FINAL REPORT

DEVELOPMENT OF MIX DESIGN GUIDELINES FOR IMPROVED PERFORMANCE OF ASPHALT MIXTURES

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by

Principal Investigator:	Reynaldo Roque, Professor
Co-Principal Investigator:	Bjorn Birgisson, Associate Professor
Researchers:	Sungho Kim, Alvaro Guarin

Department of Civil and Coastal Engineering
College of Engineering
University of Florida
365 Weil Hall
PO Box 116580
Gainesville, Florida 32611-6580
(352) 392-7575, extension 1458

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

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* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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Dr. R. Roque, Dr. B. Birgisson, S. Kim, and A. Guarin

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University of Florida
Department of Civil and Coastal Engineering
365 Weil Hall P.O. Box 116580
Gainesville, FL 32611

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16. Abstract

The importance of aggregate structure on asphalt mixture performance has been well established on the basis of experience and is well documented in the literature. Furthermore, coarse aggregate structure is most important for resistance to rutting, and recent work has shown that it can also play a significant role in resistance to damage and fracture. This study focused on the development of a conceptual and theoretical approach to evaluate coarse aggregate structure based on gradation.

A theoretical analysis procedure was developed to calculate the center-to-center spacing between specific size particles within a compacted assemblage of particles of known gradation. Calculations performed with this procedure indicated that the relative proportion of two contiguous size particles, as defined by the standard arrangement of Superpave sieves, can be no greater than 70/30 in order to form an interactive network. Thus, the 70/30 proportion can be used to determine whether particles on contiguous Superpave sieves can form an interactive network of particles in continuous contact with each other. The range of particle sizes determined to be interactive was referred to as the dominant aggregate size range (DASR) and its porosity must be no more than 50% for the particles to be in contact with each other.

The DASR concept and porosity criterion were evaluated using an extensive range of mixtures from existing databases including the Superpave Monitoring Projects, FDOT HVS test sections, as well as WesTrack and NCAT test sections. Results clearly indicated that mixtures identified by the system developed as having poor or marginal gradations (DASR porosity greater than 50% or gradations that were marginally interactive), resulted in poor rutting performance.

17. Key Word
Superpave, hot mix asphalt, gradation, dominant aggregate, porosity, spacing, interstitial, interaction

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EXECUTIVE SUMMARY

The importance of aggregate structure on asphalt mixture performance has been well established on the basis of experience and is well documented in the literature. Furthermore, coarse aggregate structure is most important for resistance to rutting, and recent work has shown that it can also play a significant role in resistance to damage and fracture. Therefore, large enough aggregates should engage dominantly in the structure for good mixture performance. This study focused on the development of a conceptual and theoretical approach to evaluate coarse aggregate structure based on gradation.

It is a well-known fact in soil mechanics that the porosity of granular materials in the loose state is approximately constant between 45% and 50%, regardless of particle size or distribution. This implies that the porosity of an assemblage of granular particles (e.g., the aggregate within an asphalt mixture) must be no greater than 50% for the particles to be in contact with each other. This also implies that one can use porosity as a criterion to assure contact between large enough particles within the mixture to provide suitable resistance to deformation and fracture. Calculations performed for gradations associated with typical dense graded mixtures indicated that the porosity of particles retained on any single sieve was significantly greater than 50%, even for gradations associated with the maximum density line. Since many dense-graded mixtures are known to provide suitable resistance to deformation and fracture, then there must be a range of contiguous coarse aggregate particle sizes that form a network of interactive particles with a porosity of less than 50%.

A theoretical analysis procedure was developed to calculate the center-to-center spacing between specific size particles within a compacted assemblage of particles of known gradation. Calculations performed with this procedure indicated that the relative proportion of two contiguous size particles, as defined by the standard arrangement of Superpave sieves, can be no greater than 70/30 in order to form an interactive network. Thus, the 70/30 proportion can be used to determine whether particles on contiguous Superpave sieves can form an interactive network of particles in continuous contact with each other. The range of particle sizes determined to be interactive was referred to as the dominant aggregate size range (DASR) and its porosity must be no more than 50% for the particles to be in contact with each other.

Analysis of an SMA mixture indicated that the DASR was composed of only one size aggregate, and as expected, its porosity was less than 50%. Analysis of dense-graded mixtures (coarse-graded and fine-graded) of known performance indicated that DASR porosity of aggregate particles coarser than the 1.18 mm sieve was less than 50% for the good performers and greater than 50% for those exhibiting relatively poor performance. Although the approach makes it evident that coarser particle DASR porosities of less than 50% are easier to achieve with coarser gradations, they are also achieved with properly proportioned fine-graded mixtures. In addition, DASR porosities less than 50% are not assured with coarse-graded mixtures; they must also be properly proportioned.

The DASR concept and porosity criterion were evaluated using an extensive range of mixtures from existing databases including the Superpave Monitoring Projects, FDOT HVS test sections, as well as WesTrack and NCAT test sections. Results clearly

indicated that mixtures identified by the system developed as having poor or marginal gradations (DASR porosity greater than 50% or gradations that were marginally interactive), resulted in poor rutting performance.

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CHAPTER 1
INTRODUCTION

1.1 Problem

The performance of Hot-Mix Asphalt (HMA) is related to particle size distribution, which affects the most important properties of the mix, such as cracking resistance, rutting resistance, durability, permeability, and workability. Therefore, having an adequate aggregate particle distribution is a very important factor in order to have good field performance. Typically the selection of aggregate gradation is made based on specification bands within control points, but the main question is how to choose the best possible blend to achieve better performance (Asphalt Institute and the Heritage Group, 2005).

The Superpave mix design method requires that gradation should pass within control points and avoid a specified restricted zone (Asphalt Institute, 2001). However, many HMA mixtures that pass through the restricted zone have been found to perform well. On the other hand, many mixtures, which meet Superpave criteria, have not exhibited good performance. Additionally, Superpave gradation specifications have not considered aggregate structure fully.

This study focused on the development of a conceptual and theoretical approach to evaluate coarse aggregate structure based on gradation. The goal was to develop a system to help evaluate and, if necessary, modify gradations to ensure that mixtures will have sufficient aggregate interlock to resist deformation and cracking. It is recognized that this alone would obviously not ensure good mixture performance, which will also depend on the characteristics and properties of the finer components of the mixture, including the binder, but it would help to eliminate mixtures that will not perform well, regardless of the quality of these other components. The study also led to concepts that may lead to the development of other useful criteria associated with these other components.

1.2 Objectives

As mentioned earlier, this study focused on the development of a conceptual and theoretical approach to evaluate coarse aggregate structure based on gradation. The main purpose was to develop an approach to analyze mixture gradation to determine whether the coarse aggregate will interlock sufficiently to provide necessary resistance to deformation and fracture (i.e., the condition commonly referred to as stone-on-stone contact). Detailed objectives may be summarized as follows:

- Develop a numerical approach to describe the aggregate structural characteristics based on gradation.
- Identify and develop an approach to determine the range of interactive coarse aggregate particles for a specified gradation (i.e., the particle size or sizes that make up the primary structure or "skeleton" of the mixture).
- Identify a criterion to assess whether the range of interactive coarse aggregate particles are sufficiently dense within the asphalt mixture to actually be in contact and provide the interlock necessary to resist deformation and fracture.
- Evaluate the approach and the criterion developed using mixtures of known performance.

1.3 Scope

The approach developed in this study was based on packing theory of spherical particles of multiple sizes. Consequently, the criteria developed are probably most applicable to aggregates that are not excessively elongated or cubicle in shape. However, the authors see no reason why it would not be possible to extend the concepts and theoretical calculations developed to particles that are not spherical. It is also recognized that aggregate angularity and texture can affect the quality of aggregate interlock and these factors were not dealt with in this study. However, the concepts and criteria developed should be valid for aggregate of any angularity and texture. In other words, gradations that result in better interlock are beneficial regardless of the aggregate angularity or texture. That being said, further research and evaluation in the future may allow for modified criteria based on measurable characterization of angularity and texture.

CHAPTER 2
LITERATURE REVIEW

2.1 Shear Resistance

Roque et al. (1997) found that the gradation characteristics of the coarse aggregate fraction had the strongest effect on mixture shear resistance for the mixtures evaluated. Eighteen mixtures were prepared with different coarse aggregate (> 2.0 mm) gradations ranging from Stone Matrix Asphalt (SMA) to those corresponding to the maximum density line. They found that asphalt mixture shear resistance appeared to be most strongly related to the gradation characteristics of the coarse aggregate fraction (> 2.0 mm) of the mixtures. Coarseness of the aggregate, and the shape (curvature) and position of the coarse aggregate gradation curve relative to the maximum density line were all found to influence mixture shear resistance. In addition, aggregate voids in mineral aggregate (VMA), which is a function of the denseness of the aggregate structure, was not found to be related to mixture shear resistance.

2.2 Criteria Associated with VMA and Restricted Zone

The Superpave^{TM} specifications have certain guidelines for gradations through the use of control points and restricted zone on a 0.45 power gradation chart. Control points limit the percent of material retained or passing some selected sieve sizes depending on the nominal maximum aggregate size (NMAS) to help ensure continuous gradations, whereas a restricted zone was proposed to prevent the production of tender mixes. Kandhal et al. (2001) showed that potentially good mixes have been rejected because their gradations pass through the restricted zone. Chowdhury et al. (2001) found that there is no relationship between the restricted zone and permanent deformation when crushed aggregates are used in the mixture design. Kandhal and Cooley (2002) found that there was no significant difference between coarse and fine-graded mixture based on limited tests.

Nukunya et al. (2001) suggested that the effective film thickness was more useful than VMA, and showed that VMA reqirements based on NMAS does not account for the effect of mixture gradation, and is therefore insufficient to correctly differentiate good-performing mixtures from bad-performing ones. Kandhal et al. (1998) also recommended using a minimum average film thickness instead of the minimum VMA requirement to ensure mixture durability. Coree and Hislop (2000) found that the specified VMA values provided by Superpave did not appear to be adequate for identifying mixture performance. They suggested the volume percentage of effective binder, V_{be}, was relatively insensitive to the level of compaction and appeared to be a critical parameter.

2.3 Gradation Parameters: n and a

Birgission and Ruth (2001) developed Power law parameters (n, a) to evaluate and classify gradation curves according to performance. Gradations were initially analyzed using power law regression that characterized the coarse aggregate gradation (retained on the 4.75 mm) and the fine aggregate gradation (from the 2.36 mm down to 0.15 mm), according to the following power relationship:

$$P = a(d)^n \tag{2-1}$$

where,

P= percent passing
d= sieve size opening, mm

a = constant
n = exponent

The key characteristics that tend to define the desired gradations for coarse or fine-graded mixtures are primarily a continuous, well-balanced, coarse aggregate gradation from the 1.18, 2.36, or 4.75 mm sizes, a reasonable reduction or increase in the amount of fine aggregate, and mineral filler content less than 6 %.

The study of these parameters was expanded by Ruth et al. (2002). The results presented the concepts and guidelines for the selection of coarse or fine-graded aggregate blends using gradation characterization factors based on power law constants (a_{CA}, a_{FA}) and exponents (n_{CA}, n_{FA}).

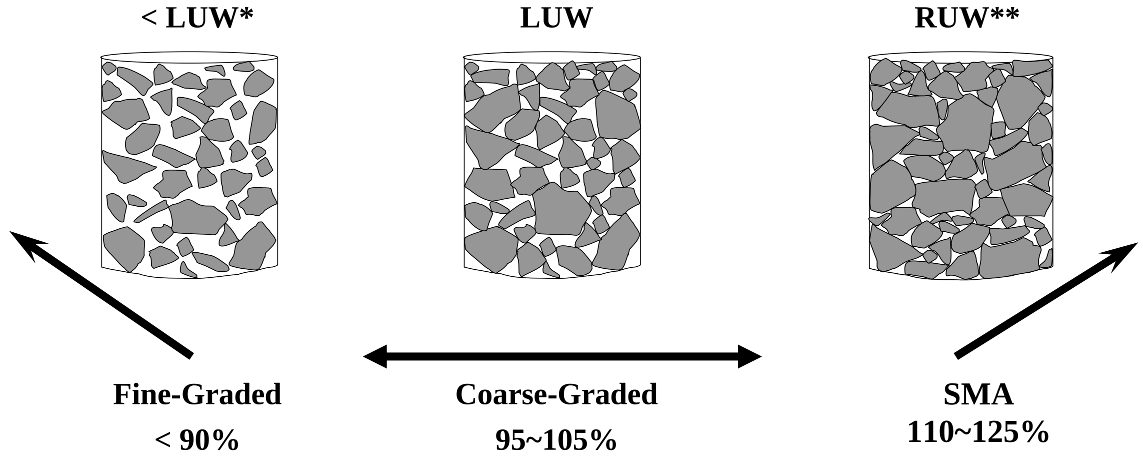
2.4 Bailey Method

Typically the selection of aggregates gradation is made based on specification bands (coarse, medium, or fine gradation), but the main question is how to choose the best possible blend to achieve good workability and field performance. The Bailey method is a more systematic way to find a starting point (Vavrik et al., 2001, 2002, and Asphalt Institute and the Heritage Group, 2005).

The Bailey method was developed by Bob Bailey in the early 1980's; the main purpose of this approach is to control the mix properties during construction, e.g. volumetric properties, workability, segregation, and compactibility.

The focus of the Bailey method is aggregate packing based on Voids in the Mineral Aggregate (VMA). The method determines coarse fraction as those particles that create voids and fine fraction as those particles that fit into the voids crated by coarse aggregates.

The Bailey method also defines three types of mixes (coarse, SMA, or fine) based on the volume of the coarse fraction, as shown in Figure 2-1.



* Loose Unit Weight, ** Rodded Unit Weight

Figure 2-1 Determination of Mix Type

There are four main principles to the Bailey method.

- Principle No. 1: Definition of coarse fraction and fine fraction.
- Principle No. 2: Coarse fraction analysis.
- Principle No. 3: Coarse part of fine fraction evaluation.
- Principle No. 4: Fine part of fine fraction analysis.

These four principles are related not only to compactibility and segregation susceptibility of the mix in the field but also to the expected change in VMA or voids from one design trial to the next, or from one QC sample to the next. Figures 2-2 and 2-3 shows how to determine four principal sieve sizes.

The Bailey method utilizes the Nominal Maximum Particle Size (NMPS) to estimate the void size within the coarse fraction. The break between coarse and fine fractions is defined as the Primary Control Sieve (PCS) which is estimated as the closest sieve to the result of 0.22×NMPS.

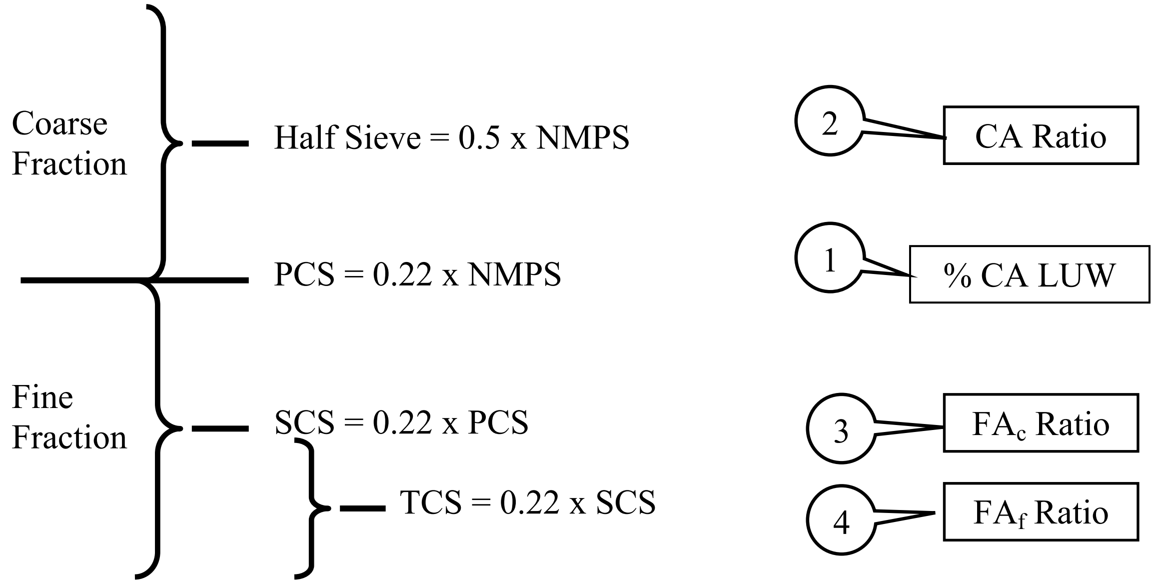


Figure 2-2 Four Main Principles of Bailey Method for Coarse Mixtures

The calculation of the Coarse Aggregate ratio (CA), Fine Coarse Aggregate ratio (FA$_c$), and Fine fine aggregate ratio (FA$_f$) can be made by using the following equations:

$$\text{CA Ratio} = \frac{\%\,\text{passing half sieve} - \%\text{passing PCS}}{100 - \%\,\text{passing half sieve}} \tag{2-2}$$

$$\text{FA}_c\ \text{Ratio} = \frac{\%\,\text{passing SCS}}{\%\text{passing PCS}} \tag{2-3}$$

$$\text{FA}_c\ \text{Ratio} = \frac{\%\,\text{passing TCS}}{\%\text{passing SCS}} \tag{2-4}$$

The use of the four principles and admissible values for the different ratios depend upon the type of gradation (coarse, fine or SMA). Table 2-1 shows the recommended values of the different ratios for coarse mixes.

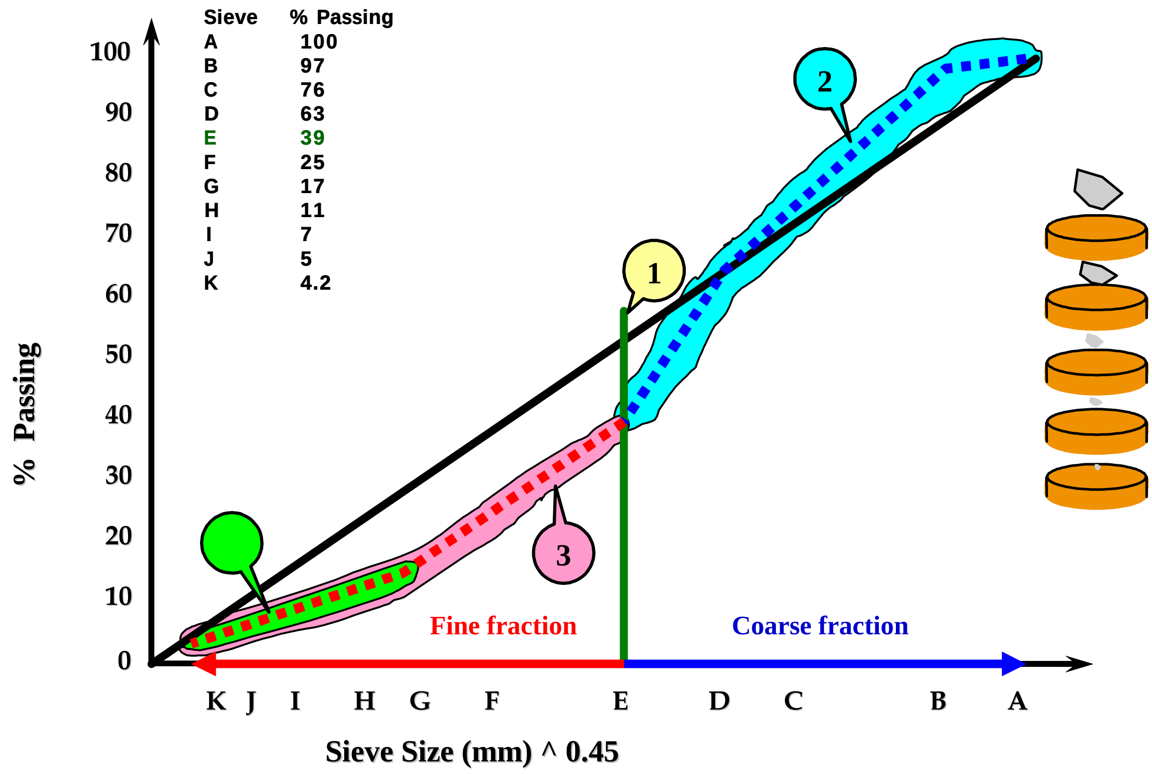


Figure 2-3 Example of Coarse Gradation Mix

Table 2-1 Recommended Aggregate Ratios for Coarse Mixtures

NMPS	37.5mm	25.0mm	19.0mm	12.5mm	9.5mm	4.75mm
CA ratio	0.80-0.95	0.70-0.85	0.60-0.75	0.50-0.65	0.40-0.55	0.30-0.45
FAc ratio	0.35-0.50					
FAf ratio	0.35-0.50					

In conclusion, the Bailey method is a pretty good tool for evaluating volumetrics and compactibilty of the mix, but further research is required to find the optimum aggregate gradation based on mixture performance, e.g., rutting, fatigue cracking, and thermal cracking resistance.

2.5 Summary

Some recent studies have focused on evaluating the effects of aggregate characteristics and structure to determine which gradations are most resistant to cracking and rutting in Superpave mixtures.

The Bailey method of mix design provided a better understanding of relationships between aggregate gradation and mixture voids, and offers a means to design and analyze the aggregate structure in an asphalt mixture. The method defined gradation parameters (CA, FA_c, FA_f ratios) that were related to air voids and VMA. In addition, the design approach attempts to achieve a suitable coarse aggregate structure by requiring the density of the coarse aggregate in the compacted mixture to be between 95% and 105% of the loose density of the coarse aggregate as determined in the laboratory.

The developers of the Bailey method clearly recognized the need to have large enough particles in contact with each other for suitable mixture performance. However, achieving a specified coarse aggregate density may not necessarily ensure a suitable coarse aggregate structure. For example, the coarse aggregates may be proportioned in such a way that the range of different sized particles is not in continuous contact. Finer coarse aggregate particles may simply be filling voids between relatively few coarser aggregate particles, or coarser aggregate particles may just be floating in a matrix of finer coarse aggregate particles. In either case, particles within the coarse aggregate range may be acting independently of each other and not providing a suitable network for resistance to deformation and fracture.

Therefore, it would be useful to have a system to determine whether different size coarse aggregate particles from a specified gradation are proportioned properly so that they can result in an interactive network of particles in continuous contact. In addition, it would also be of benefit to have a criterion to assess whether the range of interactive coarse aggregate particles are sufficiently dense within the asphalt mixture to actually be in contact and provide the interlock necessary to resist deformation and fracture. It would be particularly beneficial if the criterion did not require laboratory testing.

CHAPTER 3
NEW DEVELOPMENT

3.1 Porosity as a Criterion for Interlocking

Porosity has been used extensively in fields like soil mechanics as a dimensionless parameter that describes the relative proportion of voids to total volume. In soil mechanics, a typical element of soil contains three distinct phases: solid (mineral particles), gas, and liquid (usually water). Figure 3-1 is a phase diagram illustrating the three phases separately. Porosity (*n*) is the ratio of void volume (V_V) to total volume (*V*).

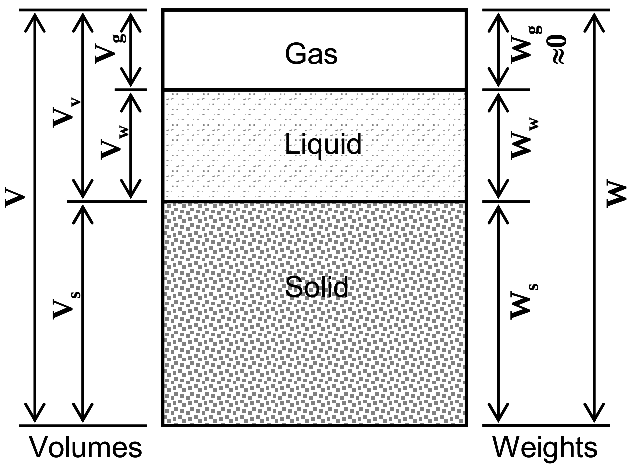


Figure 3-1 Relationship among Soil Phases

$$\text{Porosity, } n = \frac{V_{Void}}{V_{Total}} = \frac{V_V}{V} \tag{3-1}$$

It is a well-known fact in soil mechanics that the porosity of granular materials in the loose state is approximately constant between 45% and 50%, regardless of particle size or distribution (Lambe and Whitman, 1969, and Freeze and Cherry, 1979). This implies that the porosity of an assemblage of granular particles (e.g., the aggregate within an asphalt mixture) must be no greater than 50% for the particles to be in contact with each other. This also implies that one can use porosity as a criterion to assure contact between large enough particles within the mixture to provide suitable resistance to deformation and fracture. As mentioned earlier the Bailey Method of mix design takes a very similar approach by requiring the density of the coarse aggregate in the compacted mixture to be between 95% and 105% of the loose density of the coarse aggregate as determined in the laboratory. Use of a porosity criterion would preclude the need for laboratory compaction of coarse aggregate.

Therefore, a maximum porosity of 50% was selected as a starting point for evaluation as a criterion for asphalt mixture, which is essentially a granular material with asphalt and fines between the granular particles. The basic principles associated with the calculation of porosity of different components within the asphalt mixture are presented below.

3.2 Application to Asphalt Mixture

VMA in asphalt mixtures, which is the volume of available space between aggregates in a compacted mixture, is analogous to void volume in soil.

$$VMA = V - V_{AGG} \tag{3-2}$$

By assuming that a mixture has a certain effective asphalt content and air voids for a given gradation (i.e., VMA), porosity can be calculated for each aggregate particle size.

For example, the porosity of particles retained on the 4.75mm sieve and passing the 9.5mm sieve is calculated by subtracting the volume of larger aggregates (i.e., those retained on the 9.5mm sieve) from the total volume of mixture (*V*).

$$V_{T(4.75-9.5)} = V_{TM} - V_{AGG(\geq 9.5)} \tag{3-3}$$

where,

$V_{T(4.75\text{-}9.5)}$ = Total volume available for particles retained on the 4.75mm sieve and passing the 9.5mm sieve
V_{TM} = Total volume of mixture
$V_{AGG(\geq 9.5)}$ = Volume of particles retained on the 9.5mm sieve

The volume of voids within $V_{T(4.75\text{-}9.5)}$ includes the volume of aggregates passing the 4.75mm sieve, in addition to the volume of effective asphalt plus the volume of air (i.e., the VMA of the mixture).

$$V_{V(4.75-9.5)} = V_{AGG(<4.75)} + VMA \tag{3-4}$$

where,

$V_{V(4.75\text{-}9.5)}$ = Volume of voids within $V_{T(4.75\text{-}9.5)}$
$V_{AGG(<4.75)}$ = Volume of particles passing the 4.75mm sieve

The porosity of this aggregate particle size is then calculated as follows.

$$n_{(4.75-9.5)} = \frac{V_{V(4.75-9.5)}}{V_{T(4.75-9.5)}} = \frac{V_{AGG(<4.75)} + VMA}{V_{TM} - V_{AGG(\geq 9.5)}} = \left(\frac{V_{TM} - V_{AGG(\geq 4.75)}}{V_{TM} - V_{AGG(\geq 9.5)}}\right) \tag{3-5}$$

where,

$V_{AGG(\geq 4.75)}$ = Volume of particles retained on the 4.75mm sieve

Similar calculations can be performed for any other particle size or range of particle sizes within the mixture.

3.3 Porosity of Individual Particle Sizes

Some typical mixture gradations are shown in Figure 3-2, which includes coarse-graded, fine-graded, and SMA mixtures. Porosity analysis was applied to check the coarse aggregate structure in these mixtures. Figure 3-3 shows the porosity of each individual particle size for the three gradations presented in Figure 3-2. As shown in the figure, the only single aggregate size with porosity less than 50% was the aggregate retained on the 9.5 mm sieve for the SMA mixture. This finding was expected, since SMA mixtures are designed specifically to achieve stone-on-stone contact with a single-size aggregate. The finding also seems to indicate that the 50% porosity criterion is reasonable.

None of the individual particle sizes met the 50% porosity criterion for either the coarse-graded or the fine-graded mixtures. However, both of these dense-graded Superpave mixtures are known to have good resistance to deformation and fracture, so it is not logical that the coarse aggregate in these mixtures exists in a state where the particles are not in contact with each other as reflected by the porosity being much greater than 50%. Therefore, it seems clear that there must be a range of contiguous coarse aggregate particle sizes that form a network of interactive particles with a porosity of less than 50%. The challenge was to develop an approach to objectively determine what specific particle sizes, if any, are interacting such that they should be considered to be a single unit in the determination of porosity. Here again it is important to emphasize that the 50% porosity criterion is independent of particle size or distribution, so it is equally applicable to a range of interactive particle sizes as to single size particles.

A theoretical analysis procedure was developed to determine whether a given proportion of contiguous particle sizes are interacting to form a continuous network. The development and results of the analysis are presented in the following section.

3.4 Theoretical Developments

Several important concepts were employed in the theoretical development of a system to determine whether different size particles are interacting in space. Perhaps the most important one involves the physical model used to describe an asphalt mixture, which can be viewed as being composed of the following elements:

3.4.1 Dominant Aggregate Size Range (DASR)

For all asphalt mixtures, this is the interactive range of particle sizes that forms the primary structural network of aggregates. It was hypothesized that the DASR must be composed of coarse enough particles and its porosity must be no greater than 50% for a mixture to effectively resist deformation and cracking. Particle sizes smaller than the DASR will serve to fill the void space between the DASR (the interstitial volume described below) along with binder and fines. Particles larger than the DASR will simply float in the DASR matrix and will not play a major role in the aggregate structure. These concepts are illustrated in Figure 3-4, which shows the DASR for three different types of mixtures.

3.4.2 Interstitial Volume (IV)

This is the volume of material (asphalt, aggregate and air voids) that exists within the interstices of the DASR. The components within this volume are referred to as the interstitial Components (IC). This volume serves to hold together the DASR, and its characteristics, as well as the properties of the IC will strongly influence the durability

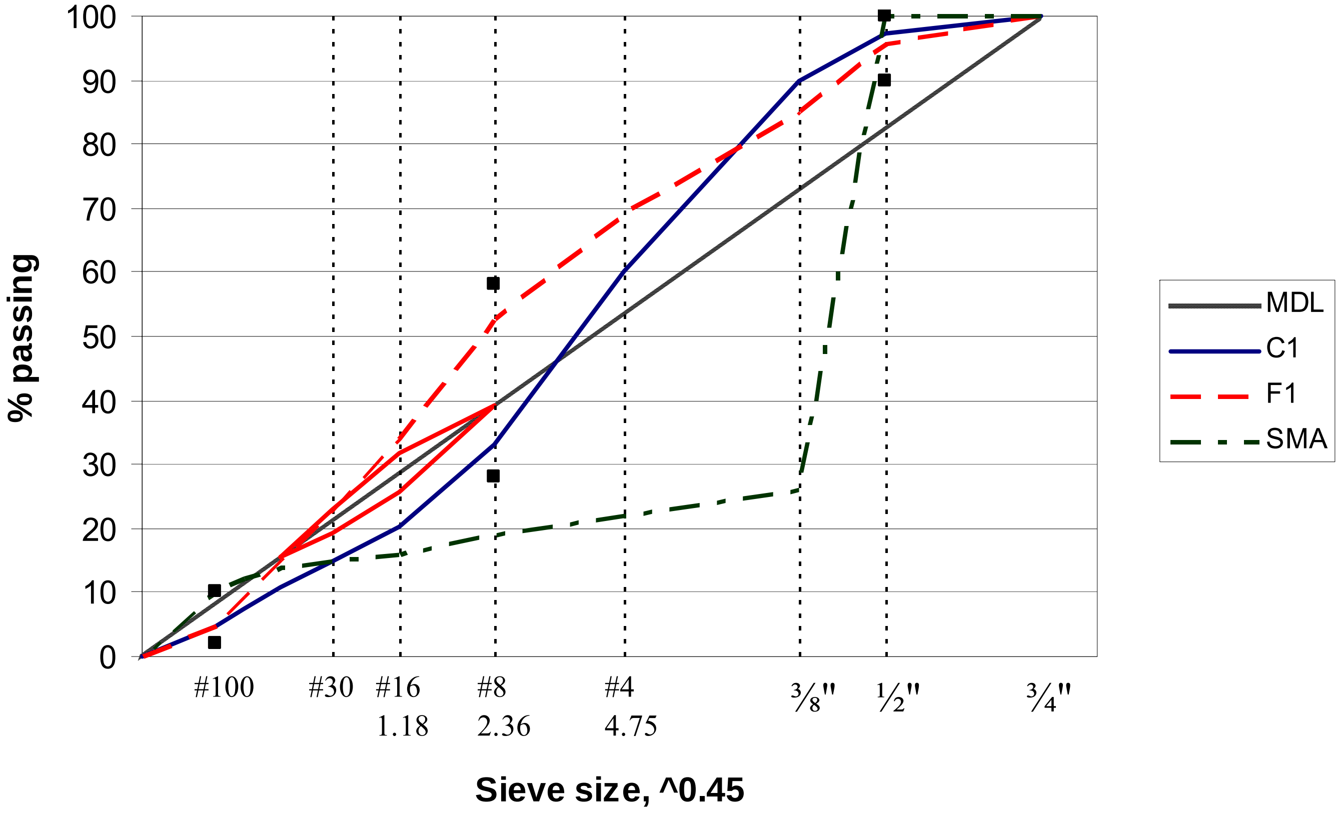


Figure 3-2 Example gradations

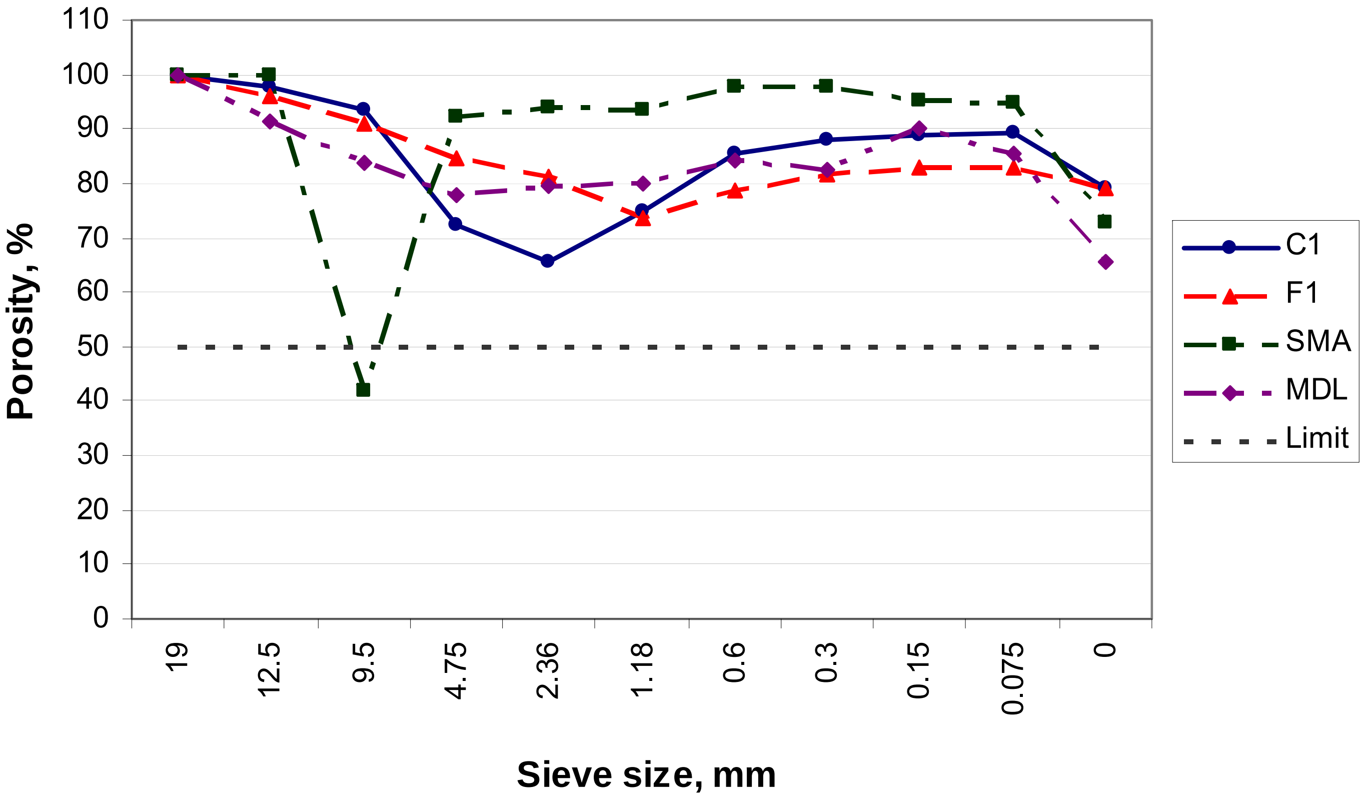
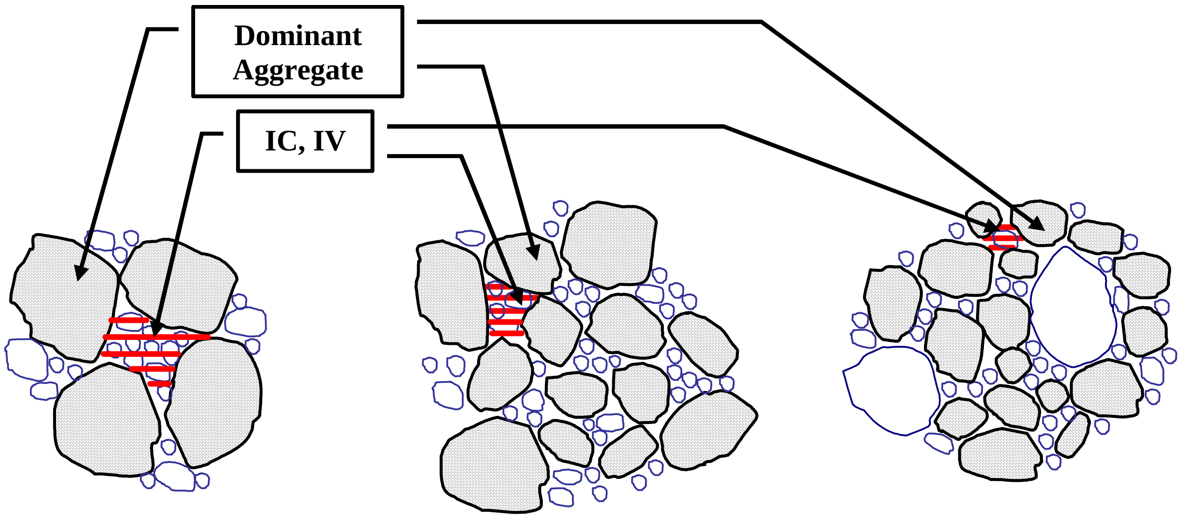


Figure 3-3 Individual porosity results



(a) SMA **(b) Coarse dense** **(c) Fine dense**

Figure 3-4 Dominant aggregates and interstitial volume and fracture resistance of mixtures. Excessively low stiffness and/or excessive IV can lead to excessive creep rate, which is related to rate of damage development. Conversely, excessively high stiffness and/or insufficient IV can make a mixture brittle and have low dissipated creep strain energy to failure ($DCSE_f$), which defines a mixture's tolerance to damage.

3.4.3 Interstitial Surface (IS)

This surface is defined by an approximately straight plane taken through the interstitial volume. It can be most easily visualized as a failure surface of an asphalt mixture pulled apart in tension, as shown in Figure 3-5. The characteristics of this surface, including its roughness, protrusion of different size aggregate particles, presence of asphalt and fines, will strongly influence the mixture's resistance to deformation and fracture, and particularly shear deformation associated with rutting. Rougher interstitial surfaces with larger particle protrusions will result in mixtures with greater shear resistance. Shear resistance will be further enhanced if particles on this surface are arranged in such a way as to form an interlocking network of particles. Therefore, determination of the characteristics of this interstitial surface, which are controlled by gradation, should provide useful parameters for mixture evaluation and design.

For example, one can determine whether or not particles are interacting with each other by determining their center-to-center spacing on the interstitial surface. A theoretical procedure was developed to determine this spacing for specified gradations and thus determine which particles within the gradation interact to form the DASR. The development and results of this procedure are presented below.

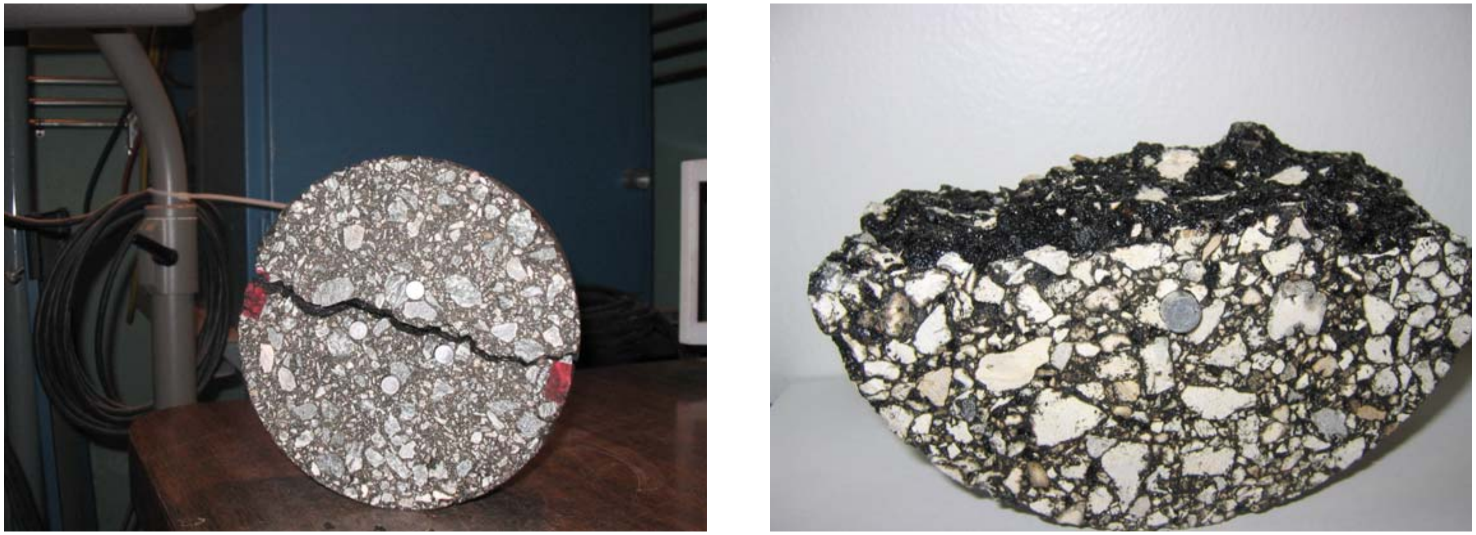


Figure 3-5 The failure surface from a broken IDT Sample

3.5 Particle Spacing on the IS

For a given particle size distribution (gradation) compacted to a specified density, one can easily calculate the number of particles of any given size that will be present within a specified representative volume. Furthermore, one also can calculate how many particles of each size will be present within a representative cross-sectional area (i.e., the interstitial surface) taken through the representative volume. The spacing between each particle size on the IS can also be calculated if certain characteristics regarding the distribution between the different particle sizes in the area are known or assumed. For asphalt mixtures it is reasonable to assume that particles are generally uniformly distributed within the representative volume or area. In addition, if the mixture is not segregated, the largest particles will be uniformly distributed over the entire volume or area, while smaller particles will be uniformly distributed within the remaining volume or area (i.e., the volume or area between the larger aggregate particles). In other words, smaller particles are uniformly distributed locally but not globally over the entire volume or area. These were the basic assumptions made in making the theoretical spacing calculations.

3.6 Determination of DASR

As explained earlier, the DASR may be composed of one size or multiple sizes. Particle sizes interacting with each other to form the primary network that carries load induced stresses have to be determined. Open-graded or uniform gradations such as SMA have a very distinct DASR, because only one size aggregate makes up most of the mixture volume. However, determination of the DASR is less clear for dense-graded mixtures. Therefore, a system is needed to determine which contiguous sizes are interacting as a unit to make up the DASR. To do this, an interaction diagram was developed based on the spacing analysis between particles on the interstitial surface.

3.7 Spacing Analysis and Interaction Diagram

As mentioned above, spacing between particles for each size in the representative volume can be calculated to check whether there is interaction between contiguous sizes for specified gradations. The spacing calculations assumed that particles are distributed according to a hexagonal pattern within the available area, which results in a uniform particle distribution. The center-to-center spacing among the same sizes of particles was calculated in order, from the biggest size to smallest size in order to account for the fact that smaller particles are only locally uniformly distributed between the larger aggregate particles. At first, the biggest particles are distributed within the total representative area, then the next smallest particles are distributed with the same pattern within the available area, which is the remaining area after subtracting the area taken up by the biggest particles from the total representative area. Figure 3-6 shows the pattern used to perform the spacing calculations for each size. The spacing within the hexagonal pattern is easily determined if the number of particles and the total area are known. This procedure was repeated down to the smallest particle size.

Figure 3-7 shows the basic principles employed in these calculations. The spacing among the biggest particles within the total area is calculated with the hexagonal pattern distribution. If the biggest particles take 20% of the total area, the remaining area, 80% will be the representative total area for the next size. The next smallest particles were distributed with the same pattern within this remaining available area.

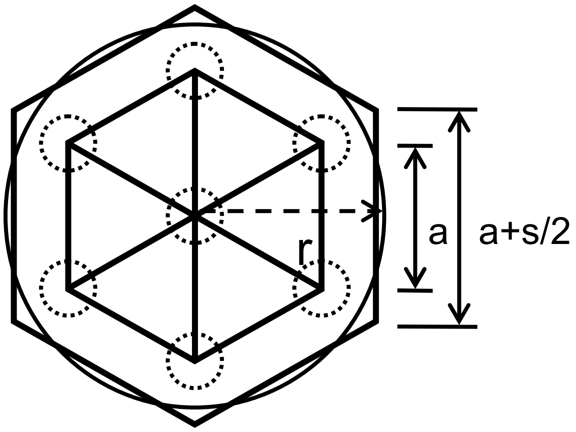
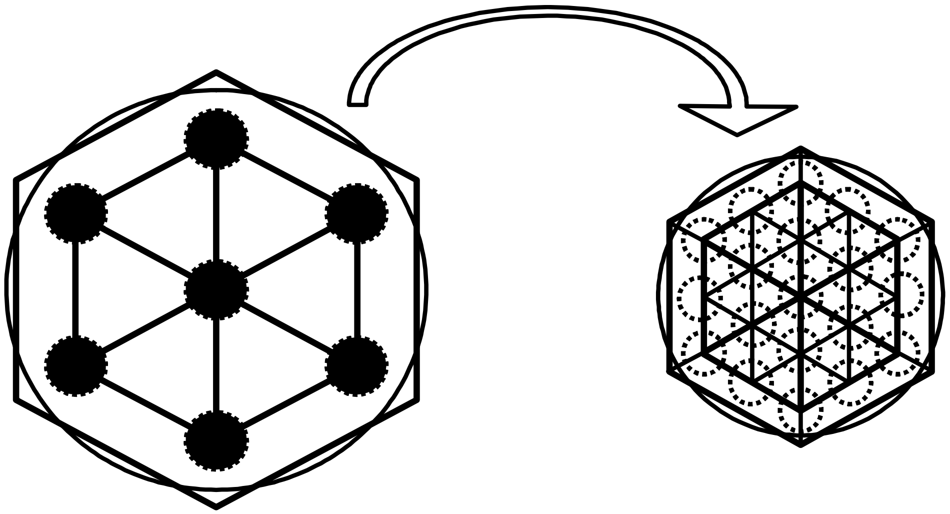


Figure 3-6 Hexagonal pattern distribution and spacing calculation for each size

Figure 3-8 shows results of spacings calculated for a binary mixture with 9.5 and 4.75mm size particles. As the proportion of larger/smaller particles decreases, the larger particle spacing increases. In other words, as the number of larger particles decreases, their spacing increases. The smaller particles (4.75mm) obviously show a reverse trend. Figure 3-8 shows that for each size particle the spacing starts to increase dramatically once the relative proportions of different sized aggregates reaches a certain level. In order to more precisely determine the relative proportion at which the particle spacing starts to change rapidly, the rate of change of the slope of the spacing diagram presented in Figure 3-8, was plotted in Figure 3-9. These results indicate that the particle spacing for either particle size begins to increase more rapidly once the relative proportion of the different size aggregate is about 70/30. It should be noted that this result would be the same for any two particle sizes having a size ratio of 2:1, which is generally the size ratio used between contiguous size sieves in asphalt mixture design.



(a) The biggest particles distribution

solid particles = **20%
*shaded rest area = **80%

(b) The 2nd size particles distribution

solid particles = 30% x 80% = **24%
*rest area = 70% x 80% = **56%

*, representative area for the next step
**, percentage of the initial total area

Figure 3-7 The representative areas based on hexagonal patterns for each step

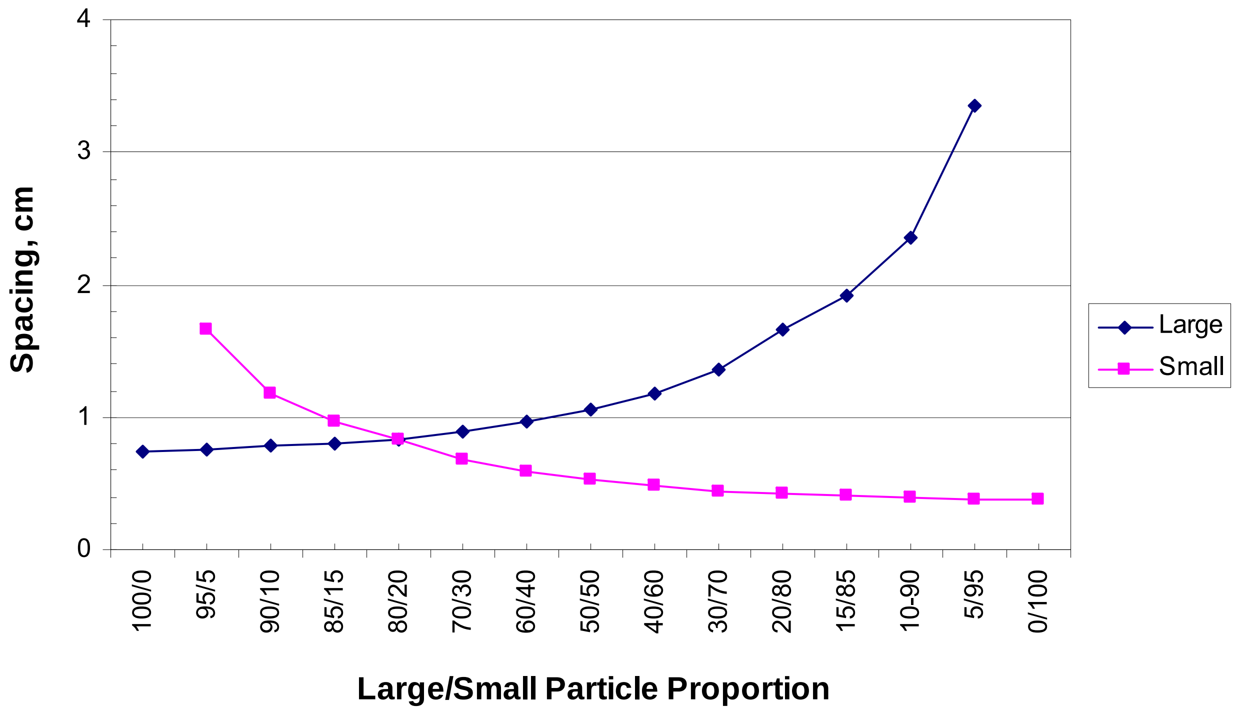


Figure 3-8 Spacing result for the binary mixture with 9.5, 4.75mm

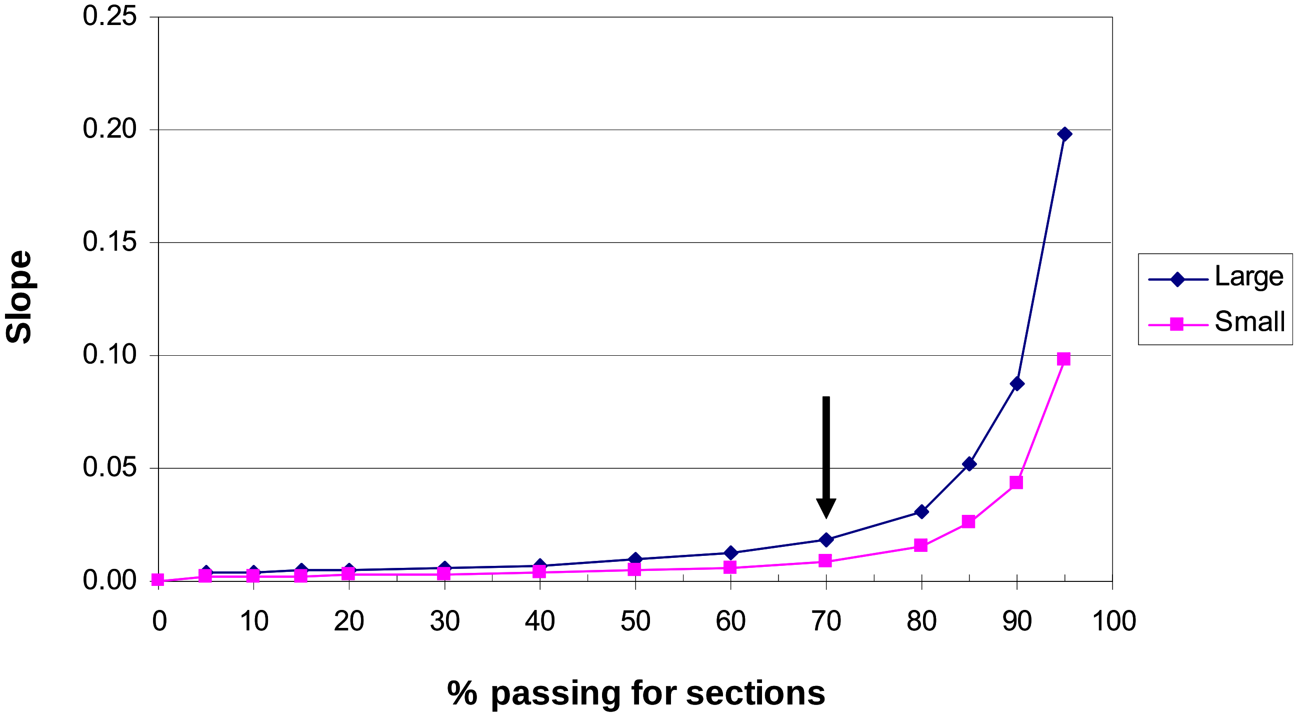


Figure 3-9 Slope (spacing change) for the binary mixture

This finding implies that one particle size will significantly disrupt the ability of another particle size to interact once the relative proportions of the particle sizes is about 70/30. In other words, once the proportions exceed this value, the spacing of the particles with the smaller proportion increases so much that these particles are simply floating in the matrix and are no longer an effective part of the aggregate structure. That is, the particles are not part of the DASR. Conversely, at proportions less than 70/30 (e.g., 40/60, 50/50, 60/40), Figures 3-8 and 3-9 show that each particle size maintains a fairly stable spacing, so both are part of the DASR. All contiguous particle sizes determined to be interactive are considered part of the DASR, and are considered to act as a unit for determination of porosity.

3.8 Interaction diagrams and DASR porosity

For any given gradation, the criteria described above can be used to determine which contiguous sizes are interacting. One simply needs to determine the relative proportion of the contiguous sizes and determine whether or not it is less than 70/30. Figure 3-10 presents an interaction diagram, showing the relative proportion of all contiguous sizes for the three gradations presented in Figure 3-2. For purposes of illustration, the interaction diagram is shown for all aggregate sizes. However, only the interaction and porosity of the coarser aggregate is relevant for this evaluation, which is intended to determine whether the range of interactive coarse aggregate particles are sufficiently dense within the asphalt mixture to actually be in contact and provide the interlock necessary to resist deformation and fracture. For this purpose, the particle size passing the 2.36 mm sieve, but retained on the 1.18 mm sieve was selected as the smallest particle coarse enough to contribute to aggregate interlocking. This selection was based on existing definitions of coarse and fine aggregates for asphalt mixture, which generally separate coarse and fine aggregate at the 2.36 mm sieve, and knowledge of soil mechanics indicating that particles finer than this have little internal friction. The Bailey method defined coarse aggregate as particles large enough to create voids of a certain size when placed in a unit volume. The primary control sieve (PCS) separates coarse and fine aggregate in the Bailey method. For a nominal maximum particle size (NMPS) of 12.5mm, the PCS is 2.36mm, based on a packing factor of 0.22. However, the packing factor can vary from 0.18~0.28 in the Bailey method. Therefore, selection of particles passing the 2.36 mm and retained on the 1.18 mm sieve for the intended purpose is also consistent with the Bailey approach.

As shown in Figure 3-10, in the coarse aggregate range, both the SMA and the coarse-graded mixture exhibit interaction between the 4.75/2.36 mm sizes and the 2.36/1.18 mm sizes. The fine-graded mixture exhibited interaction at three levels: 9.5/4.75 mm, 4.75/2.36 mm, and 2.36/1.18 mm. Therefore, the interaction diagram indicates that several potential DASR ranges need to be checked for these mixtures. The actual DASR of each mixture is the set of interactive (or single) particles that result in the lowest porosity for the mixture.

It is interesting to note that all contiguous particle sizes exhibit strong interaction for the gradation associated with the maximum density line (MDL). This result, of course, was anticipated, and lends credence to the interaction criterion established on the basis of spacing.

For example, the SMA has three potential DASR's: the aggregate retained on the 12.5 mm sieve, the aggregate passing the 12.5 mm sieve but retained on the 9.5 mm sieve, and the aggregates passing the 4.75 mm sieve and retained on the 1.18 mm sieve, which includes two interactive sizes. Because of the large amount of material retained on 9.5 mm sieve, this single aggregate size was the DASR for the SMA, even though two other sizes are interactive. As shown in Figure 3-11, the resulting DASR porosity for the SMA mixture was 42%, whether or not interaction was considered.

For both the coarse-graded and fine-graded mixtures, the interactive aggregate was the DASR, and as shown in Figure 3-11, the interaction made a dramatic difference in the determination of DASR porosity. Whereas the lowest porosity for individual coarse aggregate particles (i.e., no interaction) was 65% for the coarse-graded mixture and 74% for the fine-graded mixture, the resulting DASR porosities were 36% and 46%, respectively, once interaction was considered. Both mixtures met the proposed porosity criterion of 50%, which indicates that these gradations will result in good resistance to deformation and fracture. As indicated earlier, these mixtures are both known to be good performers in the state of Florida.

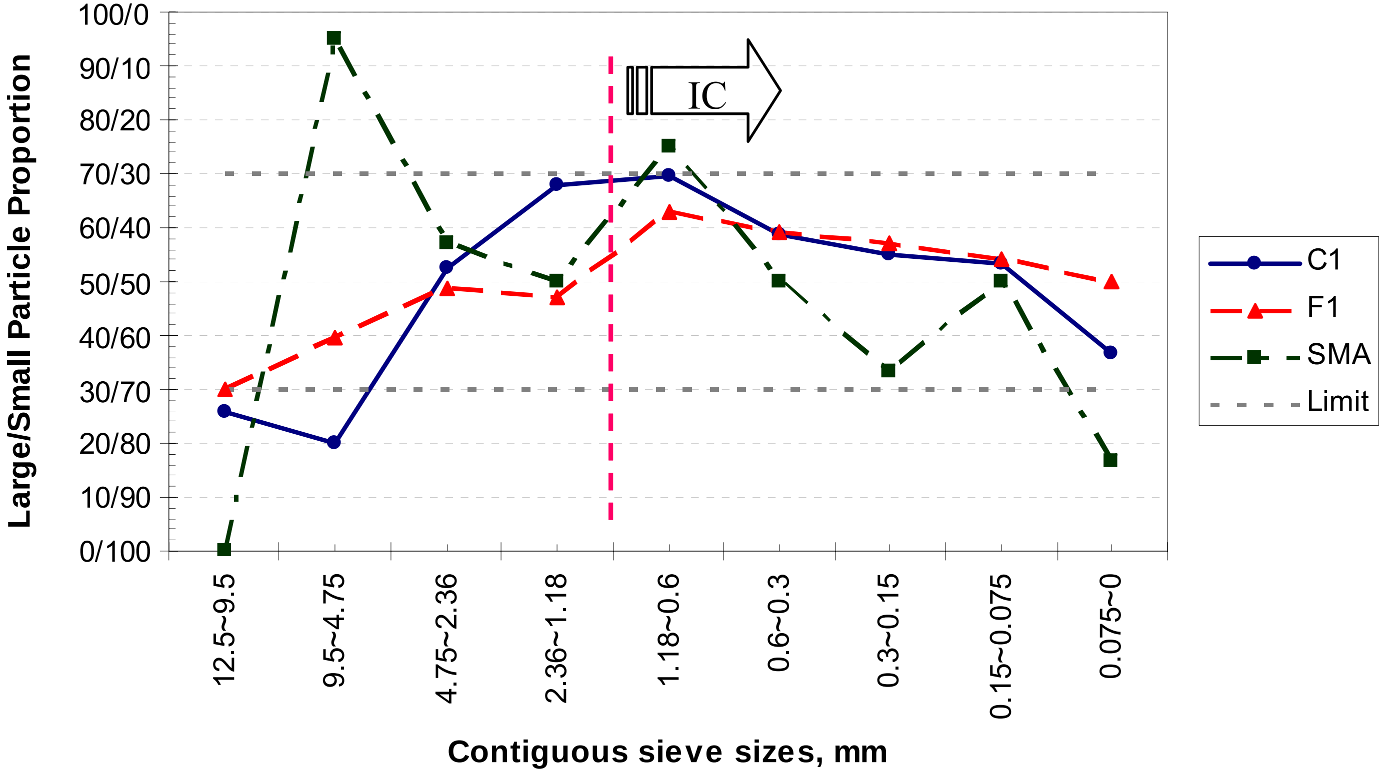
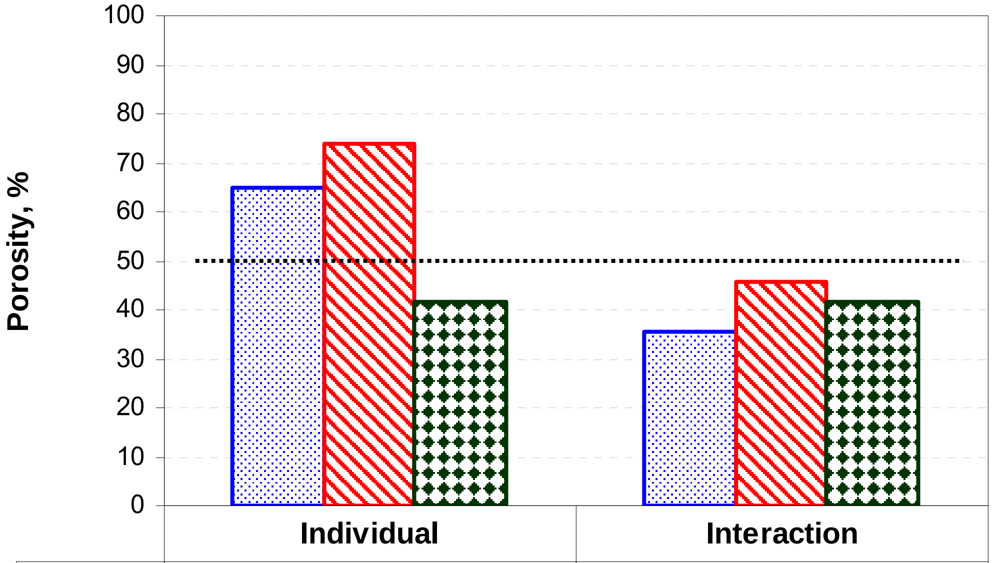


Figure 3-10 Interaction diagram



	Individual	Interaction
🟦 **Coarse**	**65**	**36**
🟥 **Fine**	**74**	**46**
🟩 **SMA**	**42**	**42**

Figure 3-11 Porosity result after considering interaction

CHAPTER 4
EVALUATION AND REFINEMENT

4.1 Introduction

Mixtures for which gradation has been well determined and documented, and for which rutting performance has been determined either from field measurements, laboratory rut tests, test track measurements, or measurements from accelerated pavement testing facilities (APT's) were used to evaluate the gradation evaluation system developed and presented in chapter 3. Five excellent sources of data were identified and obtained for this purpose:

- Field rutting performance measurements from the first eight projects associated with the comprehensive Superpave monitoring project being conducted by FDOT.
- Laboratory rutting performance determined from asphalt pavement analyzer (APA) and Servopac results on plant mixtures obtained from Projects 8 through 12 of the Superpave monitoring project (reliable field rut measurements were not yet available for these recently placed sections).
- Rutting performance measurements from fine-graded and coarse-graded mixtures placed and tested with the heavy vehicle simulator (HVS) at FDOT's APT facility in Gainesville, FL.
- Rutting performance of mixtures placed and tested at FHWA's WesTrack road test facility in Nevada.
- Rutting performance of mixtures placed and tested at NCAT's test track in Alabama.

For each data set, the gradation of each mixture evaluated was analyzed using the approach developed. Interaction diagrams were developed from the gradation data to identify the dominant aggregate size range (DASR) and the porosity of the DASR.

Mixtures were separated into one of the following three groups based on the interaction diagram characteristics and porosity of DASR:

- Group I: mixtures with DASR porosity less than 50% and having a clearly interactive DASR range. These mixtures were expected to perform well.
- Group II: mixtures with DASR porosity greater than 50%. These mixtures were expected to exhibit greater rutting than those with porosity less than 50%.
- Group III: mixtures with marginal interaction between aggregate sizes in the DASR (i.e., the relative proportion of larger to smaller aggregate sizes was very close to 70/30), and with DASR porosity less than 50% if interaction was considered, but greater than 50% if interaction was not considered. These mixtures were expected to exhibit marginal to poor performance and sensitivity to changes in asphalt content or gradation.

The rutting performance of each group was determined and compared to evaluate whether or not these criteria distinguished between mixtures exhibiting different rutting performance. Results of the evaluations are presented in the following sections.

4.2 Field Performance: Superpave Monitoring Projects 1 to 8

A comprehensive monitoring project was initiated by FDOT with the intention of studying construction and performance data of Superpave mixtures in the state of Florida to establish appropriate and realistic performance-based specifications. Twelve projects from throughout the state of Florida constructed with Superpave mixtures were monitored during and after construction. Extensive sampling was done by taking field cores from projects already constructed (Projects 1 to 7), and plant mix and field cores for Projects 8 to 12. Field performance has been continually monitored and an extensive laboratory testing program has been conducted on both field cores and plant mixtures obtained from the projects. Projects 1 to 8 have been subjected to over three years of traffic now, so valuable field rutting performance data is available for evaluation.

Interaction diagrams for mixture gradations associated with these projects are presented in Figures 4-1 to 4-10. It is emphasized that these gradations are in-place gradations as determined from field cores, and not simply job-mix-formula gradations which may or may not be representative of the final result in the field. Resulting DASR porosity of each project mixture is presented in Figure 4-11, which indicates that four mixtures were in Group I (DASR porosity < 50%), two mixtures were in Group II (DASR porosity > 50%), and two mixtures were in Group III (marginal interaction). Note that two DASR porosity values are presented for Projects 1 and 2, which had the mixtures determined to have marginal interaction within the DASR range. This is evident in Figure 4-1, which shows that the relative proportion of the 4.75/2.36 mm and the 2.36/1.18 mm aggregate sizes was right at 70/30. As indicated in Figure 4-11, the

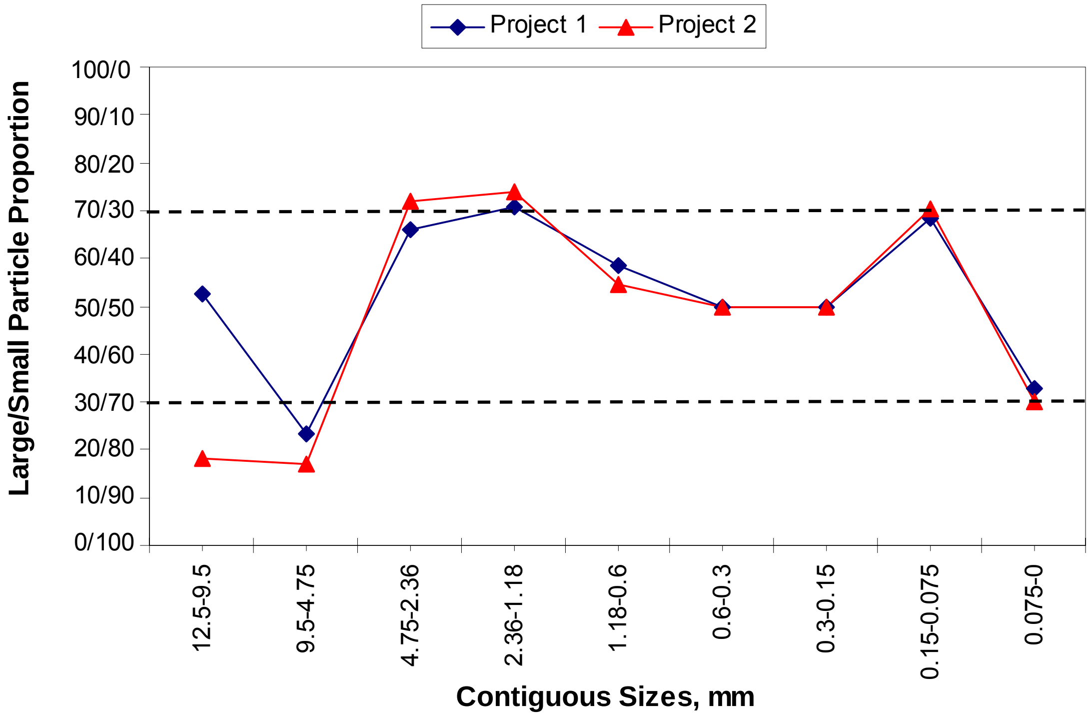


Figure 4-1 Interaction Diagram for Field Mixtures of Project 1 and 2

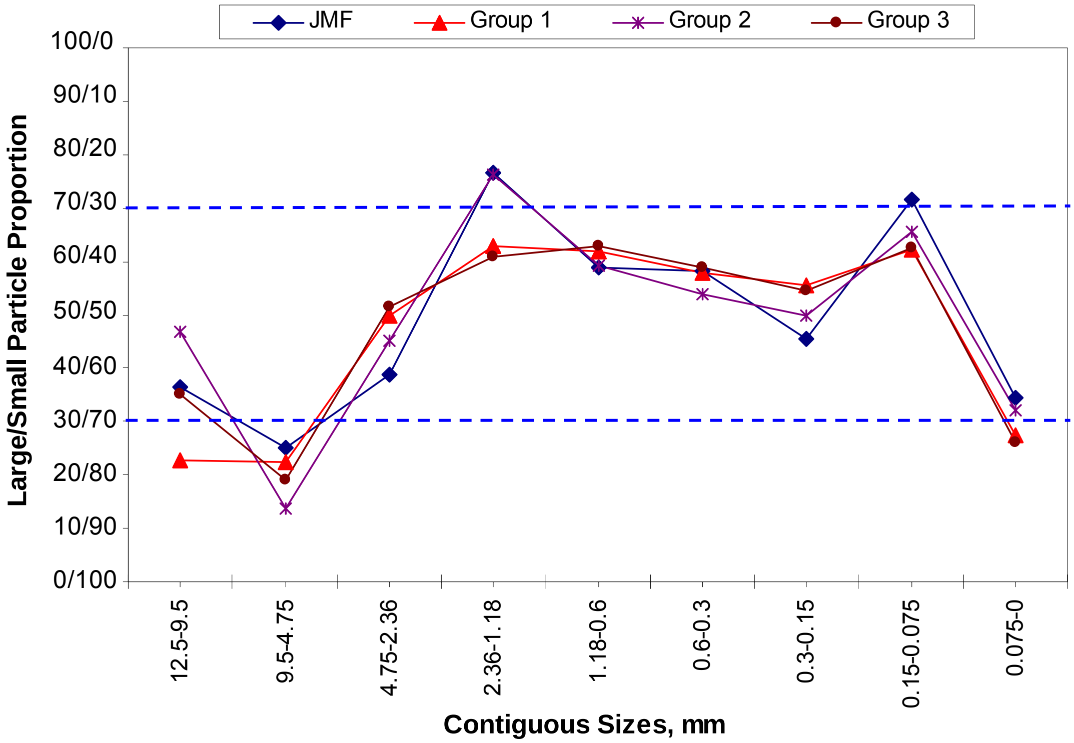


Figure 4-2 Interaction Diagram for Field Mixtures of Project 3 Layer A

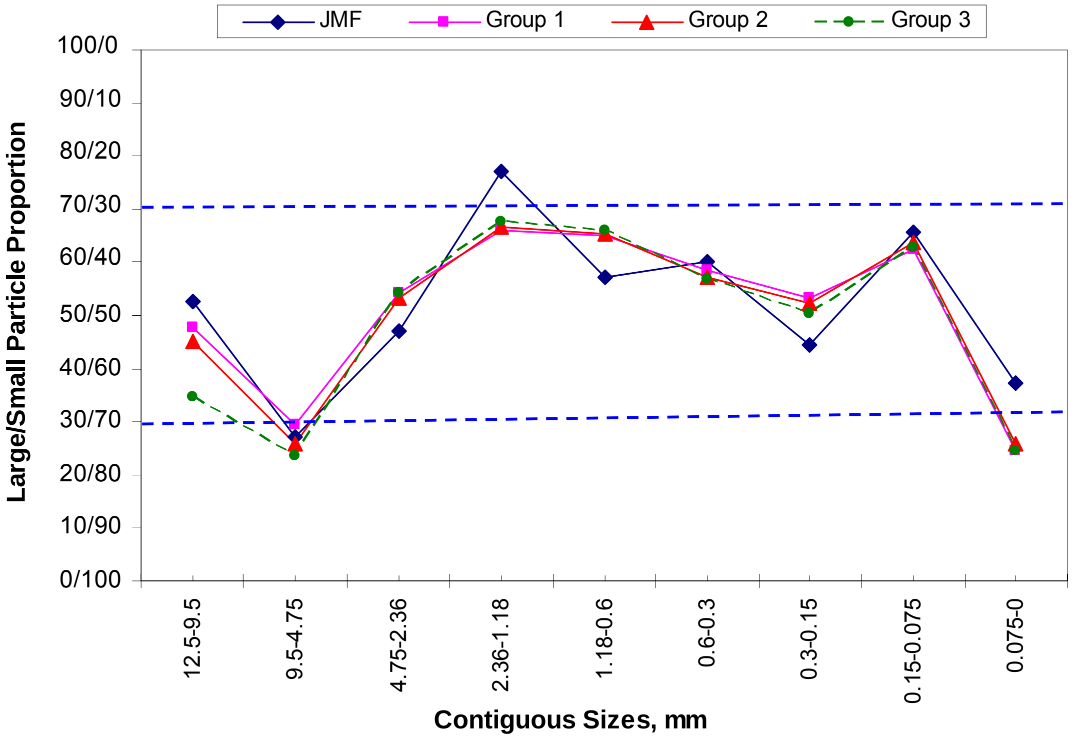


Figure 4-3 Interaction Diagram for Field Mixtures of Project 3 Layer B

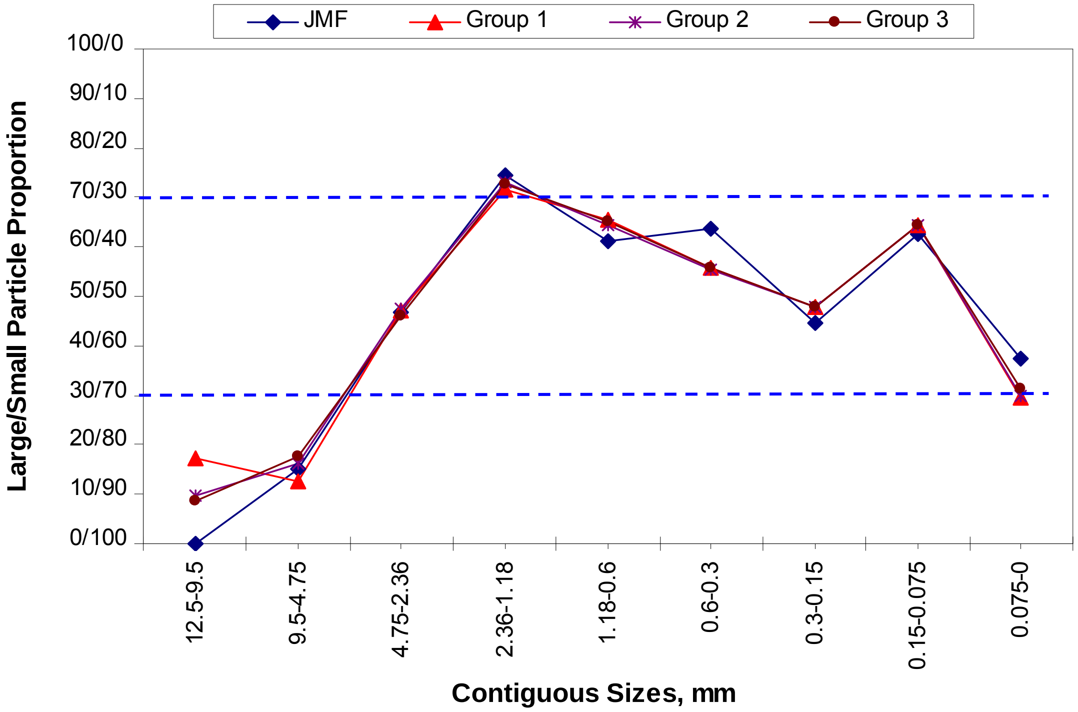


Figure 4-4 Interaction Diagram for Field Mixtures of Project 4 Layer A

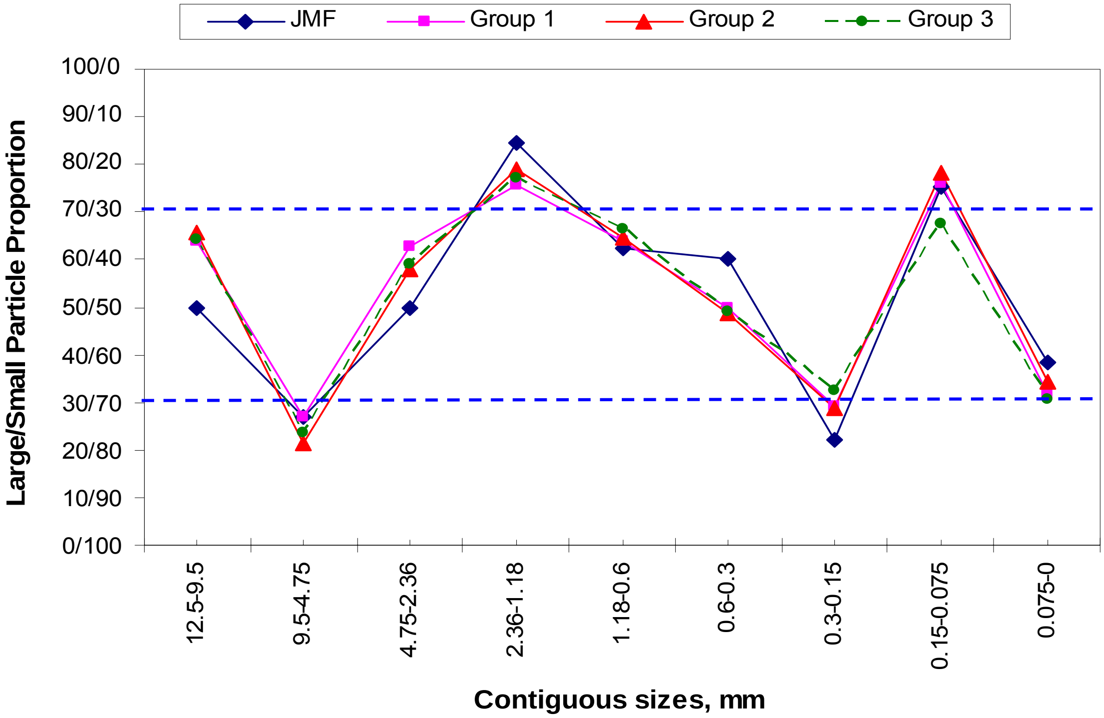


Figure 4-5 Interaction Diagram for Field Mixtures of Project 4 Layer B

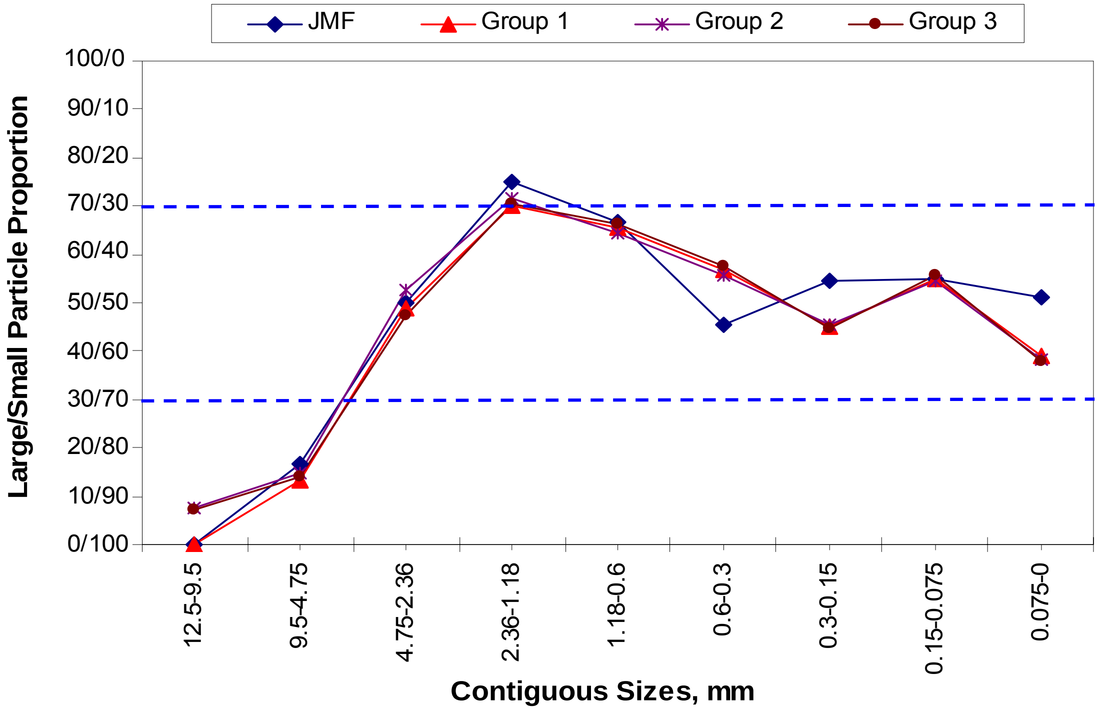


Figure 4-6 Interaction Diagram for Field Mixtures of Project 5 Layer A

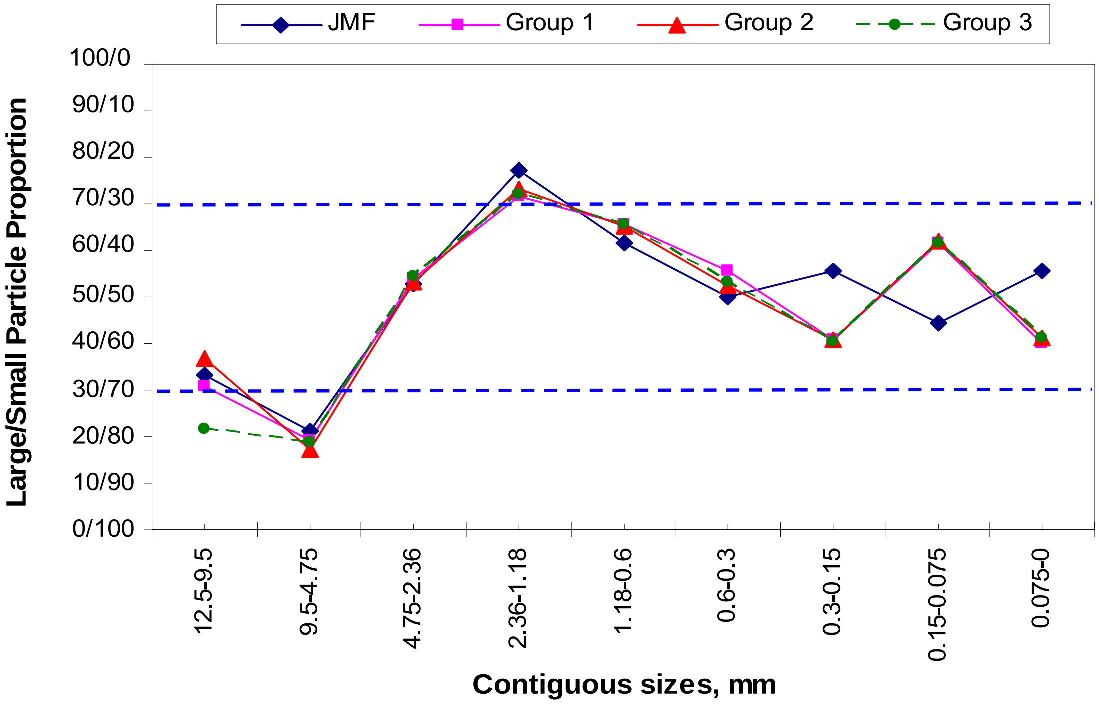


Figure 4-7 Interaction Diagram for Field Mixtures of Project 5 Layer B

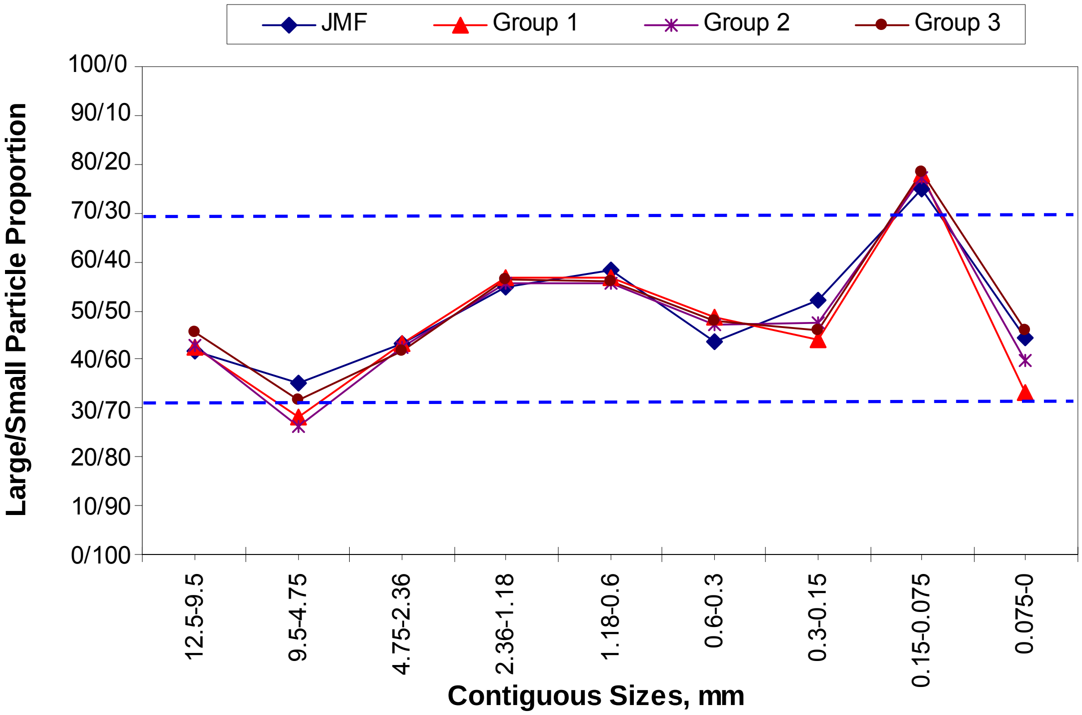


Figure 4-8 Interaction Diagram for Field Mixtures of Project 6

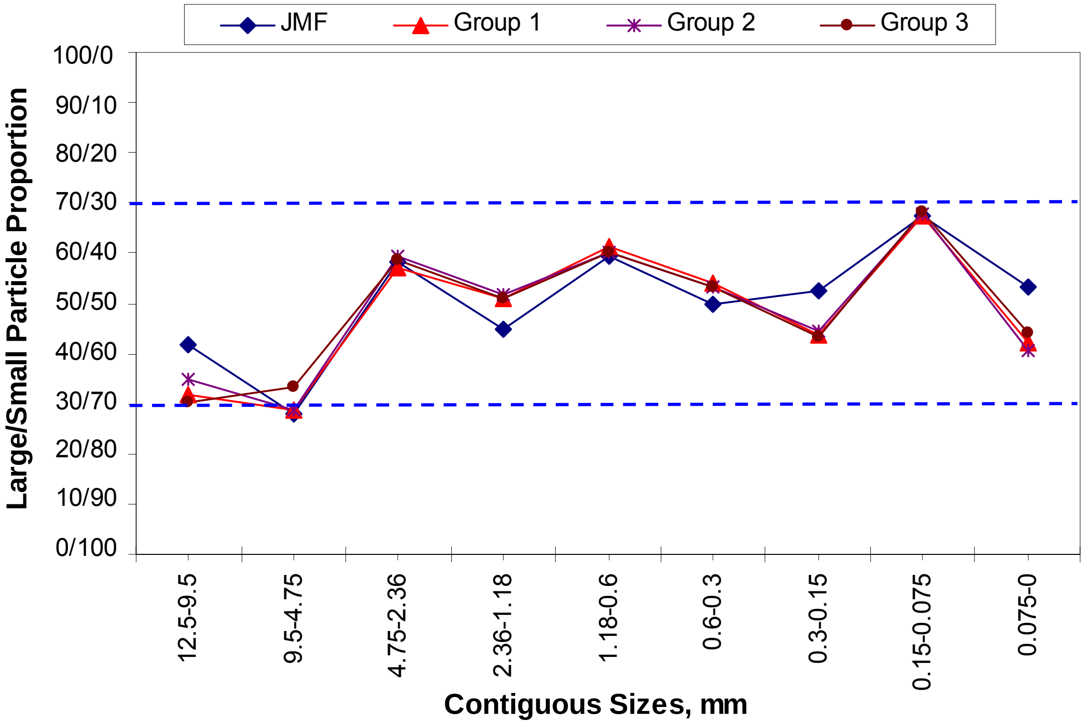


Figure 4-9 Interaction Diagram for Field Mixtures of Project 7

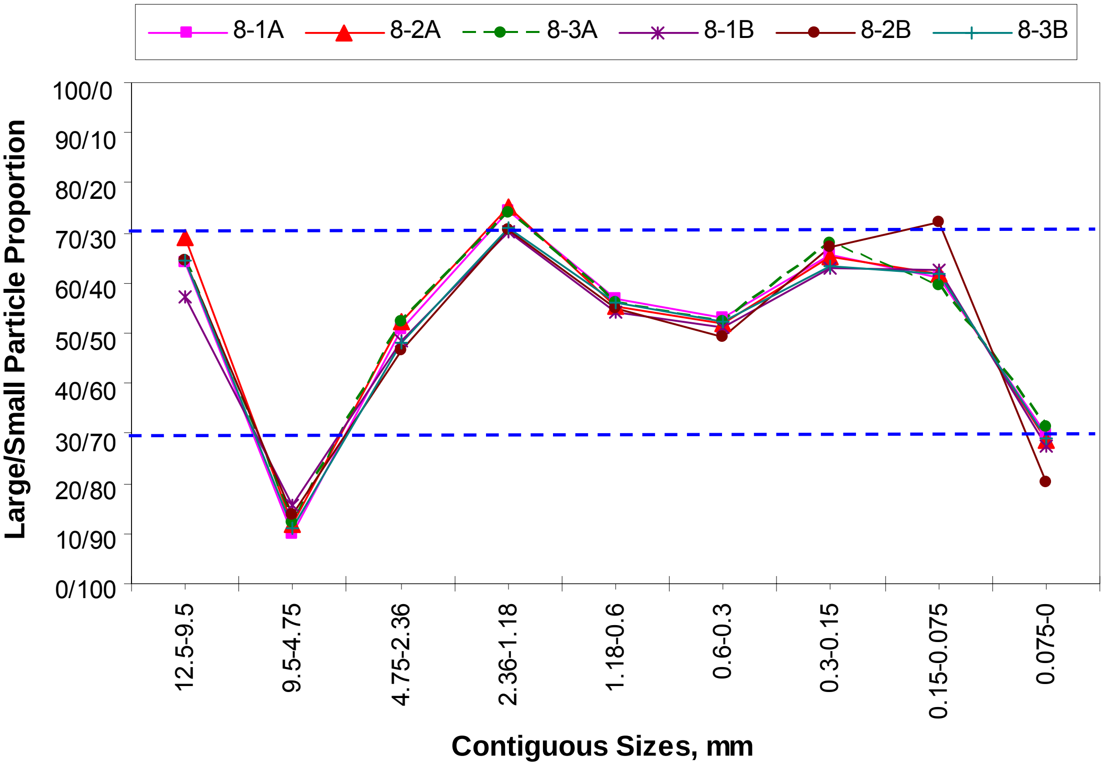


Figure 4-10 Interaction Diagram for Field Mixtures of Project 8

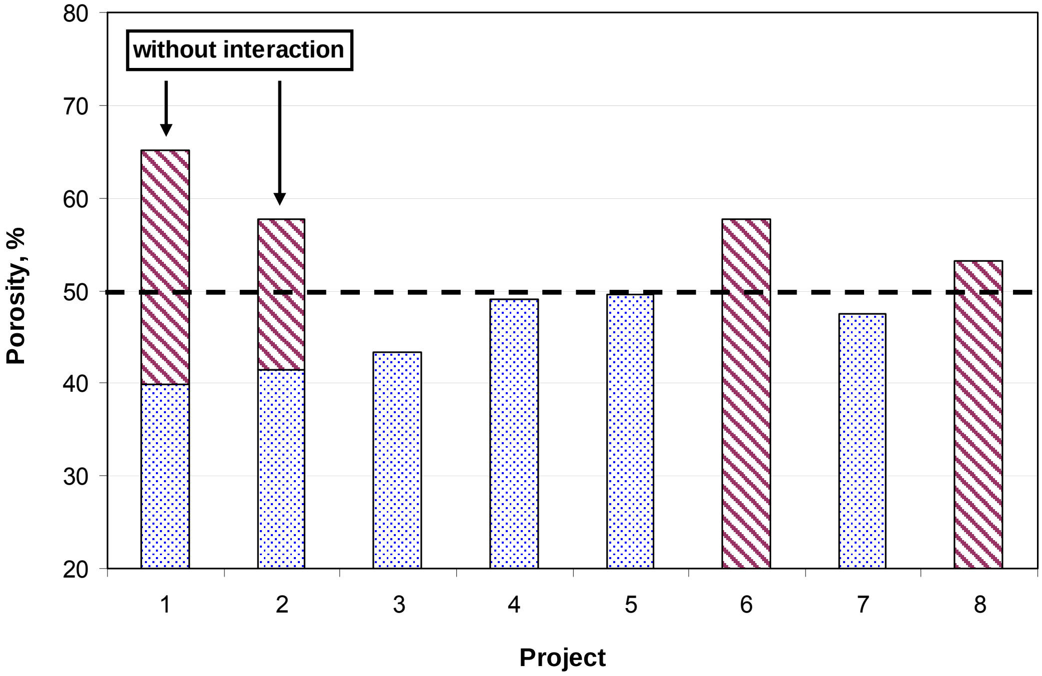


Figure 4-11 Porosity Result for Field Mixtures

DASR porosity of both mixtures is less than 50% if these sizes are considered interactive, but significantly greater than 50% if these sizes are not interactive.

Field rut depths obtained from transverse profilograph measurements on each project are presented in Figure 4-12. The results are presented in terms of rut depth/ESAL's (mm/ESAL*10^6) in order to normalize the effect of traffic between the different sections. Two sets of rut depth measurements are presented (Round I and Round II), which refer to measurements obtained at two different times after construction. Round I measurements were obtained approximately 1~2 years after construction, while round II measurements were obtained about one year later.

A cursory evaluation of Figure 4-12 indicates that Projects 3, 4, 5, and 7 exhibited the best rutting performance, while projects 1, 2, 6, and 8 had relatively higher rutting. As shown in Figure 4-11, Projects 3, 4, 5, and 7 were the four projects in Group I with DASR porosity less than 50%, while Projects 6 and 8 were in Group II (DASR porosity > 50%) and Projects 1 and 2 were in Group III (marginal interaction).

Figure 4-13 and 4-14 presents the average rut depth/ESAL for the three groups of mixtures, for Round I and II, respectively. These figures clearly indicate that mixtures with DASR porosity < 50% exhibited significantly lower field rutting performance than mixtures with DASR porosity > 50% or mixtures with marginally interactive aggregates. The minimum and maximum rut depth/ESAL for each group is also shown in Figures 4-13 and 4-14, which show that all mixtures within each group exhibited similar performance.

The results of these evaluations indicate the following:

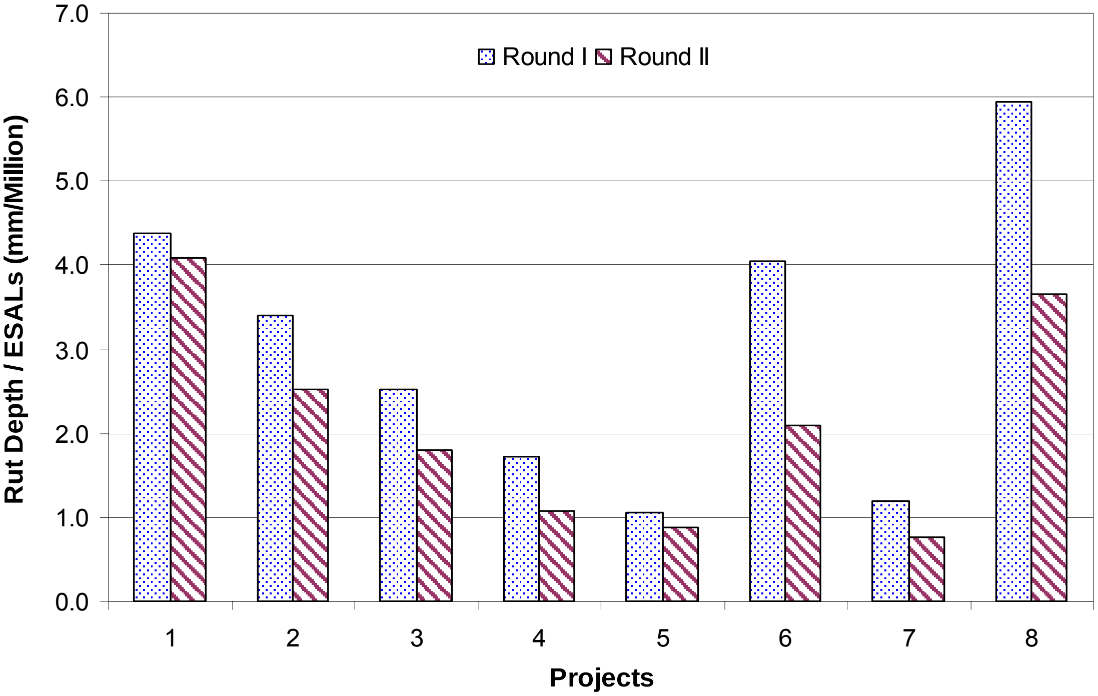


Figure 4-12 Rut Depth/ESALs from Field Measurement

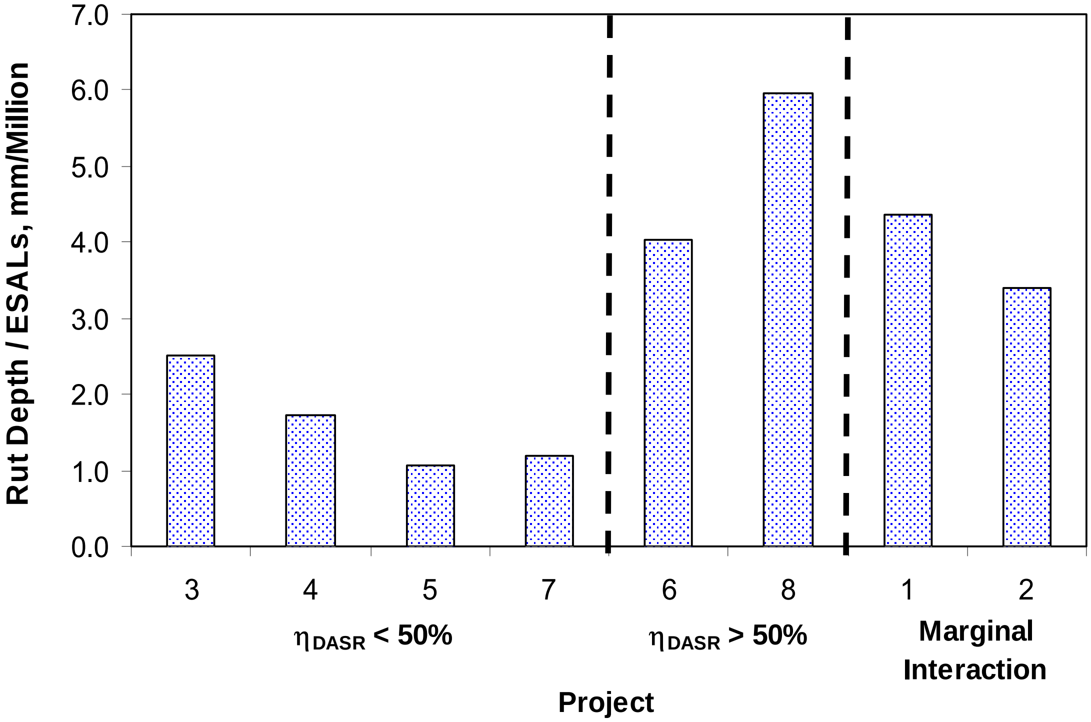


Figure 4-13 Average Rut Depth/ESALs for Different Porosity Groups (Round I)

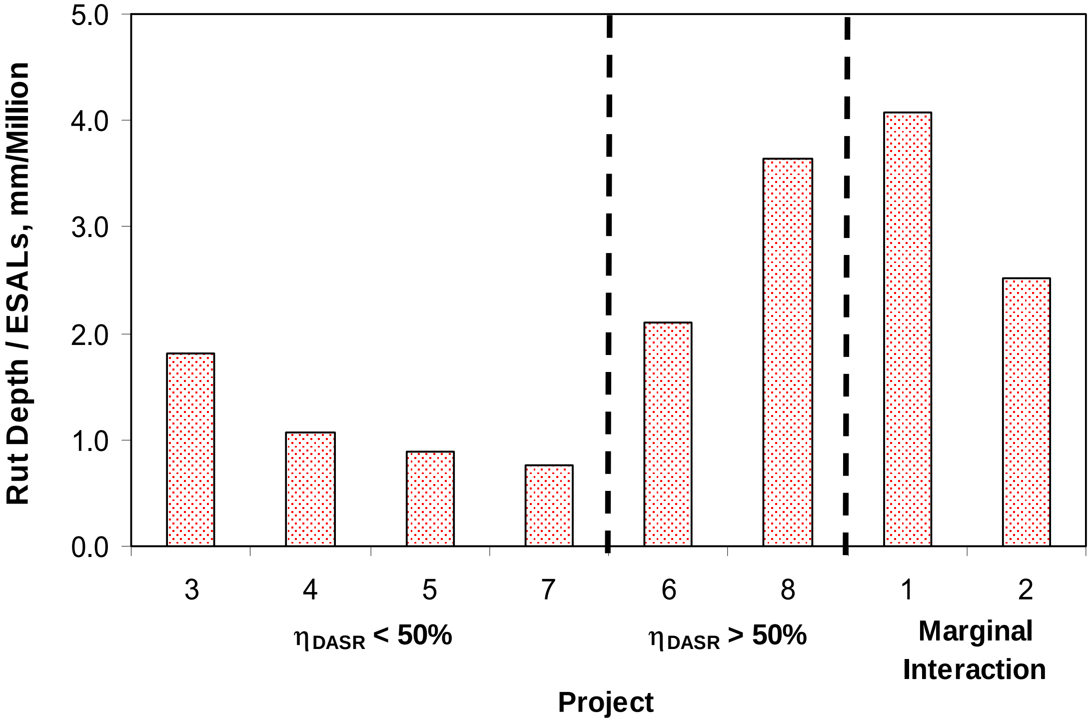


Figure 4-14 Average Rut Depth/ESALs for Different Porosity Groups (Round II)

- The DASR porosity criterion of 50% based on the gradation evaluation system developed as part of this research effort appears to accurately distinguish between the relative rutting performance of Superpave mixtures in the field. Mixtures meeting the porosity criterion exhibited less rutting than mixture that did not.

- The interaction criterion of 70/30 for the relative proportion of contiguous aggregate sizes within the DASR range appears to distinguish well between coarse aggregate structures that interact properly and those that do not. Marginal interaction as determined according to this criterion resulting mixtures with higher rutting than mixtures with gradations that were not marginal.

4.3 Laboratory Performance: Superpave Monitoring Projects 8 to 12

These projects have been monitored from the time of construction to the present. Consequently, and in contrast to projects 1 to 7 that had already been constructed at the time the Superpave monitoring project began, it was possible to obtain samples of plant mixture for laboratory testing. These samples were used to perform rut tests with the asphalt pavement analyzer and the Servopac Gyratory compactor. Unfortunately, these test sections were recently constructed and have not been subjected to enough traffic in the field, so reliable measurements of field rutting were not yet available for evaluation.

Interaction diagrams for mixture gradations associated with these projects are presented in Figures 4-15 to 4-19. It is emphasized that these gradations were determined from the same plant mix samples that were used to perform the laboratory tests reported in this section. It should be noted that the gradation of plant mixtures from project 8 was different than the field gradation because of breakdown that occurred during compaction in the field. Resulting DASR porosity of each project mixture is presented in Figure 4-20, which indicates that two mixtures were in Group I (DASR porosity < 50%), two mixtures were in Group II (DASR porosity > 50%), and one mixture was in Group III (marginal interaction). Once again, two DASR porosity values are presented for Project 10, which had the mixture determined to have marginal interaction within the DASR range.

This is evident in Figure 4-17, which shows that the relative proportion of the 4.75/2.36 mm and the 2.36/1.18 mm aggregate sizes was right at 70/30 (actually slightly above for the 2.36/1.18 mm sizes). As indicated in Figure 4-20, the DASR porosity of this mixture is less than 50% if these sizes are considered interactive, but significantly greater than 50% if the these sizes are not interactive.

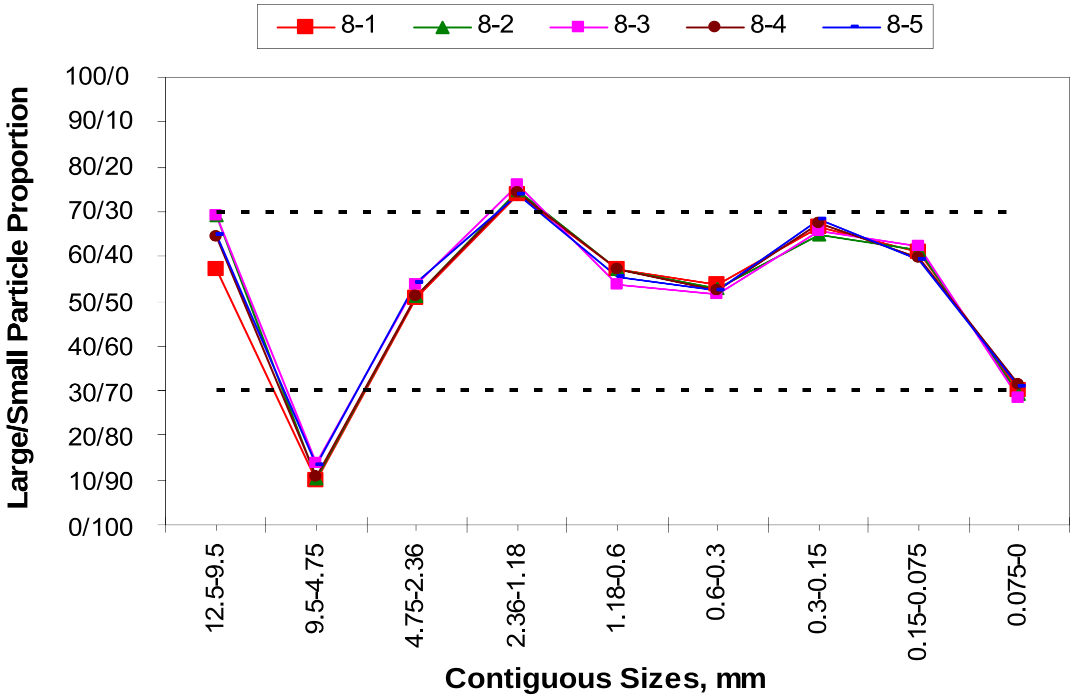


Figure 4-15 Interaction Diagram for Plant Mixtures of Project 8

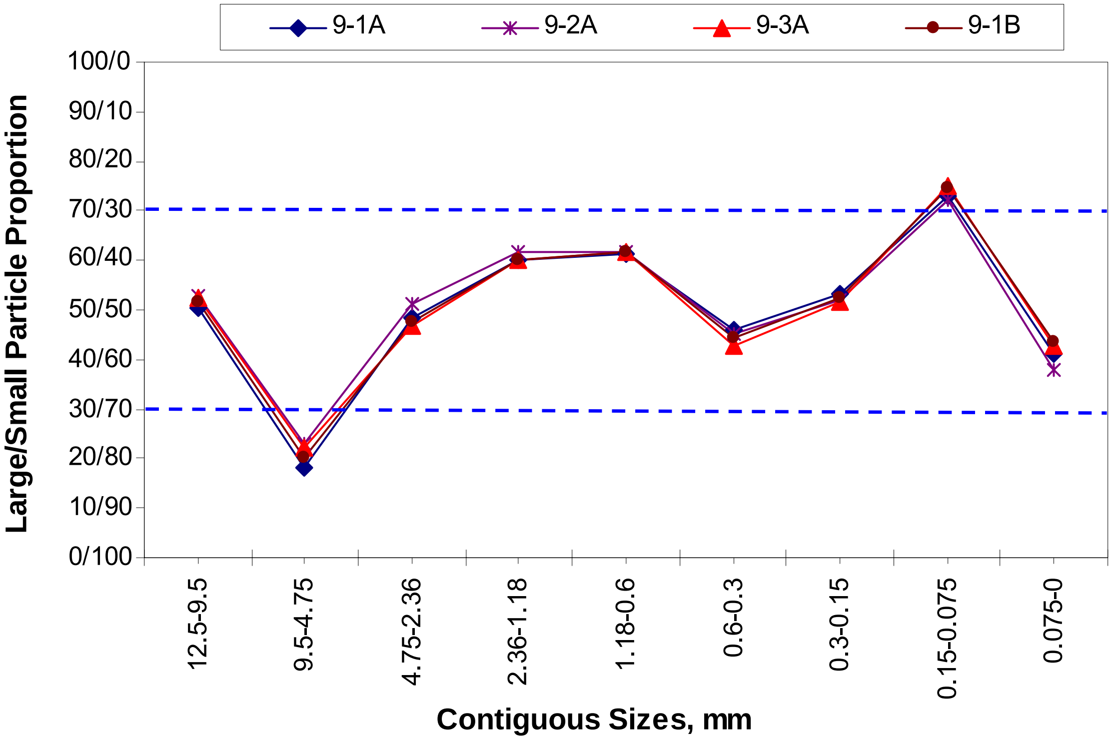


Figure 4-16 Interaction Diagram for Plant Mixtures of Project 9

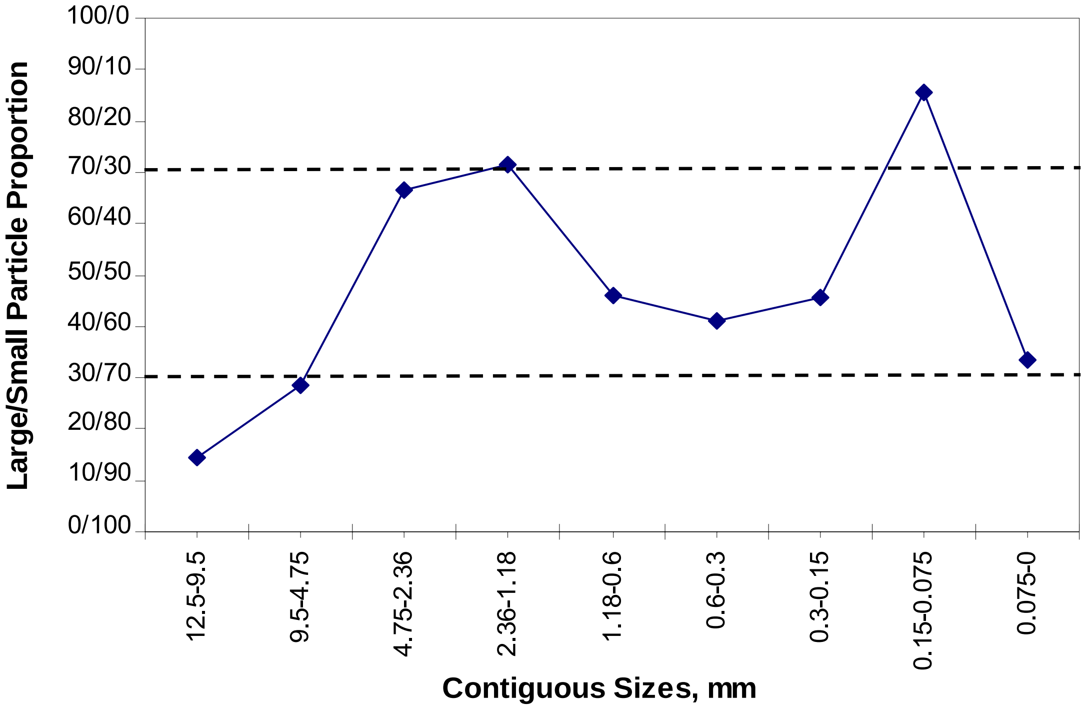


Figure 4-17 Interaction Diagram for Plant Mixtures of Project 10

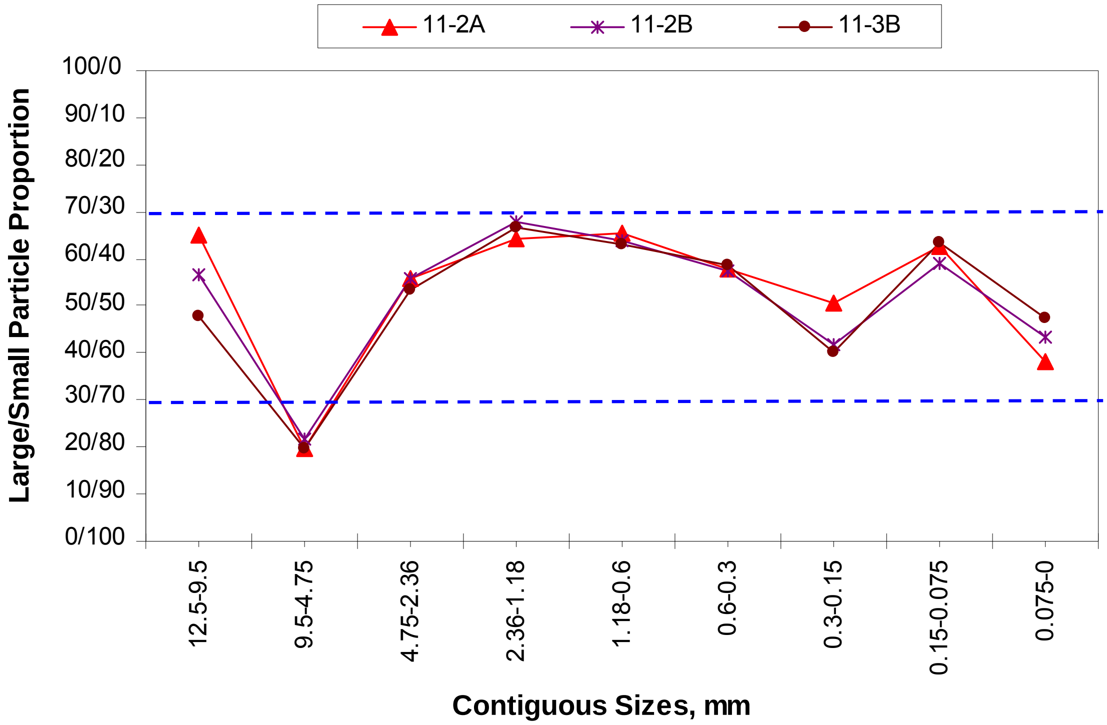


Figure 4-18 Interaction Diagram for Plant Mixtures of Project 11

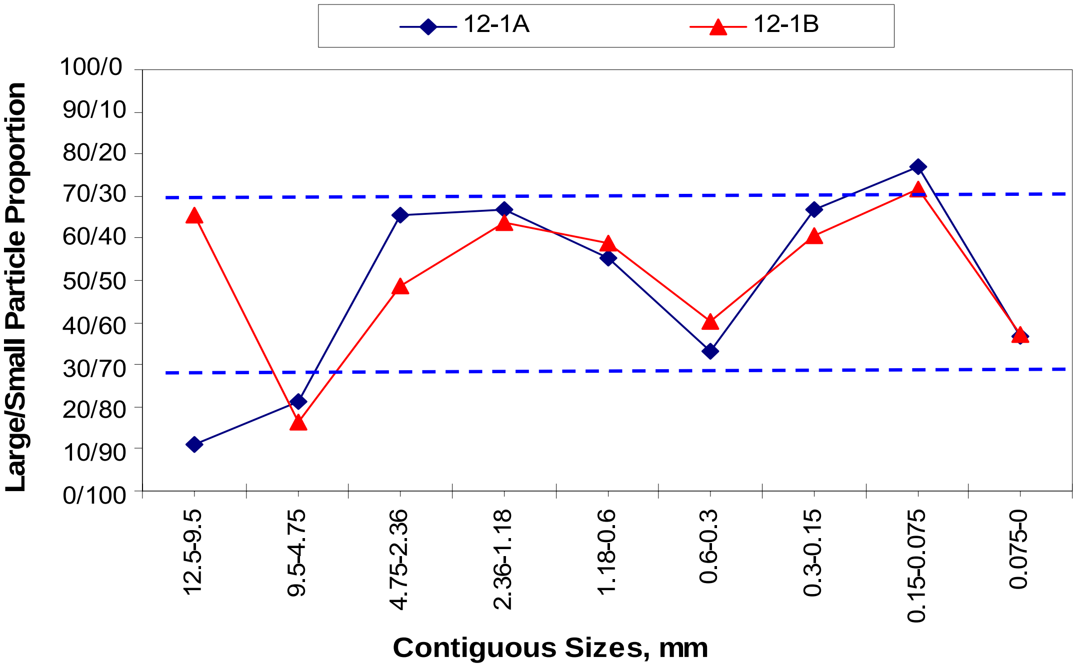


Figure 4-19 Interaction Diagram for Plant Mixtures of Project 12

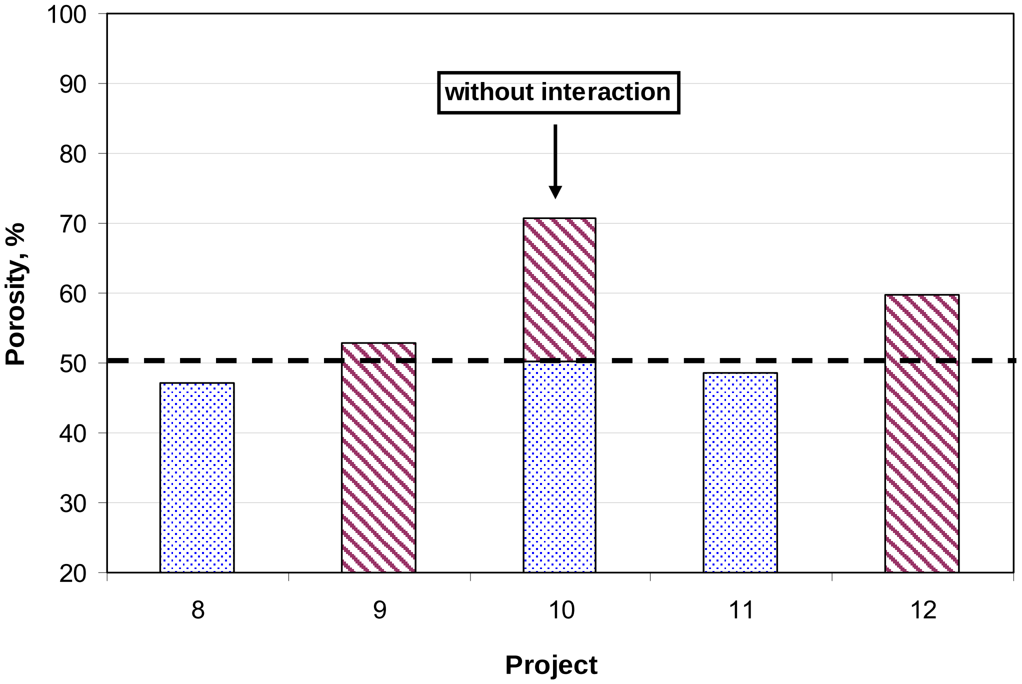


Figure 4-20 Porosity Result for Plant Mixtures

Rut depths obtained from the modified APA system, which was developed by the University of Florida as part of a recent FDOT research project (Drakos et al., 2001, 2005), are presented for each of the mixtures in Figure 4-21. The modified system involved the use of a simulated tire rib for loading, instead of the hose used in the conventional system. Research showed that the rib induces stresses that are more representative of an actual radial truck tire. The new system also involved measurements of rut profiles in addition to the absolute rut depth measurement obtained in the conventional APA system. The rut profiles allow for the determination of differential rut depth and change in cross-sectional area of profile, which can be used to identify the presence of mixture instability. Positive area changes indicate dilation associated with instability, while zero or negative area change indicates contraction or no volume change, which indicates that no instability has occurred. Results of area change calculations for

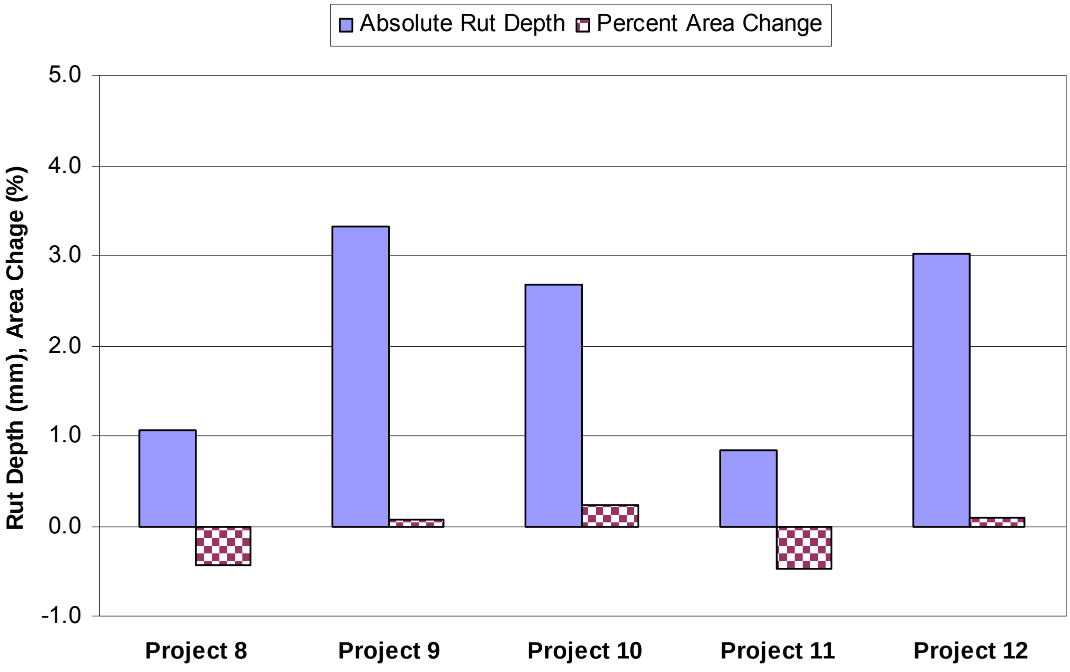


Figure 4-21 APA Test Result (Rib) for Plant Mix Gradations

the mixtures are also presented in Figure 4-21.

A cursory evaluation of Figure 4-21 indicates that Projects 8 and 11 exhibited the best rutting performance (lowest rut depth and negative area change, indicating no instability), while Projects 9, 10, and 12 exhibited higher APA rut depths and positive area change, indicating the presence of instability). As shown in Figure 4-20, Projects 8 and 11 were the two projects in Group I with DASR porosity less than 50%, while Projects 9 and 12 were in Group II (DASR porosity > 50%) and Projects 10 was in Group III (marginal interaction).

Figure 4-22 and 4-23 present the average APA rut depth and percent area change, respectively, for the three groups of mixtures. Figure 4-22 clearly indicates that mixtures with DASR porosity < 50% exhibited significantly lower APA rut depths than mixtures with DASR porosity > 50% or mixtures with marginally interactive aggregates. Figure 4-23 clearly shows that mixtures with DASR porosity < 50% exhibited negative area change (no instability), while mixtures with DASR porosity > 50% and mixtures with marginally interactive aggregates exhibited positive area changes (instability). The minimum and maximum rut depth and area change values for each group are also shown in Figures 4-22 and 4-23, which show that all mixtures within each group exhibited similar performance.

Results of Servopac rutting analysis procedures, which were developed by the University of Florida as part of a recent FDOT research project (Birgisson et al., 2004), are presented for each of the mixtures in Figure 4-24. The two parameters obtained from the procedure, which is based on shear stress measurements obtained during compaction with the Servopac unit at compaction angles of 1.25 and 2.5 degrees, are:

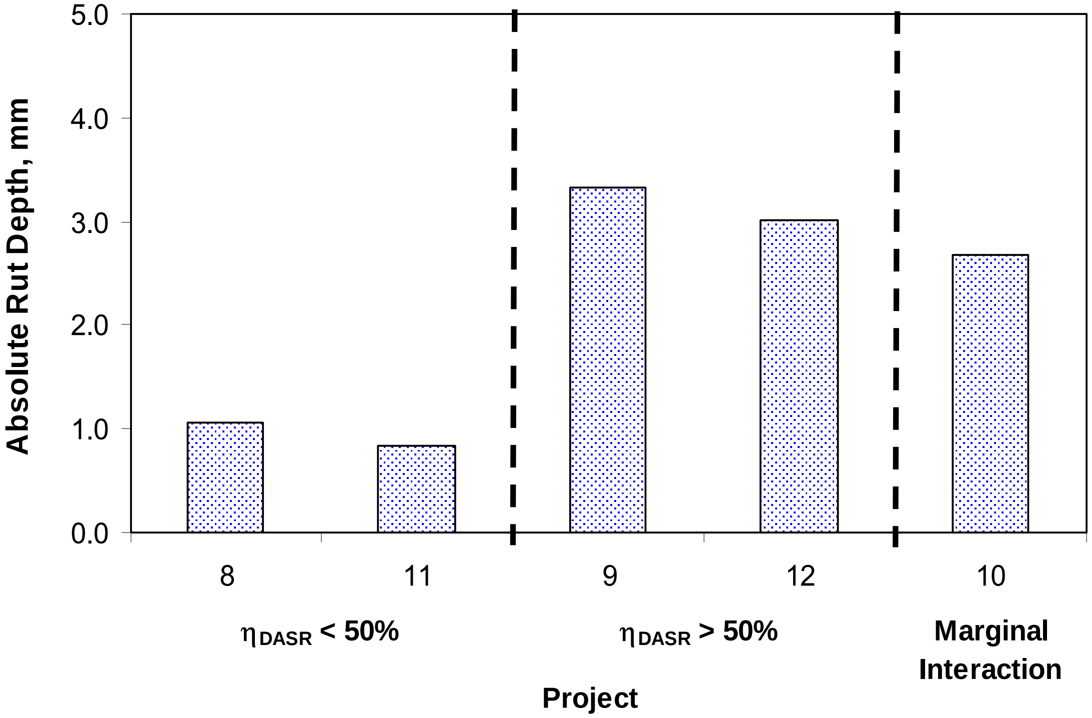


Figure 4-22 Absolute Rut Depth for Different Porosity Groups (APA)

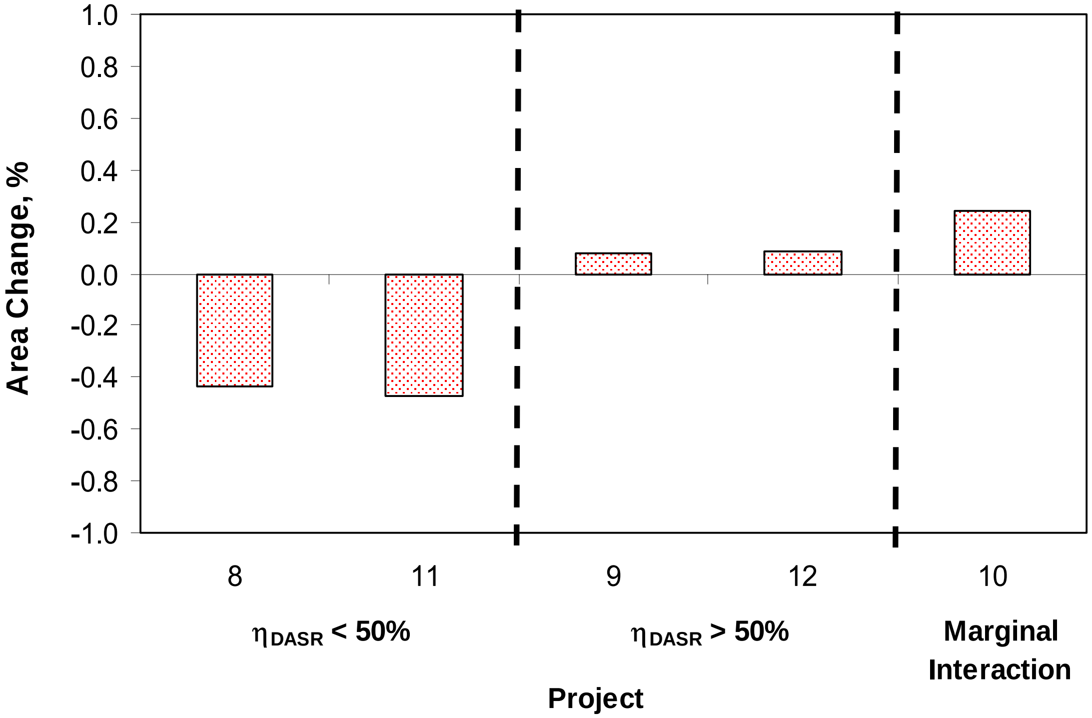


Figure 4-23 Area Change for Different Porosity Groups (APA)

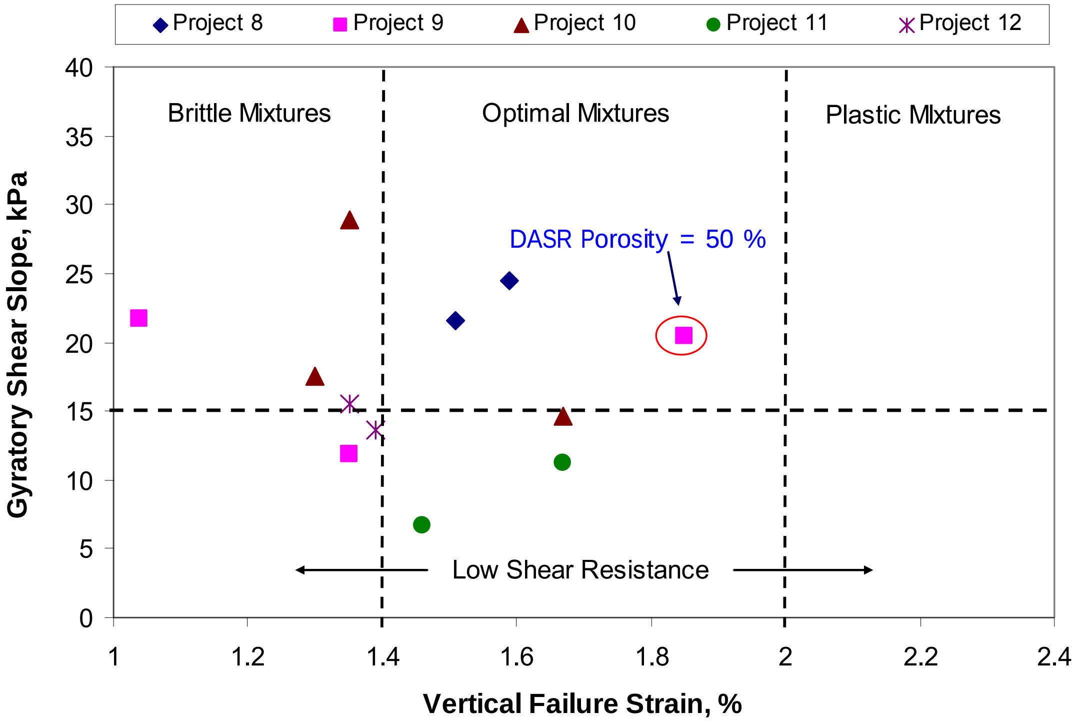


Figure 4-24 Servopac Result for Plant Mix Gradations

- Gyratory shear slope, which is the rate of change in shear resistance during the densification portion of compaction at 1.25 degrees; and

- Vertical failure strain, which is the amount of vertical strain developed in the mixture between the time instability is induced by increasing the compaction angle to 2.5 degrees and the time the mixture begins to regain strength after instability.

Based on the criteria developed in the research, mixtures are considered to exhibit optimal behavior when the percent vertical failure strain is between 1.4 and 2, and the gyratory shear slope is greater than 15 kPa.

The results presented in Figure 4-24 indicate that only mixtures from projects 8 and 11 consistently have vertical failure strains in the optimal range. Except for two specimens tested, vertical strains for projects 9, 10, and 12 were outside the optimal range (in the brittle range). As shown in Figure 4-20, Projects 8 and 11 were the two projects in Group I with DASR porosity less than 50%, while Projects 9 and 12 were in Group II

(DASR porosity > 50%) and Projects 10 was in Group III (marginal interaction). It is interesting to note that the two specimens from the Group II and III mixture that were in the optimal range were: 1) a plant mix specimen obtained from a location along Project 9 where the DASR porosity was 50%; and 2) one Project 10 mixture, which was considered marginal, indicating that small changes could potentially make the mixture good or bad (i.e., sensitivity). The results are presented by grouping according to the gradation analysis in Figure 4-25.

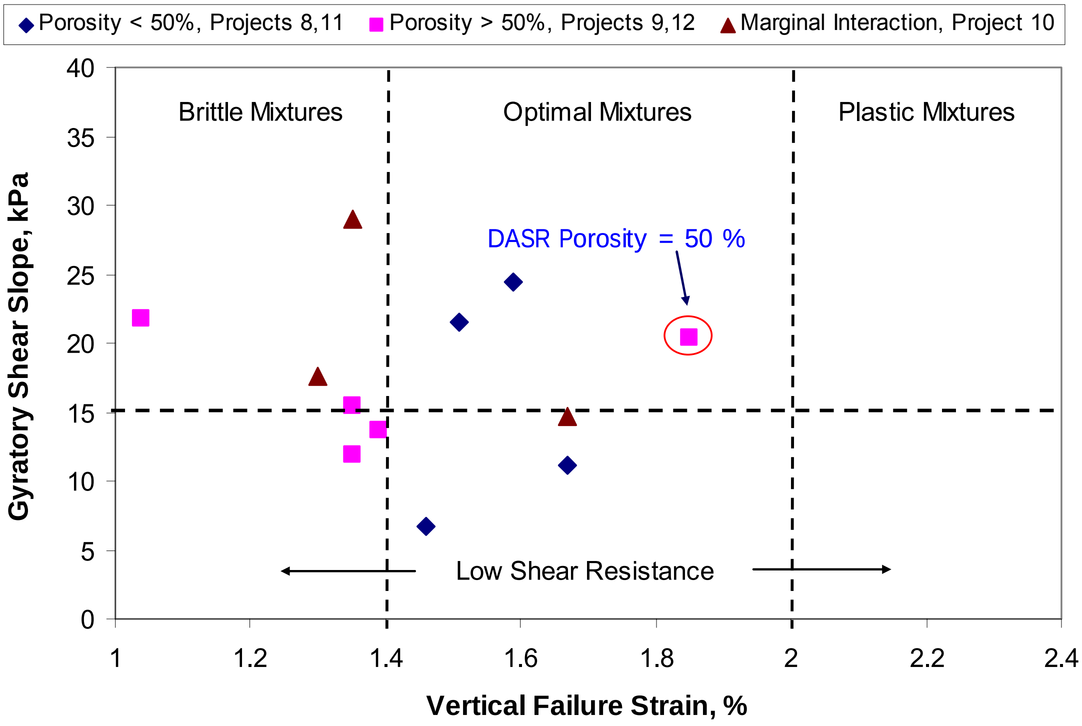


Figure 4-25 Servopac Result for Different Porosity Groups

In summary, the evaluation based on laboratory rut depths also appear to verify the validity of the criteria established based on the gradation evaluation system developed as part of this research effort. These are promising outcomes based on 12 Superpave mixtures of varying gradation and aggregate type that are currently used throughout the state of Florida.

4.4 HVS Test Sections: Fine- and Coarse-Graded Superpave Mixtures

An ongoing experiment at FDOT's accelerated pavement testing (APT) involves the evaluation of the relative rutting potential of two different Superpave gradations: one coarse-graded and one fine-graded. At the APT site, three lanes were paved with the fine-graded mixtures and two lanes with the coarse-graded mixture. Each lane consists of three test sections that can independently be subjected to traffic using the Heavy Vehicle Simulator (HVS). Each lane was constructed with two lifts of the same mixture. All mixtures are 12.5 mm NMAS (Nominal Maximum Aggregate Size) with granite aggregates.

Table 4-1 and 4-2 present the mixture design properties and in-place gradations for the top and bottom lifts (the JMF was the same for both lifts). The section ID is composed of the lift position, lane, and section. For example, 'T-3-A' refers to the mixture on the top lift of the first section (A) of lane 3.

For the writing of this report, one lane of the fine-graded mixture (lane 3) and one lane of the coarse-graded mixture (lane 5) had been subjected to traffic with HVS. The results of these tests will be presented below, along with an evaluation of the gradations using the system developed in this research project.

4.4.1 HVS results

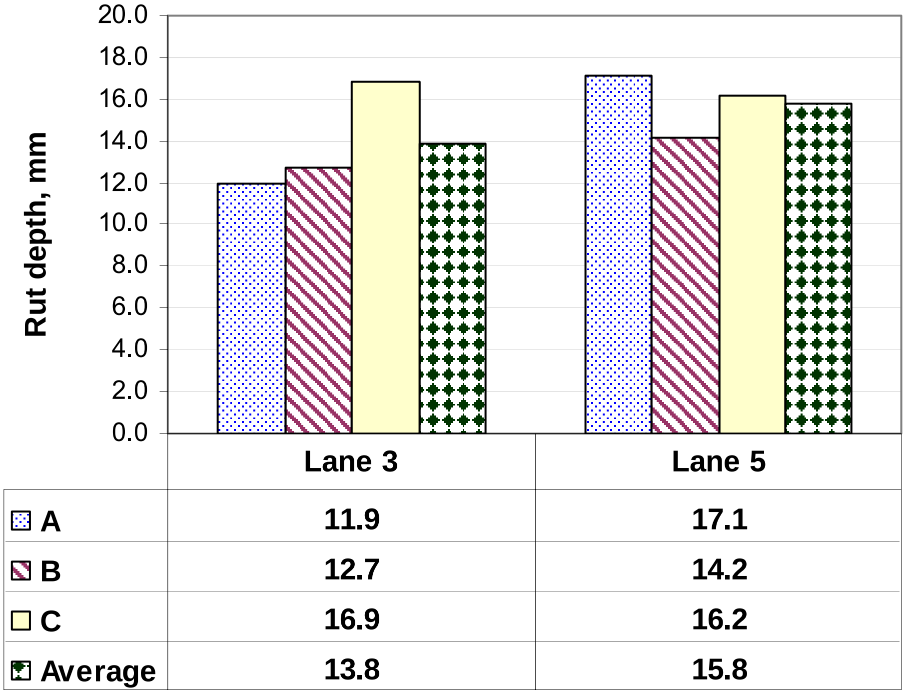
Rut depth measurements after 90,000 passes of the HVS are presented in Figure 4-26. Although some variability was observed, the average rut depth of the coarse-graded mixture (15.8 mm) was greater than for the fine-graded mixture (13.8 mm).

Table 4-1 Mixture Design Properties for the Top Lift

Top Lift								
	Fine Graded Mix				Coarse Graded Mix			
Lane		3	3	3		5	5	5
Section		A	B	C		A	B	C
ID	JMF	T-3-A	T-3-B	T-3-C	JMF	T-5-A	T-5-B	T-5-C
Truck	JMF	4	4	5	JMF	1	1	2
G_{mm}	2.579	2.602	2.602	2.591	2.589	2.573	2.573	2.579
G_{mb}	2.475	2.491	2.491	2.506	2.485	2.457	2.457	2.468
G_{sb}	2.768	2.778	2.778	2.779	2.779	2.780	2.780	2.777
AC content	4.6	4.1	4.1	4.2	4.5	4.5	4.5	4.6
Air Voids	4.0	4.3	4.3	3.3	4.0	4.5	4.5	4.3
VMA	14.7	14.0	14.0	13.6	14.6	15.6	15.6	15.2
VFA	73	69	69	76	73	71	71	72
P_{be}	4.5	4.1	4.1	4.2	4.4	4.5	4.5	4.6
Dust Ratio	1.1	1.3	1.3	1.2	1.0	0.8	0.8	0.8
3/4”	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2”	98.0	97.5	97.5	97.0	98.0	96.8	96.8	96.6
3/8”	90.0	88.2	88.2	85.2	90.0	88.0	88.0	85.8
#4	68.0	61.6	61.6	59.1	54.0	47.3	47.3	47.8
#8	48.0	44.6	44.6	43.0	32.0	29.5	29.5	30.1
#16	34.0	33.7	33.7	32.8	23.0	22.8	22.8	23.1
#30	25.0	26.9	26.9	26.4	17.0	18.7	18.7	19.0
#50	16.0	17.2	17.2	17.2	11.0	12.1	12.1	12.6
#100	8.0	8.2	8.2	8.2	5.0	5.7	5.7	5.9
#200	4.9	5.2	5.2	5.1	4.5	3.6	3.6	3.8
Density	93.0	92.7	91.4	92.3	94.5	93.4	93.7	93.4

Table 4-2 Mixture Design Properties for the Bottom Lift

Bottom Lift								
	Fine Graded Mix				Coarse Graded Mix			
Lane		3	3	3		5	5	5
Section		A	B	C		A	B	C
ID	JMF	B-3-A	B-3-B	B-3-C	JMF	B-5-A	B-5-B	B-5-C
Truck	JMF	4	4	5	JMF	7	7	8
G_{mm}	2.579	2.607	2.607	2.609	2.589	2.572	2.572	2.568
G_{mb}	2.475	2.504	2.504	2.484	2.485	2.548	2.548	2.451
G_{sb}	2.768	2.770	2.770	2.767	2.779	2.880	2.880	2.777
AC content	4.6	4.1	4.1	4.3	4.5	4.6	4.6	4.6
Air Voids	4.0	4.0	4.0	4.8	4.0	4.4	4.4	4.6
VMA	14.7	13.3	13.3	14.1	14.6	15.6	15.6	15.8
VFA	73	70	70	66	73	72	72	71
P_{be}	4.5	3.8	3.8	3.9	4.4	4.6	4.6	4.6
Dust Ratio	1.1	1.1	1.1	1.2	1.0	0.8	0.8	0.8
3/4”	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2”	98.0	97.2	97.2	96.8	98.0	97.2	97.2	96.9
3/8”	90.0	84.8	84.8	87.7	90.0	86.4	86.4	85.9
#4	68.0	56.7	56.7	60.3	54.0	44.4	44.4	43.0
#8	48.0	39.9	39.9	43.2	32.0	28.1	28.1	27.0
#16	34.0	30.5	30.5	32.8	23.0	21.8	21.8	21.3
#30	25.0	24.6	24.6	26.4	17.0	17.9	17.9	17.6
#50	16.0	15.8	15.8	17.6	11.0	11.9	11.9	11.6
#100	8.0	7.5	7.5	8.0	5.0	5.9	5.9	5.8
#200	4.9	4.4	4.4	4.7	4.5	3.8	3.8	3.7
Density	93.0	92.5	92.1	91.9	94.5	93.3	92.8	94.4



	Lane 3	Lane 5
▦ A	11.9	17.1
▧ B	12.7	14.2
☐ C	16.9	16.2
▩ Average	13.8	15.8

Figure 4-26 Rut Depth from HVS Test after 90,000 Passes

4.4.2 Gradation Analysis

Figures 4-27 to 4-29 show the in-place gradations of each lift compared to the JMF. It is interesting to note, that the in-place gradation was coarser than the JMF for both the fine- and coarse-graded mixtures. It will be shown later that this may have proved to be particularly relevant in the case of the coarse-graded mixture.

Interaction diagrams determined from the in-place gradations and JMF for the top and bottom lifts of the fine- and coarse-graded mixtures are presented in Figures 4-31 to 4-34. Interaction diagrams showed little difference between the top and bottom lifts of either mixture. Figures 4-31 and 4-32 indicate that for the fine-graded mixture, aggregate sizes between 4.75 mm and 1.18 mm are clearly interactive, while the 9.5 mm size appears to be marginally interactive with a relative proportion between the 9.5/4.75 mm sizes right at 70/30. Therefore, the dominant aggregate size range (DASR) of the fine-

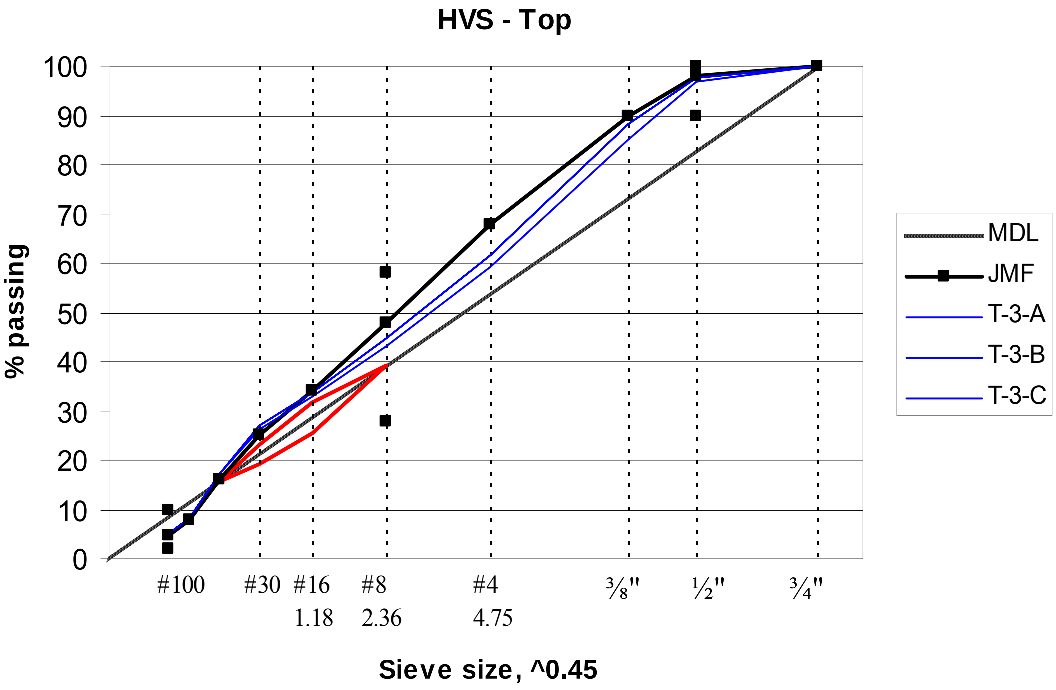


Figure 4-27 Fine-graded Gradations (Lane 3) for the Top Lift

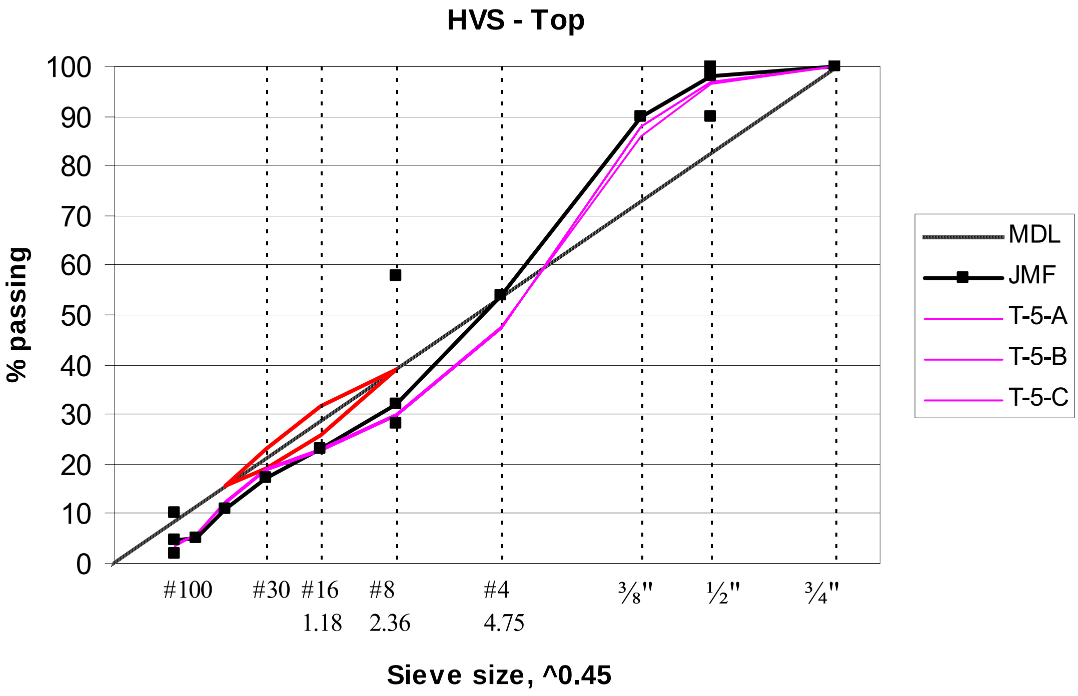


Figure 4-28 Coarse-graded Gradations (Lane 5) for the Top Lift

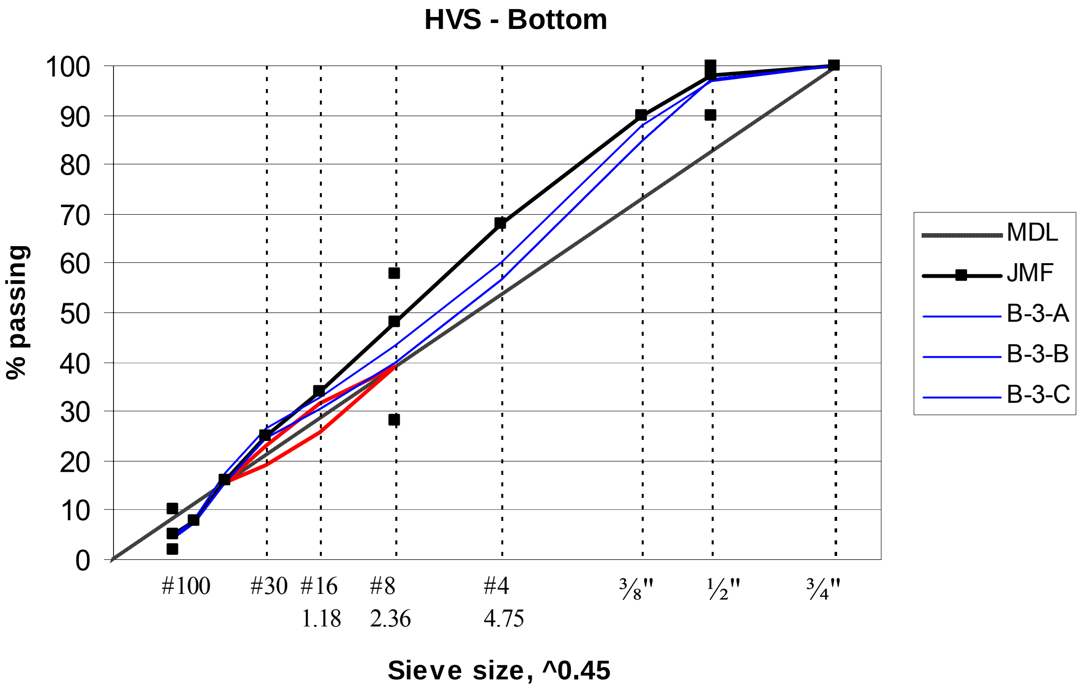


Figure 4-29 Fine-graded Gradations (Lane 3) for the Bottom Lift

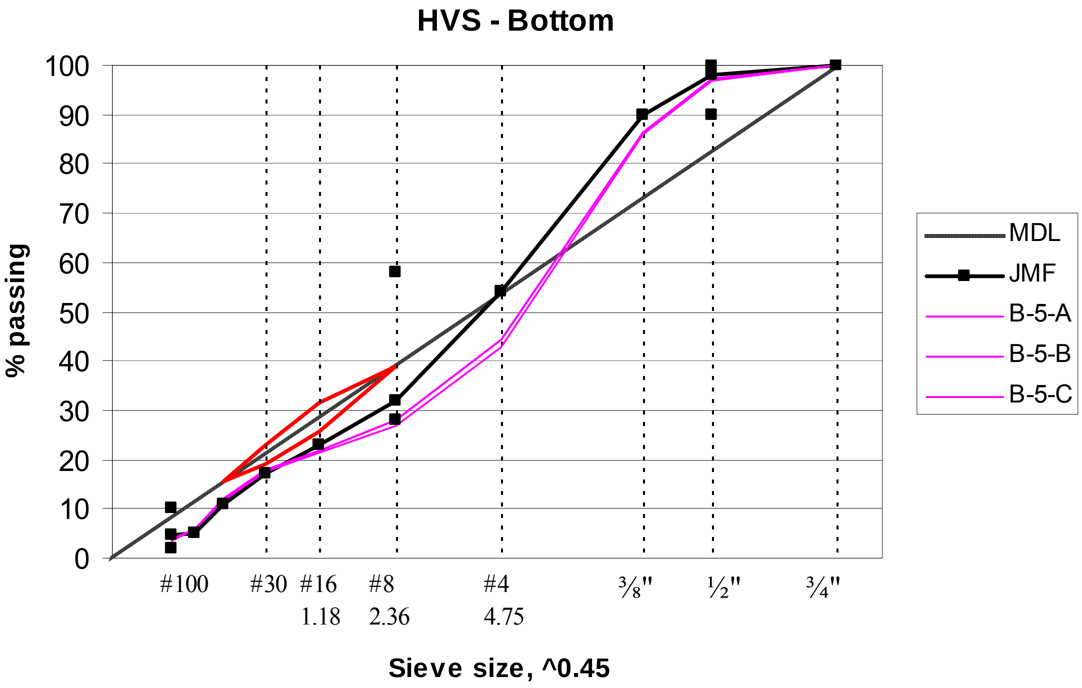


Figure 4-30 Coarse-graded Gradations (Lane 5) for the Bottom Lift

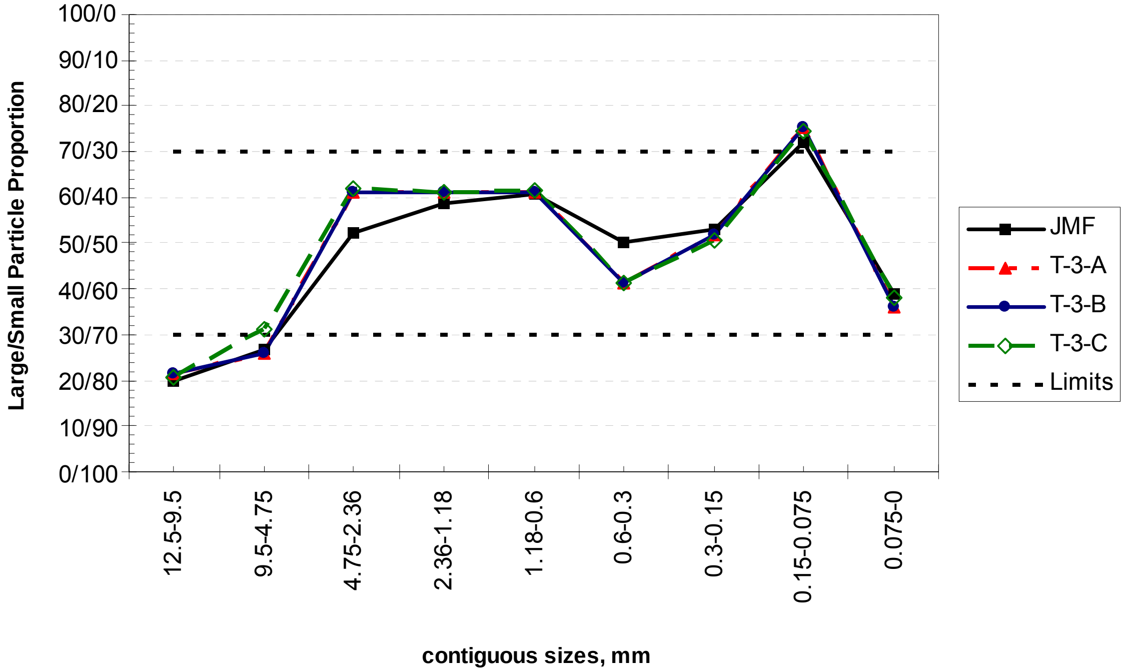


Figure 4-31 Interaction Diagram for the Top Lift of Fine-graded Gradations

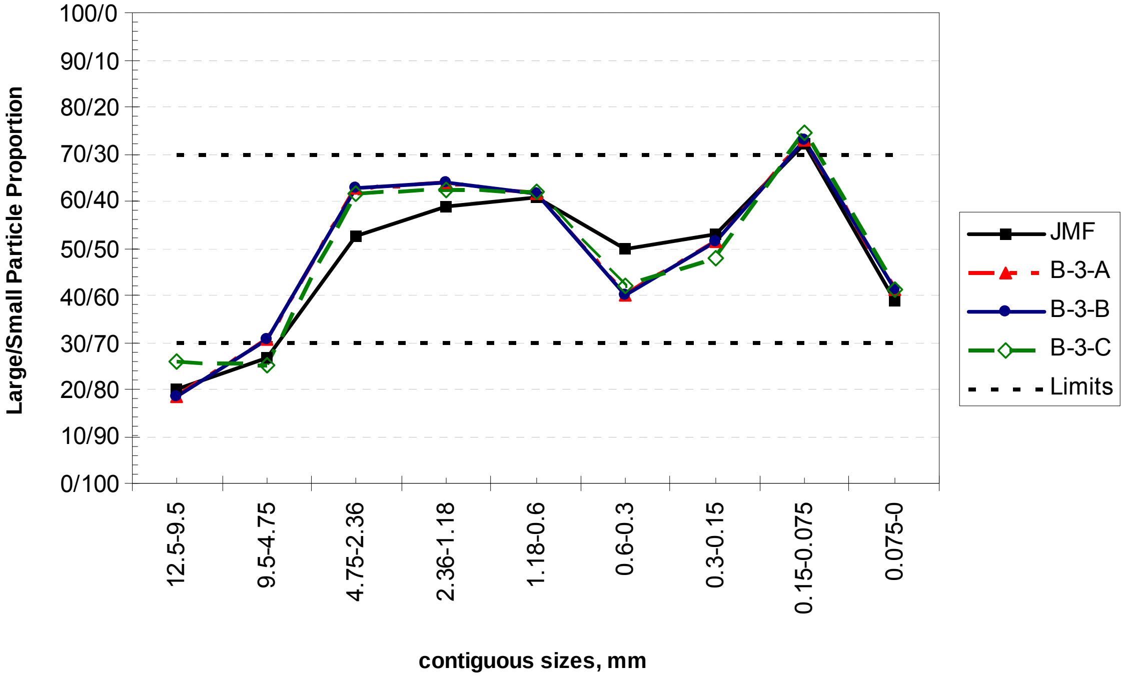


Figure 4-32 Interaction Diagram for the Bottom Lift of Fine-graded Gradations

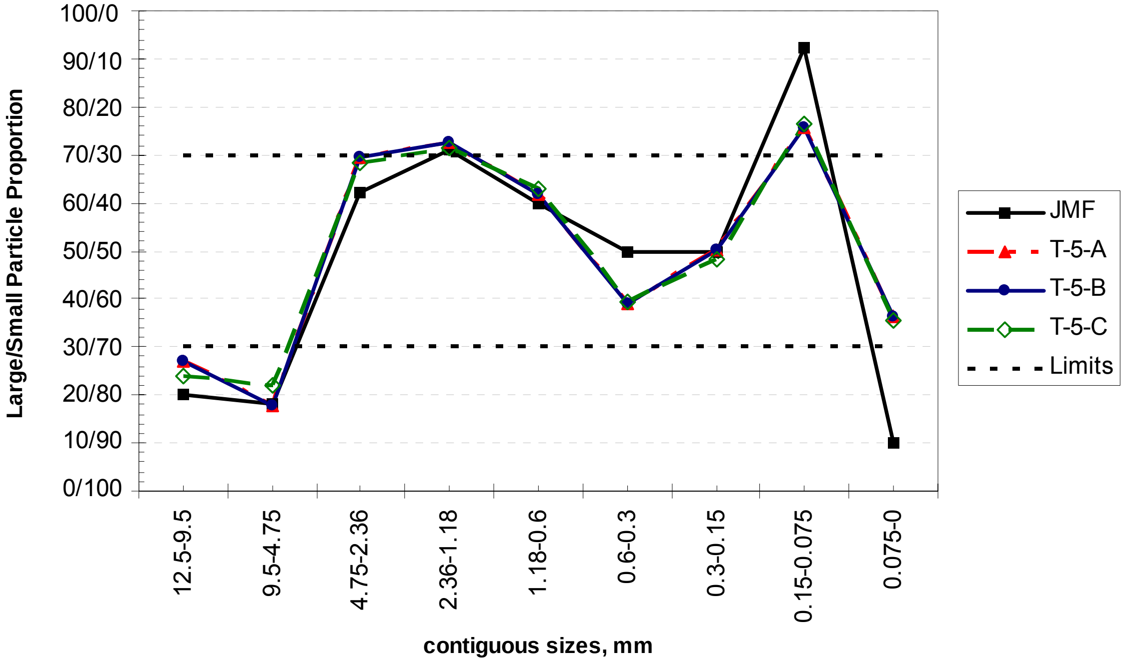


Figure 4-33 Interaction Diagram for the Top Lift of Coarse-graded Gradations

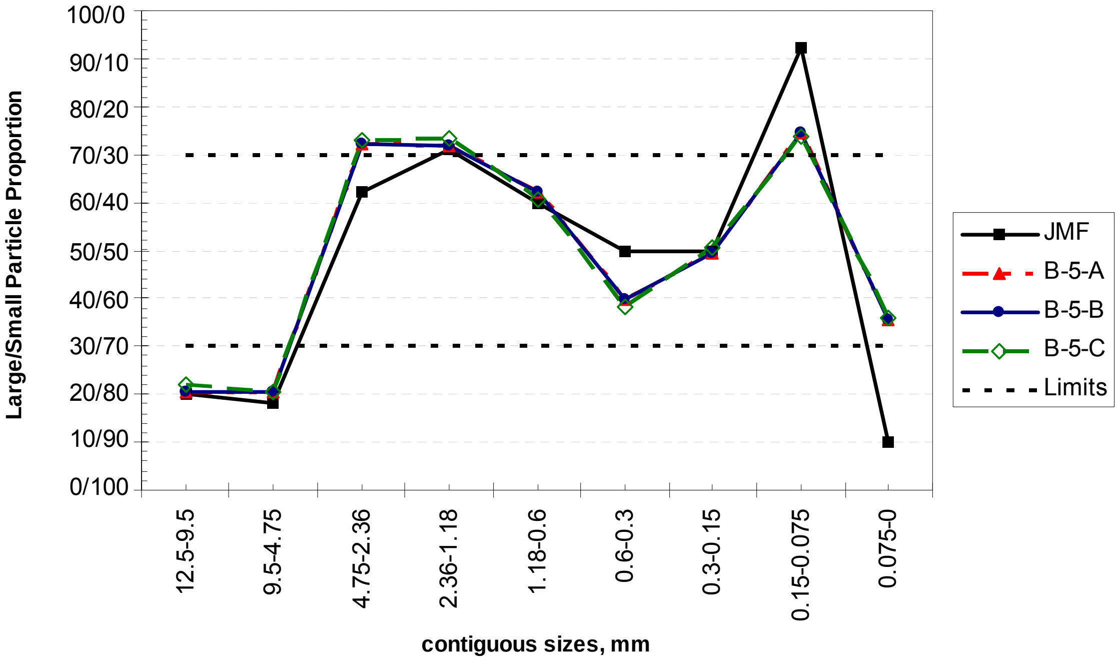
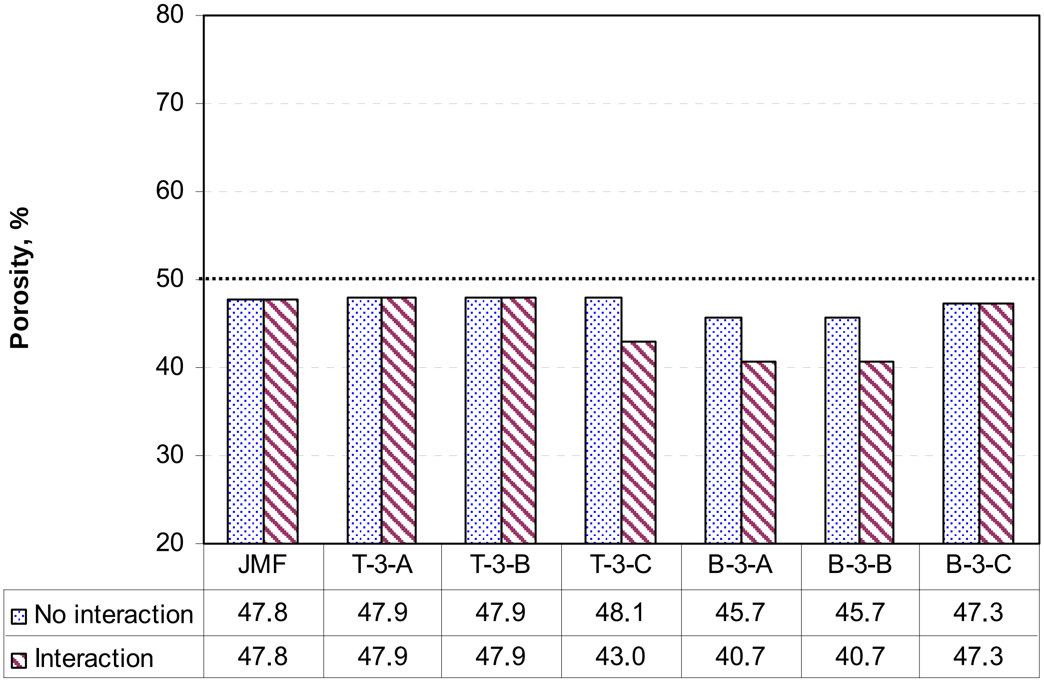


Figure 4-34 Interaction Diagram for the Bottom Lift of Coarse-graded Gradations

graded mixture is either from 9.5 mm to 1.18 mm, or from 4.75 mm and 1.18 mm, depending on whether or not the 9.5 mm size is considered interactive.

Figure 4-35 shows calculations of the DASR porosity for the fine-graded mixture, considering both cases (i.e. 9.5 mm interacting and not interacting). As shown in the figure, this had very little effect on the DASR porosity of this mixture, primarily because there are very few 9.5 mm particles in the mixture. The DASR porosity of the fine-graded mixture was less than 50%, regardless of whether or not the 9.5 mm size was considered interactive.

Figures 4-33 and 4-34 indicated that for the in-place coarse-graded mixture, two key size combinations were marginally interactive: 4.75/2.36 mm and 2.36/1.18 mm. It is interesting to note that the 4.75/2.36 mm combination was clearly interactive for the JMF.

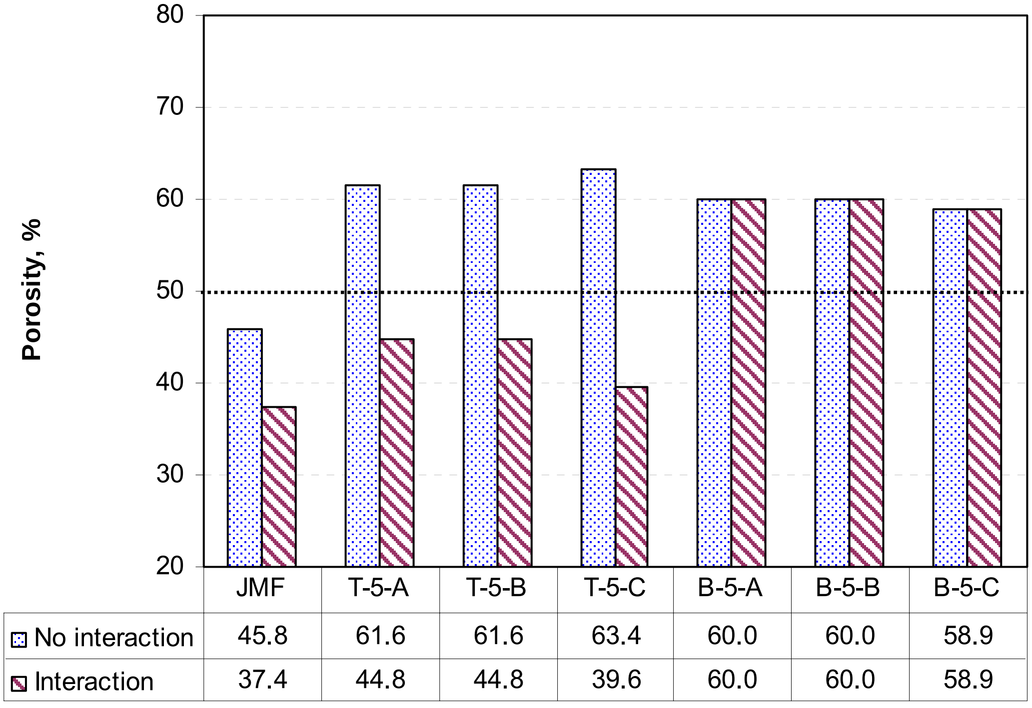


	JMF	T-3-A	T-3-B	T-3-C	B-3-A	B-3-B	B-3-C
░ No interaction	47.8	47.9	47.9	48.1	45.7	45.7	47.3
▧ Interaction	47.8	47.9	47.9	43.0	40.7	40.7	47.3

Figure 4-35 Porosity Results for Fine-graded Gradations

The DASR porosity results for the coarse-graded mixture are presented in figure 4-36. Results were calculated for two cases: considering the marginally interactive sizes to be interactive and not interactive. For the top layer, the DASR porosity was less than 50% when interaction was considered, but greater than 50% when it was not. For the bottom layer, the DASR porosity was greater than 50% whether or not interaction was considered. The DASR porosity of the JMF was less than 50%.

These results indicate that the rutting performance of the coarse-graded mixture would have been much better if the in-place mixture had been placed according to the JMF. In fact, it was unexpected that the coarse-graded mixture would exhibit higher rutting than the fine-graded mixture. However, the results of the gradation analysis based on the approach developed herein, provide a rational explanation for the rutting results obtained at the APT facility.



	JMF	T-5-A	T-5-B	T-5-C	B-5-A	B-5-B	B-5-C
▒ No interaction	45.8	61.6	61.6	63.4	60.0	60.0	58.9
▧ Interaction	37.4	44.8	44.8	39.6	60.0	60.0	58.9

Figure 4-36 Porosity Results for Coarse-graded Gradations

4.5 WesTrack Test Sections

4.5.1 General description

WesTrack is the Federal Highway Administration's (FHWA) road test facility located in Nevada (Epps et al., 1997, 1999, 2002). The project, entitled "Accelerated Field Test of Performance-Related Specifications for Hot-Mix Asphalt Construction", had two primary objectives:

Development of performance-related specifications (PRS) for HMA construction.

Early field verification of the SHRP SUPERPAVE(TM) Level III mix design.

The track was designed and constructed during the period between October 1994 and October 1995. The 2.9-km oval track consists of two tangent and the superelevated curves connecting them. Each tangent contains 13 test sections, each of which is 70 meters (m) long (Figure 4-37). There are no test sections along the curves.

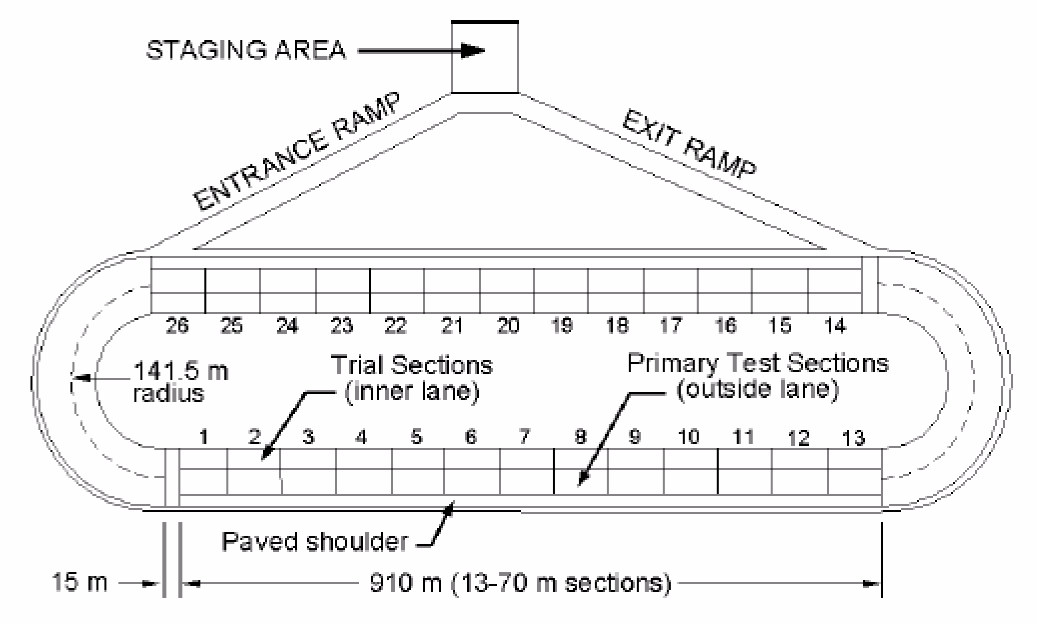


Figure 4-37 WesTrack - Layout of Test Track (not to scale)

As it neared the end of its planned loading in June 1998, WesTrack had been trafficked for more than 2 years, during that time, more than 4.5 million 80-kN (18,000-lb) equivalent single-axle loads (ESALs) were applied to the track.

4.5.2 Experiment design and performance history

The experiment design was based on seven experimental factors and target levels shown in Table 4-3.

Table 4-3 Original Experimental Factors

Factor	Target levels
Coarse Aggregate Type	One level: local Dayton, Nevada pit
Aggregate Gradation	Three levels: Coarse, fine, and fine plus
Aggregate Shape/Texture	One level: high percent fractured faces
Asphalt Cement Type	One level: PG 64-22
Asphalt Content	Three levels each: 4.7, 5.4 and 6.1 percent for the fine mixes; 5.0, 5.7 and 6.4 percent for the coarse mixes
Air Void Content	Three levels: 4, 8 and 12 percent
Hot-Mix Asphalt Thickness	One level: 150 mm or 6 inch

These factors and associated levels were selected to obtain the most information relative to the effects of materials and construction variability on pavement performance.

A complete factorial was not feasible because of economic constraints, therefore three factors were ultimately chosen, based on the potential on performance and/or experience from previous investigations.

The factorial experiment is shown in Table 4-4; note that six cells out of the matrix were eliminated because of construction impracticality, leaving 21 potential mixes. To this, 5 replicates were added, resulting in 26 total sections. The numbers within each cell represent the randomized paving sequence of each section. In June 1997 an additional eight sections were built to replicate the coarse aggregate experiment with a different aggregate source.

Table 4-4 Experiment Design

Design air void content %	**Original 1995 construction**									**1997 Rehabilitation**		
	Aggregate gradation design											
	Fine			**Fine plus**			**Coarse**			**Coarse**		
	Design asphalt contents (%)											
	4.7	5.4	6.1	4.7	5.4	6.1	5.0	5.7	6.4	5.1	5.8	6.5
4	■	4	18	■	12	21/9	■	23	25	■	39	55
8	2	1/15	14	22	19/11	13	8	5/24	7	38	35/54	37
12	3/16	17	■	10	20	■	26	6	■	56	36	■

The description of the materials used in this project is presented in Table 4-5.

Table 4-5 Materials

	Original Test Sections	Replacement Test Sections
Binder grade and source	PG 64-22 West coast	PG 64-22 Idaho
Aggregate source and gradations	Quarry near Dayton, Nevada (partially crushed fluvial deposit) Sand from Wadsworth, Nevada coarse, fine and fine-plus	Quarry near Lockwood, Nevada (crushed andesite) Sand from Wadsworth, Nevada coarse

All the mixes in this project are 19mm NMPS; by spring 1997, the application of more than 2.7 million ESALs resulted in rutting in almost every test section and fatigue cracking in many of the test sections. Several sections had rutted more than 25 mm and severe fatigue cracking had occurred in others. As a result, 10 sections (Sections 5-9, 13, 21, and 24-26) had to be removed and replaced during May and June 1997.

A new mix design was developed for eight of the replacement sections. This mix design duplicated the coarse-graded mix experiment in the original construction, but changed to a more angular aggregate. A quarried andesite replaced the crushed gravel used in the original construction. The change in aggregate resulted in changes in the volumetric properties from those obtained with the original coarse-graded mixes. The other two replacement sections (Sections 43 and 51) utilized conventional Nevada Department of Transportation (DOT) mixtures containing polymer-modified binders.

The replacement sections were placed in June 1997 and loading began in mid-July. Most of the new sections exhibited significant deformation in the first 5 days of trafficking. As a result of this early rutting and a concern that Superpave mixture design or construction procedures might be missing a critical step or steps, FHWA assembled a team of academicians, asphalt industry representatives, and State highway agency engineers to investigate the performance at WesTrack.

The main conclusions from different reports about WesTrack are:

- The main cause of rutting at WesTrack was a relatively high design binder content. Over-asphalting during construction compounded the problem.
- Much of the rutting appeared to be related to high binder contents due to high VMA values, in conjunction with relatively low mastic stiffnesses.
- For fatigue cracking, both field performance and laboratory test results have shown the effects of compaction and asphalt content. With low air void content or medium to high asphalt content the mixes showed much better fatigue resistance. Also, aggregate gradation was significant, particularly for the coarse gradation. The most important mix parameter, however, is compaction. As the degree of compaction is increased, fatigue life is significantly improved.
- For permanent deformation (rutting), field performance and laboratory RSST-CH results have demonstrated the effects of asphalt content, compaction, pavement temperature and, to some extent, the effects of aggregate gradation.

4.5.3 Interaction diagrams

Figure 4-38 shows the JMF's for each of the four mixture types used at WesTrack. Interaction diagrams for the coarse-graded mixtures are presented in Figure 4-39, while those for the fine-graded mixtures are presented in Figure 4-40. Interaction diagrams indicate that both the coarse- and fine-graded mixtures used at Westrack exhibited marginal interaction and potential sensitivity to variations in gradation. Figures 4-38 and 4-39 indicate that although the original coarse-graded mixture did not exhibit marginal interaction for any particle size combination, the relatively minor change in gradation implemented with the replacement mixture resulted in marginal interaction between the 9.5/4.75 mm sizes. This appears to indicate that the mixture was potentially sensitive to variations in gradation. Unfortunately, the actual gradation of the original coarse-graded

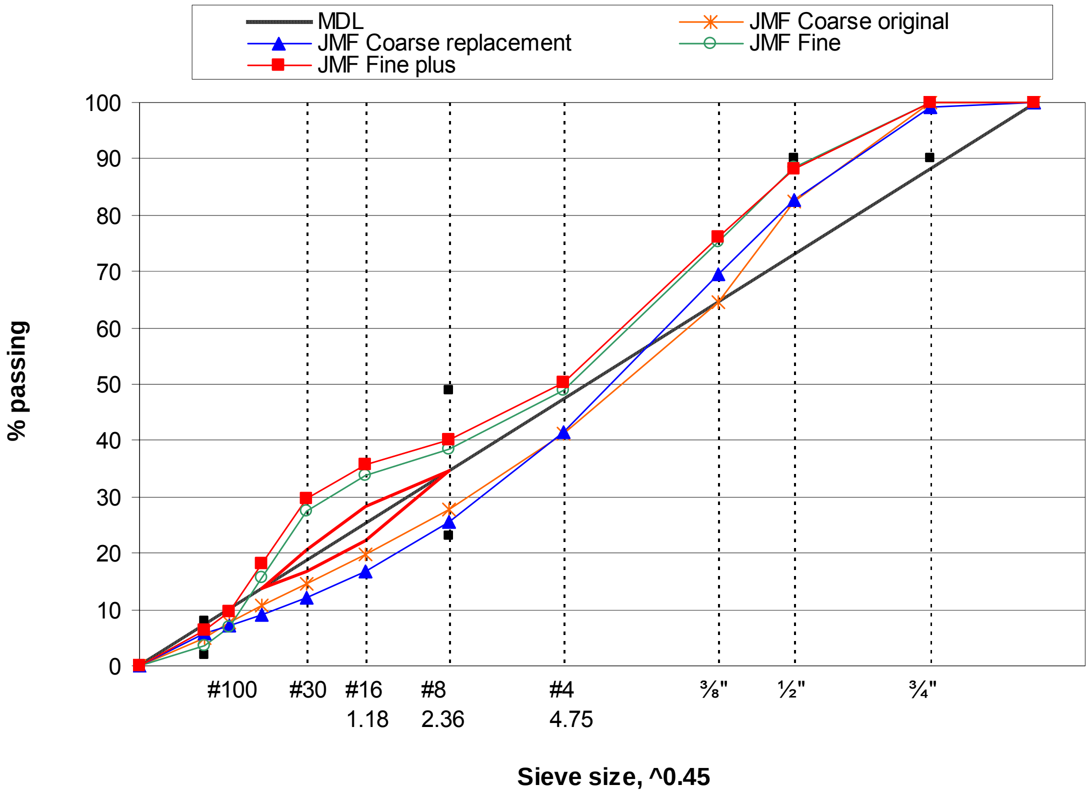


Figure 4-38 JMF Mixtures Gradations

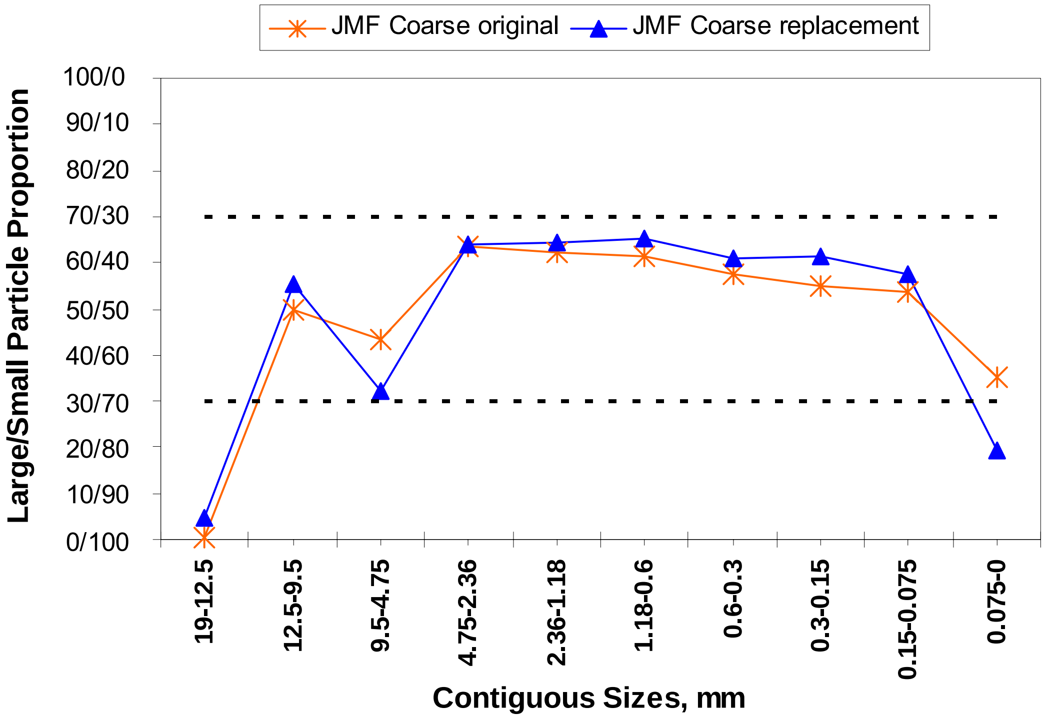


Figure 4-39 Interaction Diagram for JMF Coarse and JMF Coarse Replacement

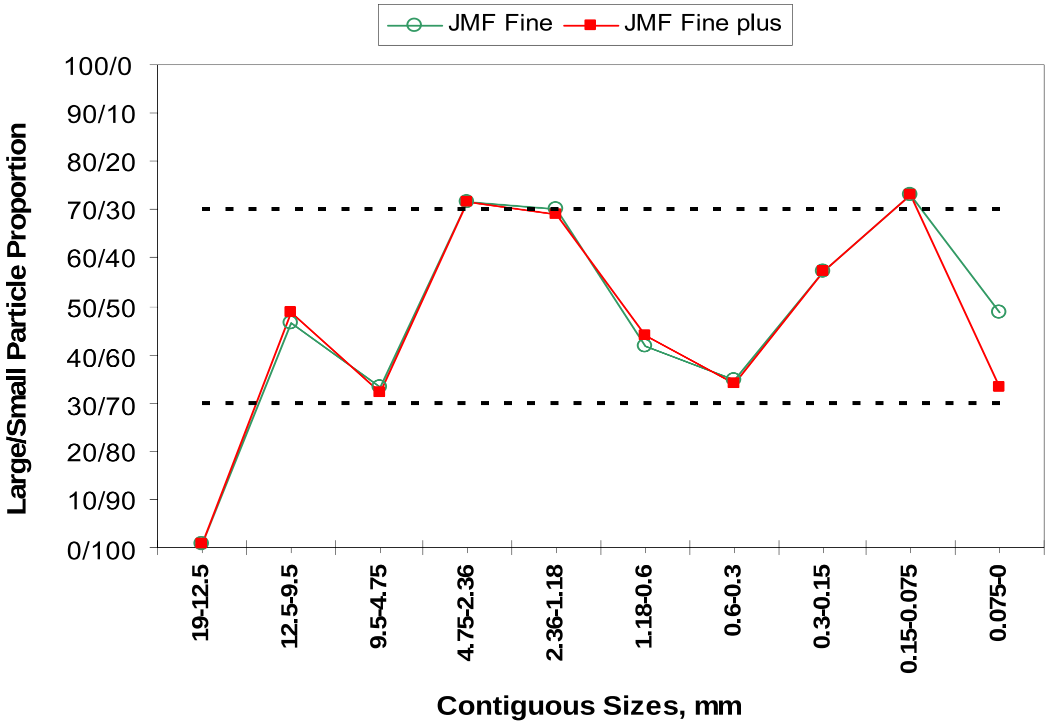


Figure 4-40 Interaction Diagram for JMF Fine and JMF Fine plus

mixture placed at the track could not be found in the available reports, so a direct analysis of DASR porosity of these mixtures for comparison to observed performance was not possible.

However, the in-place gradations of the replacement sections were available and are presented in Figure 4-41 for one set of coarse-replacement sections. The interaction diagrams for these mixtures are presented in Figures 4-42 and 4-43, which indicate that the in-place mixtures exhibited marginal interaction between two or more sets of particle size combinations. Sections 36 and 37 (Figure 4-42) exhibited marginal interaction between the 9.5/4.75 mm sizes and between the 4.75/2.36 mm sizes, while sections 55 and 56 (Figure 4-43) exhibited marginal interaction between the 2.36/1.18 mm sizes in addition to the other two combinations.

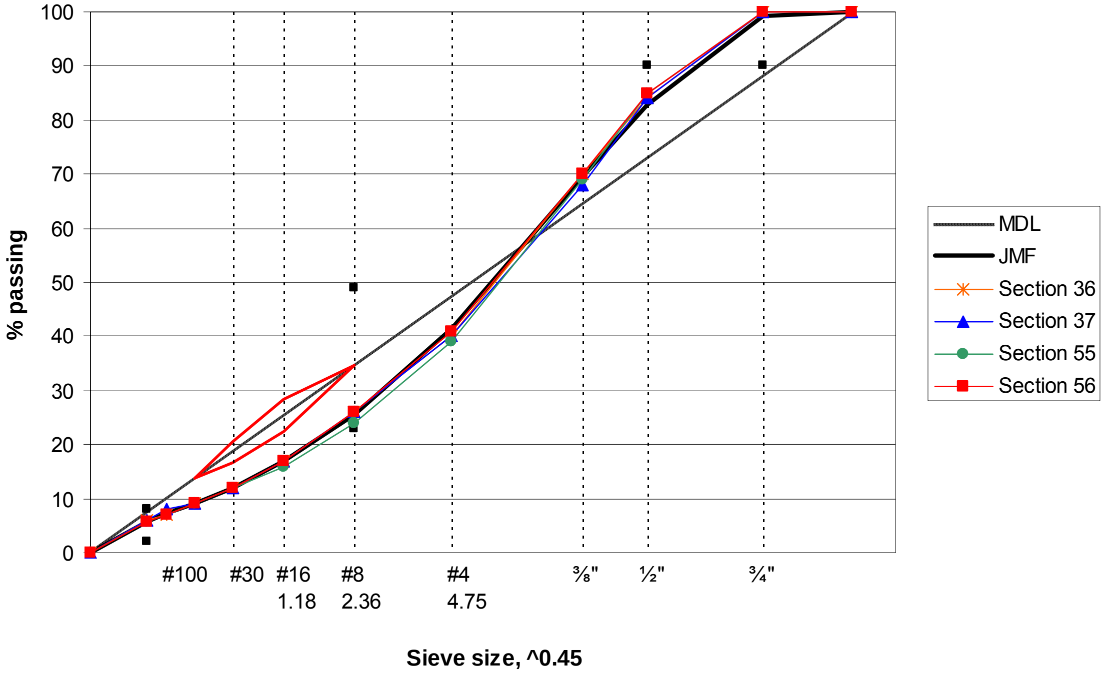


Figure 4-41 Gradation of Coarse Replacement Sections (36, 37, 55, 56)

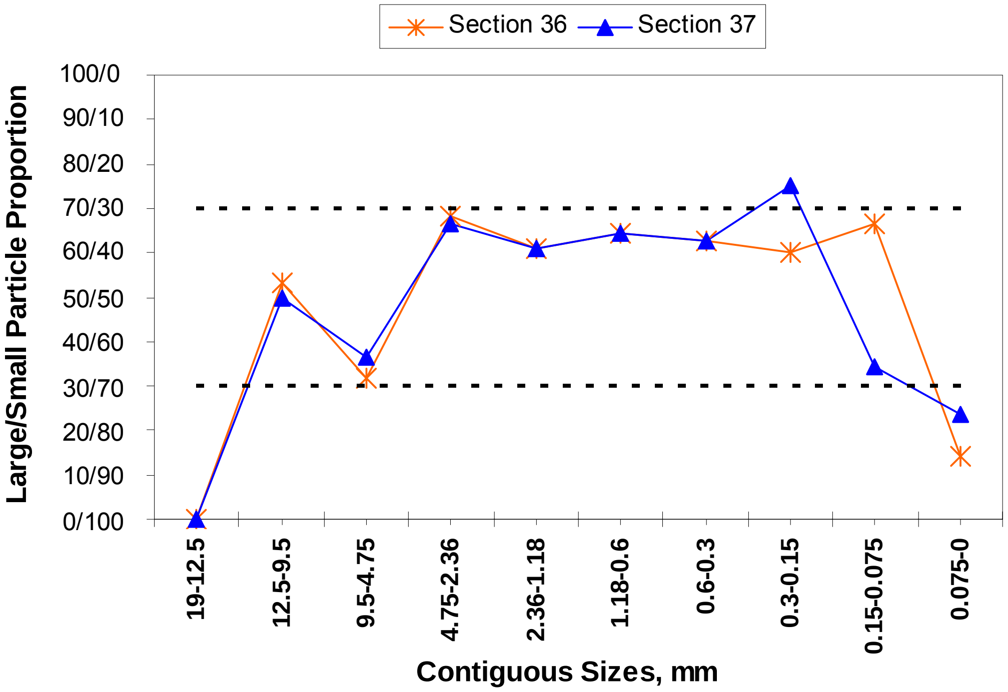


Figure 4-42 Interaction Diagram for Sections 36 and 37

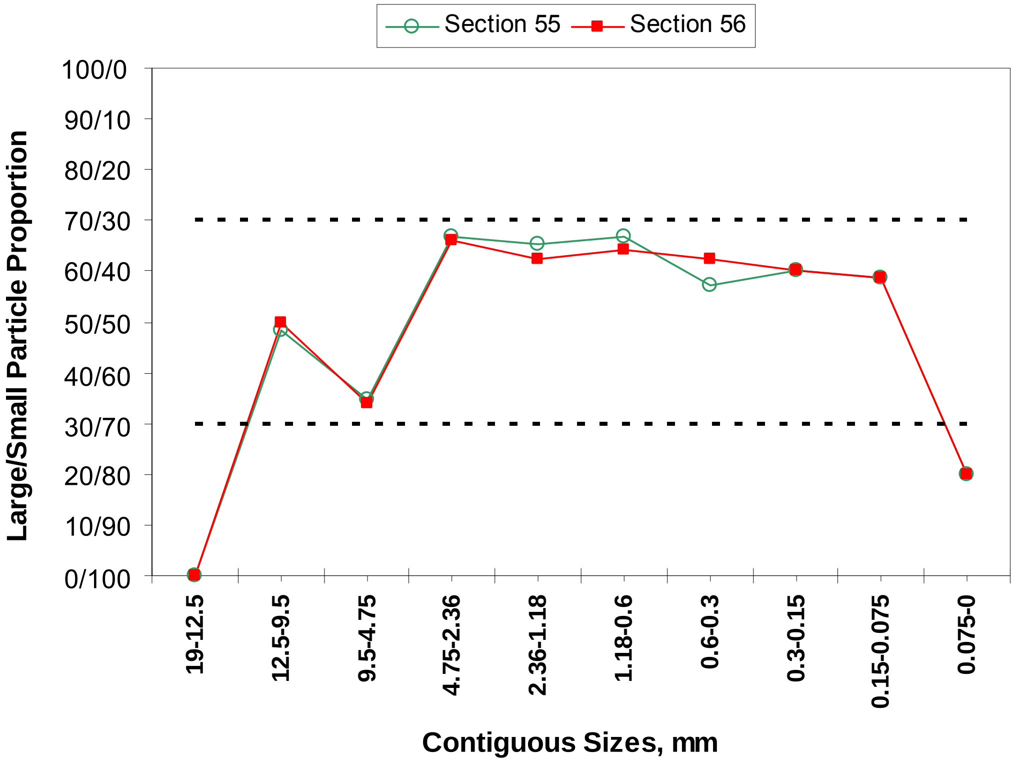
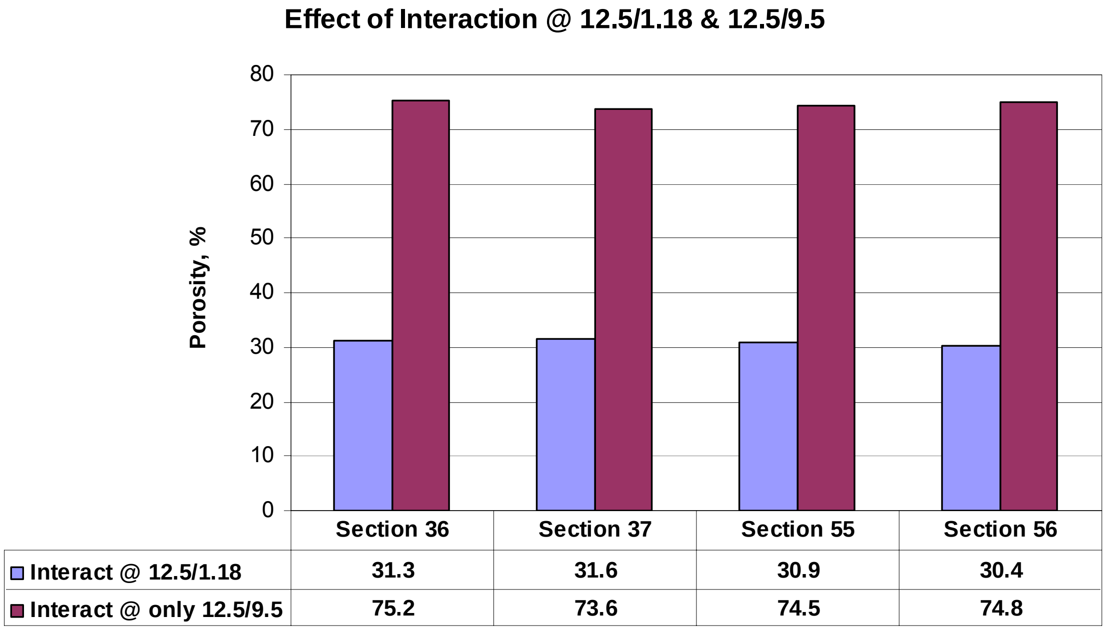


Figure 4-43 Interaction Diagram for Sections 55 and 56

Figure 4-44 shows DASR porosity values calculated for each of the coarse replacement sections. As shown in this figure, the DASR porosity varies tremendously depending on whether or not the marginally interactive size combinations are considered to be interactive. The DASR porosity is well below 50% if full interaction is considered and well over 50% if interaction is not considered.



	Section 36	Section 37	Section 55	Section 56
🟦 Interact @ 12.5/1.18	31.3	31.6	30.9	30.4
🟥 Interact @ only 12.5/9.5	75.2	73.6	74.5	74.8

Figure 4-44 DASR Porosity (η_{DASR}) of Coarse Replacement Sections (36, 37, 55, 56)

Rut depth measurements for the original and replacement coarse-graded sections are presented in Tables 4-6 and 4-7, respectively. These results clearly indicate that both the original and replacement sections exhibited significant rutting, and the replacement sections actually rutted more severely than the original sections. Rutting in the replacement mixtures ranged from 20.5 to 34.6 mm after only 582,000 ESAL's. It should be noted that this more severe rutting occurred even though a more angular aggregate was used in the replacement mixtures. This seems to indicate that better aggregate cannot compensate for poor gradation.

Table 4-6 Rut depth for Original Coarse Mixtures

Section	**Rut depth (mm) - peak to valley**	**ESALs $\times 10^6$**
5	22	2.8
6	30	1.5
7	36	2.8
8	23	1.5
23	12	2.8
24	26	2.8
25	27	1.5
26	19	2.8

Table 4-7 Rut Depth for Coarse Replacement Sections (36, 37, 55, 56)

Section	**Field rut depth (Peak to valley), mm – After 582,000 ESAL's**
Section 36	34.6
Section 37	24.3
Section 56	20.5
Section 57	25.2

A second set of coarse replacement sections was placed and similar results were obtained. Gradation and interaction diagrams for this second set of sections are presented in Figures 4-45, 4-46, and 4-47. DASR porosity results are shown in Figure 4-48. Clearly, the results are very similar to the previous set of sections and these sections also rutted severely (although not as severely as the first set), exhibiting rut depths of between 11.4 and 15.8 mm after only 582,000 ESAL's (see Table 4-8).

The sensitivity of the fine-graded mixtures resulting from the marginal interaction between different coarse particle sizes (see Figure 4-40) was revealed in the observed rutting performance of these mixtures. Measured rut depths for the fine and fine- plus

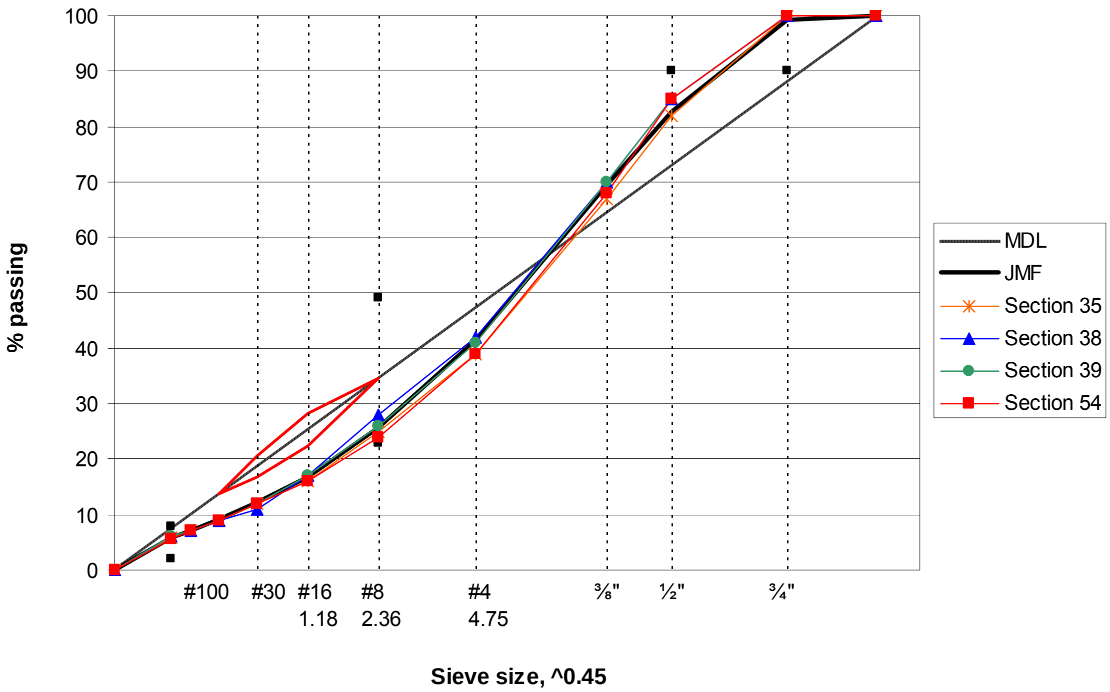


Figure 4-45 Gradation of Coarse Replacement Sections (35, 38, 39, 54)

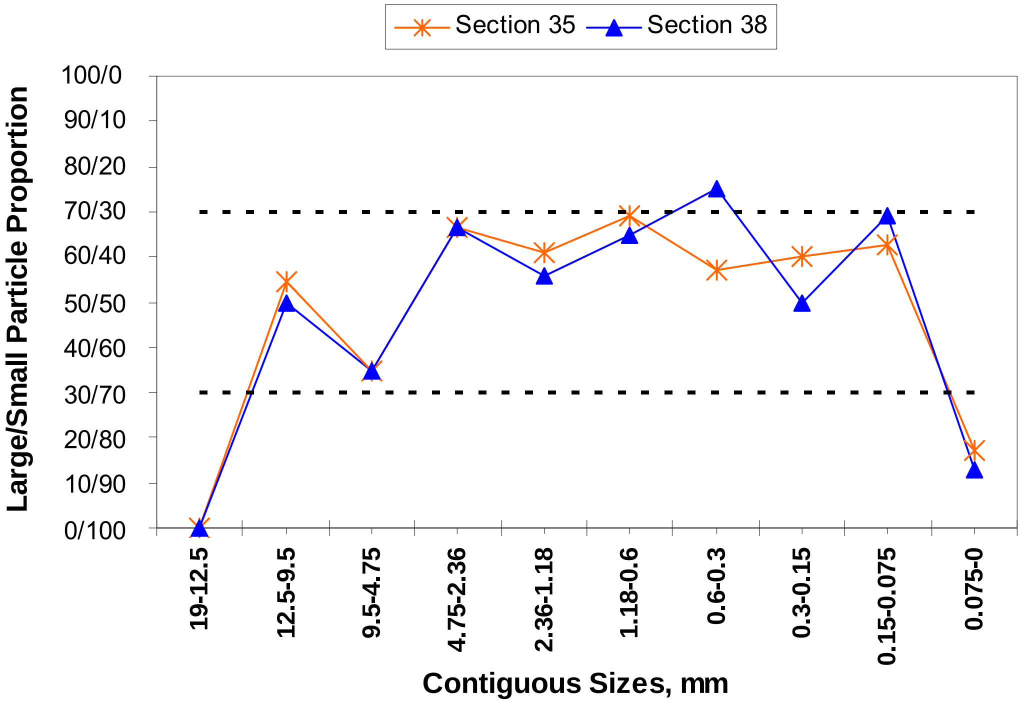


Figure 4-46 Interaction Diagram for Sections 35 and 38

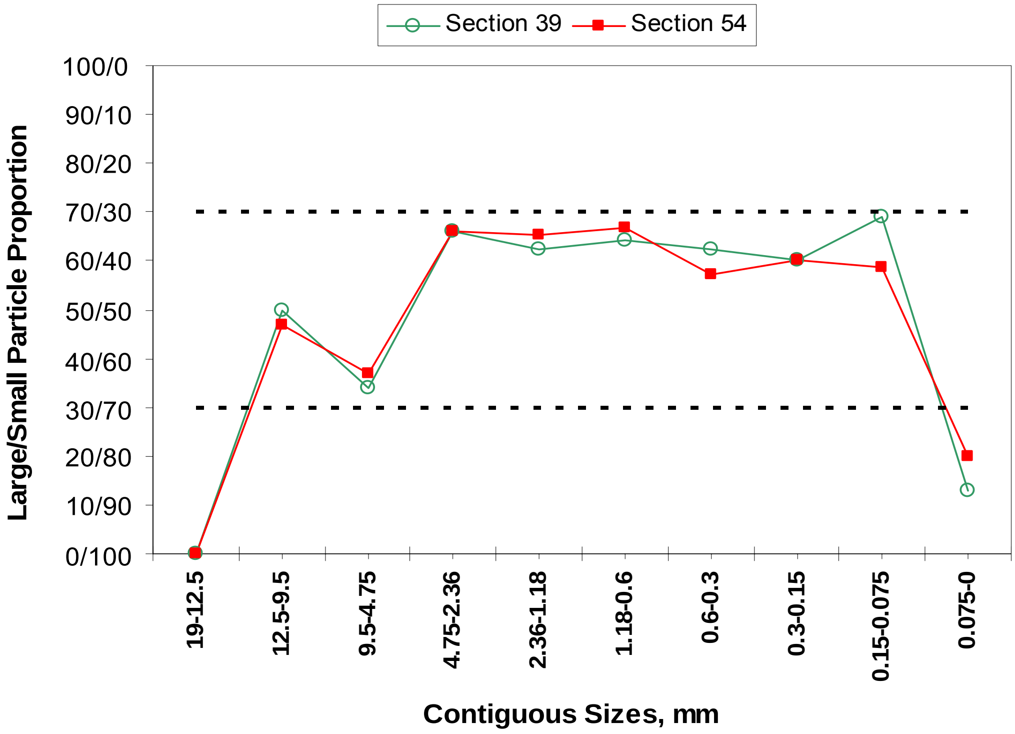


Figure 4-47 Interaction Diagram for Sections 39 and 54

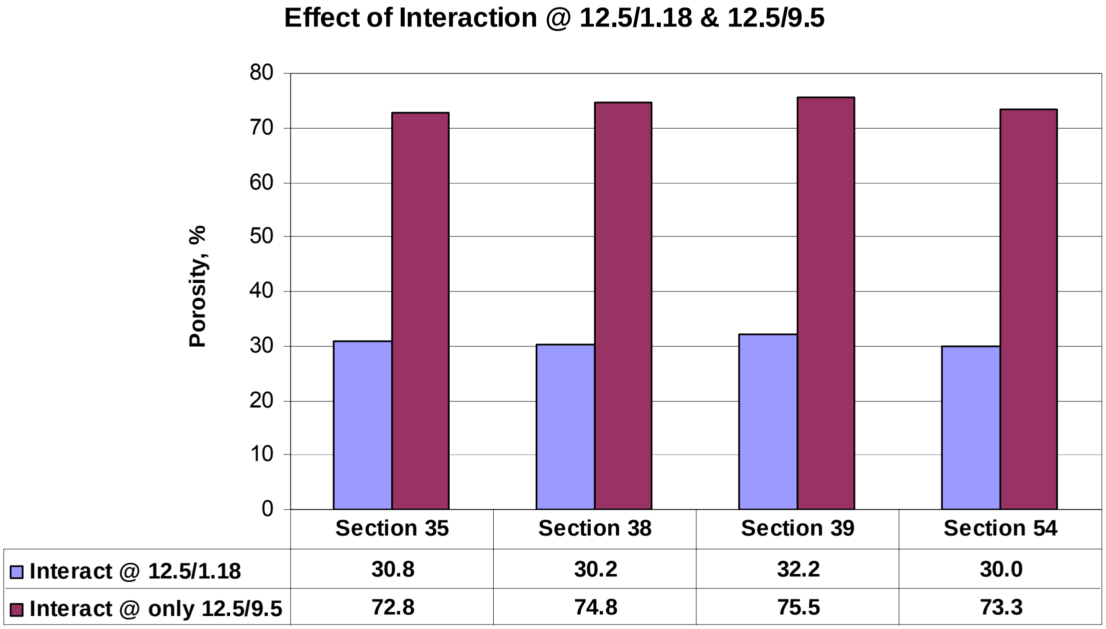


Figure 4-48 DASR Porosity (η_{DASR}) of Coarse Replacement Sections (35, 38, 39, 54)

Table 4-8 Field Rut Depth for Coarse Replacement Sections (35, 38, 39, 54)

Section	**Field rut depth (Peak to valley), mm – After 582.000 ESAL's**
Section 35	15.8
Section 38	11.6
Section 39	11.4
Section 54	12.3

mixtures are presented in Tables 4-9 and 4-10, respectively. The results are also presented in Figure 4-49, which shows that significantly different rutting performance was observed for the fine mixture than for the fine-plus mixture, even though the gradation differences between them were relatively minor (see Figure 4-38). Unfortunately, the in-place gradations of these mixtures were not available for these mixtures, so DASR porosity calculations could not be performed for the fine mixtures. It is anticipated that DASR porosity would be less than 50% if interaction were considered and greater than 50% if it were not. The ultimate performance would be dictated by the in-place gradation, which was apparently more favorable for the fine than for the fine-plus mixture.

Table 4-9 Rut Depth for Fine Mixtures

Section	**Rut depth (mm) - peak to valley**	**ESALs $\times 10^6$**
1	9	2.8
2	6	2.8
3	10	2.8
4	9	2.8
14	10	2.8
15	10	2.8
16	9	2.8
17	10	2.8
18	7	2.8

Table 4-10 Rut Depth for Fine plus Mixtures

Section	Rut depth (mm) - peak to valley	ESALs ×10^6
9	30	1.5
10	12	2.8
11	11	2.8
12	10	2.8
13	20	1.5
19	10	2.8
20	11	2.8
21	35	1.5
22	10	2.8

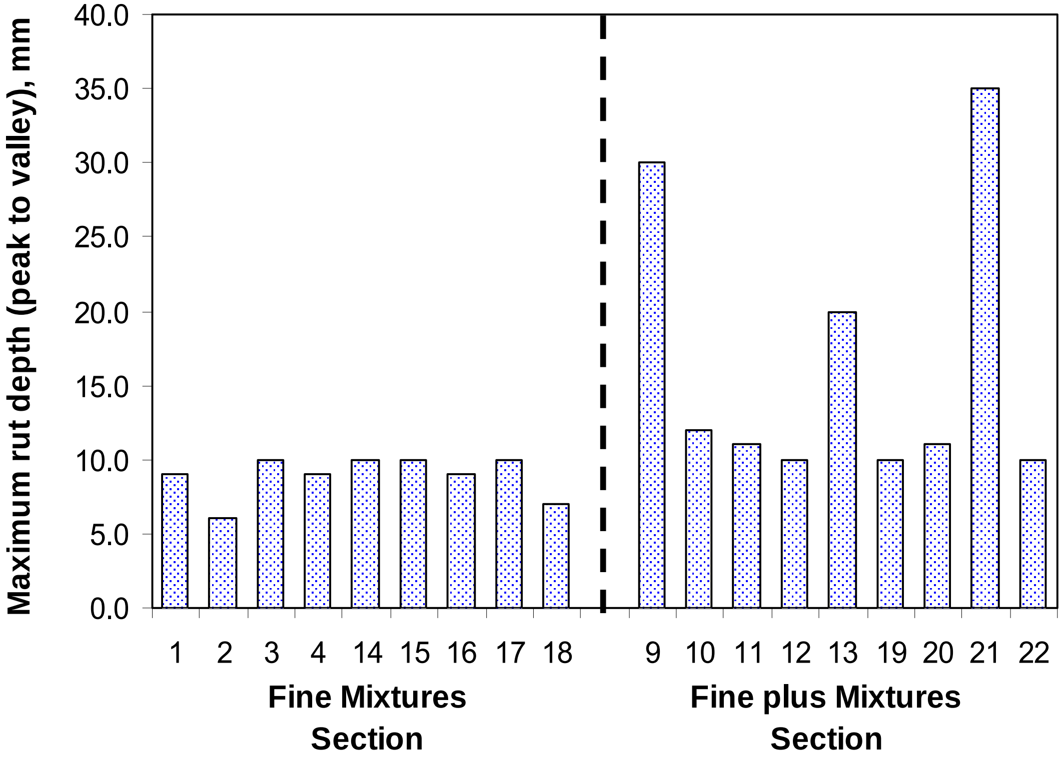


Figure 4-49 Maximum Rut Depth for Fine and Fine plus Mixtures

4.5.4 Summary

All mixtures placed at WesTrack were identified as having gradations exhibiting marginal interaction as determined by the gradation analysis system developed in this research. All coarse-graded mixtures rutted, even after a more angular aggregate was introduced. It was noted that the gradation used with the more angular aggregate was even more marginal and potentially sensitive than the original coarse gradation. The modified gradation with the more angular aggregate resulted in even more severe rutting than the original mixture. The fine-graded (fine and fine plus) mixture exhibited highly variable rutting performance, as expected based on the marginally interactive gradation.

4.6 NCAT Test Sections

NCAT Pavement Test Track is a 1.7 mile oval divided in 200 ft test sections (Brown et al., 2002, 2004); the primary purpose of the work at the NCAT test track is to use the performance at the track to verify or help develop performance tests (Figure 4-51). Secondary objectives of the project are to look at fine-graded vs. coarse-graded mixes, to evaluate the effect of grade bumping (modified AC vs. non-modified AC), compare performance of various mix types, and to evaluate the effect of aggregate type (limestone, slag, gravel, granite, etc.).

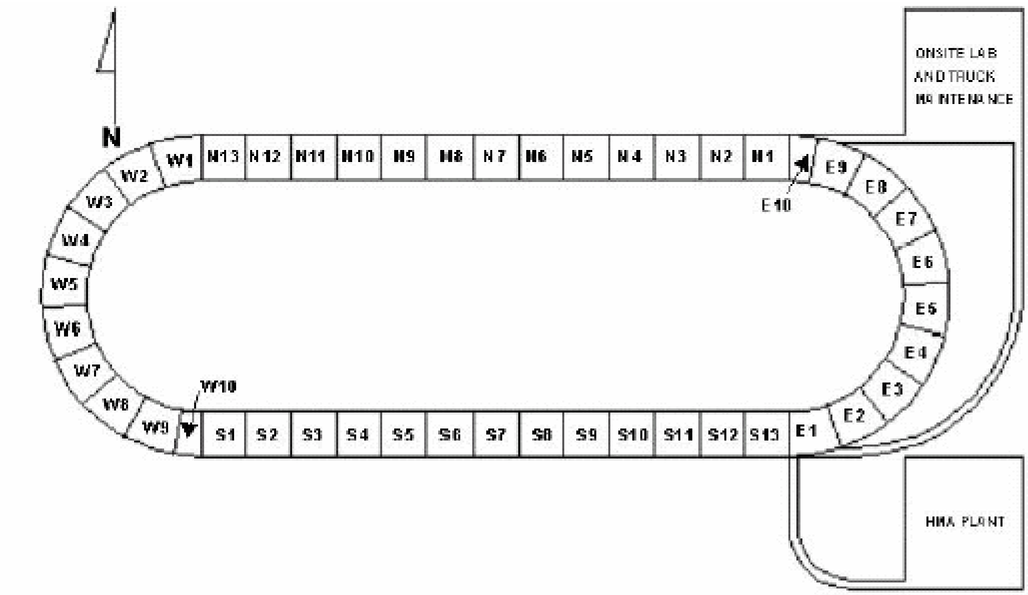


Figure 4-50 NCAT - Layout of Test Track (not to scale)

The track was designed to be sufficiently strong so that fatigue cracking would not occur resulting in rutting as the expected form of distress. The average rutting at the track was approximately 0.12 inches (3 mm) after approximately 9 million ESALs. Rutting is typically not considered to be a problem until the magnitude reaches approximately 0.5 inches (12.5 mm), so the rutting observed at the track was minimal. All the cases presented in this report are 12.5mm NMPS mixes. They were divided into four groups based on their gradations; coarse, fine, dense-coarse and SMA. Table 4-11 shows the reference figures and tables applied by the DASR porosity approach.

Table 4-11 Reference Figures and Tables for NCAT

Gradation Type	Gradations	Rut Depth	Interaction	Porosity
Coarse	Figure 4-51	Table 4-12	Figure 4-52	Figure 4-53
Fine	Figure 4-54	Table 4-13	Figure 4-55	Figure 4-56
Dense-Coarse	Figure 4-57	Table 4-14	Figure 4-58	Figure 4-59
SMA	Figure 4-60	Table 4-15	Figure 4-61	Figure 4-62

All the sections meet the interaction and DASR porosity requirements, and as expected, they performed well in terms of rutting even for different aggregate types. Even though marginal interactions were considered, DASR porosities were below 50%. The specifics of the interaction diagrams for each set of mixtures are discussed in the sections below.

4.6.1 Interaction Diagrams: Coarse Mixtures

Gradations for the three coarse mixtures placed at the NCAT test track are presented in Figure 4-51. The resulting interaction diagrams, which are presented in Figure 4-52, indicate that for all three mixtures, there was marginal interaction between the 4.75/2.36 mm sizes and the 2.36/1.18 mm sizes. However, the DASR porosity calculations presented in Figure 4-53 show that the DASR porosity was less than 50% whether or not these interactions were considered. In other words, it appears that these mixtures have very good gradations.

The rutting results presented in Table 4-12 indicate that all the rut depth was less between 2.8 and 6.2 mm after 9 million ESALs. These results support the findings from the gradation analysis based on the approach developed in this study.

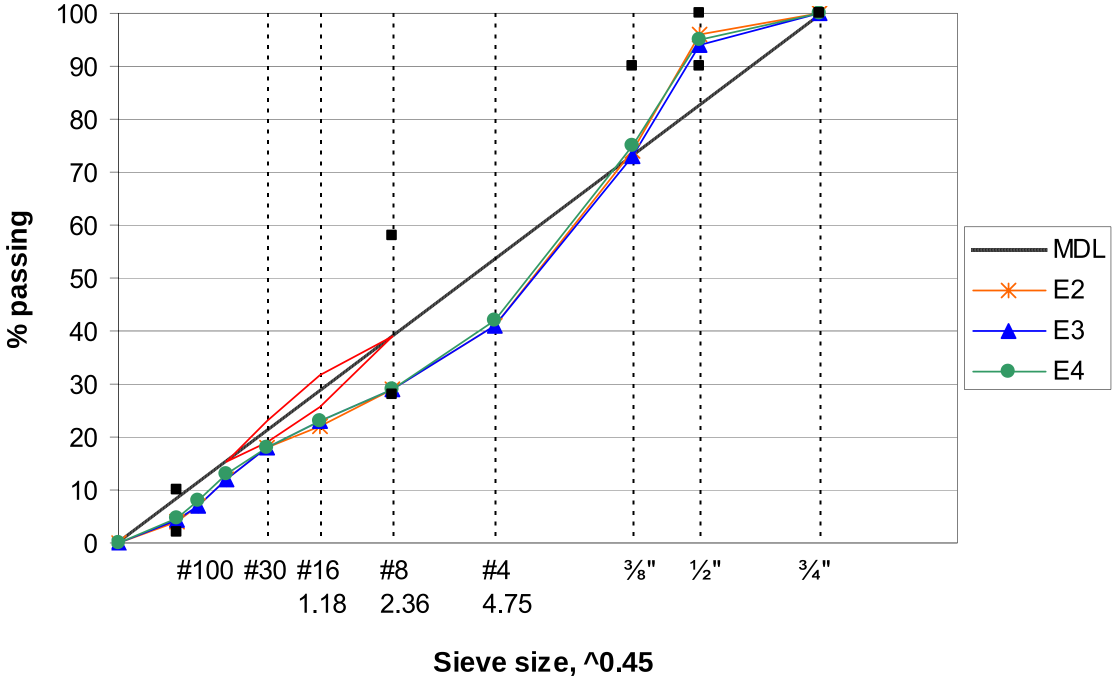


Figure 4-51 Gradation of Sections E2, E3, and E4

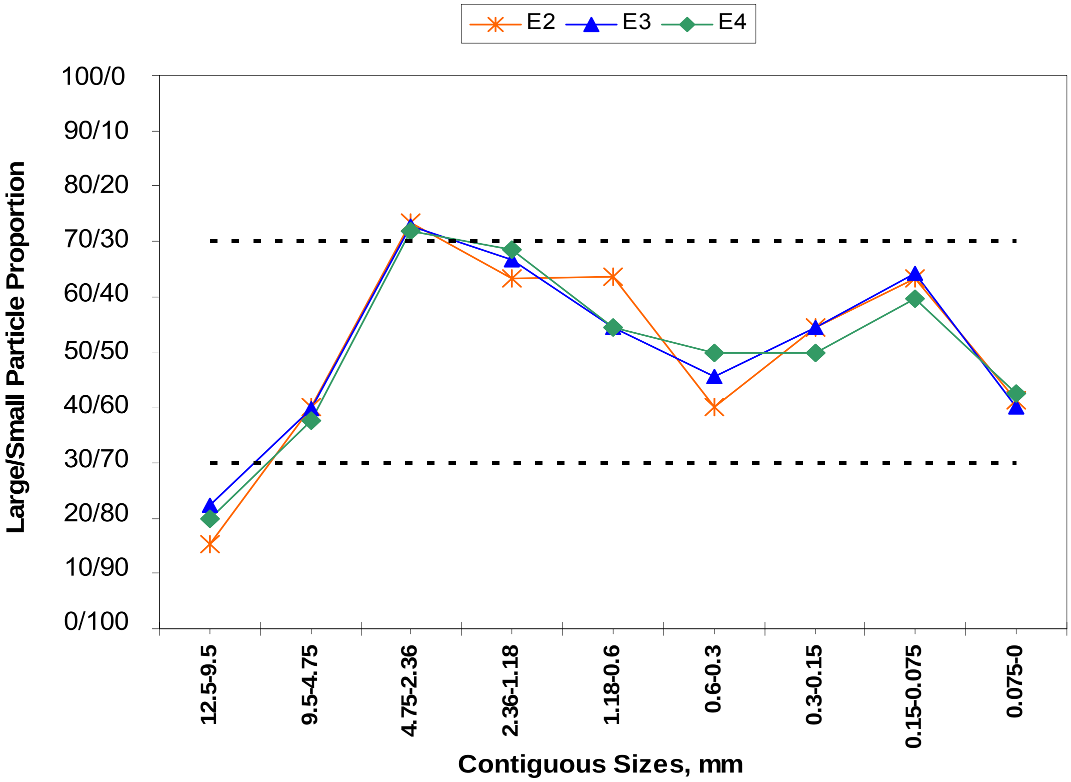


Figure 4-52 Interaction Diagram for Sections E2, E3, and E4

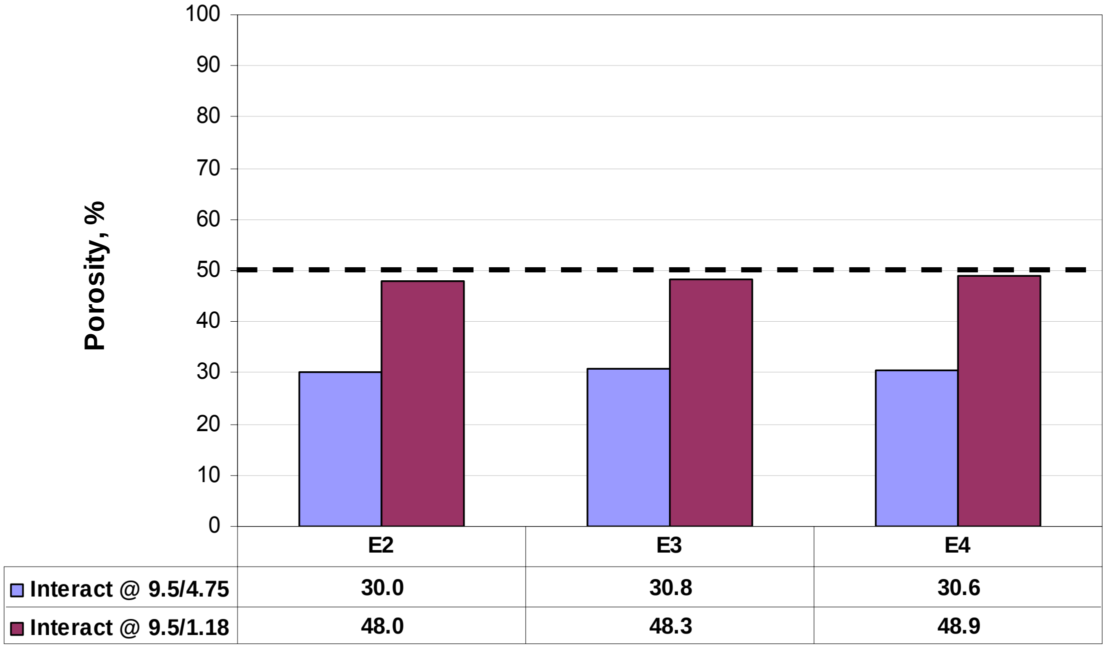


Figure 4-53 DASR Porosity of Sections E2, E3, and E4

Table 4-12 Field Rut Depth for Sections E2, E3, and E4

Section	Aggregate type	ESAL's	Field rut depth , mm
Section E2	Limestone	4,172,787	6.2
Section E3	Limestone	4,172,787	3.1
Section E4	Granite	4,172,787	2.8

4.6.2 Interaction Diagrams: Fine Mixtures

Gradations for the three fine mixtures placed at the NCAT test track are presented in Figure 4-54. The resulting interaction diagrams, which are presented in Figure 4-55, indicate that for all three mixtures, there was excellent interaction from the 4.75 mm to the 1.18 mm sizes. Although the interaction between the 9.5/4.75 mm sizes is within the 70/30 criterion identified for marginal interaction, it was treated as marginally interactive to evaluate the effect on DASR porosity.

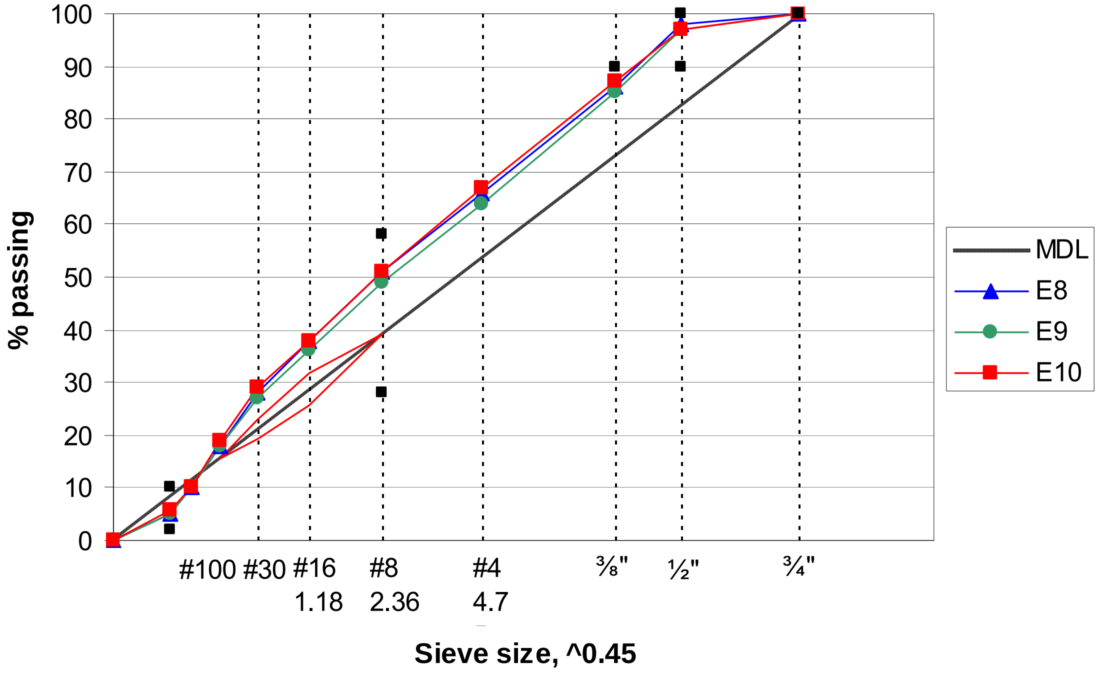


Figure 4-54 Gradation of Sections E8, E9, and E10

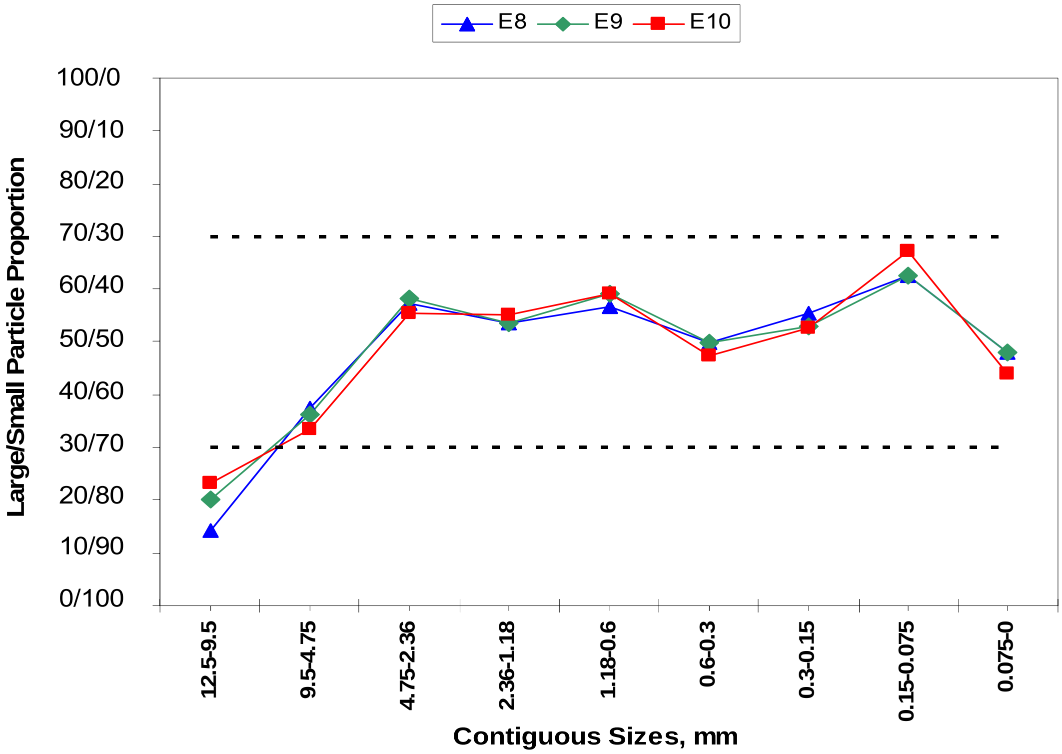


Figure 4-55 Interaction Diagram for Sections E8, E9, and E10

DASR porosity calculations presented in Figure 4-56 show that the DASR porosity was right at 50% when interaction was not considered and well below 50% when it was considered. The rutting results presented in Table 4-13 indicate that all the rut depths for sections with these mixtures were less than 3.3 mm after 9 million ESALs. These results also support the findings from the gradation analysis based on the approach developed in this study, which indicate that these fine mixtures have good aggregate structure.

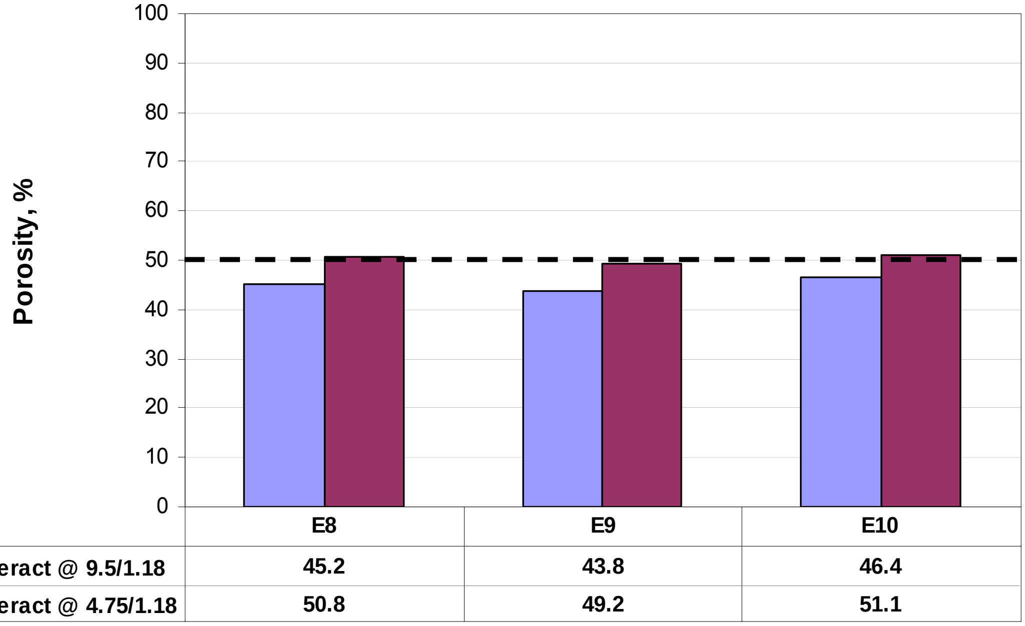


Figure 4-56 DASR Porosity of Sections E8, E9, and E10

Table 4-13 Field Rut Depth for Sections E8, E9, and E10

Section	Aggregate type	ESAL's	Field rut depth , mm
Section E8	Granite	4,172,787	3.3
Section E9	Granite	4,172,787	1.9
Section E10	Granite	8,972,237	N/A

4.6.3 Interaction Diagrams: Dense-Coarse Mixtures

Gradations for the four dense-coarse mixtures placed at the NCAT test track are presented in Figure 4-57. The resulting interaction diagrams, which are presented in Figure 4-58, indicate that for all four mixtures exhibited marginal interaction between the 9.5/4.75 mm sizes, and one or two exhibited marginal interaction between the 4.75/2.36 mm sizes. However, the DASR porosity calculations presented in Figure 4-59 show that the DASR porosity was well under 50% for all four mixtures, whether or not these interactions were considered. In other words, it appears that these mixtures have very good gradations.

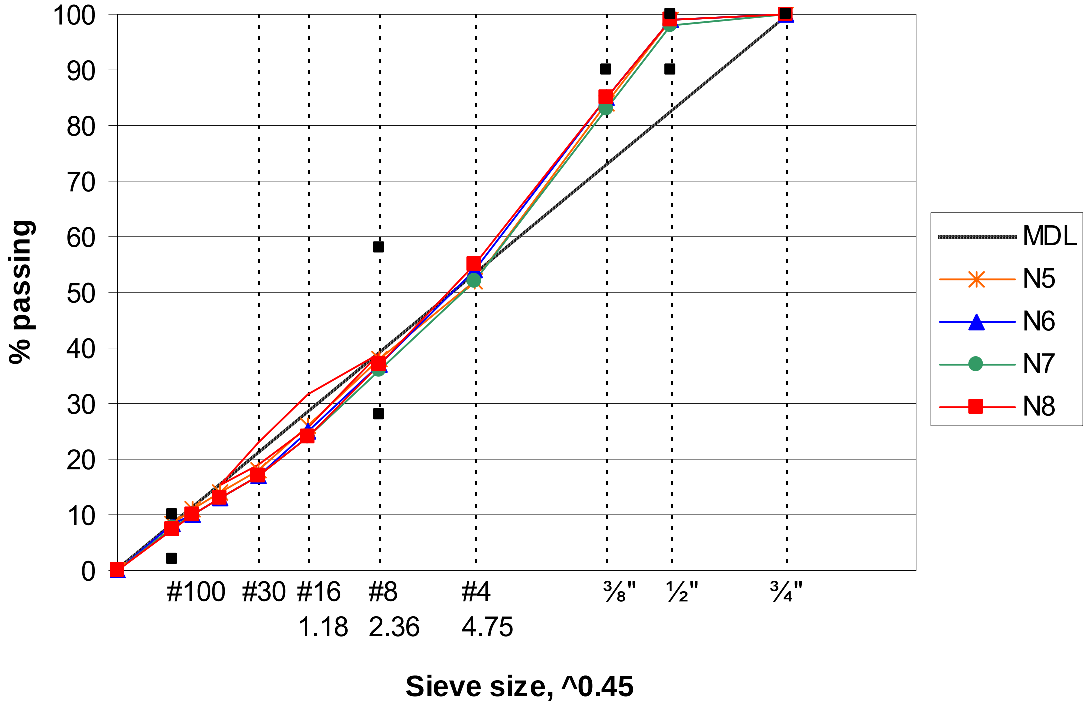


Figure 4-57 Gradation of Sections N5, N6, N7, and N8

The rutting results presented in Table 4-14 indicate that all the rut depth was less between 3.0 and 5.6 mm after 9 million ESALs. Once again, these results support the findings from the gradation analysis based on the approach developed in this study.

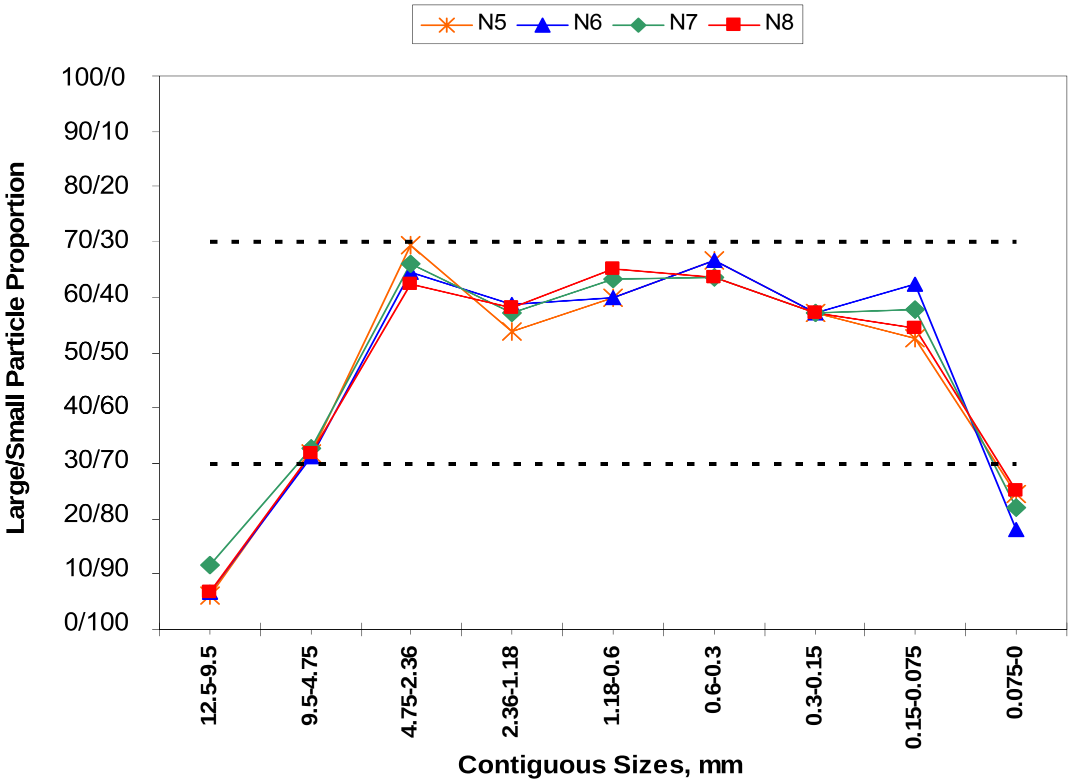
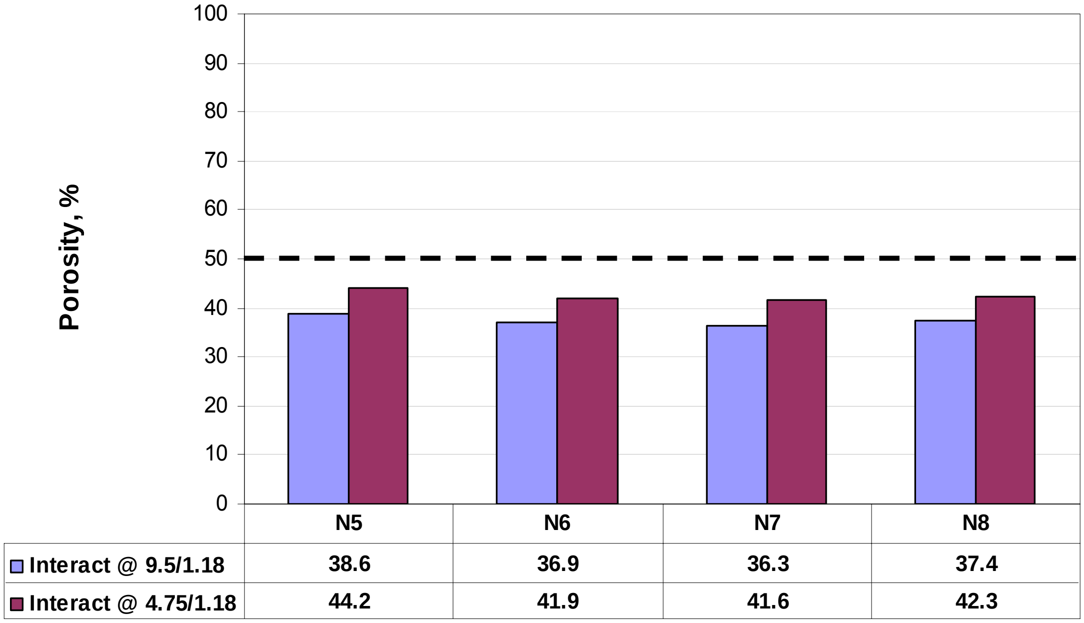


Figure 4-58 Interaction Diagram for Sections N5, N6, N7, and N8



	N5	N6	N7	N8
🟦 Interact @ 9.5/1.18	38.6	36.9	36.3	37.4
🟥 Interact @ 4.75/1.18	44.2	41.9	41.6	42.3

Figure 4-59 DASR Porosity of Sections N5, N6, N7, and N8

Table 4-14 Field Rut Depth for Sections N5, N6, N7 and N8

Section	Aggregate type	ESAL's	Field rut depth , mm
Section N5	Grn/Lms/Snd	4,172,787	3.0
Section N6	Grn/Lms/Snd	4,172,787	4.8
Section N7	Granite	4,172,787	4.3
Section N8	Granite	4,172,787	5.6

4.6.4 Interaction Diagrams: SMA Mixtures

Gradations for the four SMA mixtures placed at the NCAT test track are presented in Figure 4-60. The resulting interaction diagrams, which are presented in Figure 4-61, indicate that only the 9.5/4.75 mm sizes were interactive for these mixtures. This is expected for SMA mixtures, which are designed to have one or two dominant sizes.

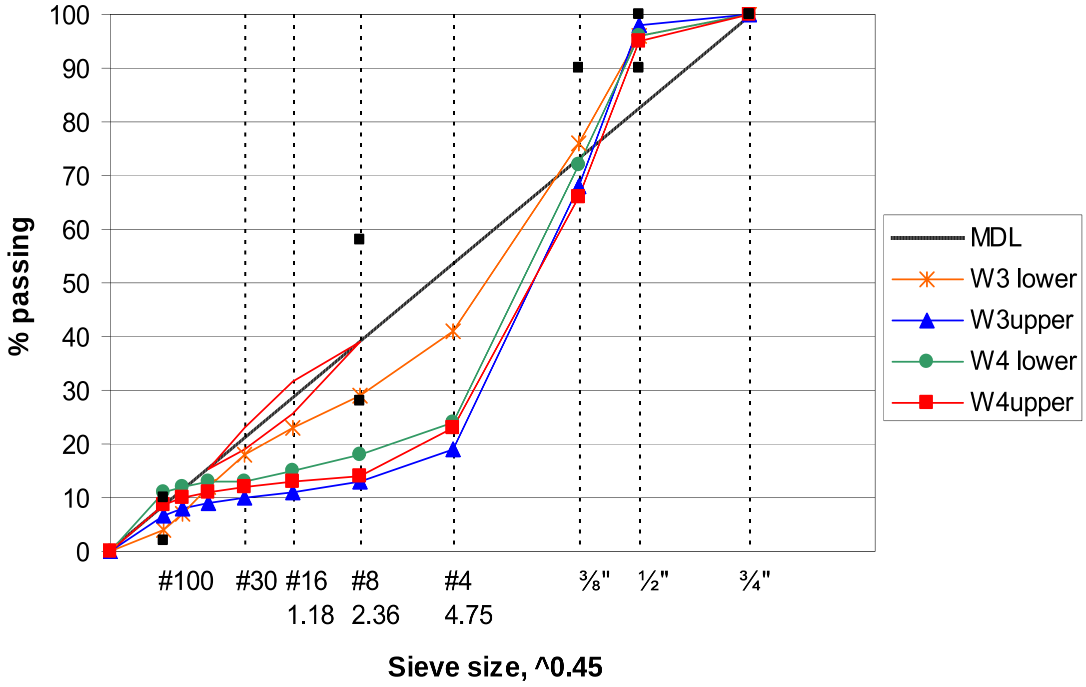


Figure 4-60 Gradation of Sections W3 lower, W3 upper, W4 lower, and W4 upper

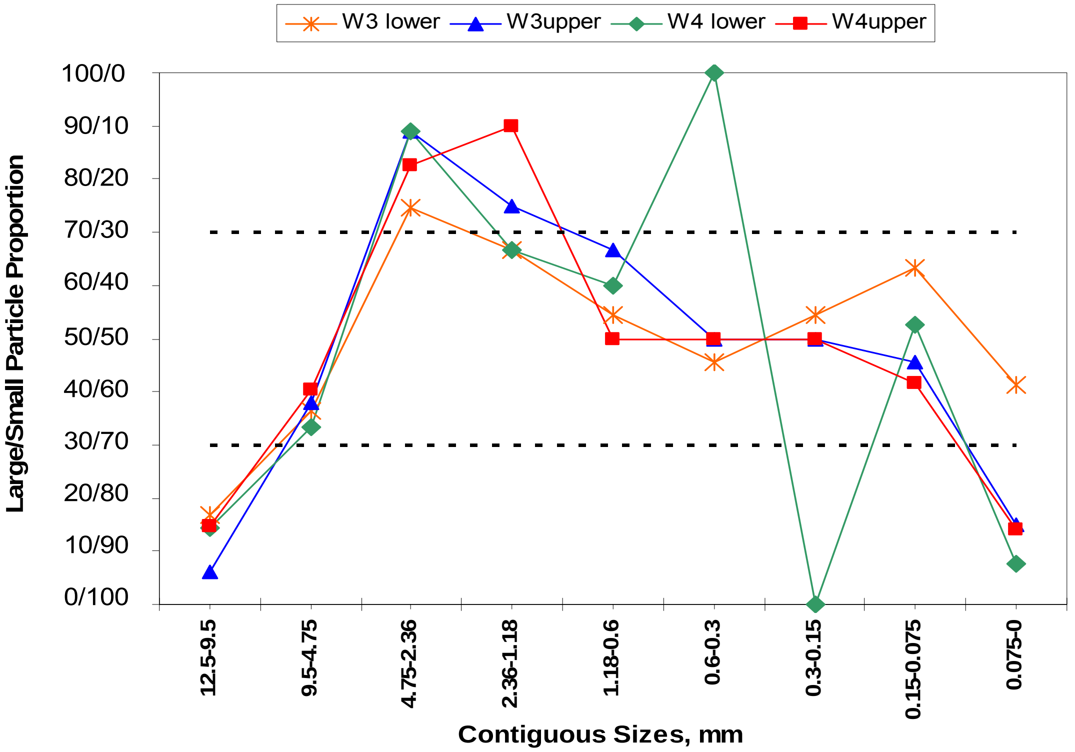


Figure 4-61 Interaction Diagram for Sections W3 lower, W3 upper, W4 lower, and W4 upper

As shown in Figure 4-62, the DASR porosity of all SMA mixtures was less than 50%. The SMA mixture closest to the maximum density line had a DASR porosity close to 50%, while the DASR porosity of the others was well below 50%.

The rutting results presented in Table 4-15 indicate that rut depths for all four SMA mixtures were less than 5 mm after 9 million ESALs. As with all other mixtures evaluated, these results support the findings from the gradation analysis based on the approach developed in this study.

4.6.4 Summary

All mixtures placed at the NCAT test track were identified as having good gradation characteristics by gradation analysis system developed in this research.

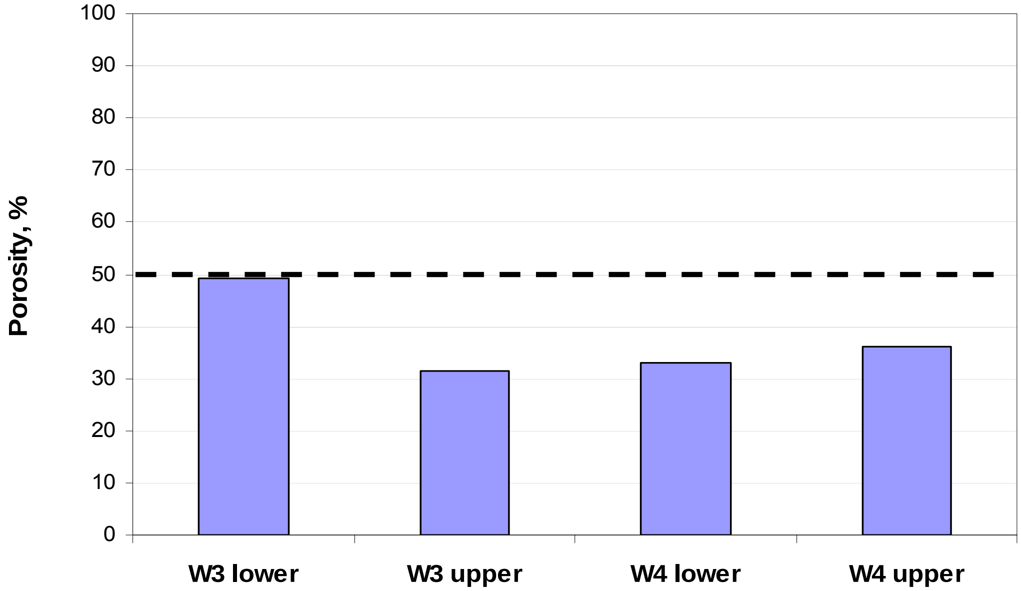


Figure 4-62 DASR Porosity of Sections W3 lower, W3 upper, W4 lower, and W4 upper

Table 4-15 Field Rut Depth Sections W3 lower, W3 upper, W4 lower, and W4 upper

Section	Aggregate type	ESAL's	Field rut depth , mm
Section W3 lower	Limestone	4,172,787	4.6
Section W3 upper	Limestone	4,172,787	4.6
Section W4 lower	Granite	4,172,787	4.1
Section W4 upper	Granite	4,172,787	4.1

The DASR porosity of all mixtures was less than 50%, even when marginally interactive aggregate sizes were treated as non-interactive in the DASR calculations. All mixtures exhibited good rutting performance, where the maximum rut depth for any mixture was 6.2 mm after 9 million ESALs.

These results indicate that the gradation analysis system developed in this study accurately identified the rutting performance of a broad range of mixtures under realistic traffic conditions. These mixtures encompassed a broad range of gradations, from fine-graded to SMA, and aggregate types. This appears to indicate that the criteria established may be fundamental enough in nature to be independent of mixture or aggregate type.

4.7 Additional Observations

Results of evaluations presented in the previous sections of this chapter clearly indicate that the following criteria, which were based on the gradation analysis system developed in this study, resulted in reasonable agreement with observed laboratory and field performance of asphalt mixture:

- DASR porosity of asphalt mixture should be less than 50% to ensure coarse aggregate interlock.
- The relative proportion of contiguous size particles within the DASR must be no greater than 70/30 to ensure proper interaction among the different size particles in the DASR.

It was also observed that mixtures may exhibit marginal performance if the gradation exhibits either of the following two characteristics:

- DASR porosity is very close to 50% and small changes in gradation would result in significantly higher DASR porosity.
- The relative proportion of one or more sets of contiguous size particles in the DASR is very close to 70/30 and the interaction of this set of particle sizes is critical to achieve a DASR porosity lower than 50%.

The implication is that for mixtures having these gradation characteristics, small changes in field gradation may result in DASR porosity greater than 50% and unacceptable performance. This effect was evident in several cases evaluated in this chapter, including mixtures used in the WesTrack studies and mixture involved in the FDOT Superpave monitoring projects. These cases illustrated how these types of mixtures, which were called marginal mixtures, resulted in variable and even catastrophic performance, particularly when marginal interaction was observed between the 4.75/2.36 mm or the 2.36/1.18 mm sizes.

Based on these observations, the following recommendations are presented to reduce the potential of selecting gradations that are likely to result in marginal performance:

- In addition to having a DASR porosity less than 50%, gradations should be evaluated to ensure that acceptable gradation variances do not result in DASR porosity greater than 50%.
- The relative proportions between contiguous size aggregates in the DASR range should be well below 70/30 (e.g., 65/35) when the interaction of these sizes is critical to maintain the DASR porosity below 50%.

4.7.1 Excessively Low DASR Porosity

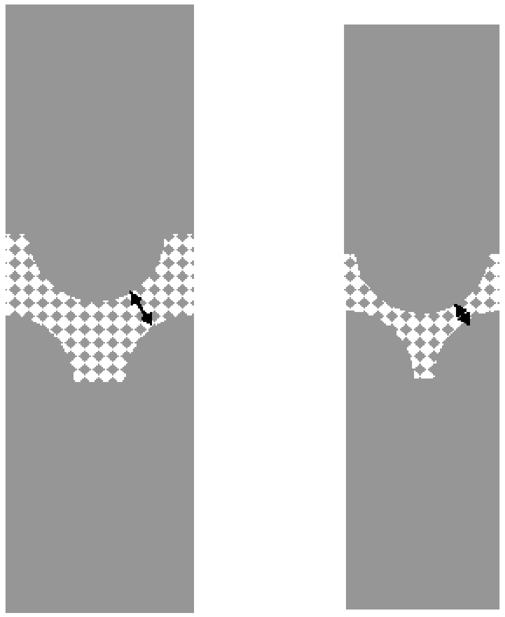
Although the available data did not allow for direct evaluation of a lower DASR porosity limit, existing knowledge of mixture behavior indicates that excessively low porosity may result in the following problems:

- Mixtures may be difficult to compact and have generally poor workability.
- Mixtures may exhibit brittle behavior.

Therefore, an investigation of the use of a minimum allowable DASR porosity is highly recommended for future work.

As a start, a series of finite element (FEM) analyses was conducted as part of this study to investigate the potential effects of low DASR porosity on stress concentrations within the asphalt aggregate structure. FEM analyses were conducted for three levels of DASR porosity, corresponding to three levels of interstitial volume (IV). Note that IV is directly related to DASR porosity, since IV is the volume occupying the pores represented by the DASR porosity.

The system modeled in the FEM analysis is represented in Figure 4-63. As shown in the figure, the mixture was modeled as a two-part system composed of aggregate, representing the DASR, and the asphalt, aggregate, and air void system within the IV, which is referred to as the interstitial component (IC). The same level of tensile stress was applied to the mixtures with different IV's to evaluate the effect on the resulting tensile stress within the IC.



(a) More IV **(b) Less IV**

Figure 4-63 Finite Element Model of Aggregate and Interstitial Volume

The results plotted in Figure 4-64 clearly indicate that the tensile stress within the IC increases as the IV decreases, even though the applied tensile stress was the same in all cases. These higher internal stresses imply that mixtures with lower IV will fail at lower strain levels, because lower applied tensile stress would be required to reach the failure strength of the material.

These results also imply that IV may be a good indicator of brittle mixtures. Currently, there is no commonly accepted mixture parameter that reliably predicts brittle behavior. However, additional study is required to investigate this further and establish rational criteria for this purpose. These preliminary results indicate that IV is promising, but additional characteristics of the interstitial component (IC) and mixture type also likely play a significant role.

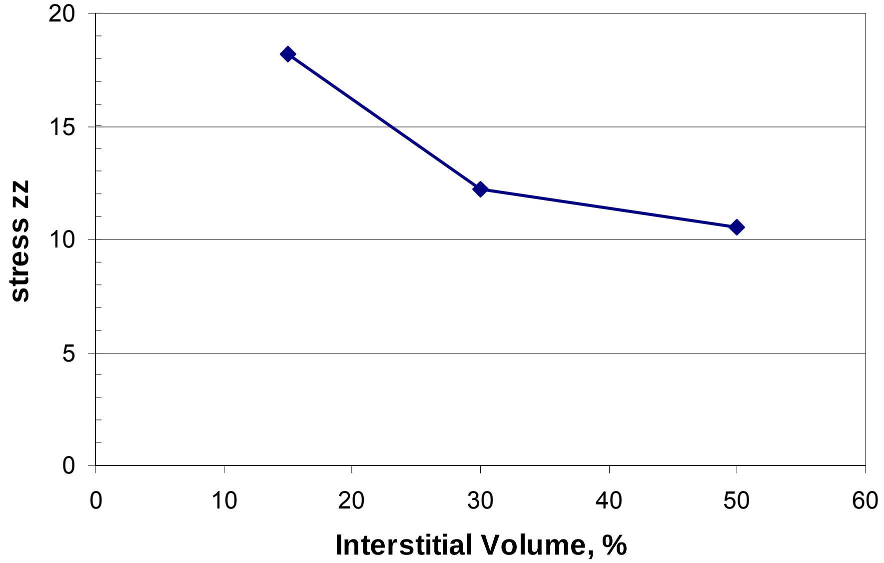


Figure 4-64 Interstitial Spacing (Volume) vs. Local Stress

CHAPTER 5
CLOSURE

5.1 Summary of Findings

The importance of aggregate structure on asphalt mixture performance has been well established on the basis of experience and is well documented in the literature. Furthermore, coarse aggregate structure is most important for resistance to rutting, and recent work has shown that it can also play a significant role in resistance to damage and fracture. Therefore, large enough aggregates should engage dominantly in the structure for good mixture performance. This study focused on the development of a conceptual and theoretical approach to evaluate coarse aggregate structure based on gradation.

It is a well-known fact in soil mechanics that the porosity of granular materials in the loose state is approximately constant between 45% and 50%, regardless of particle size or distribution. This implies that the porosity of an assemblage of granular particles (e.g., the aggregate within an asphalt mixture) must be no greater than 50% for the particles to be in contact with each other. This also implies that one can use porosity as a criterion to assure contact between large enough particles within the mixture to provide suitable resistance to deformation and fracture. Calculations performed for gradations associated with typical dense graded mixtures indicated that the porosity of particles retained on any single sieve was significantly greater than 50%, even for gradations associated with the maximum density line. Since many dense-graded mixtures are known to provide suitable resistance to deformation and fracture, then there must be a range of contiguous coarse aggregate particle sizes that form a network of interactive particles with a porosity of less than 50%.

A theoretical analysis procedure was developed to calculate the center-to-center spacing between specific size particles within a compacted assemblage of particles of known gradation. Calculations performed with this procedure indicated that the relative proportion of two contiguous size particles, as defined by the standard arrangement of Superpave sieves, can be no greater than 70/30 in order to form an interactive network. Thus, the 70/30 proportion can be used to determine whether particles on contiguous Superpave sieves can form an interactive network of particles in continuous contact with each other. The range of particle sizes determined to be interactive was referred to as the dominant aggregate size range (DASR) and its porosity must be no more than 50% for the particles to be in contact with each other.

Analysis of an SMA mixture indicated that the DASR was composed of only one size aggregate, and as expected, its porosity was less than 50%. Analysis of dense-graded mixtures (coarse-graded and fine-graded) of known performance indicated that DASR porosity of aggregate particles coarser than the 1.18 mm sieve was less than 50% for the good performers and greater than 50% for those exhibiting relatively poor performance. Although the approach makes it evident that coarser particle DASR porosities of less than 50% are easier to achieve with coarser gradations, they are also achieved with properly proportioned fine-graded mixtures. In addition, DASR porosities less than 50% are not assured with coarse-graded mixtures; they must also be properly proportioned.

The DASR concept and porosity criterion were evaluated using an extensive range of mixtures from existing databases including the Superpave Monitoring Projects, FDOT HVS test sections, as well as WesTrack and NCAT test sections. Results clearly indicated that mixtures identified by the system developed as having poor or marginal gradations (DASR porosity greater than 50% or gradations that were marginally interactive), resulted in poor rutting performance.

5.2 Conclusions

Several key conclusions were drawn based on the findings of this study. These conclusions, which are summarized below, appear to apply to the broad range of mixtures typically used for roads from fine-graded to SMA:

- DASR porosity of asphalt mixture, determined using the gradation analysis system developed in this study, should be less than 50% to ensure coarse aggregate interlock, which is required for good mixture performance.

- The relative proportion of contiguous size particles within the DASR must be no greater than 70/30 to ensure proper interaction (interlock) among the different size particles in the DASR.

- Gradation evaluation for asphalt mixture should include a sensitivity analysis to evaluate the effects of potential changes in gradation on DASR porosity. Adjustments should be made to JMF’s when accepted gradation variances result in DASR porosity greater than 50%.

- Relative proportions between contiguous size aggregates in the DASR should be significantly lower than 70/30 (e.g., 65/35) when the interaction of these sizes is critical to maintain the DASR porosity below 50%.

- Mixtures with excessively low DASR porosity (low IV) should be avoided, as they may be brittle. However, additional study is necessary to identify specific criteria, which are likely to depend on other variables like mixture type and characteristics of the interstitial components.

5.3 Recommendations

Following are the recommendations resulting from this study:

- FDOT should begin using the gradation analysis system developed in this study to screen potentially unsuitable mixtures and as a guide to make adjustments to improve these mixtures.

- FDOT should initiate a series of controlled laboratory experiments to specifically evaluate the hypotheses used as the basis for the gradation analysis system developed in this study, as well as the criteria established and evaluated using available mixture data.

- Experiments should also be conducted to identify mixtures for evaluation of the gradation analysis system using full-scale pavements with the heavy vehicle simulator (HVS).

- Research should continue to further develop and refine this very promising approach to establishing gradation guidelines for mixture performance. Specifically, the following areas need further development:
    - Effects of aggregate characteristics and properties including shape, angularity and texture on the criteria identified.
    - Establishment of criteria for minimum interstitial volume (IV) or minimum DASR porosity for different types of mixture.
    - Develop further understanding of the effects of the interstitial component (IC) characteristics and properties, which most likely has the greatest effect on fracture resistance of mixture. This should lead to the identification of criteria and guidelines for IC characteristics to optimize mixture performance.

APPENDIX A
GRADATIONS FOR SUPERPAVE MONITORING PROJECT

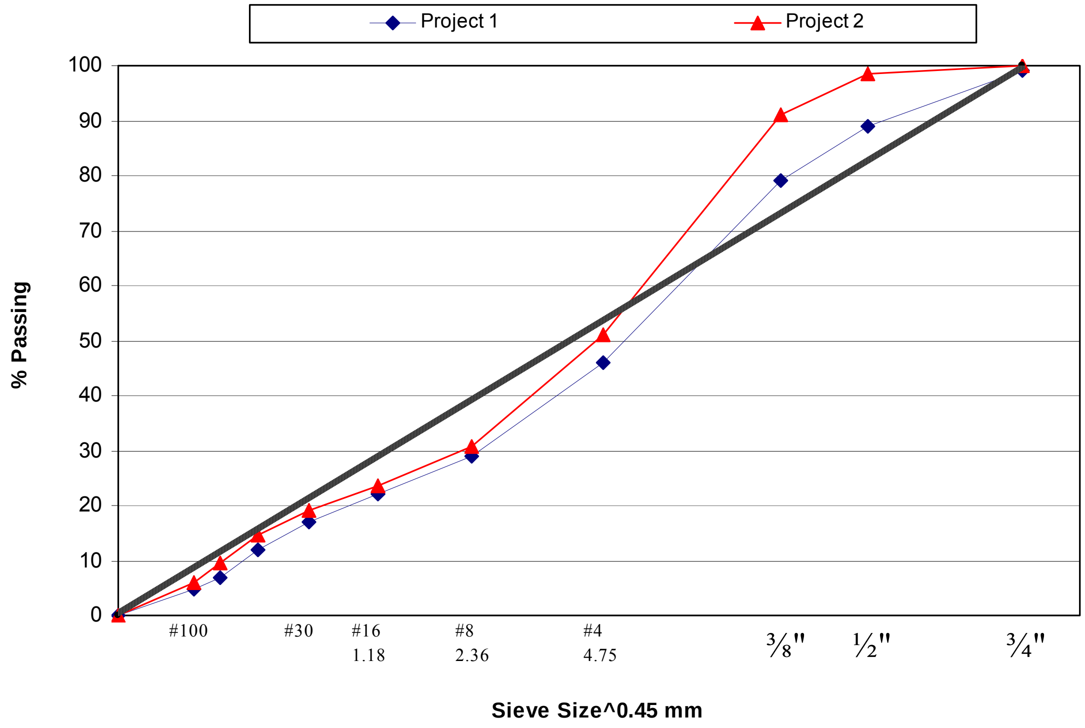


Figure A-1 Gradations for Project 1 and 2

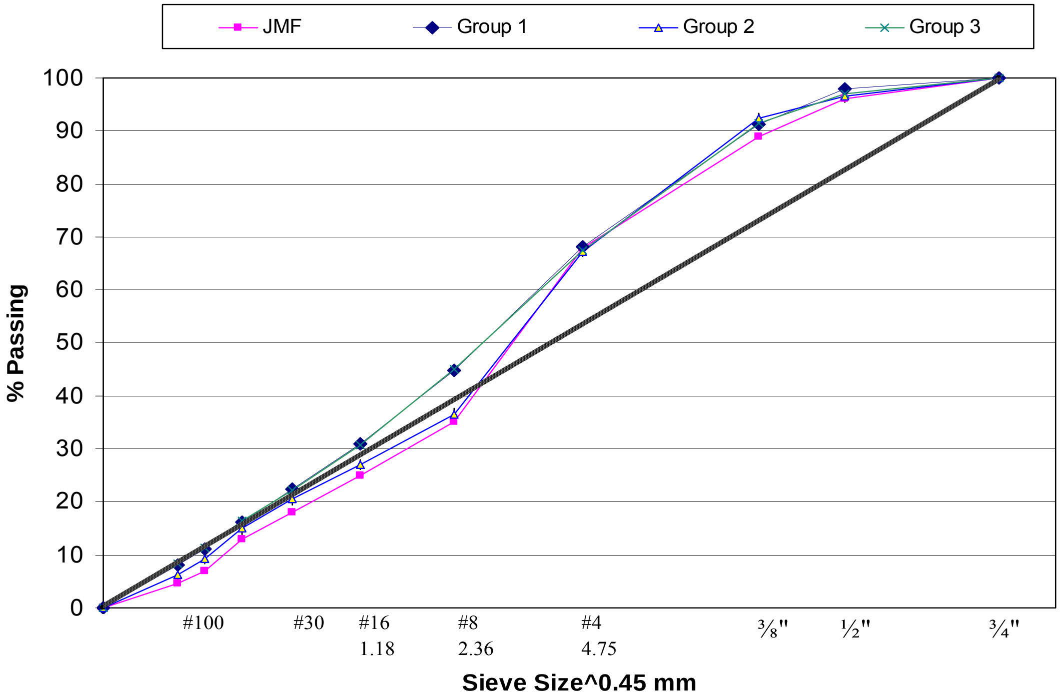


Figure A-2 Gradations for Project 3 Layer A

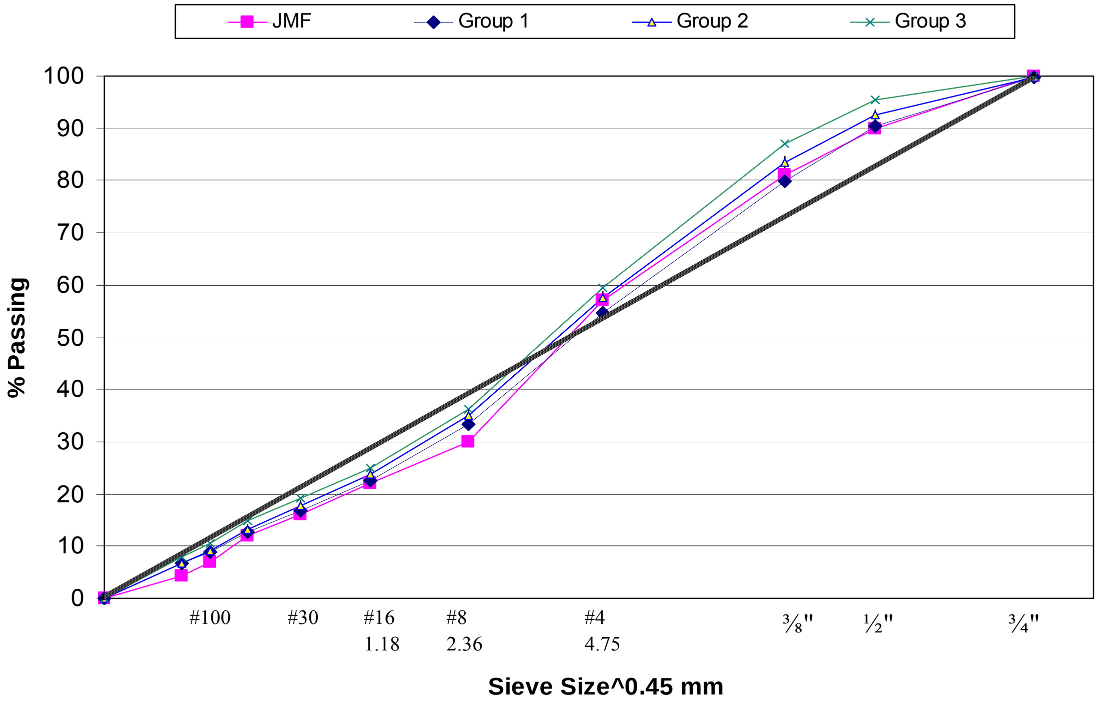


Figure A-3 Gradations for Project 3 Layer B

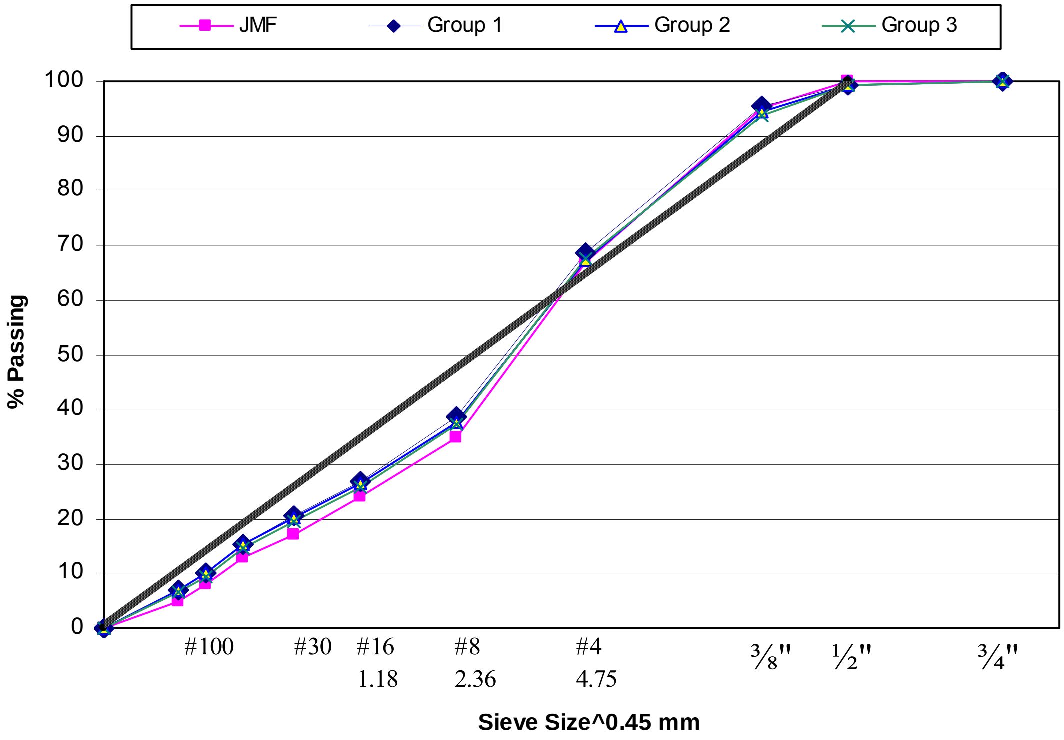


Figure A-4 Gradations for Project 4 Layer A

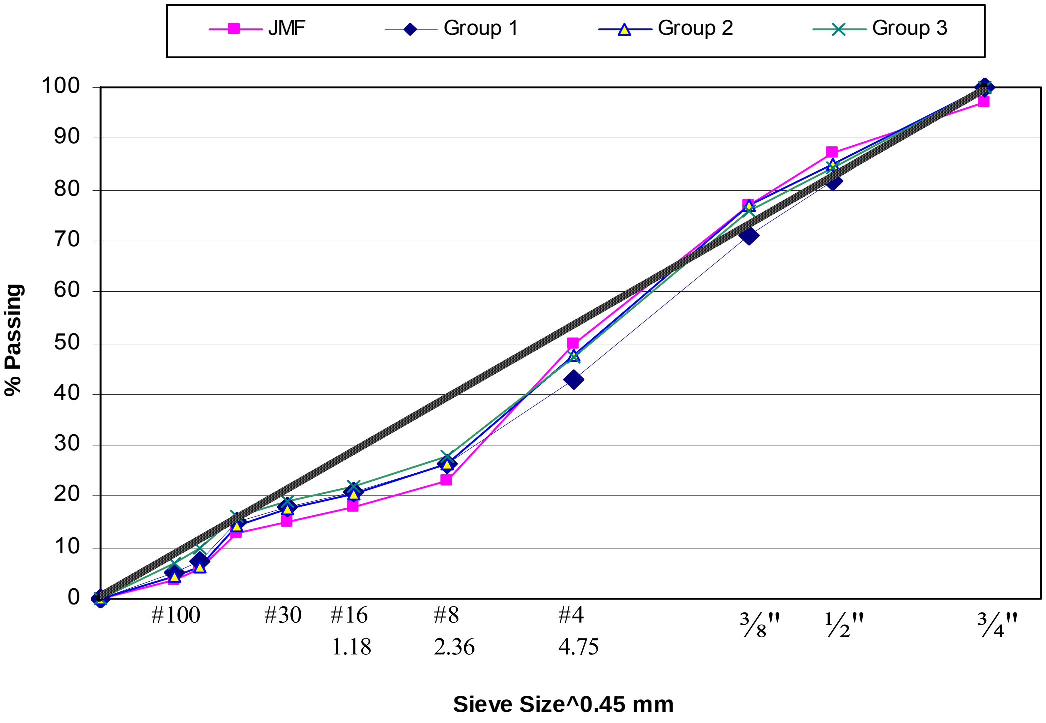


Figure A-5 Gradations for Project 4 Layer B

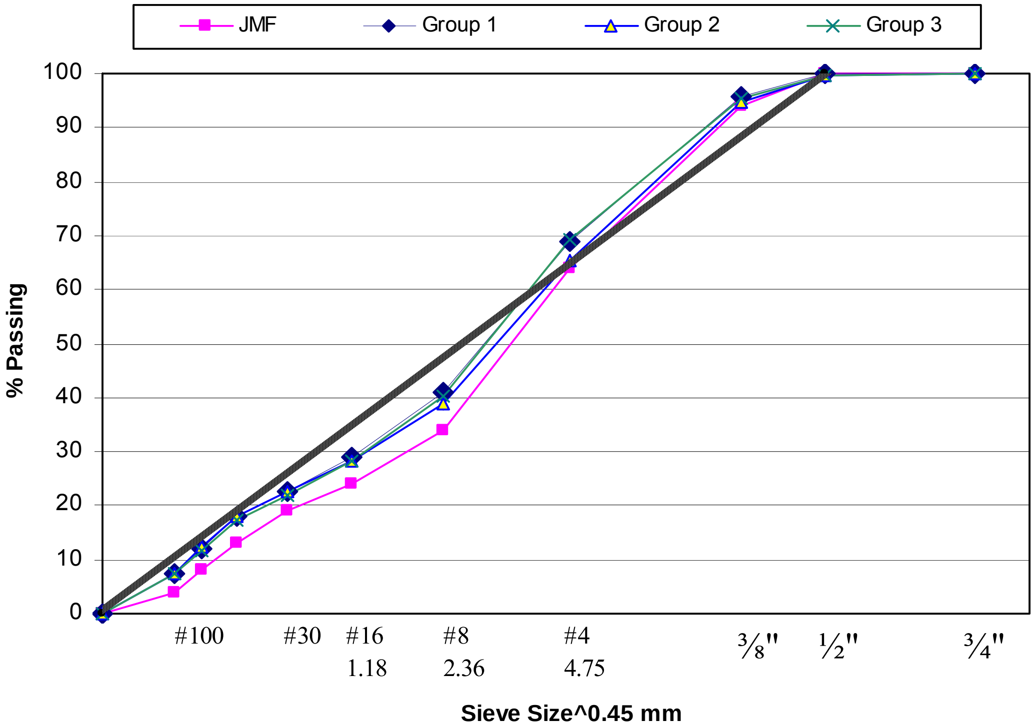


Figure A-6 Gradations for Project 5 Layer A

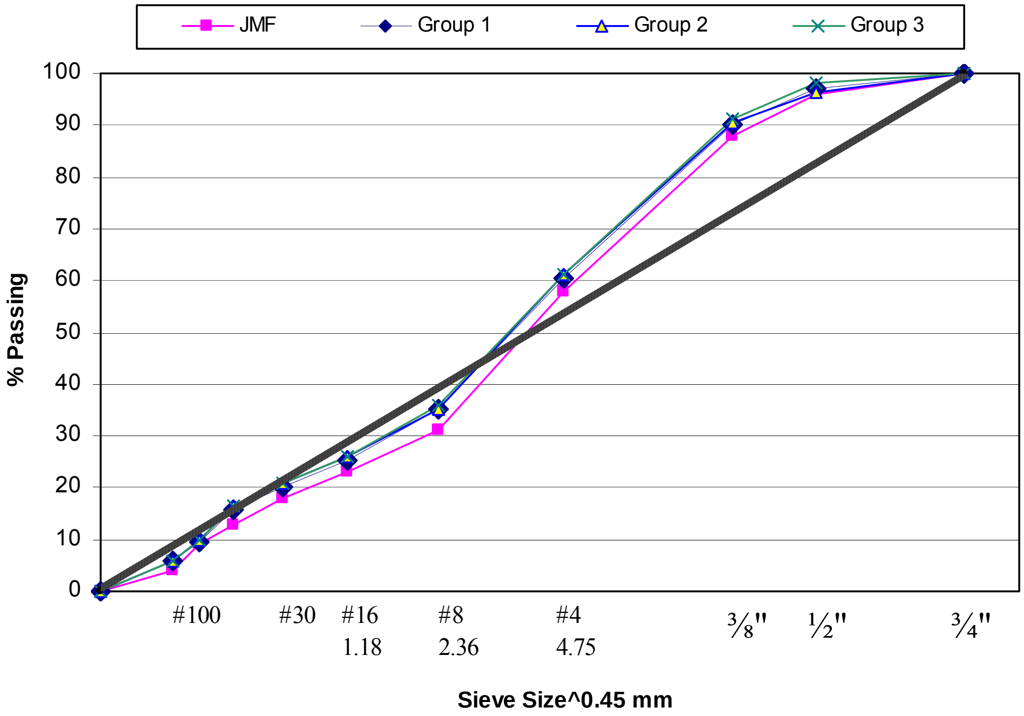


Figure A-7 Gradations for Project 5 Layer B

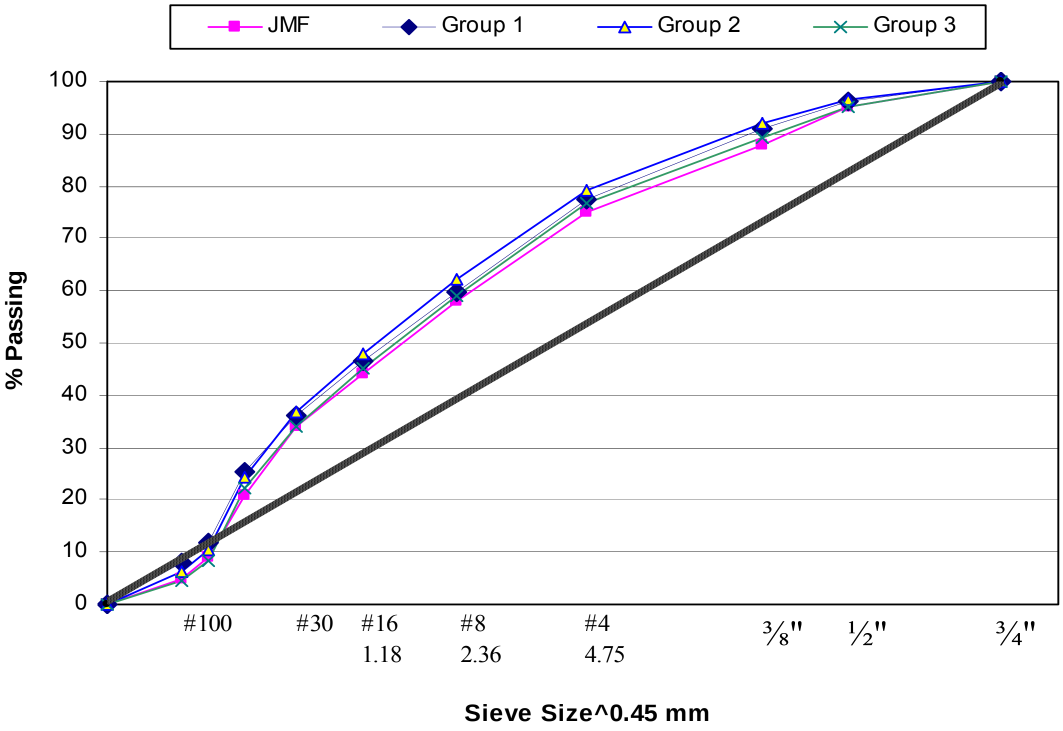


Figure A-8 Gradations for Project 6

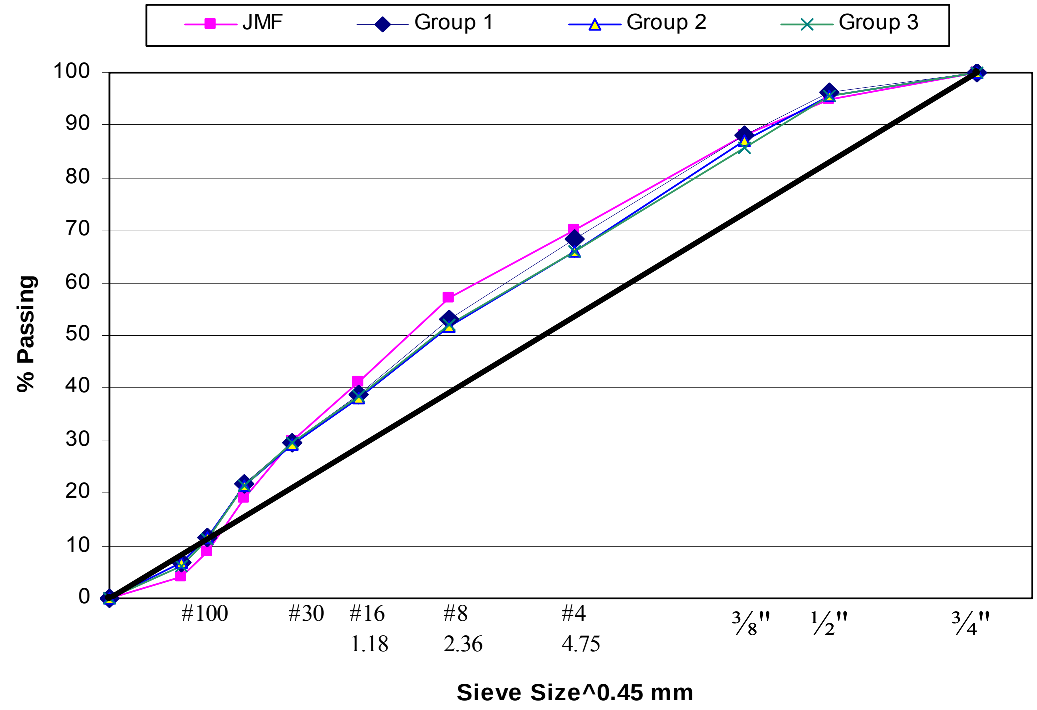


Figure A-9 Gradations for Project 7 Layer A

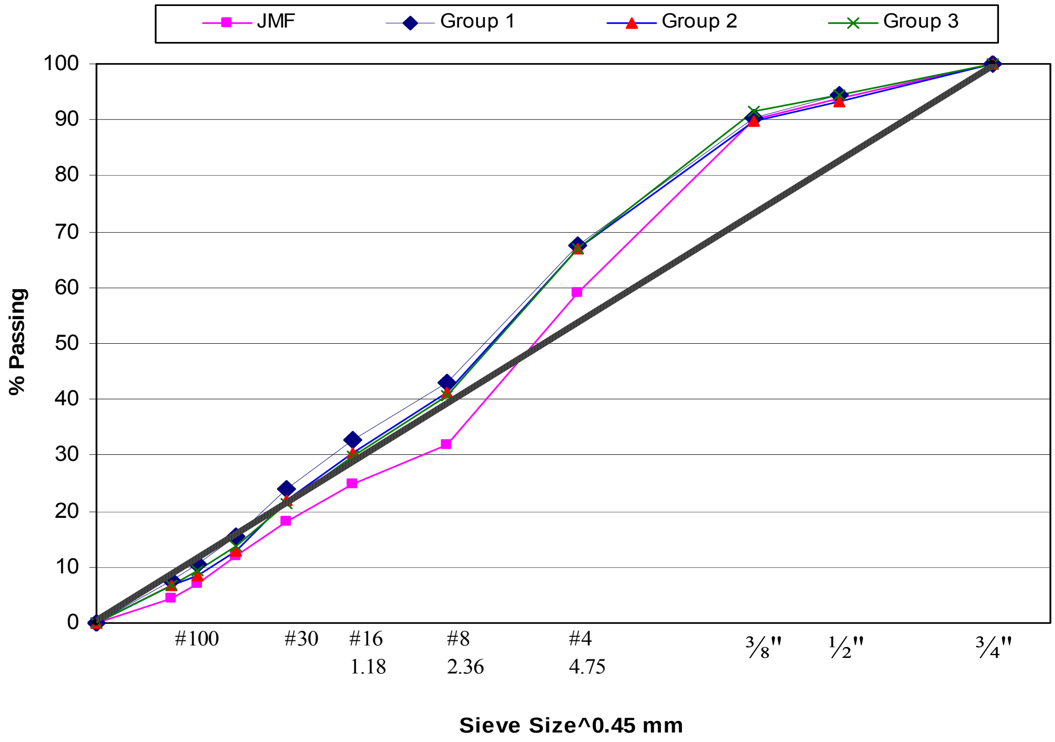


Figure A-10 Gradations for Project 8 Layer A

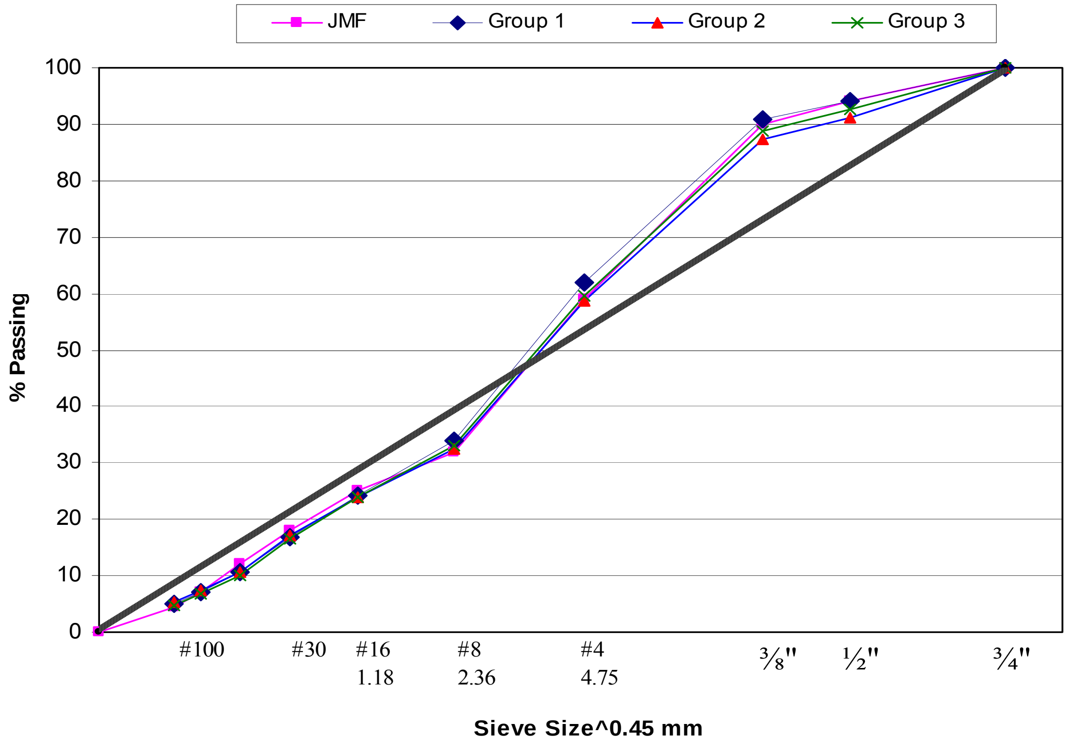


Figure A-11 Gradations for Project 8 Layer B

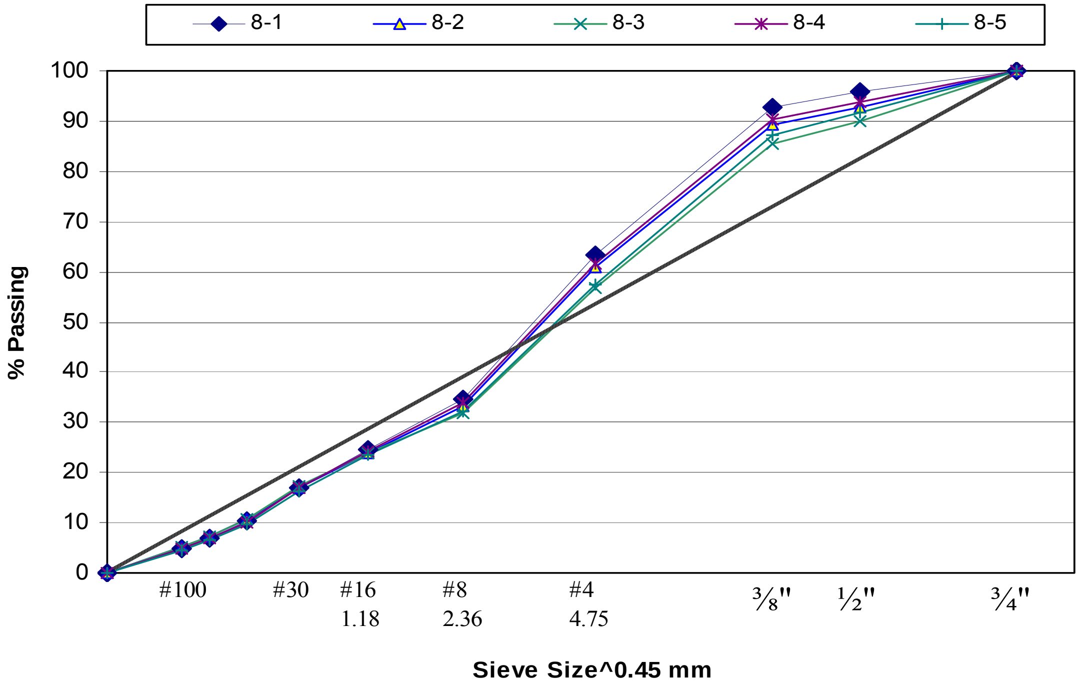


Figure A-12 Gradations for Project 8 Plant Mixture

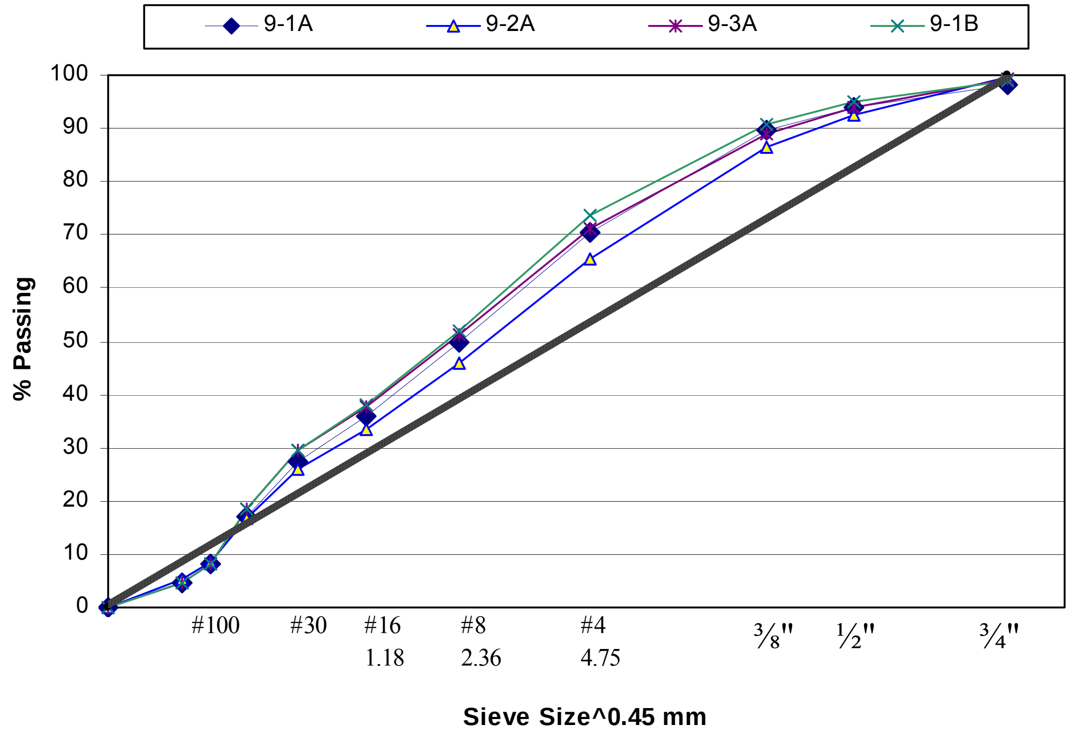


Figure A-13 Gradations for Project 9

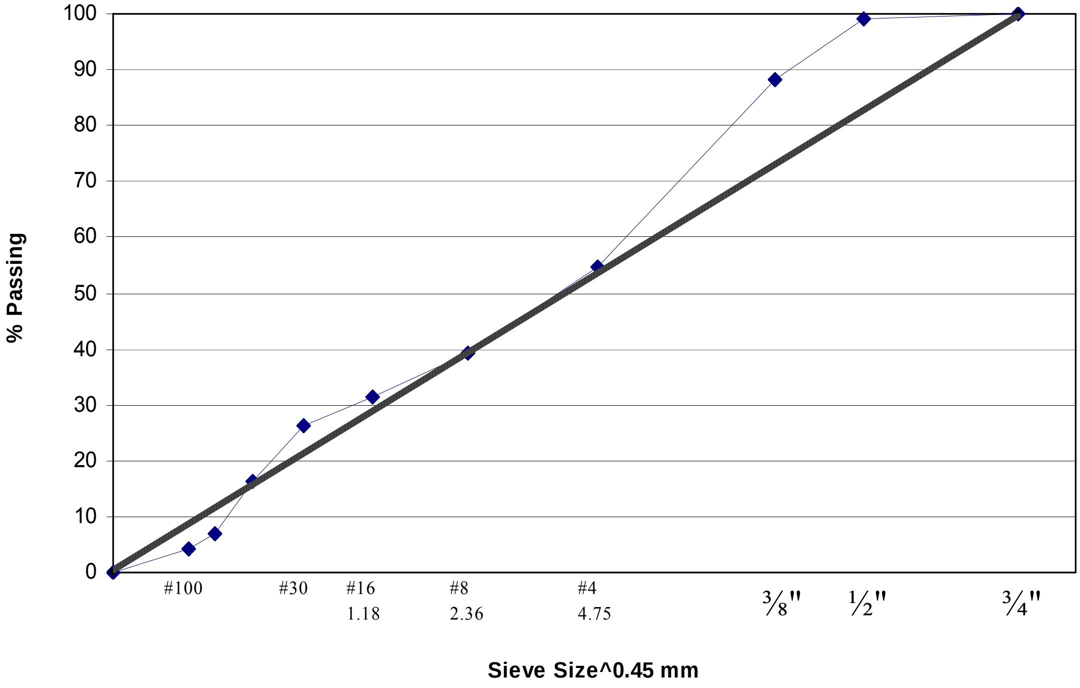


Figure A-14 Gradations for Project 10

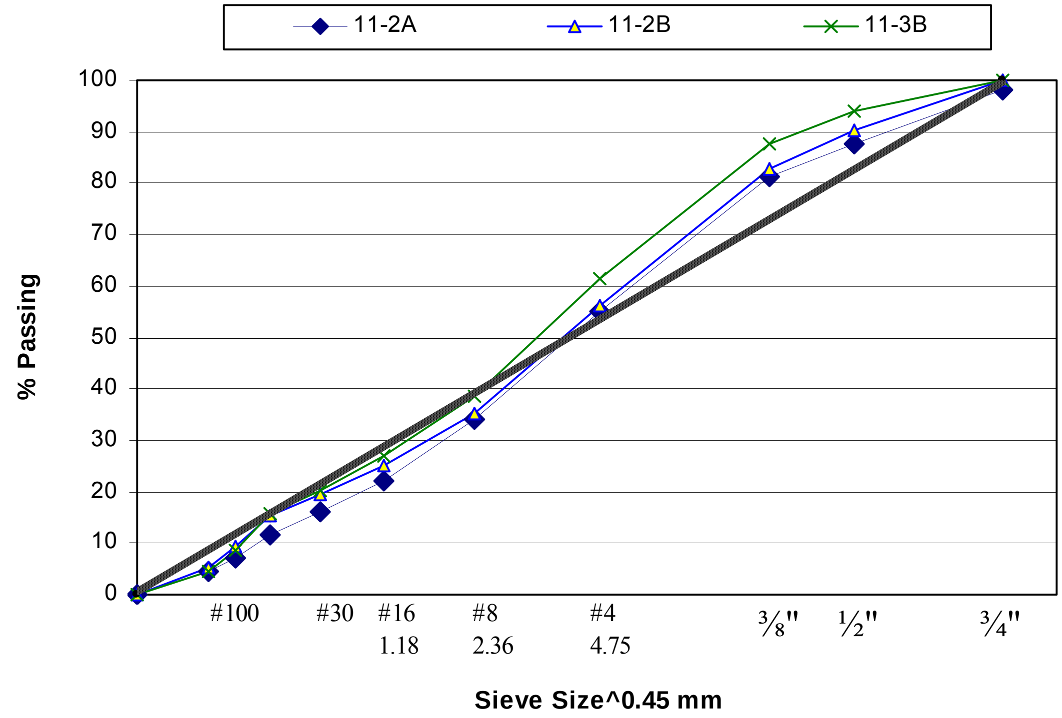


Figure A-15 Gradations for Project 11

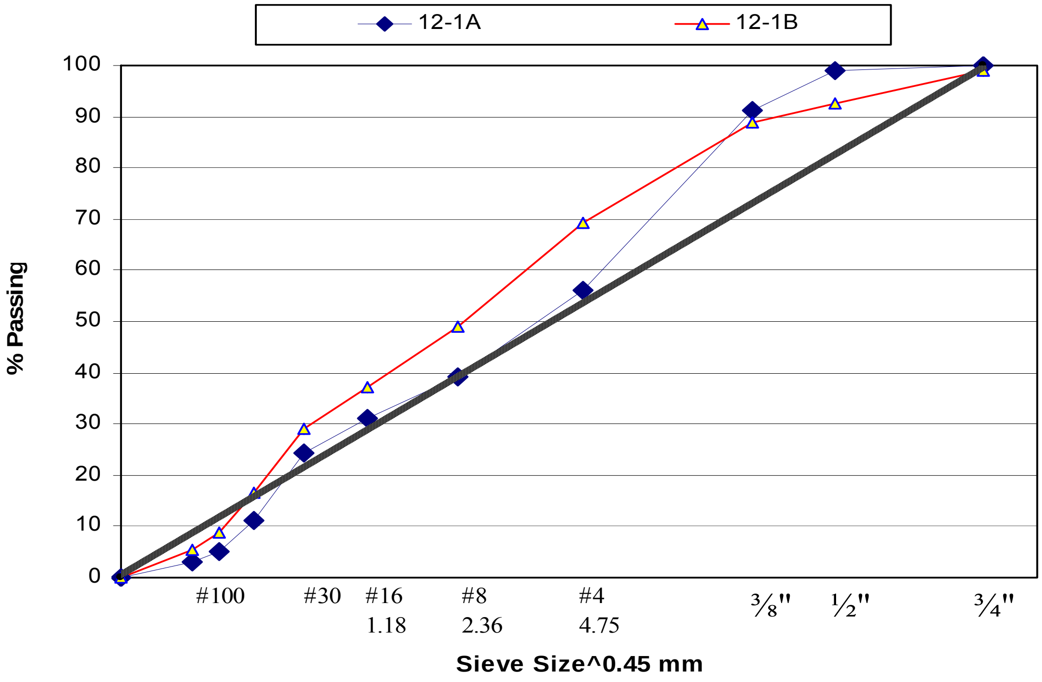


Figure A-16 Gradations for Project 12

APPENDIX B
POROSITY RESULTS FOR SUPERPAVE PROJECTS

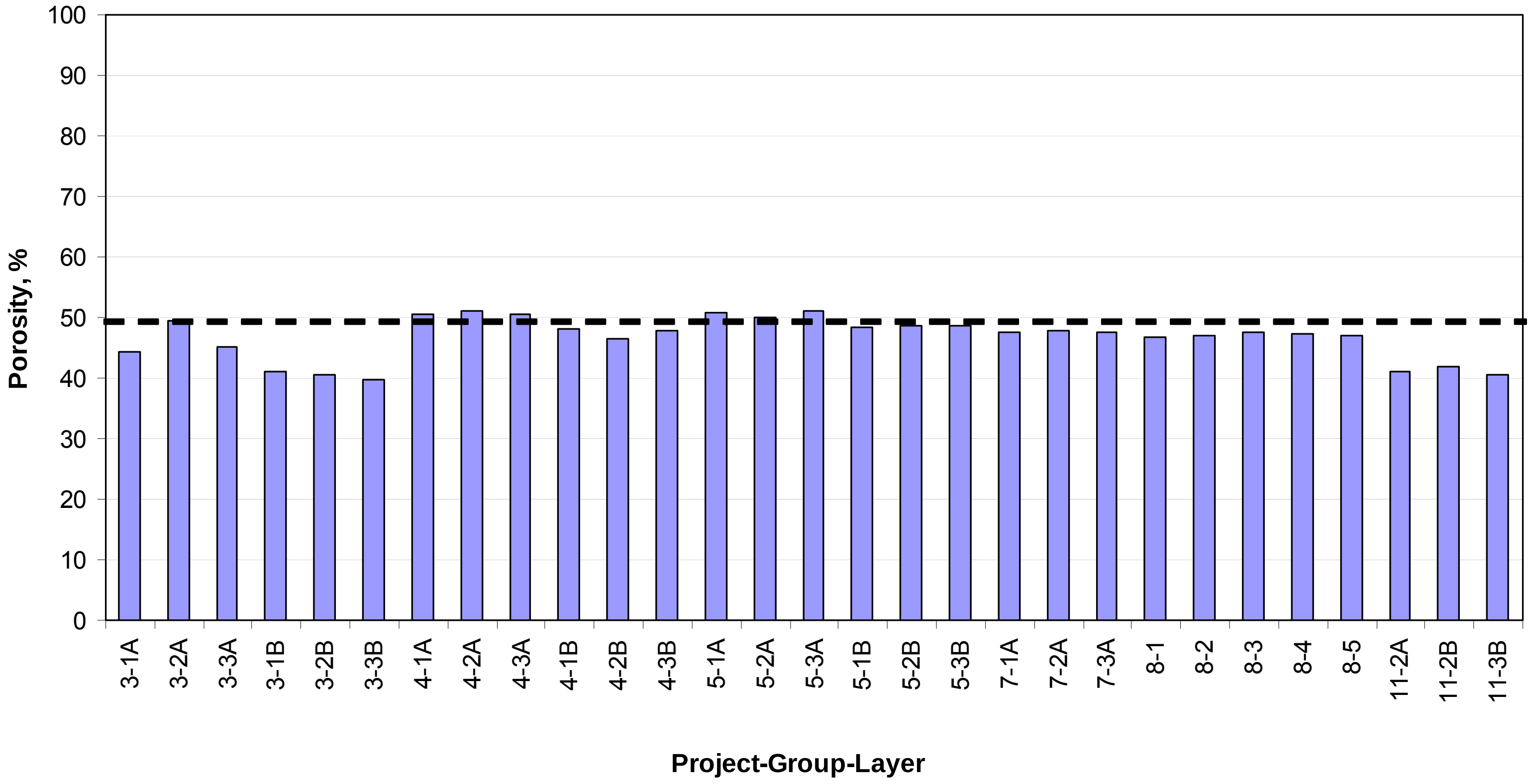


Figure B-1 Porosity Results for Group 1 (Field Gradations for Projects 3, 4, 5, 7, and 8, and Plant-Mix Gradations for Project 11)

Figure B-2 Porosity Results for Group 2 (Field Gradation for Projects 6, and Plant-Mix Gradations for Projects 8, and 12)

APPENDIX C
TRAFFIC AND RUT DEPTH DATA FOR SUPERPAVE MONITORING PROJECT

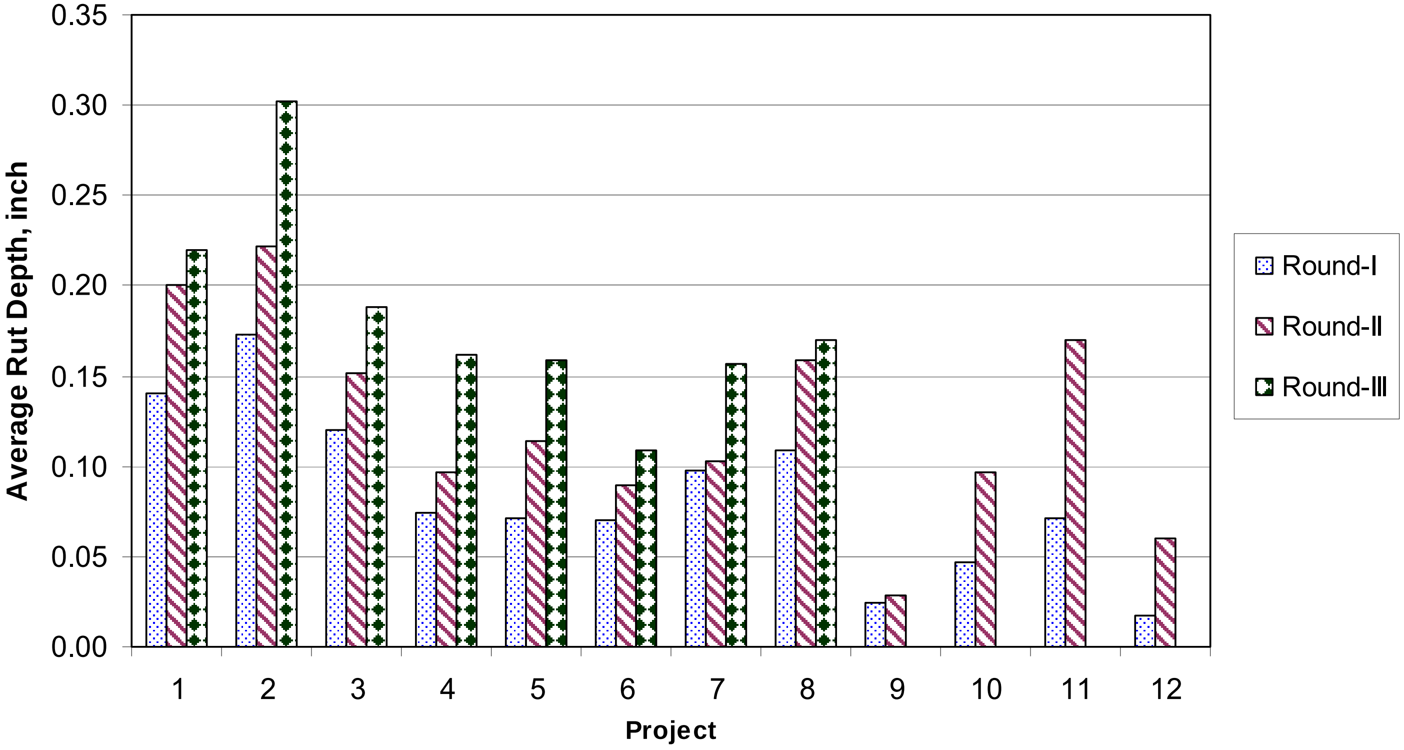


Figure C-1 Cumulative Average Rut Depth for Each Round

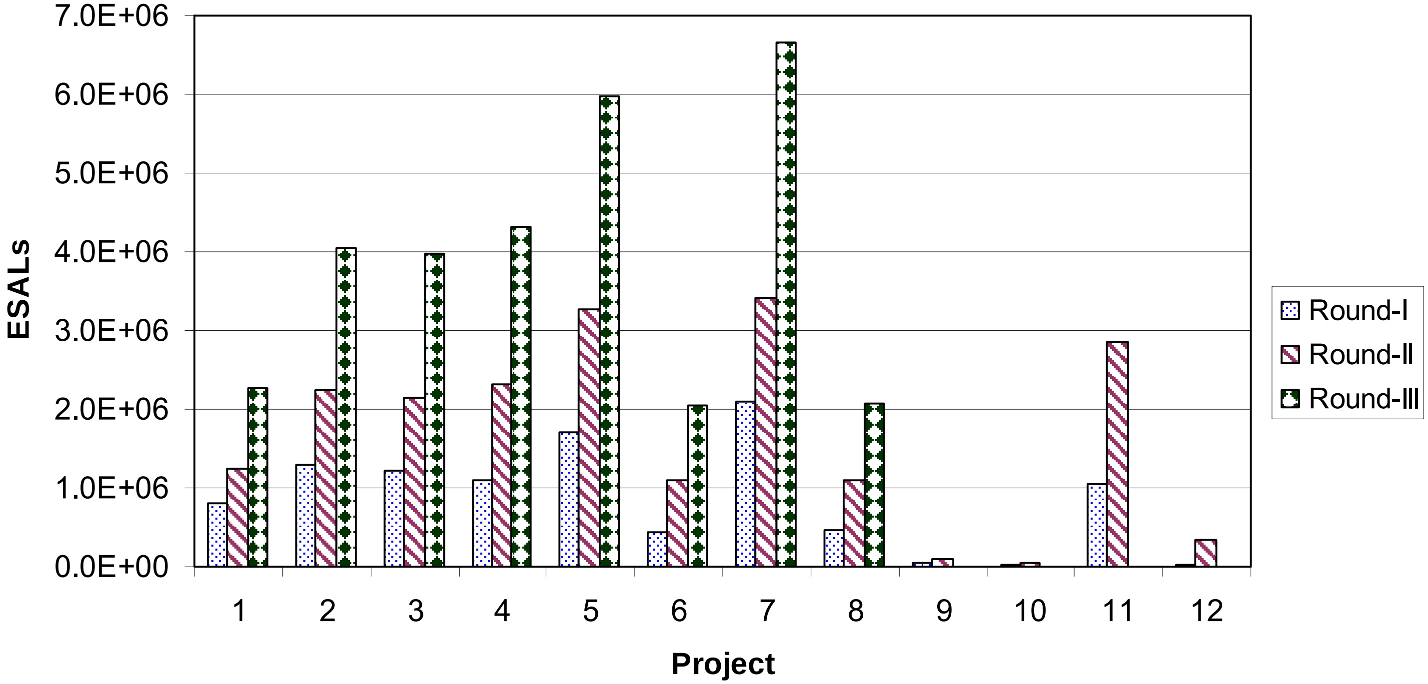


Figure C-2 Cumulative ESALs for Each Round

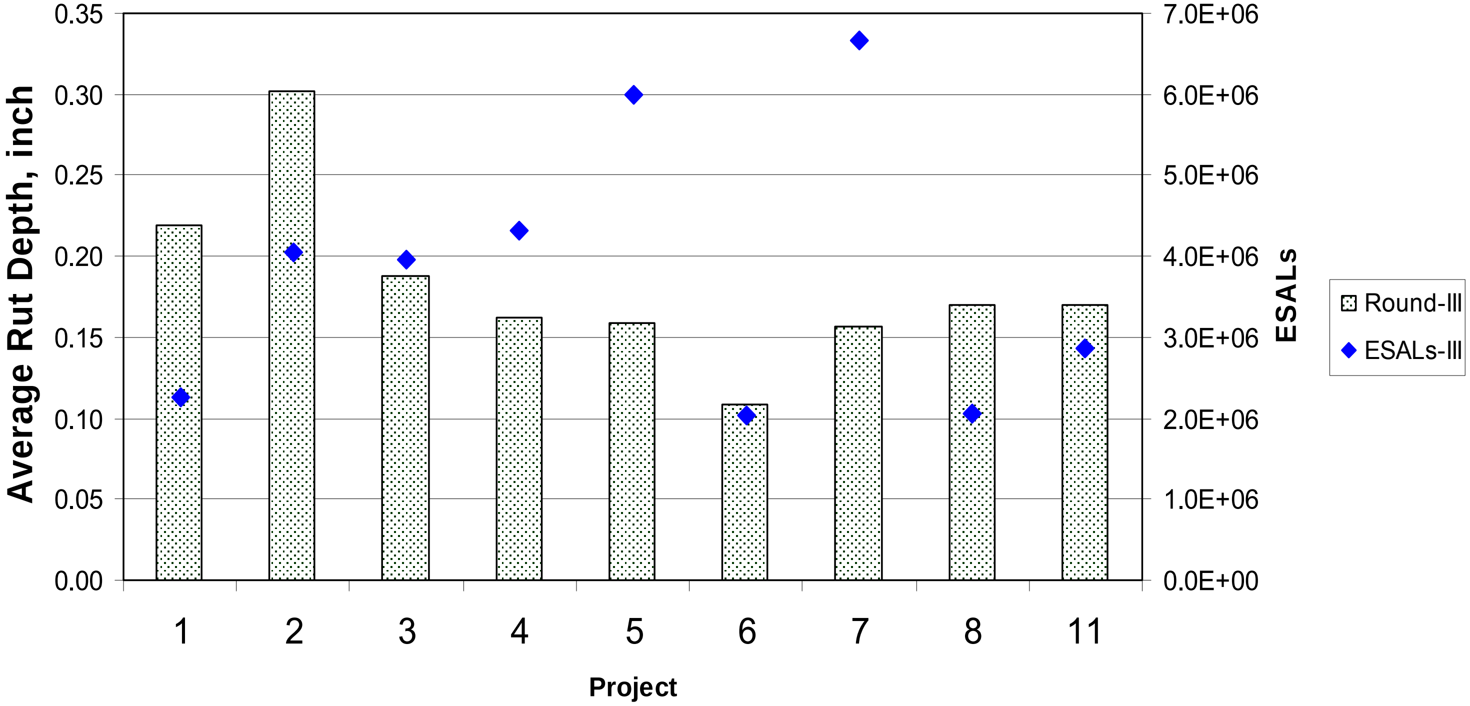


Figure C-3 Total Rut Depth and ESALs

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