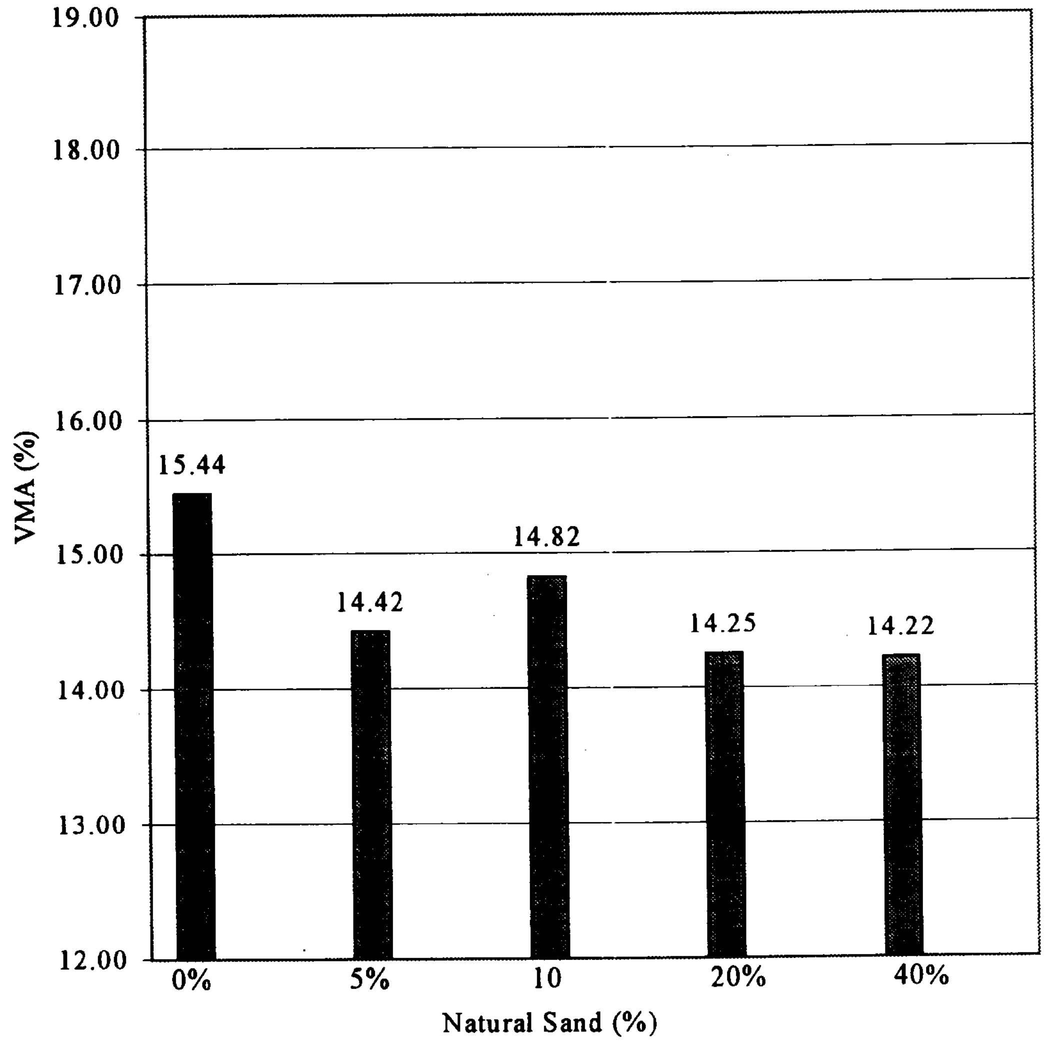

FIGURE 7 VMA vs. Percent Natural Sand for SM-1B Gradation

10% natural sand samples. It has been shown in previous research (20) that small percentages of natural sand seem to lubricate mixes and the variety of particle shape allows for higher densities. As the natural sand content is increased the uniformity of the particles decreases the maximum density that can be achieved and, therefore, increases VMA. It is this behavior that is seen here.

SM-2A Samples

Figure 8 is a plot of the relationship between FAA and VMA for the SM-2A samples. Just as it was seen in the SM-1B samples, FAA does not effect VMA for lower values. For the SM-2A samples FAA values below 45% had no effect on VMA. Increasing FAA above 45% resulted in increased VMA. Nearly one half of a percent VMA was gained for each percent increase in FAA. Figure 9 shows VMA versus percent natural sand. Here again less natural sand resulted in higher VMA. The noted behavior of the SM-1B 5% natural sand samples resulting in slightly lower VMA than the 10% natural sand samples is also seen with the SM-2A samples.

Summary

Both the coarse and fine mixes behaved similarly. VMA increased nearly one half percent with an increase of one percent in FAA for both gradations after a minimum FAA value was reached. Since the minimum value at which FAA affected VMA was different for the two gradations, a single minimum value for which an increase in VMA results in an increase in FAA could not be determined.

Figure 10 represents VMA versus percent natural sand for both mixes. By looking at the trends they create we can see that both mixes behaved similarly. This is

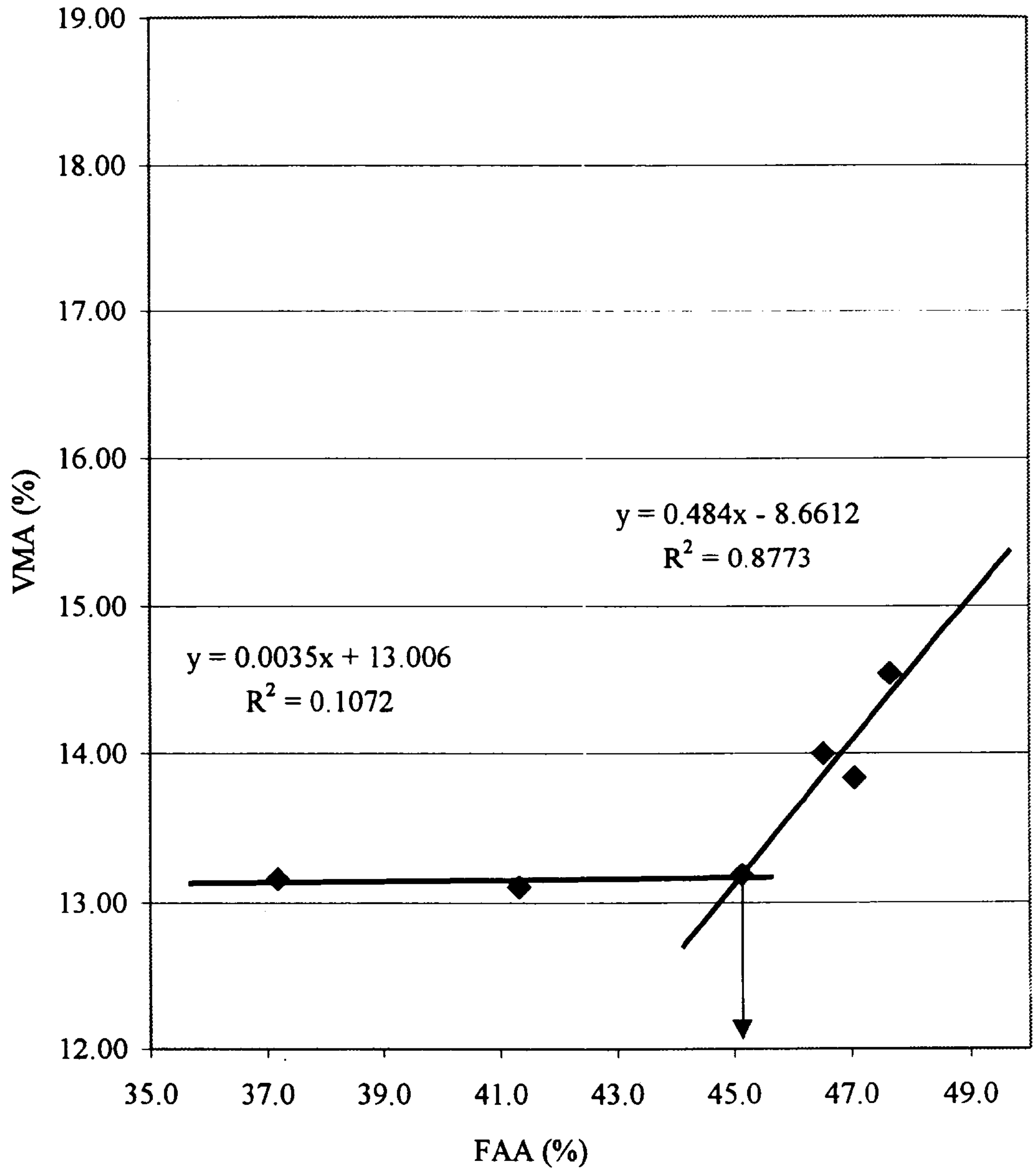

FIGURE 8 VMA vs. FAA for SM-2A Gradation

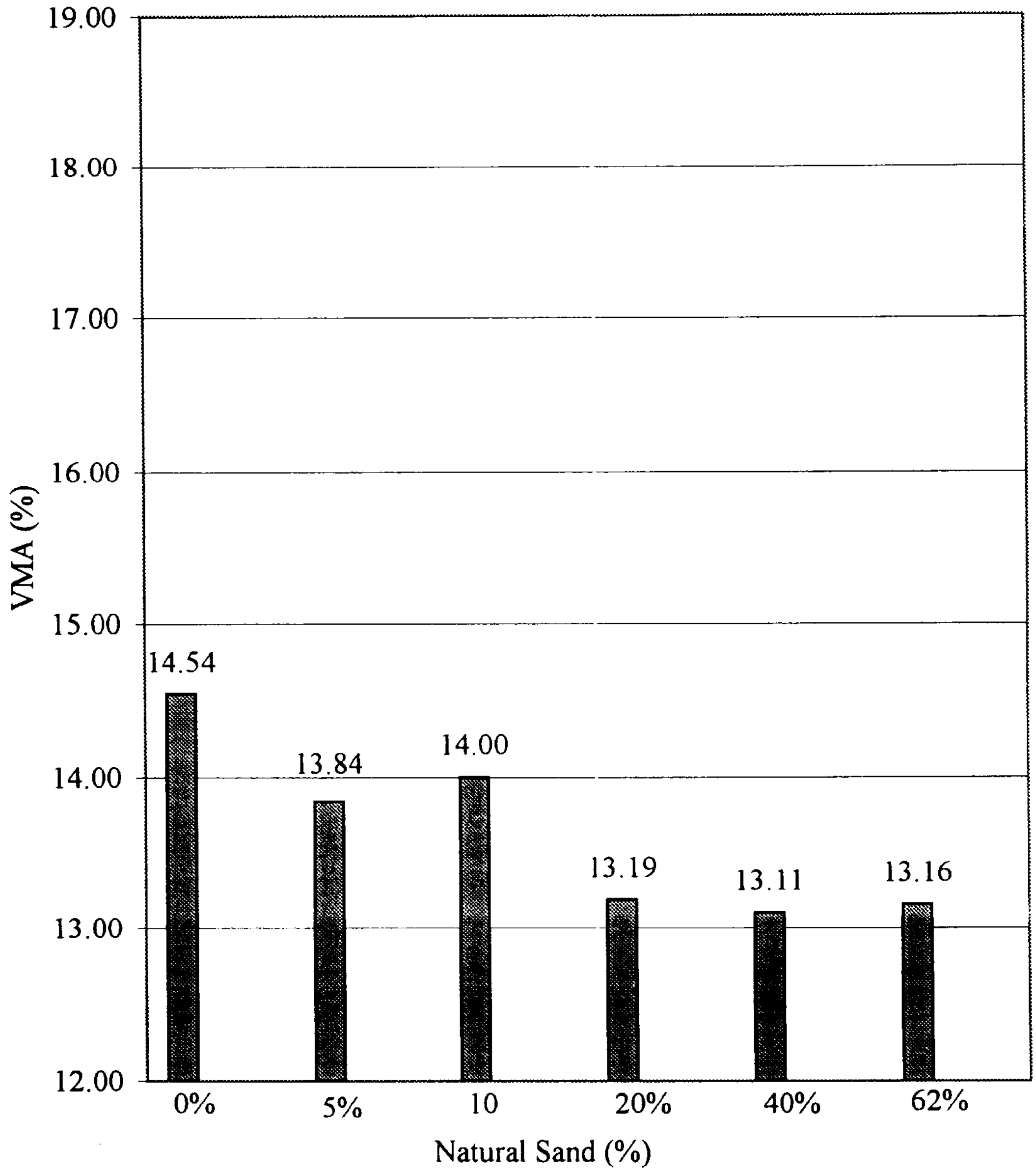

FIGURE 9 VMA vs. Percent Natural Sand for SM-2A Gradation

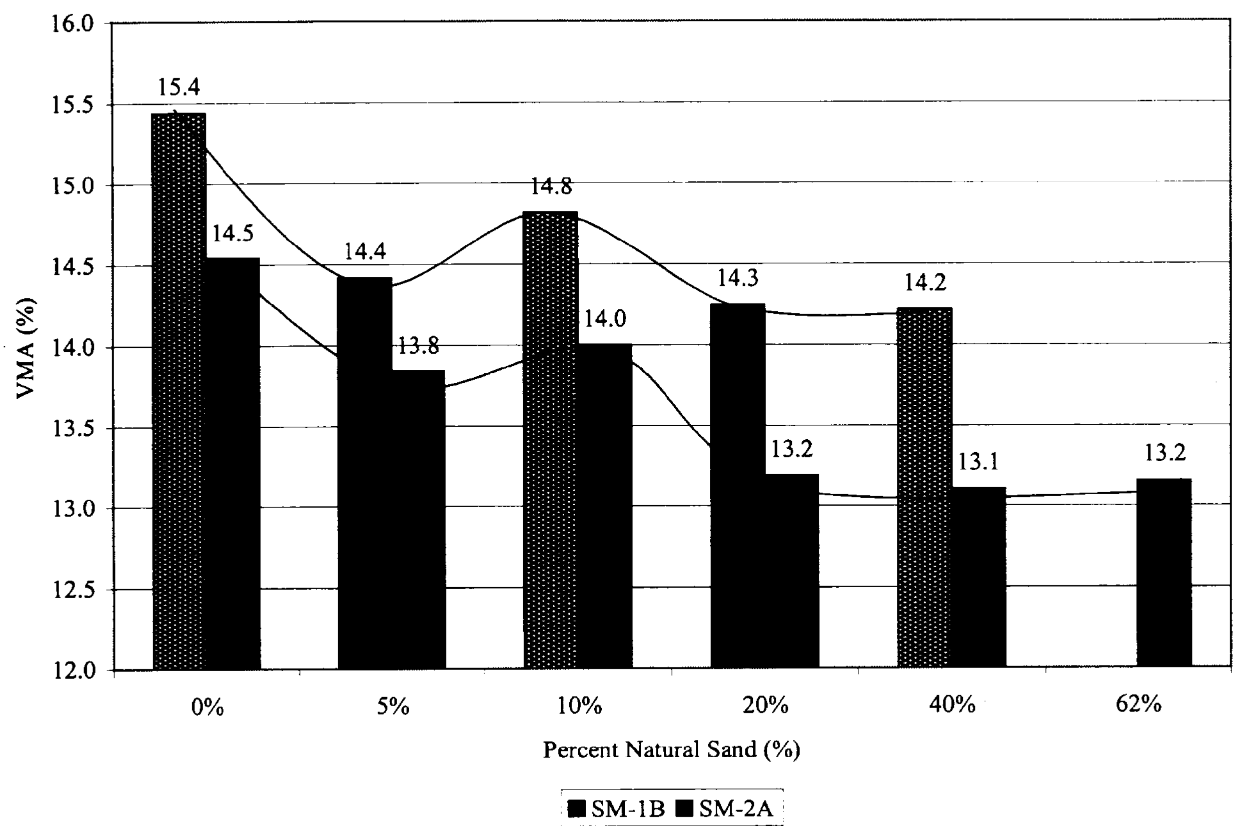
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
VMA (%)
15.4
14.5
14.4
13.8
14.8
14.0
14.3
13.2
14.2
13.1
13.2
0%
5%
10%
20%
40%
62%
Percent Natural Sand (%)
SM-1B
SM-2A

Figure 10

particularly helpful since samples could not be made with 62% natural sand for the SM-1B gradation due to mix instability. When viewed together it is apparent that for both gradations VMA reaches a minimum and levels off around 20% natural sand. This could be due to gradation. As the natural sand content increases the rounded nature of the aggregates allows for all the particles in the mix to slide passed one another. This allows for greater density, i.e. lower VMA. Since the shape of the material is uniform due to the high natural sand content, there is a maximum density that can be achieved, much like apples placed in a crate. Above 20% natural sand the mix is reaching a maximum density for the gradation. When the angularity of the mix is increased to a point that it can reduce the rearranging of particles during the compaction process, it decreases the density that can be achieved, resulting in greater VMA. This explains the two-line trend of Figures 6 and 8.

Figure 11 shows the relationship between percent natural sand and FAA. For both gradations this relationship is linear. The SM-1B and the SM-2A gradations fit a linear equation with an R^2 greater than 0.99. This is why the plots of FAA and percent natural sand versus VMA depict the same trends.

Effect of Rounded Fine Aggregate Angularity on Rutting Performance

Rut susceptibility testing was conducted with an Asphalt Pavement Analyzer (APA) in the dry condition at 58° C. Hose pressure was set at 690 kPa with a normal force of 0.44 kN. The samples tested were the same samples prepared for the voids analysis and had VTM values of 4% ±1%.

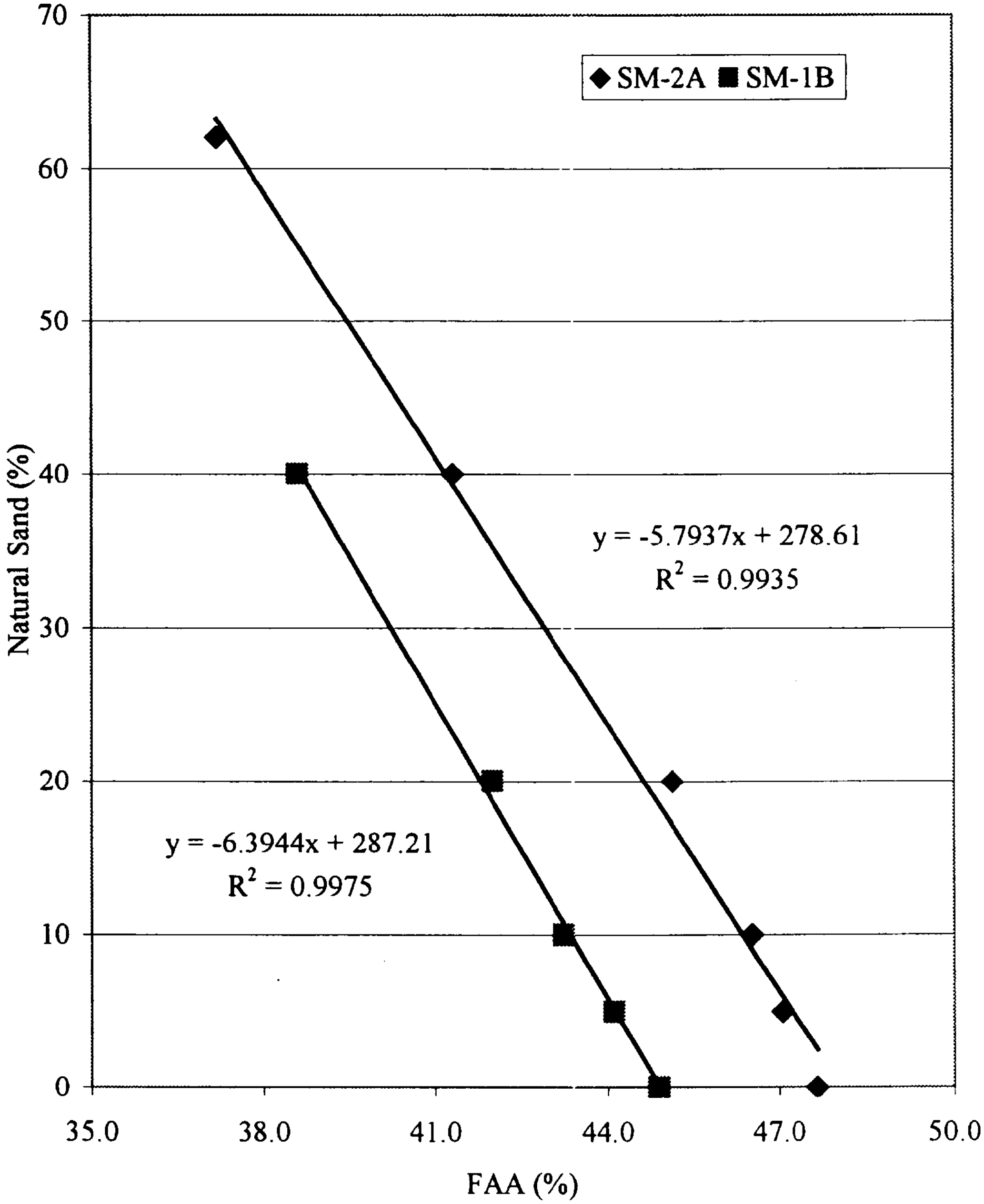

FIGURE 11 Percent Natural Sand vs. FAA

SM-1B Samples

Rut depths for the SM-1B samples are reported for both 4,000 and 8,000 cycles. The values from 4,000 cycles are used for analysis since rutting was greater than 10 mm at 8,000 cycles. Values greater than 10 mm are inaccurate due to mold support of the hose. Figure 12 depicts rut depth versus FAA for the SM-1B samples made with limestone and natural sand. As the angularity of the fine aggregate increases, the amount of rutting decreases. An increase of 1% FAA resulted in a decrease of 0.76 mm at 4,000 cycles. This linear relationship is strong with an R^2 of 0.96. The effect sand percentage has on rutting can be seen in Figure 13. Increased amounts of natural sand result in greater rut depths. From Figure 13 it can be seen that above 10% natural sand rutting increases at a greater rate and above 20% natural sand rutting increases dramatically. This is the point were the natural sand content and/or FAA begin to affect VMA. This trend is not as visible in Figure 12 showing rut depth as a function of FAA. Only when the trend from the previous figures are viewed does the indication of a change in slope occur.

SM-2A Samples

The trends seen in the SM-1B samples are also seen in the SM-2A samples. For these samples, results are provided for 8,000 cycles, which is the typical testing range for the Asphalt Pavement Analyzer. Figure 14 shows the relationship between rut depth and FAA values. Rutting decreases with an increase in FAA. This relationship is nearly as strong as the SM-1B samples with an R^2 of 0.88.

Looking at the effect of natural sand on rutting, Figure 15 shows that with increased natural sand, greater than 10%, rut depths increase then dramatically rise for sand contents above 40%. This is the same break point seen for VMA as a function of

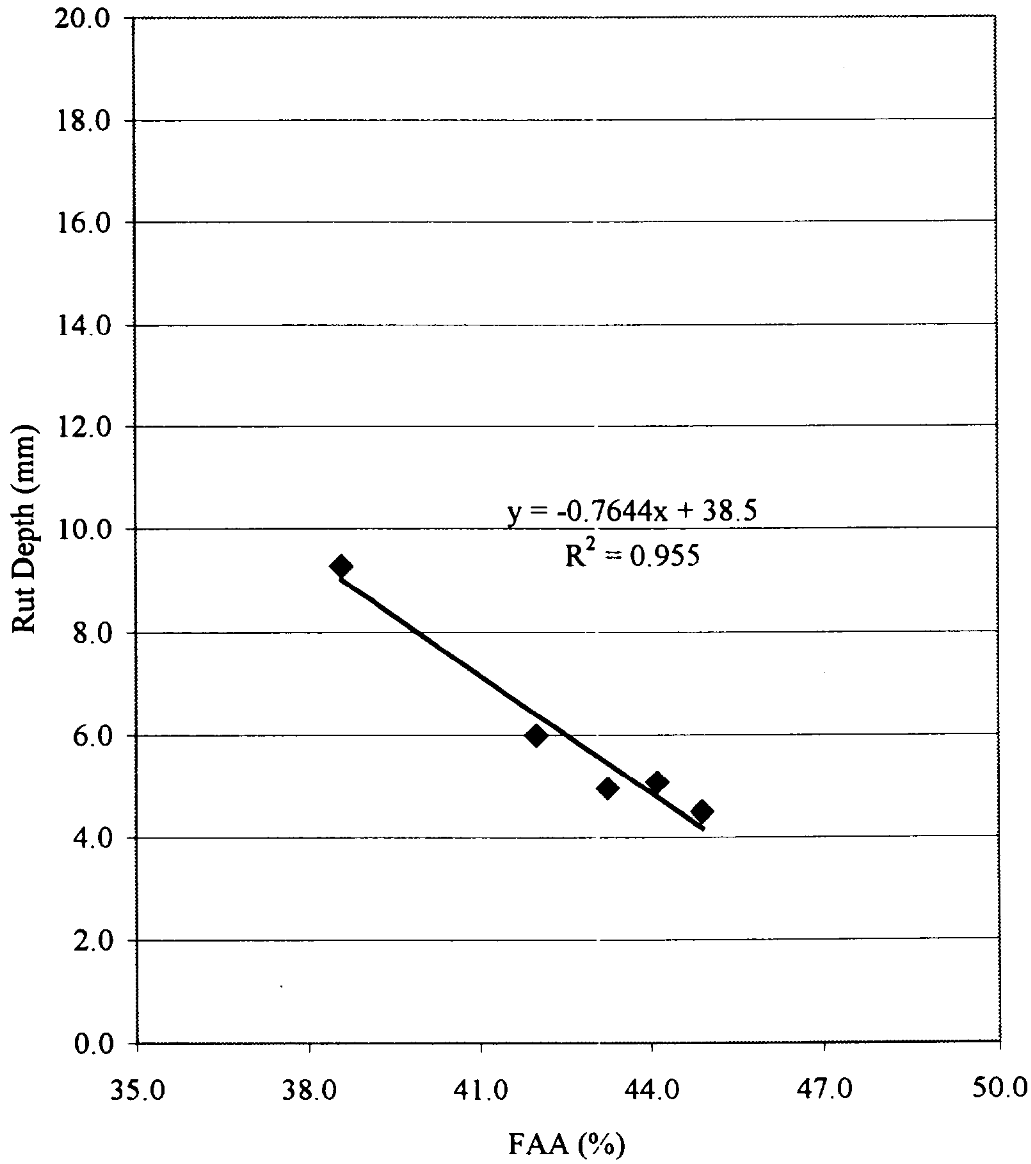

FIGURE 12 Rut Depth vs. FAA for SM-1B Gradation at 4,000 Cycles

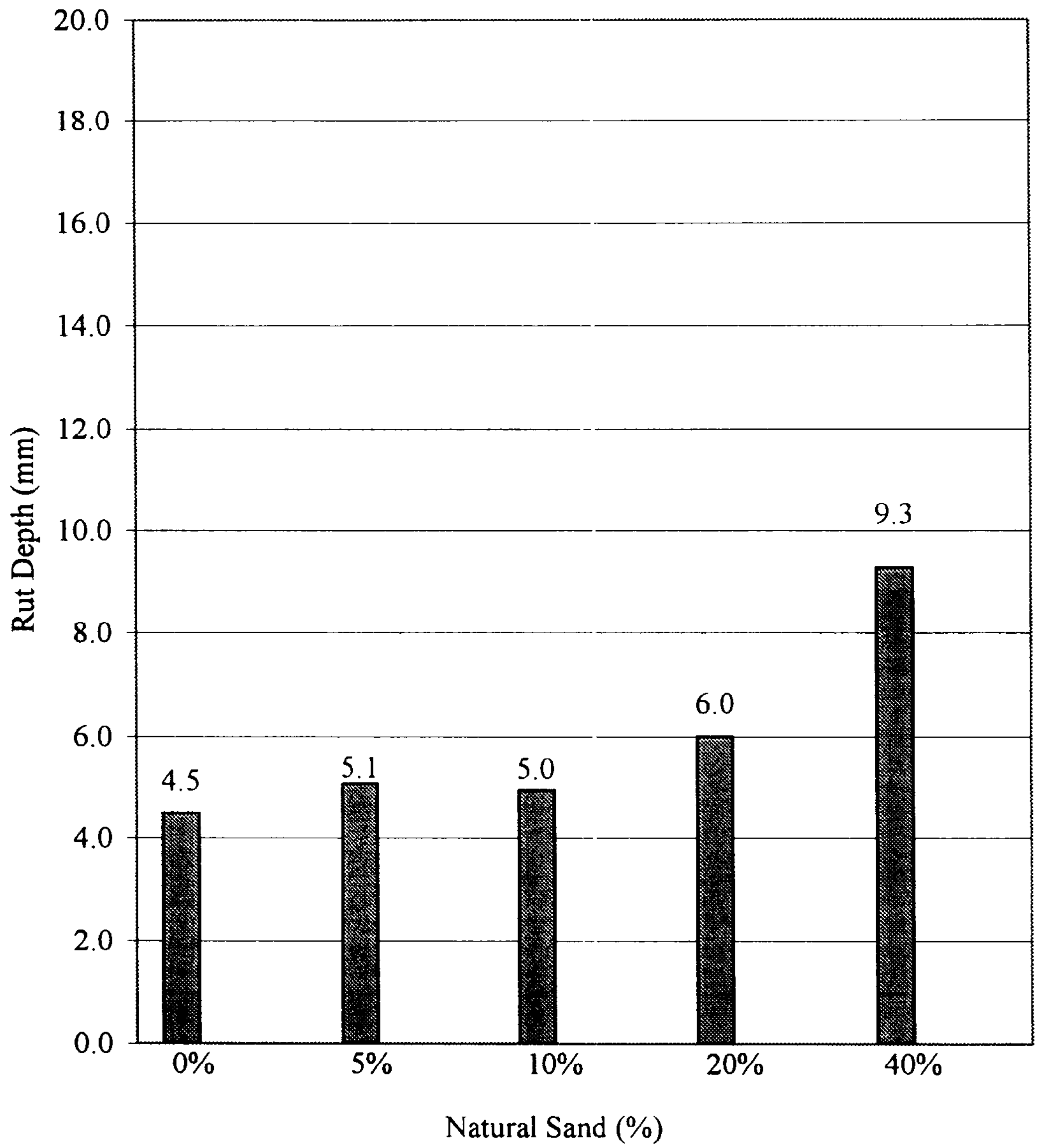

FIGURE 13 Rutting vs. Percent Natural Sand for SM-1B Gradation at 4,000 Cycles

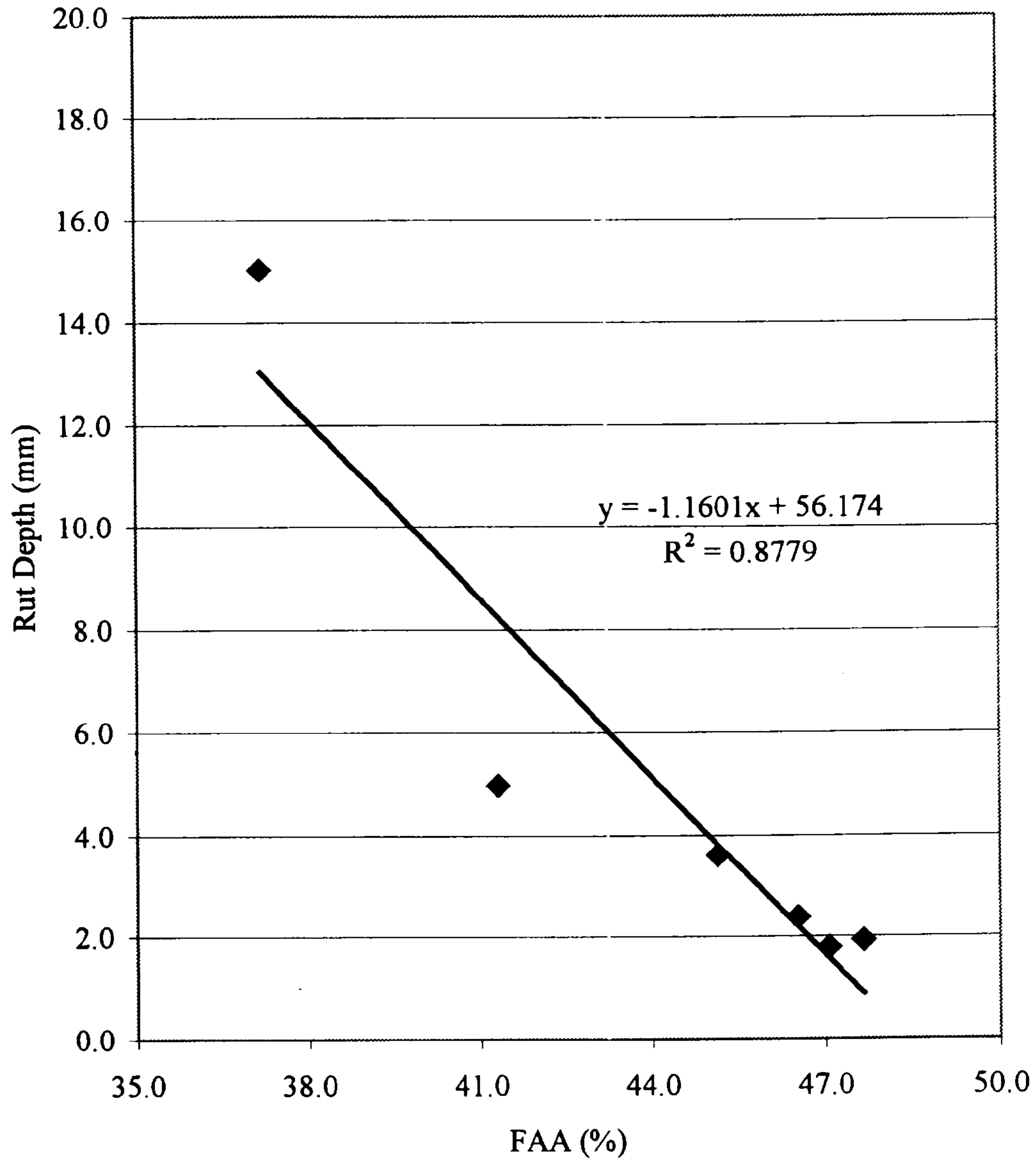

FIGURE 14 Rut Depth vs. FAA for SM-2A Gradation at 8,000 Cycles

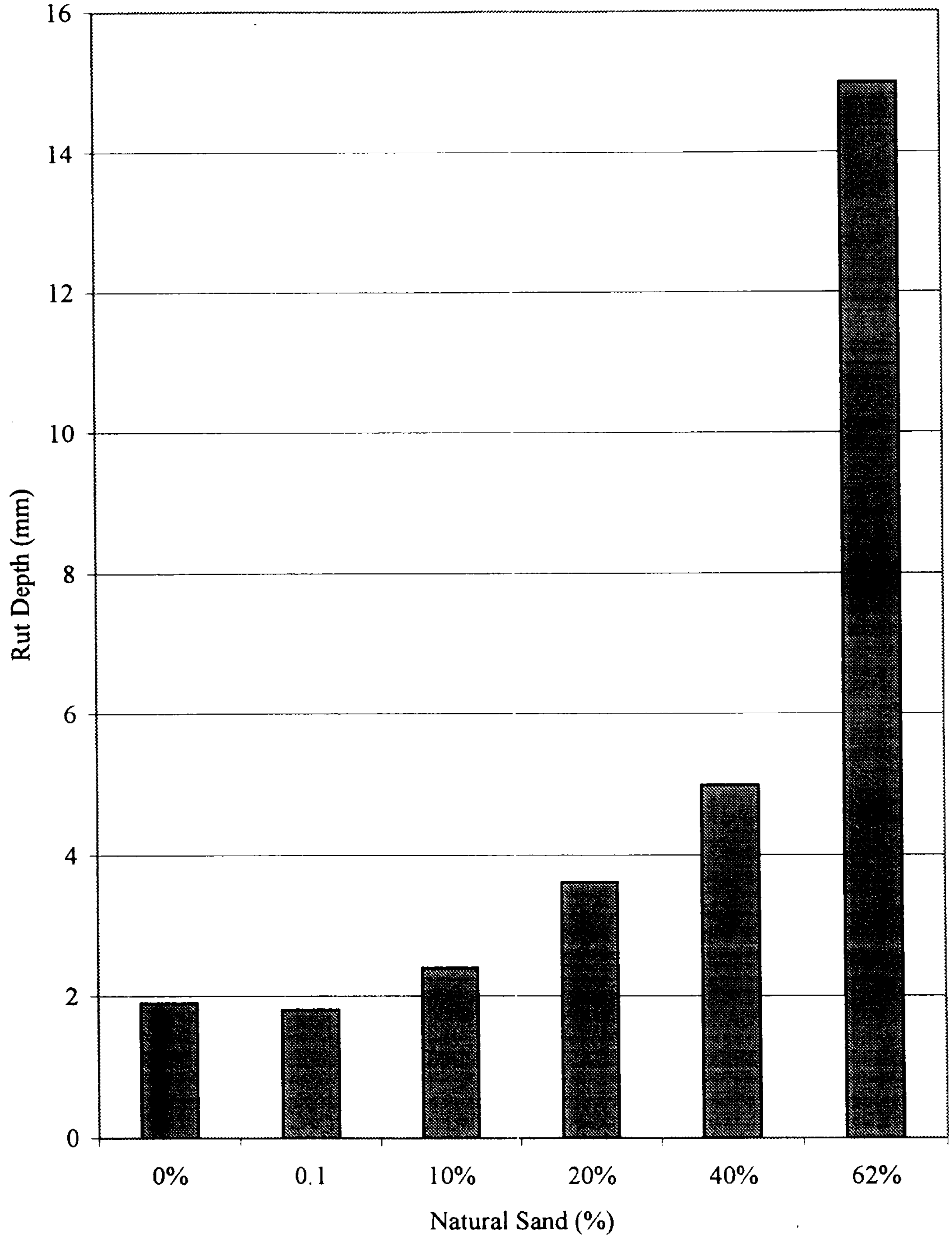

FIGURE 15 Rutting vs. Percent Natural Sand for SM-2A Gradation at 8,000 Cycles

sand content. Again as with the SM-1B samples, a change in slope in not apparent in the plot of rut depth vs. FAA (Figure 14). Here the variability of the samples further hinders a comparison of an FAA value at which VMA increases and rutting decreases.

Summary

Both gradations show that samples with greater FAA values rut less and the relationship between FAA and rutting appears to be linear. Both gradations show that when the natural sand percentage exceeds 10%, rutting begins to increase. While the plots of rutting versus natural sand content, Figures 13 and 15, indicate a change in slope as sand content increases, a two-slope trend is not apparent in the plots of rutting vs. FAA, Figures 12 and 14. The R^2 for the linear relationship between rutting and FAA is strong for both gradations, but when viewed with the trend lines of the VMA plots, Figures 6 and 8, there is the possibility of a two-slope trend. These trends would have break points that are coincident with the break points of the VMA versus FAA plots at 42% and 45%.

Since the SM-1B samples rutted so severely, they cannot be directly compared with the SM-2A samples to determine if either gradation is more susceptible to angularity adjustments. However, the slope of the trend line for rutting versus FAA for the SM-2A gradations was 1.5 times greater than that of the SM-1B gradation. The higher slope indicates that FAA effects rut depth more for mixes that are above the maximum density line than mixes that are below the maximum density line. However, the gradation of the SM-1B samples is more susceptible to rutting compared to the SM-2A gradation.

The severe rutting of the SM-1B samples in comparison to the SM-2A samples confirms that gradation does play a role in rutting susceptibility. Both of these gradations meet SHRP and KDOT specifications for gradation. Since the SM-1B samples met these specifications, yet performed poorly, it can be seen that there is a need for strength testing with the Superpave design method.

FLAKY FINE AGGREGATE

Effect of Flaky Fine Aggregate Angularity on VMA

SM-1B Samples

Figure 16 shows the VMA results for the SM-1B samples made holding the natural sand constant at 22% and 42% while replacing limestone with chat sand. VMA increases with increased chat content. This trend can be seen for both natural sand contents. The 42% natural sand samples showed slightly higher VMA results than those made with 22% natural sand. It was expected that the samples made with more natural sand would have less VMA, as found in the first part of this research. It is possible that particle uniformity is causing the slightly higher VMA in the 42% natural sand samples.

Figure 17 shows the VMA results for the SM-1B samples made holding the crushed limestone constant at 42% and replacing natural sand with chat sand. As the chat percentage increases the resultant VMA increases. These results are combined with the data from the samples made holding the natural sand constant and are shown in Figure 18. VMA increases 1.5% with a 10% increase in chat sand. An R^2 of 0.87 reinforces this direct correlation.

Figure 19 shows the relationship between FAA and VMA for the SM-1B samples made with chat sand. If all of the data is viewed as a whole, VMA does not appear to be a function of FAA, with an R^2 of 0.05. When the data is viewed as three separate sets, by chat sand content, it can be seen that the effect of chat sand on VMA is far greater than its effect on FAA. Within each subgroup of samples in Figure 19, it can be seen that

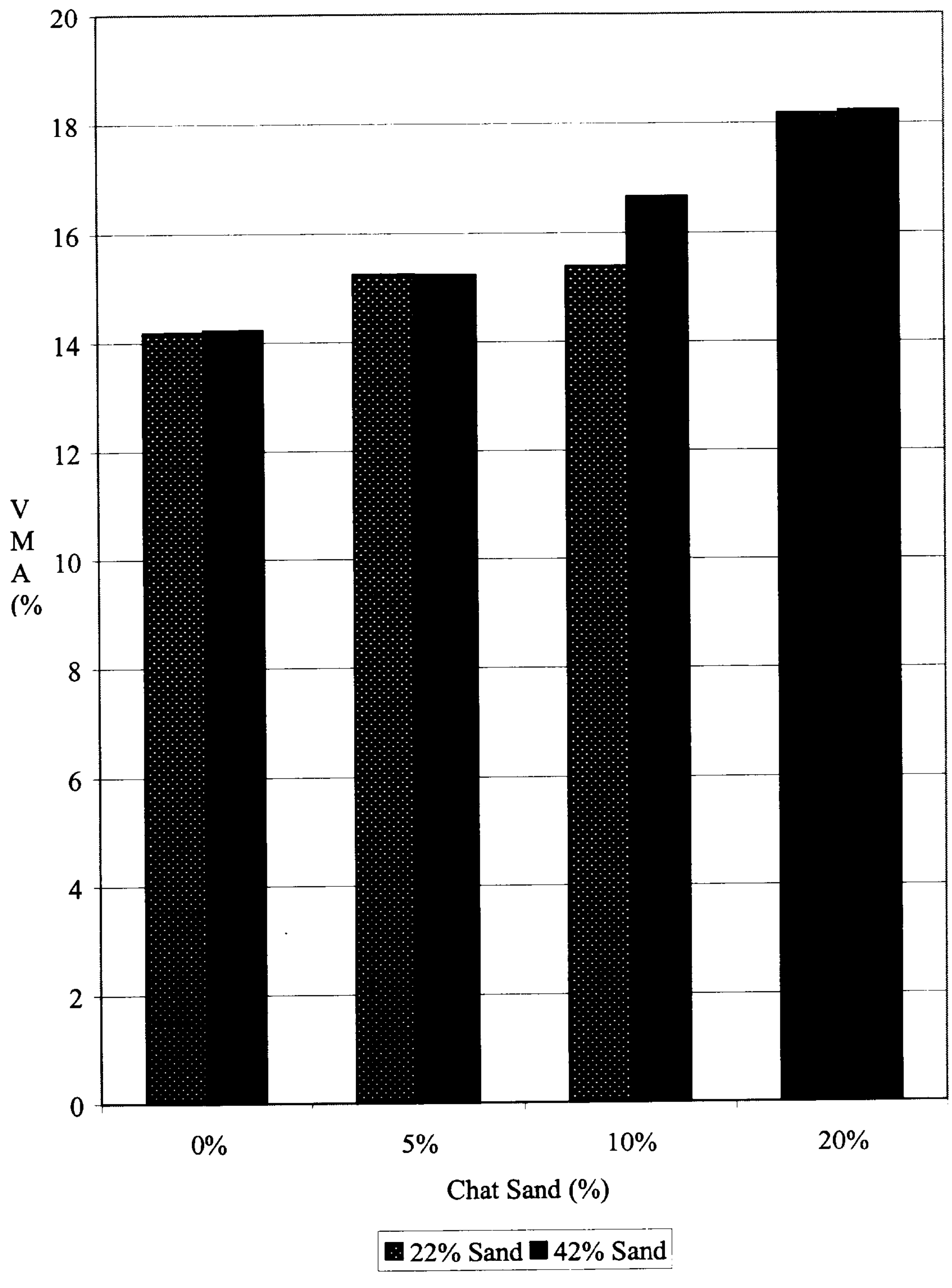

FIGURE 16 VMA vs. Percent Chat Sand for SM-1B Gradation

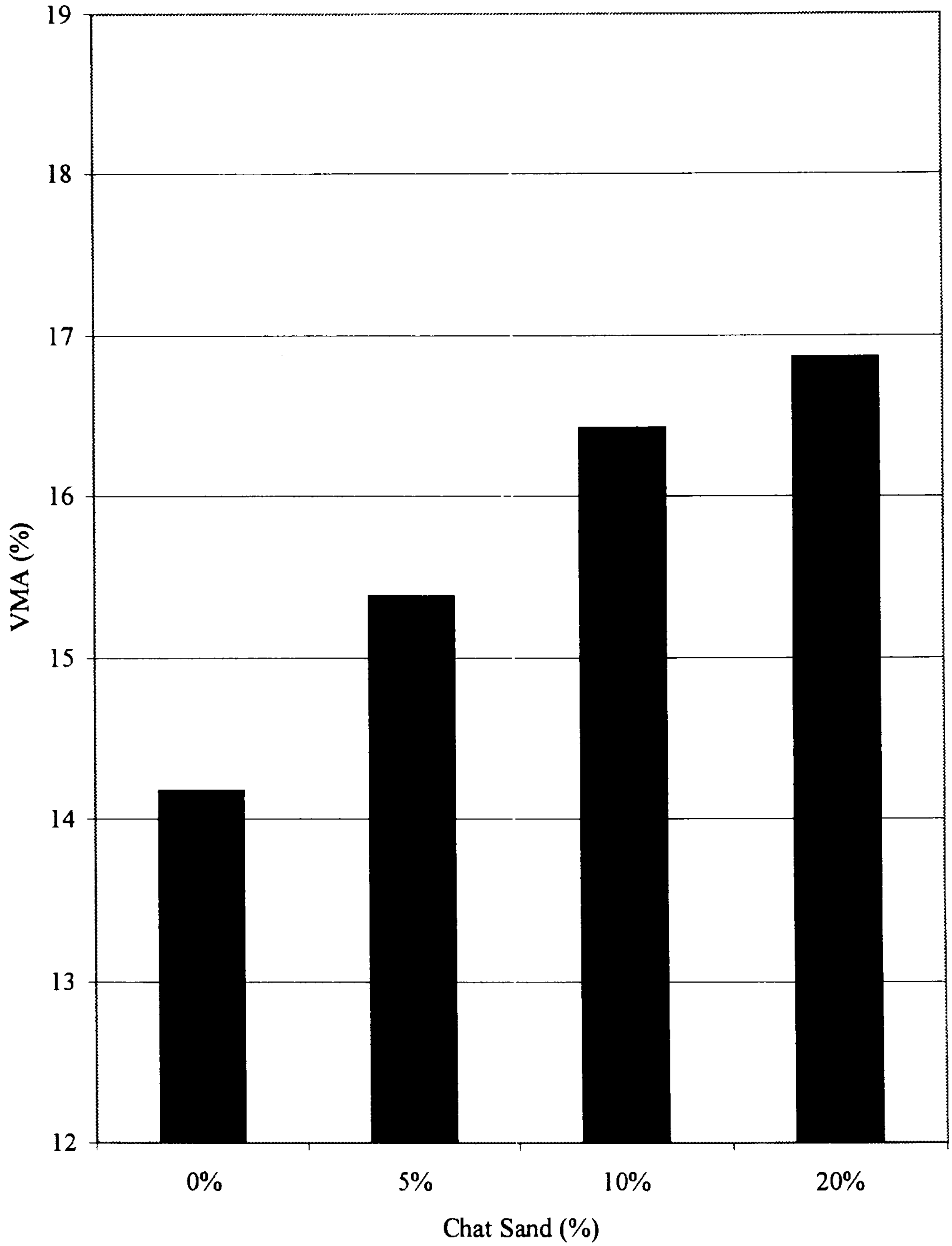

FIGURE 17 VMA vs. Percent Chat sand for SM-1B Samples With 42% Limestone

increased FAA results in increased VMA. It is possible that the flaky structure of the chat sand is increasing VMA, but having only a small effect on FAA. Chat sand is, therefore, acting as an effective sweetener.

SM-2A Samples

Figure 20 shows VMA versus percent chat sand for the SM-2A samples made holding the natural sand constant at 22% and 42% and exchanging chat for limestone. Increased chat sand content results in higher VMA. This trend is distinct for both the 22% and the 42% natural sand samples. With the exception of the 20% chat sand samples, the 22% natural sand samples had greater VMA than those made with 42% sand. This is consistent with the behavior seen in the angularity samples made with just limestone and natural sand.

Figure 21 shows the VMA results for the SM-2A samples made holding the crushed limestone constant at 42%. As seen with the natural sand held constant, increased chat sand content results in increased VMA.

Figure 22 shows the VMA versus percent chat sand for the SM-2A samples. An increase in chat sand results in an increase in VMA. This increase is slight, with only a 0.8% increase in VMA for a 10% increase in chat sand, but has a strong R^2 of 0.89.

Figure 23 depicts the relationship between FAA and VMA for the SM-2A samples made with chat sand. There appears to be no relationship between FAA and VMA. Here again by looking at chat sand content we can see that chat is controlling VMA. Unlike the SM-1B samples, FAA does not consistently relate to VMA within data sets for each natural sand or limestone content. The slope of the trend lines for the samples made holding the natural sand constant are negative while the trend line of the samples made holding the limestone constant has a positive slope. The crushed limestone

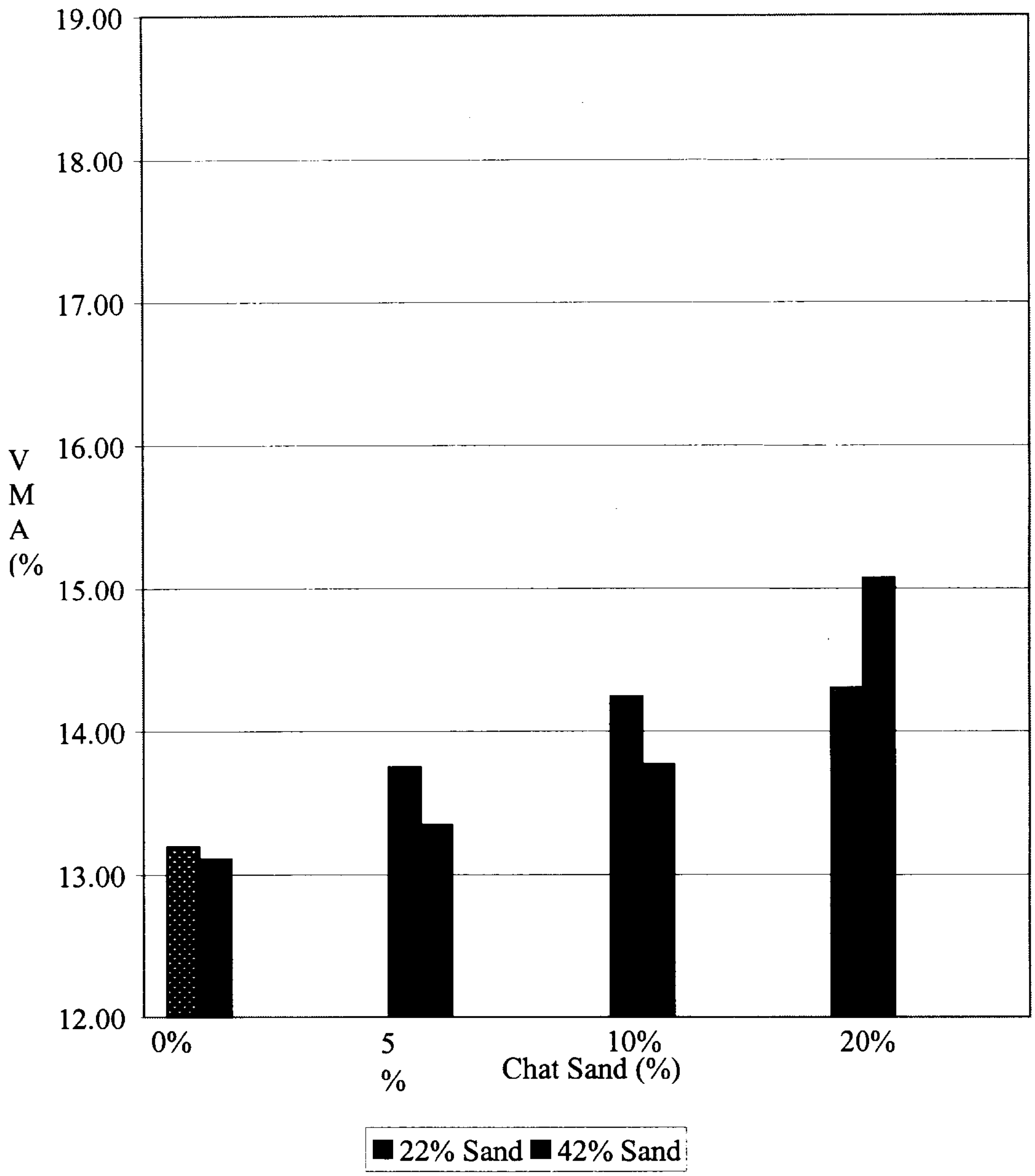

FIGURE 20 VMA vs. Percent Chat Sand for SM-2A Gradation

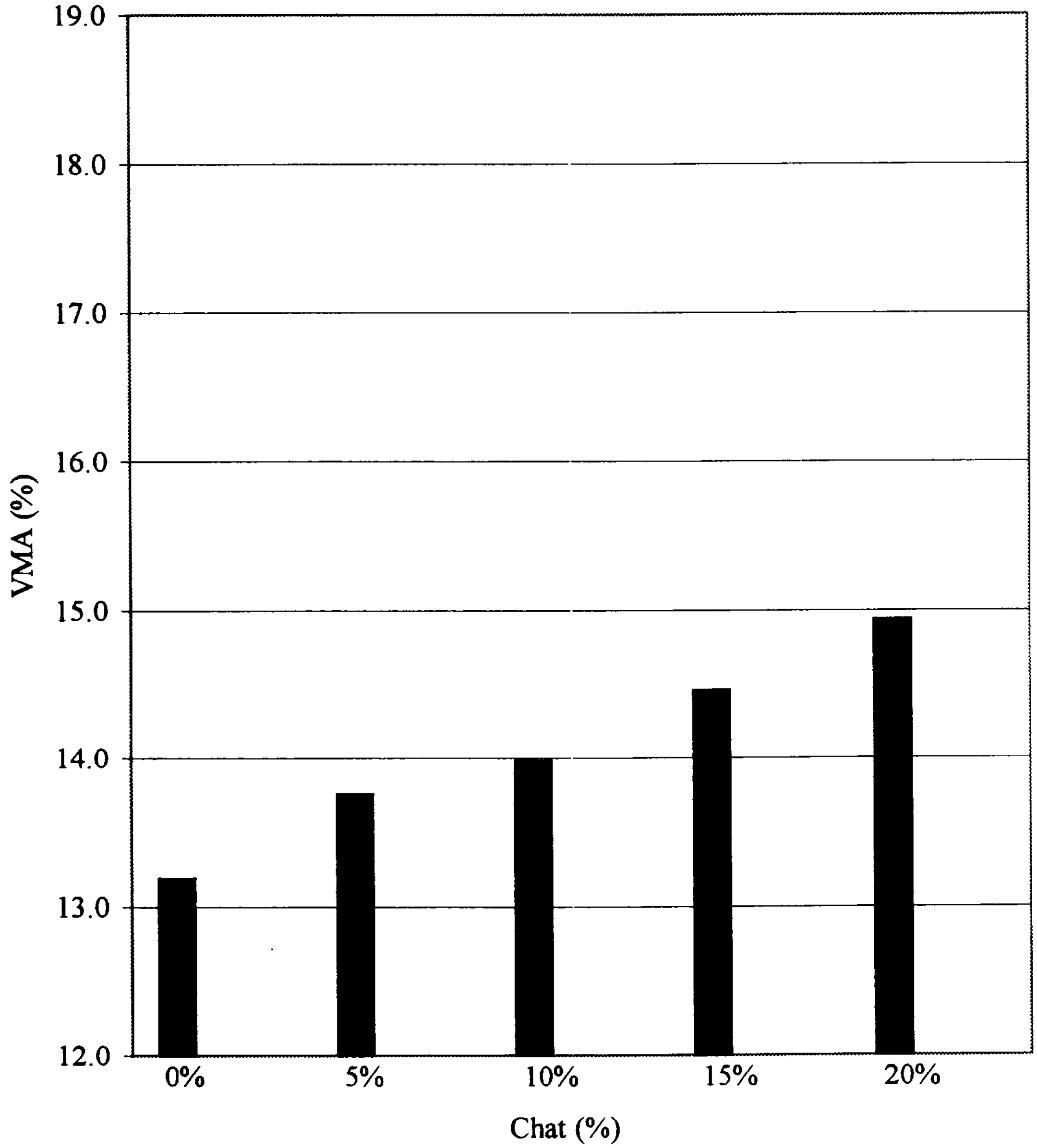

FIGURE 21 VMA vs. Percent Chat Sand for SM-2A Samples With 42% Limestone

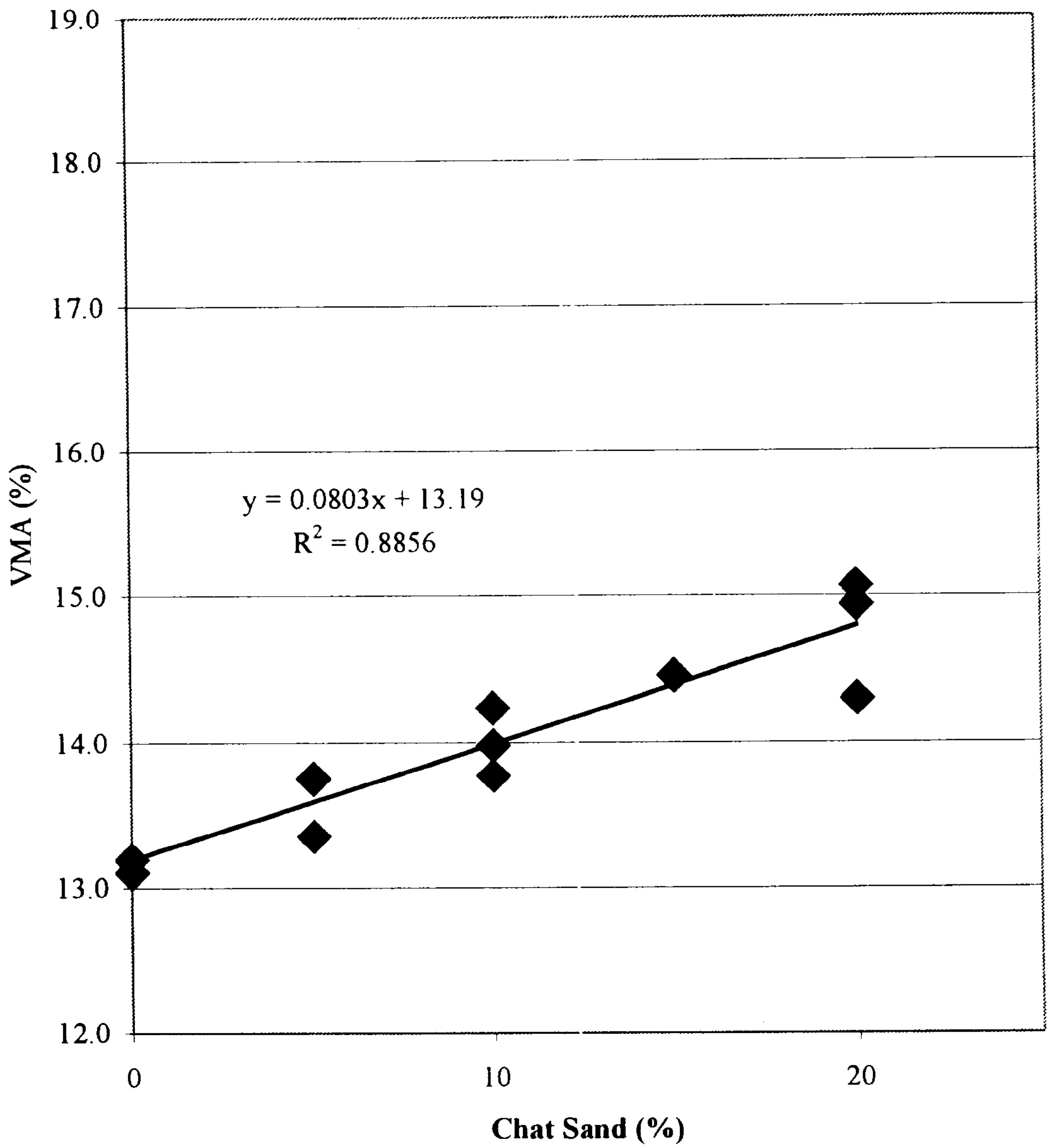

FIGURE 22 VMA vs. Percent Chat Sand for All SM-2A Samples

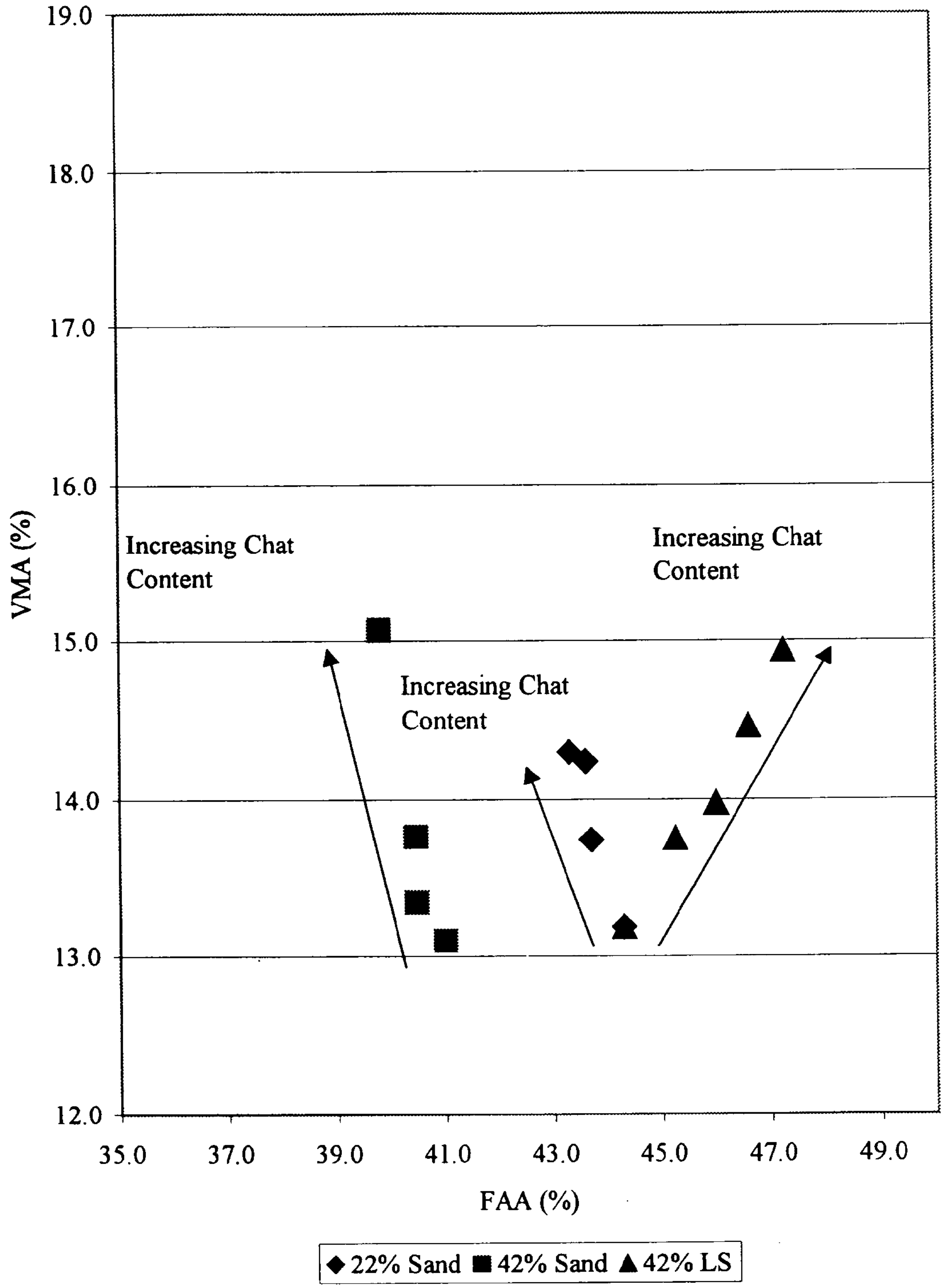

FIGURE 23 VMA vs. FAA for SM-2A Samples Made With Chat Sand

used for the SM-2A samples has an FAA value greater than that of the chat, 46.0 to 47.7, respectively in contrast to the CS-2 used for the SM-1B sample which has an FAA value that is less than that of the chat, 44.6 and 46.0, respectively. As chat sand replaces limestone the FAA decreases, yet the VMA increases. For samples containing chat sand FAA is not a predictor of VMA.

Summary

Both gradations showed that an increase in chat sand content results in increased VMA. This is true whether chat sand is substituted for natural sand or crushed limestone. The SM-1B samples appear to be more affected by the addition of chat sand. By comparing the slopes of the trend lines from Figures 18 and 22, depicting VMA as a function of percent chat sand, it can be seen that the VMA of the SM-1B gradation is more affected by changes in chat content. An increase in chat sand increased VMA of the SM-1B samples twice as much as the SM-2A samples.

The effect of the percentage of natural sand in the mix with the addition of chat sand is unclear. The first part of this research indicated that increased natural sand content resulted in lower VMA. This was mostly true for the SM-2A samples, but not for the SM-1B samples. The difference was minor and could be due to normal variability.

As seen in Figure 24, FAA was a poor predictor of VMA for both gradations. While VMA increases as FAA increases for the SM-1B samples this trend is only seen by looking at the samples made with a single sand or limestone content individually (Figure 19). This trend could not be used for the purposes of mix design for mixes that contain chat sand. The VMA of the SM-2A samples increases and decreases as FAA increases depending on whether sand or limestone is replaced with chat (Figure 23). By looking at

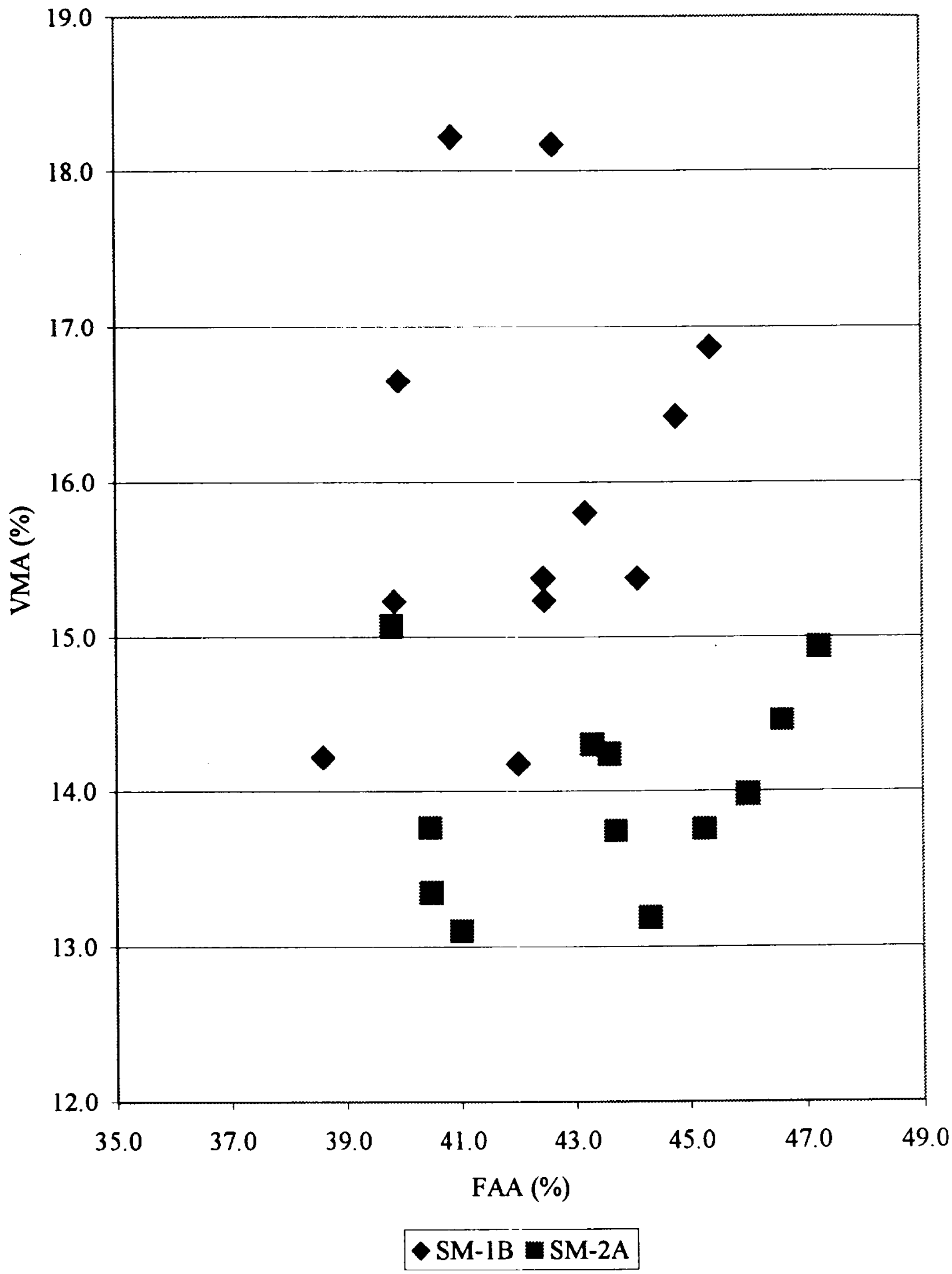

FIGURE 24 VMA vs. FAA for All Samples Made With Chat Sand

both the SM-1B and SM-2A data it can be seen that for mixes that contain chat sand, FAA is not a reasonable predictor of VMA (Figure 24).

While the percentage of chat sand was not a direct predictor of VMA, it was shown by using all samples that increasing the chat content of a mix increases VMA (Figures 18 and 22). An increase of 10% chat sand in the SM-1B samples resulted in a 1.5% increase in VMA and a 0.8% increase in the SM-2A samples.

Effect of Flaky Fine Aggregate on Rutting Performance

SM-1B Samples

Figure 25 shows a plot of rut depth versus FAA for the SM-1B samples made with flaky fine aggregate (chat sand). From this plot it can be seen that for samples made with chat sand, FAA does not predict rutting susceptibility (R^2 = 0.49), but in general, rutting is reduced as FAA increases. By taking into account chat content it can be seen that chat sand is affecting rut depth more than FAA. This is better illustrated by Figure 26. Figure 26 is a plot of rut depth as a function of chat sand percentage. For the samples made with the natural sand held constant at 22% and 42%, rutting increases as limestone is replaced by chat. The correlation between chat sand content and rutting is strong with R^2 values of 0.80 and 0.93 for the 22% and 42% natural sand samples, respectively. Rutting increased by over 1.0 mm with a 5% increase in chat sand content.

The addition of chat sand to samples made by holding the limestone content constant to 42% showed no increase in rutting. The horizontal slope of the trend line indicates that a change in chat sand content does not relate to a change in rut depth. Since the chat sand content was increased by replacing natural sand, and there was no change in rutting, the effect of chat sand on rutting is shown to be similar to that of natural sand.

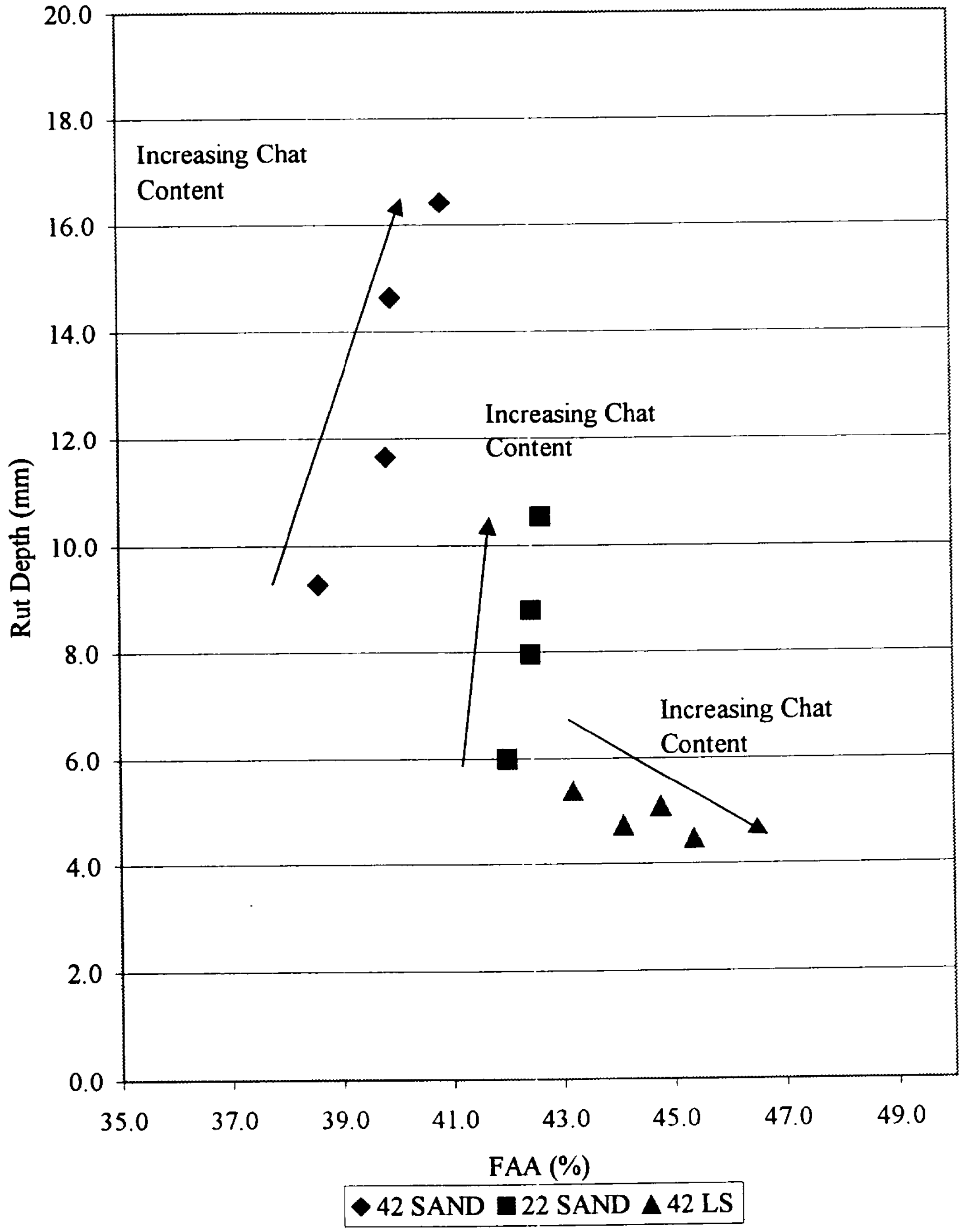

FIGURE 25 Rut Depth vs. FAA for SM-1B Chat Sand Samples at 4,000 Cycles

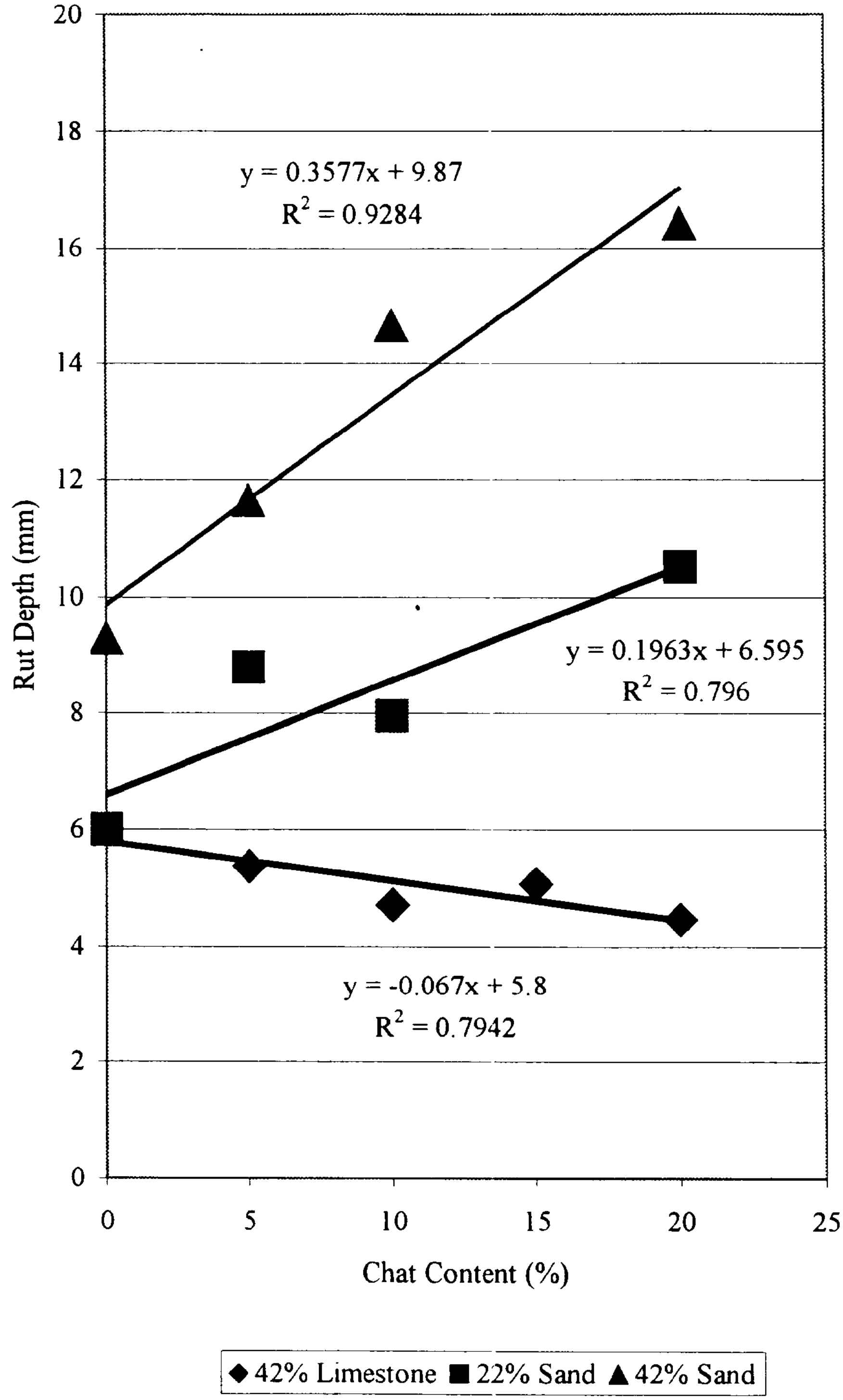

FIGURE 26 Rut Depth vs. Chat Sand for SM-1B Samples at 4,000 Cycles

Figure 27 shows rut depth as a function of limestone content for the samples made with chat sand. As the limestone content increases, rutting decreases linearly with an R^2 of .95 regardless of the sand to chat ratio. A 5% increase in crushed limestone sand results in more than 1.0 mm decrease in rutting. This further strengthens the argument that chat and natural sand have the same negative effect on the rutting performance of a mix.

SM-2A Samples

The SM-2A samples with flaky fine aggregate behaved similarly to the SM-1B samples. Figure 28 is a plot of rut depth as a function of FAA. There is a linear relationship (R^2 0.69) between FAA and rut depth when all of the samples are viewed together. The relationship shows that as the FAA increases, rutting decreases. By looking at the same plot and noting the chat sand content, the relationship of chat content and rutting stands out. Figure 29 shows rut depth as a function of chat sand content. For the samples made exchanging chat for limestone, an increase in chat results in a linear increase in rut depth. This relationship is strong with an R^2 value of 0.83 and 0.94, respectively, for both trend lines. For the samples made with 42% limestone, replacing natural sand with chat sand showed little change in rut depth with an increase in chat content. Rutting increases when chat replaces limestone, but when chat replaces natural sand there is little effect on rutting. The chat sand is behaving like natural sand even though it has a FAA value of 46.0 compared to 37.2 of the natural sand. Figure 30 shows rutting as a function of limestone content. Rutting increases over 2 mm for each 10% replacement of limestone with natural sand or chat sand (R^2 0.84). This is true regardless of the ratio of natural

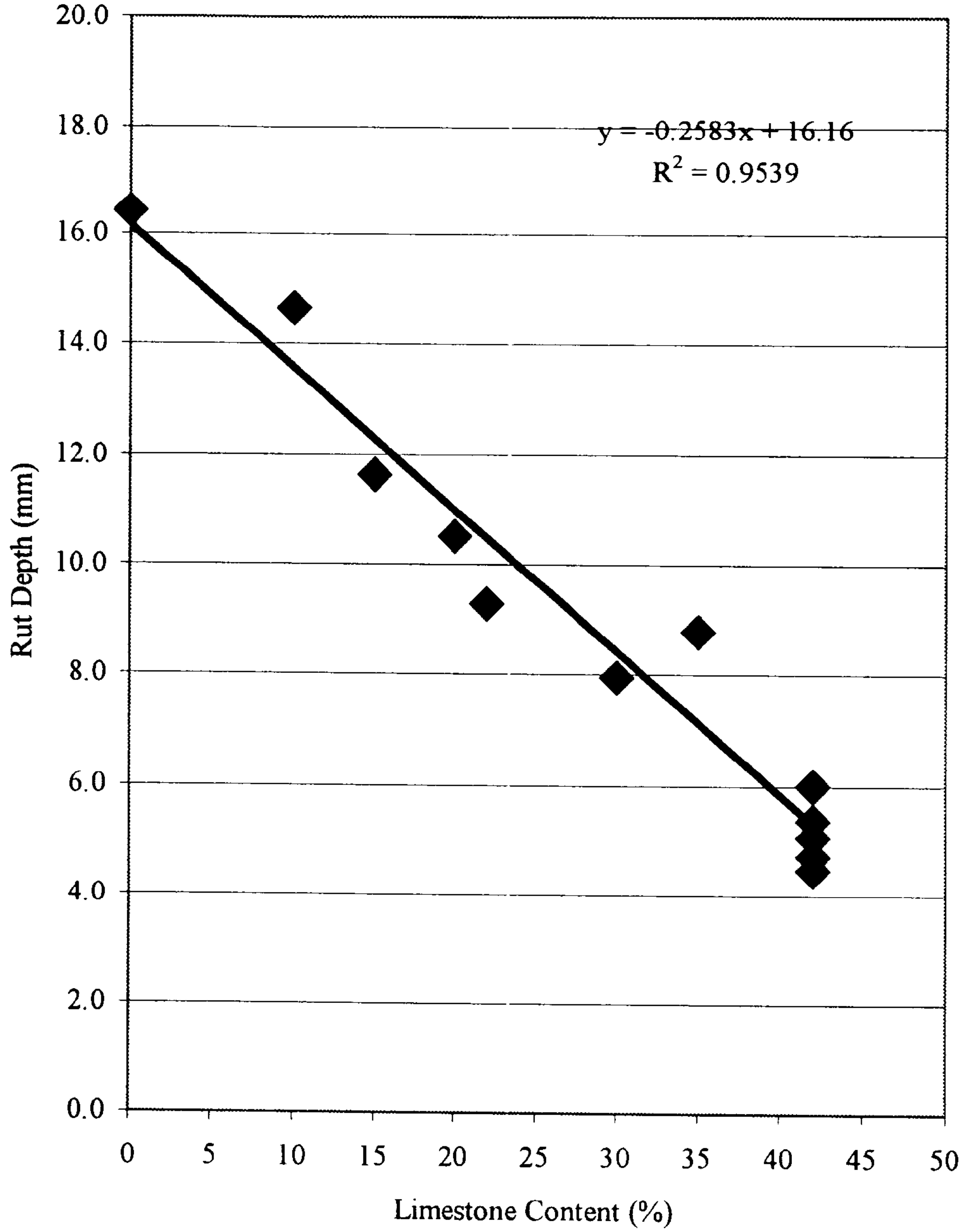

FIGURE 27 Rut Depth vs. Percent Limestone for SM-1B Samples at 4,000 Cycles

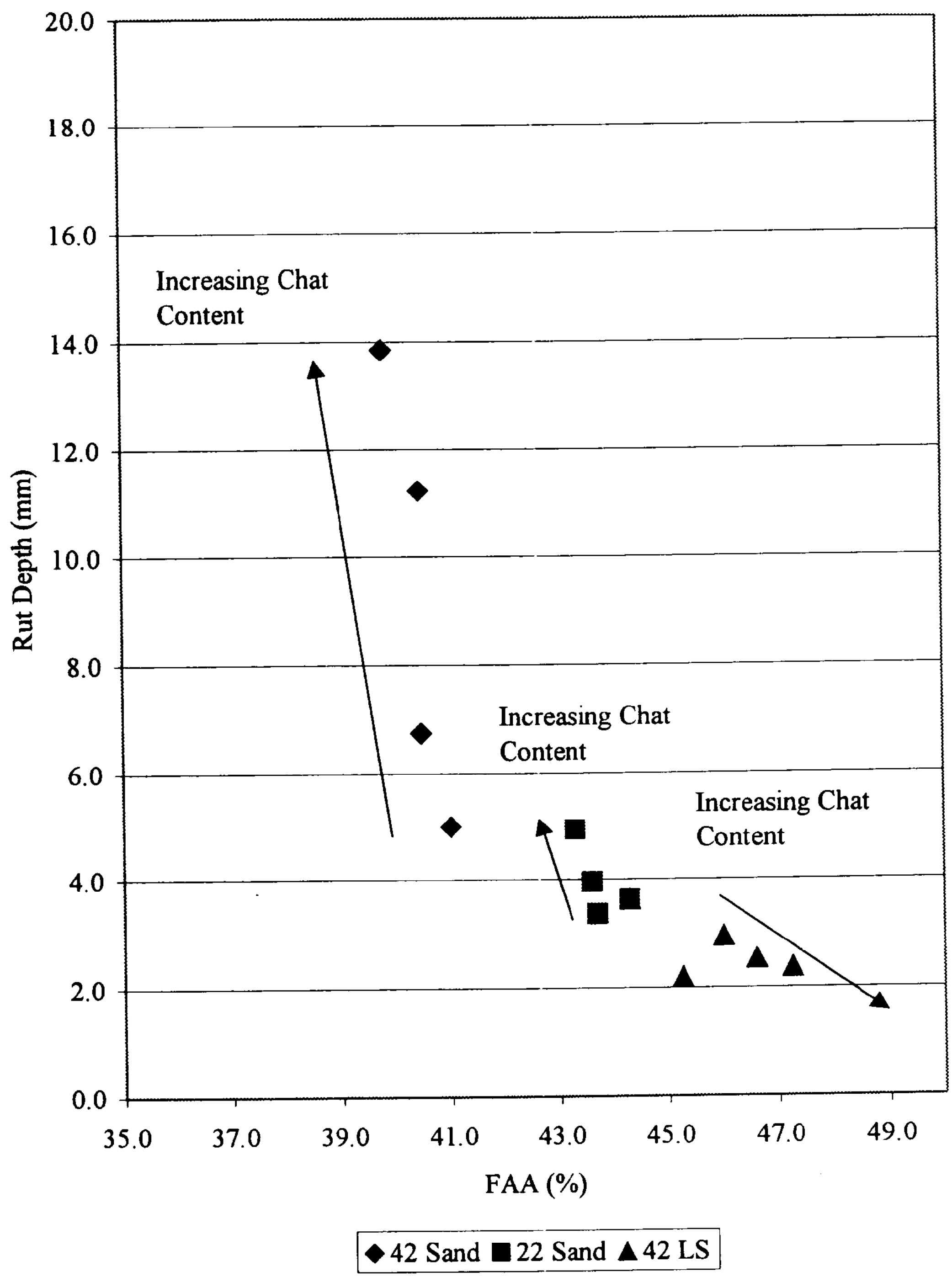

FIGURE 28 Rut Depth vs. FAA for SM-2A Chat Sand Samples at 8,000 Cycles

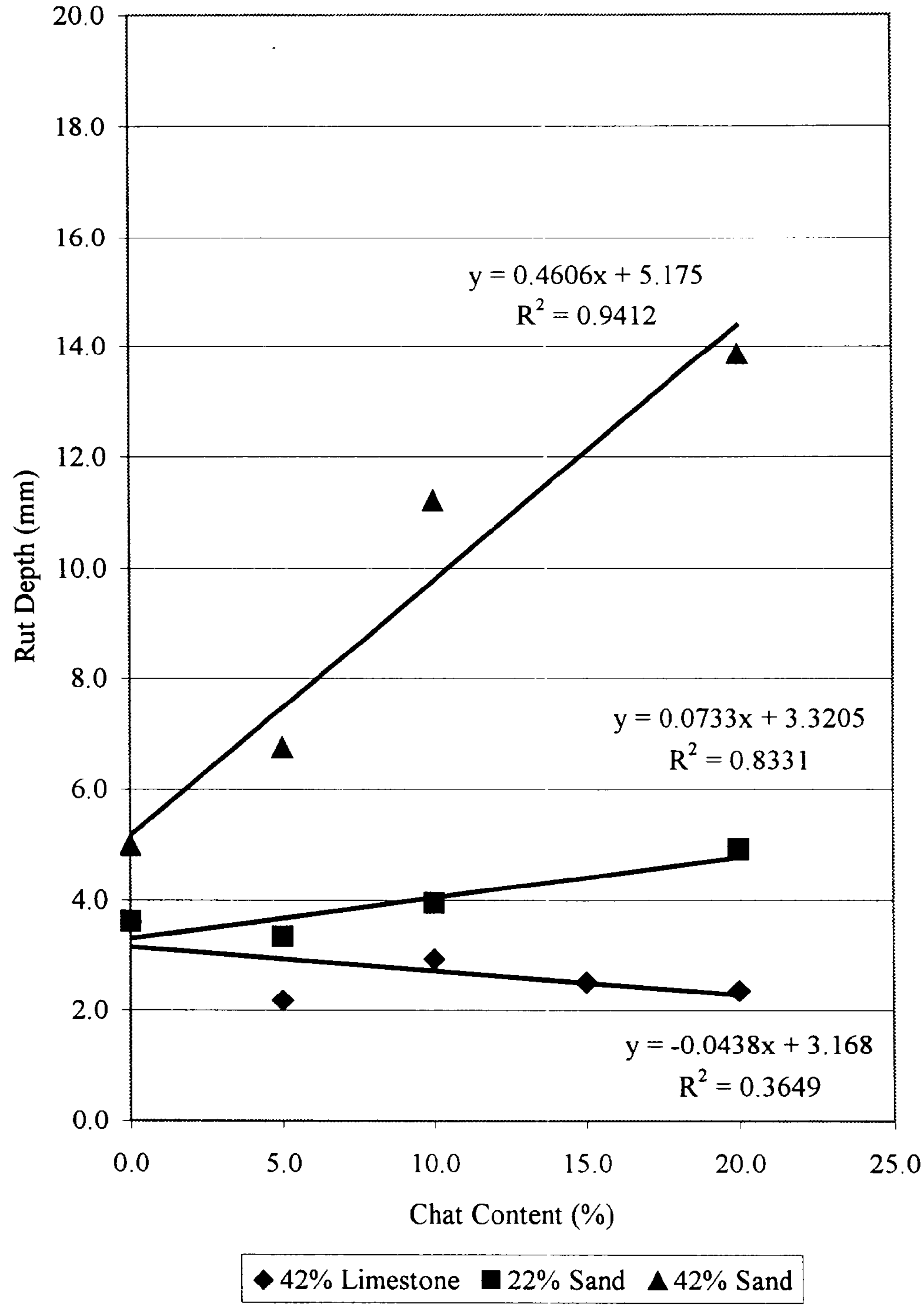

FIGURE 29 Rut Depth vs. Chat Sand for SM-2A Samples at 8,000 Cycles

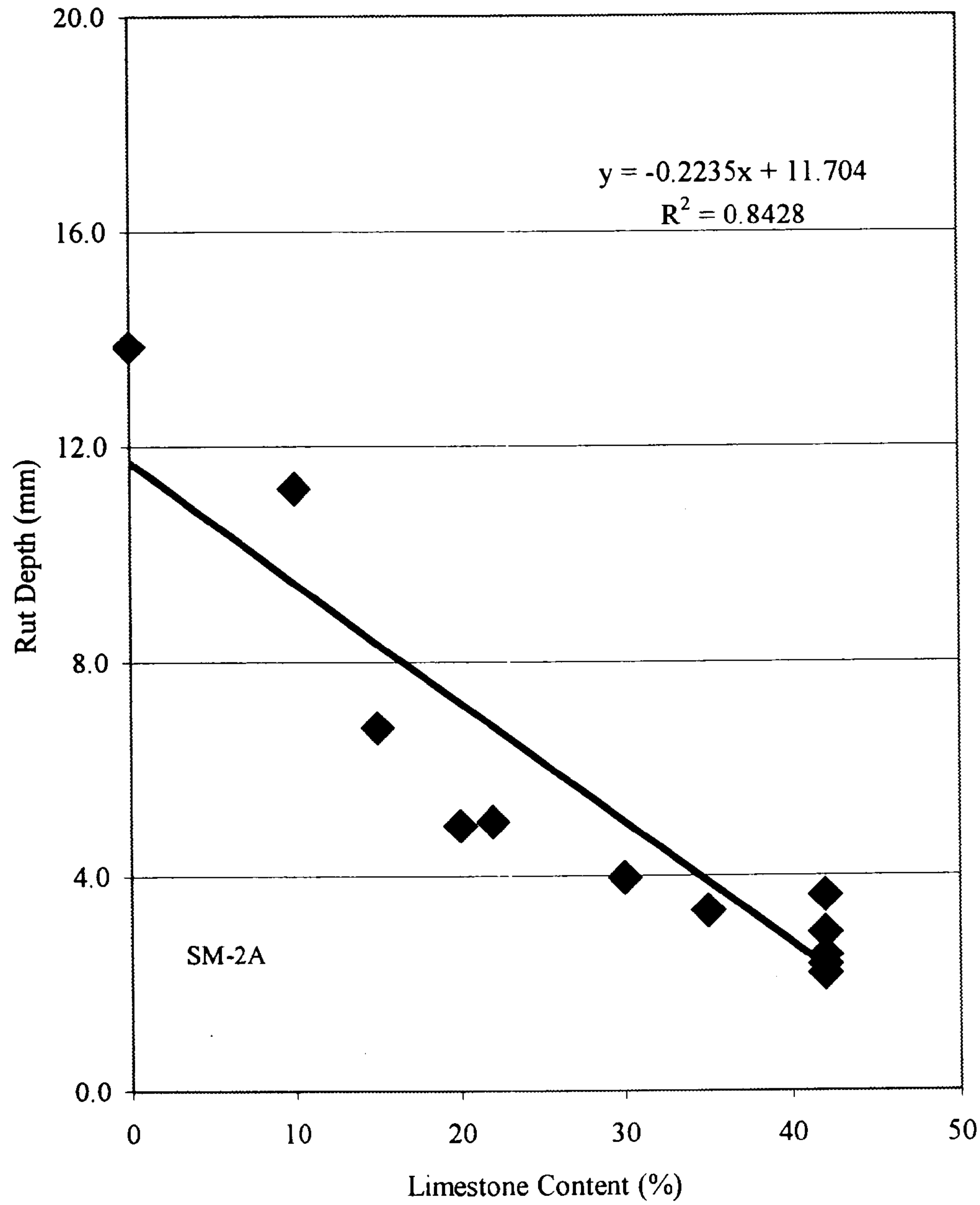

FIGURE 30 Rut Depth vs. Percent Limestone for SM-2A Samples at 8,000 Cycles

sand to chat sand. This indicates that natural sand and chat sand both increase a mix's susceptibility to rutting.

Summary

Both the SM-1B and SM-2A gradations showed that FAA was not directly related to rutting performance for mixes that contain chat sand. Exchanging chat sand for manufactured limestone sand increases rutting potential. Chat had no effect on rutting when it replaced natural sand. The correlation of limestone content to rutting, regardless of the sand chat ratio, reinforces this. By looking at these trends in both gradations (Figures 27 and 29) it is apparent that natural sand and chat sand have the same effect on rut susceptibility.

The effect of gradation can been seen by contrasting the rut depth of the two mixes. While both mixes met both SHRP and KDOT gradation specifications, the SM-1B mix rutted nearly twice as much as the SM-2A mix. This indicates the need for a strength test in addition to the gradation limits and aggregate property restrictions currently used in Superpave mix design.

Chapter 6

CONCLUSIONS, RECOMMENDATIONS AND IMPLEMENTATION

CONCLUSIONS

For the mixes and materials evaluated in this study the following conclusions are valid.

FAA

The calculated FAA values of the aggregate blends, obtained from the FAA of the individual aggregates as recommended by Superpave, were found to be equal to those found by testing the individual blends. For the two gradations tested it is reasonable to use the weighted average as suggested by SHRP.

Rounded Fine Aggregates

Effect of Fine Aggregate Angularity on VMA

When using rounded natural sands, both gradations showed that until a minimum FAA was reached, the effect of FAA on VMA was negligible. This minimum FAA value was different for both gradations, and was above the 40% minimum FAA recommended by SHRP for mixes with less than 3 million design ESALs. Above this point, 42.5% for the SM-1B mix and 45% for the SM-2A mix, both gradations showed nearly a one half percent increase in VMA with a one percent increase in FAA.

Effect of Fine Aggregate Angularity on Rutting Performance

For the samples made with crushed limestone and natural sand, rutting susceptibility decreases as FAA increased. This trend was observed to be linear with strong R^2

values of 0.96 and 0.88 for the SM-1B and SM-2A mixes, respectively. When rut depth is observed as a function of natural sand content, as shown in Figures 13 and 15, a two-slope trend is apparent with an increased rate of rutting occurring between 10% and 20% natural sand. A similar change in slope is seen with VMA as a function of natural sand content (Figure 10). The same change in slope between 10% and 20% natural sand is observed. When the plots of VMA as a function of FAA (Figures 6 and 8) are compared to the figures of FAA and VMA versus rutting, there is an indication that FAA versus rutting could be a two-slope trend. The break points appear to match the break points of VMA vs. FAA, 42.5% and 45% for the SM-1B and SM-2A mix, respectively. Since this comparison is weak and the R^2 values for a linear relationship between rutting and FAA are strong, the only conclusion that can be made from this study is that increased FAA decreases rutting susceptibility.

Flaky Fine Aggregate

Effect of Fine Aggregate Angularity on VMA

VMA can be boosted with the introduction of chat sand into a mix. Both mixes indicated that increasing chat sand content increased VMA. The chat sand had the greatest effect on the coarser SM-1B samples, resulting in twice the VMA gain for an increase in chat content as compared to the SM-2A gradation.

For mixes containing chat sand, VMA was not a function of FAA. The effect of chat sand on VMA was so great that the effect of FAA could only be seen within groups of samples made with the same natural sand or limestone content. It is

While there are no well-established pass-fail criteria for the APA, rutting increased at natural sand contents above 10% and dramatically increased at natural sand contents above 20%. The corresponding FAA values are in the 42% to 45% range. The magnitude of the rut depth was a function of the gradation as well as FAA, indicating the need for a stability test. This combined with the results of the VMA testing indicate that FAA values should be limited to less than 43% (10% natural sand) for low traffic and 45% (10% natural sand) for high traffic roadways. If the FAA value is below the above recommendations, then stability testing is necessary to ensure satisfactory performance.

Chat sand is an effective sweetener and can be used to increase VMA for a given gradation, but its effect on rutting needs to be addressed. Chat sand increases rutting susceptibility of a mix at the same rate as the addition of natural sand. Chat sand should replace natural sand rather than manufactured limestone sand in a mix in order to maintain stability. The FAA test does not adequately characterize chat sand. This means that the natural sand and chat sand content of a mix should be added and this combined percentage kept under the 10% and 20% recommendations to maintain a stable mix.

While meeting minimum FAA requirements and/or limiting natural sand and chat sand contents to below 20% will decrease the rutting susceptibility of a mix, this will not ensure a quality mix. As seen from the SM-1B mix, gradation also plays an important role in mix performance, both for meeting minimum VMA requirements and limiting rutting potential. Because meeting the voids and aggregate requirements of Superpave does not ensure adequate resistance to rutting, it is recommended that mixes be subjected to a stability test like the Asphalt Pavement Analyzer as part of the Superpave design method.

The FAA test was implemented by SHRP as an easy test to predict the rutting characteristics of the aggregate in a proposed mix. While this test method was valid for the natural sand and crushed limestone used in this research, the test was not effective in predicting the behavior of the chat sand. There is evidence that it may not be valid for sands made from crushed gravel either. The flaky structure of the chat may be fooling the FAA test. Further research is needed to determine a test that would better predict the rutting performance of non-typical shaped aggregates. Tests to investigate include repeated direct shear, rotational shear and consolidated-drained (CD) triaxial testing. All three give a value for the aggregate's friction angle (ø angle) and residual friction angle. The friction angle may be a better indicator of an aggregate's susceptibility to rutting.

IMPLEMENTATION

Until a suitable strength test is developed and adopted for use in the Superpave mix design system it is recommended that the APA be utilized to evaluate the stability of Kansas mixes. The following mixture stability testing criteria is recommended for implementation by the Materials and Research Bureau of KDOT.

Low Traffic Roads

Twenty year design ESALs: < 0.3 million.

Depth from surface: less than 100 mm.

Stability testing in the APA will be required unless:

a) FAA value (no sweeteners) exceeds 43%.

b) Combined percent natural sand and sweeteners less than 20%.

Intermediate Traffic Roads

Twenty year design ESALs: 0.3 to 1.0 million.

Depth from surface: less than 100 mm.

Stability testing in the APA will be required unless:

a) FAA value (no sweeteners) exceeds 45%.

b) Combined percent natural sand and sweeteners less than 10%.

High Traffic Roads

Twenty year design ESALs: > 1 million.

Depth from surface: less than 100 mm.

Stability testing in the APA will be required.

Stability Testing

Stability testing will be performed in the APA. The test shall be conducted according to the latest Asphalt Pavement Analyzer Users Group recommendations (19). The mixtures will be tested at the LTPP design PG grade temperature of 58°C. Table 15 gives the recommended pass/fail criteria pending completion of K-TRAN project KU: 00-1 *Evaluation of the Rutting Potential of KDOT Mixtures Using the Asphalt Pavement Analyzer*.

TABLE 15 Preliminary APA Acceptance Criteria

Traffic Level	Criteria	Comments
Low Traffic (< 0.3 million ESALs)	Maximum dry rut depth 6.0 mm	
Intermediate Traffic (0.3 – 1.0 million ESALs)	Maximum dry rut depth 6.0 mm	
High Traffic (> 1 million ESALs)	Maximum dry rut depth 4.0 mm	Rut depth less than 6.0 mm approved on case by case basis

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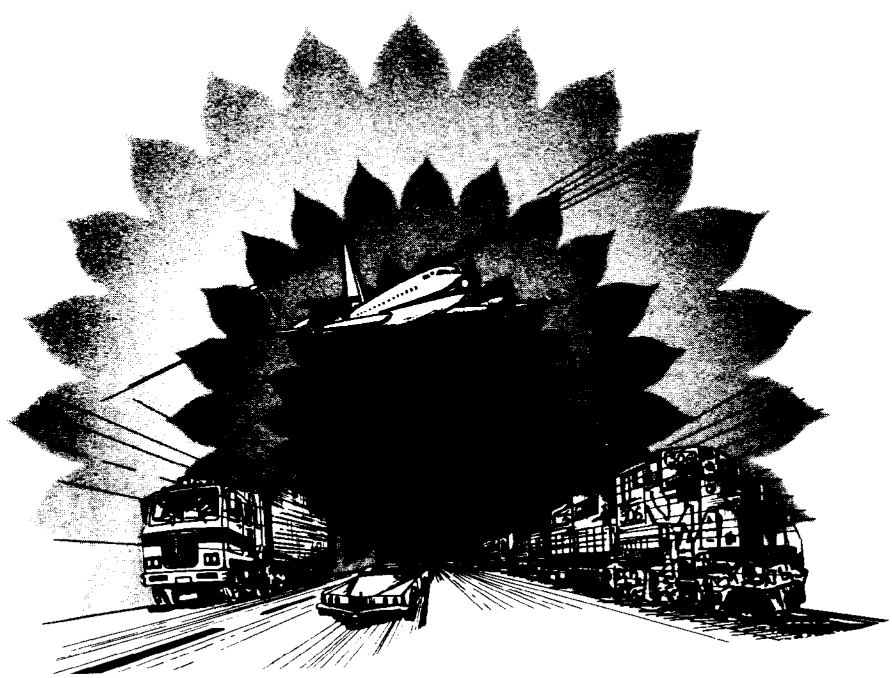

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION

THE KANSAS STATE UNIVERSITY

THE UNIVERSITY OF KANSAS