POTENTIAL OF USING STONE MATRIX ASPHALT (SMA) IN MISSISSIPPI

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TABLE OF CONTENTS

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INTRODUCTION

Stone matrix asphalt (SMA) has been used in Europe for over 30 years. SMA was first used in Europe as a mixture that would resist the wear of studded tires; however, an additional benefit found with SMA was that it was durable and highly rut resistant. Because of the success of SMA in Europe, five state agencies within the U.S. constructed SMA pavements during 1991. These agencies designed the SMA mixtures using "recipe" procedures adopted from European practices. The recipe generally consisted of a single aggregate gradation band that followed the "60-30-10" rule. This rule indicates that 60 percent of the aggregate gradation was made up of a coarse aggregate, 30 percent was a fine aggregate, and 10 percent was mineral filler.

The first publication within the United States that provided guidance on the design of SMA mixtures was produced by the SMA Technical Working Group (TWG) and published in 1994 (1). Within this publication, a single gradation band was provided (Table 1). Depending upon the actual gradation within the band, SMA gradations that met the TWG's requirements had either a 12.5 or 19.0 mm nominal maximum aggregate size (Superpave definition).

In 1997, the National Center for Asphalt Technology (NCAT) conducted a performance evaluation of more than 140 SMA pavements from throughout the United States (2). The evaluation consisted of collecting data concerning mix design, plant production, lay down, and performance for each of the 140 SMA pavements. With respect to performance, over 90 percent of the evaluated SMA pavements had rut depths of 4 mm or less. There were only six of the 140 projects in which rutting (more than 6 mm) could be attributed to the SMA layer. However, most of these problems could be attributed to construction problems. Another observation made during the performance review was that there was no evidence of raveling on any of the projects.

Table 1: SMA Gradation Band Recommended by SMA TWG (1)

Sieve, mm	Percent Passing
19.0	100
12.5	85 - 95
9.5	75 (max)
4.75	20 - 28
2.36	16 - 24
0.60	12 - 16
0.30	12 - 15
0.075	8 - 10

In 1999, NCAT developed and validated a mix design procedure for SMA through NCHRP Project 9-8, "Designing Stone Matrix Asphalt Mixtures for Rut-Resistant Pavements," using the Superpave gyratory compactor (3). Within this document, mix design criteria and construction guidelines were provided for SMA mixes having nominal maximum aggregate size (NMAS) gradations ranging from 4.75 to 25.0 mm. Design criteria for SMA mixes included aggregate properties, binder properties, mortar properties (which were optional), stone-on-stone contact, gradations, and volumetrics. Table 2 presents the recommended gradation requirements for SMA mixes, while Table 3 provides the recommended mix design criteria.

Table 2: Recommended Gradation Limits from NCHRP 9-8 (3)

Sieve, mm	25.0 mm NMAS Lower	25.0 mm NMAS Upper	19.0 mm NMAS Lower	19.0 mm NMAS Upper	12.5 mm NMAS Lower	12.5 mm NMAS Upper	9.5 mm NMAS Lower	9.5 mm NMAS Upper	4.75 mm NMAS Lower	4.75 mm NMAS Upper
37.5	100	100								
25.0	90	100	100	100						
19.0	30	86	90	100	100	100				
12.5	26	63	50	74	90	100	100	100		
9.5	24	52	25	60	26	78	90	100	100	100
4.75	20	28	20	28	20	28	26	60	90	100
2.36	16	24	16	24	16	24	20	28	28	65
1.18	13	21	13	21	13	21	13	21	22	36
0.60	12	18	12	18	12	18	12	18	18	28
0.30	12	15	12	15	12	15	12	15	15	22
0.075	8	10	8	10	8	10	8	10	12	15

Table 3: Mix Design Criteria for SMA Mixes (3)

Property	Requirement
Air Voids at N_{design}, %	4.0
Voids in Mineral Aggregate, %	17 min.

Voids in Coarse Aggregate for Mix (VCA_{MIX}), %	Less than VCA_{DRC}
Tensile Strength Ratio (AASHTO T283), %	70 min.
Draindown at Production Temperature, %	0.30 max.

SMA is a premium type of hot mix asphalt. On average, SMA is 20 to 30 percent higher in price than Superpave designed mixtures. For this reason, its use in Mississippi would not likely be widespread. However, there are numerous potential applications which include:

1. Interstates 20, 55, and 220 within the Jackson metropolitan area.
2. Interstate 10 and Highway 90 along the Gulf coast.
3. Interstate 55 in the northern part of the state.
4. Interstate 20/59 from the Alabama border through Meridian.

The above listed highway sections are a portion of potential areas that SMA may be applicable as all carry high traffic volumes that contain significant amounts of heavy trucks. In addition, the Alabama Department of Transportation has used SMA at some trouble intersections with good success and, thus, this application may be appropriate in Mississippi.

Because of the good performance of SMA, for rutting and durability, within the United States, a study was needed to evaluate the potential of using SMA within Mississippi. This study should investigate SMAs designed utilizing native Mississippi materials.

OBJECTIVE

The objective of this study was to evaluate whether native Mississippi materials can be used to successfully design rut resistant stone matrix asphalt mixtures.

RESEARCH APPROACH

The objective of this study was accomplished by designing sixteen SMA mixtures using various sources and combinations of aggregates. A single unmodified PG 67-22 asphalt binder and marble dust mineral filler was used for the entire study. Five different aggregate types were evaluated, each from a different source. Two of the five sources were native Mississippi crushed gravels. One of these gravels was obtained from the northern part of the state and the other from the southern portion. The other three aggregates have been used within Mississippi and include: Alabama limestone, Arkansas sandstone, and Nova Scotia granite.

Two nominal maximum aggregate sizes (NMASs) were included in this study: 9.5 mm and 4.75 mm. A NMAS of 9.5 mm has been used for SMA mixes in the United States with success. The use of 9.5 mm NMAS SMA mixes has not been widespread, but Virginia has placed them with success. The NMAS of 4.75 mm has not been used in the field, to date, but has been successively evaluated in the laboratory by NCAT (3, 4). A 4.75 mm NMAS was investigated because this type of mix would be ideal for maintenance overlays. Because of the relatively small aggregate sizes, a 4.75 mm SMA could be used as a thin overlay and, therefore, more square yardage can be overlaid with the same tonnage of mix (as compared to larger NMAS mixes). Work by NCAT has suggested that 4.75 mm SMAs are rut resistant and less permeable than larger NMAS SMAs (4).

Initially, mix designs were conducted for both NMAS utilizing 100 percent of each native Mississippi gravel source. This equated to four mix designs using 100 percent native Mississippi gravels (2 gravels * 2 NMAS). Next, mix designs were conducted utilizing approximately 70/30 percent blends. Both of the Mississippi gravels were combined at 70 percent with the limestone, sandstone, and granite at 30 percent. Again, both NMAS were included. This equated to an additional 12 mix designs (2 gravels * 3 aggregates * 2 NMAS), for a total of 16 SMA mix designs. The design compactive effort for all mix designs was 100 gyrations of the Superpave gyratory compactor in accordance with current AASHTO requirements.

Mixes meeting all design requirements were subjected to rut testing utilizing the Asphalt Pavement Analyzer. Samples used for rut susceptibility testing were compacted at optimum binder content to the design number of gyrations (≈ 115 mm height). A wheel load of 120 lb and hose pressure of 120 psi were used for the loading of samples to 8,000 cycles. A test temperature of 64°C was used. This testing was conducted to verify that the designed SMA mixes achieved the particle-on-particle contact required for SMA mixes.

TEST METHOD AND MATERIALS

Within this section, results of testing conducted on the materials used during the course of this study are provided. Additionally, the SMA mix design procedure and associated tests are discussed.

Material Properties

As mentioned, five different aggregate sources were utilized in this study: a south

Mississippi gravel, north Mississippi gravel, Nova Scotia granite, Alabama limestone, and Arkansas sandstone. Properties of these aggregates are presented in Table 4.

Table 4: Aggregate Properties

		South Miss. Gravel				North Miss. Gravel		Nova Scotia Granite	
		-3/4"	-1/2"	-3/8"	C. Sand	5/8"	1/2"	#89's	1/4" Scrns
Fine Aggregate Properties	Bulk Specific Gravity			2.368	2.610				2.586
	Apparent Specific Gravity			2.628	2.645				2.673
	FAA			41.9	38.7				45.7
	Water Absorption			4.2	0.5				1.3
Coarse Aggregate Properties	Bulk Specific Gravity	2.409	2.406			2.552	2.467	2.603	
	Apparent Specific Gravity	2.621	2.623			2.62	2.598	2.659	
	Water Absorption	3.4	3.5			1.0	2.0	0.8	
	LA Abrasion	14.5	13.8			18.4	15.3	17.8	
	Fractured Face Count	90.0/80.4	97.0/71.6			99.6/84.7	95.4/84.3	100.0/100.0	
	Coarse Aggregate Flow	42.6	44.4			46.6	44.1	44.9	

Note: For Crushed Face Count, First Number is % 1 Crushed Face and Second Number is % 1 or More Crushed Faces

Table 4: Aggregate Properties (cont.)

		Alabama Limestone		Arkansas Sandstone		Marble Dust	Hyd. Lime
		#89's	#821's	1/4X1/8	3/8X1/4	-	-
Fine Aggregate Properties	Bulk Specific Gravity		2.641	2.497	2.529	2.566	2.300
	Apparent Specific Gravity		2.732	2.658	2.652	2.566	2.300
	FAA		46.6	45.0	42.4		
	Water Absorption		1.3	2.4	1.8		
Coarse Aggregate Properties	Bulk Specific Gravity	2.624					
	Apparent Specific Gravity	2.727					
	Water Absorption	1.4					
	LA Abrasion	31.7					
	Fractured Face Count	100.0/100.0					
	Coarse Aggregate Flow	44.0					

Note: For Crushed Face Count, First Number is % 1 Crushed Face and Second Number is % 2 or More Crushed Faces

The asphalt binder used in this study was an unmodified PG 67-22. An unmodified binder was selected so that the aggregate structures of the designed mixes could be better evaluated. If a polymer modified binder (e.g., PG 76-22) had been utilized, the increased stiffness of the binder may have masked the evaluation of particle-on-particle contact. Marble dust was included, where needed, as added mineral filler. Hydrated lime was also incorporated into each mixture in accordance with MDOT policy. A cellulose fiber was included at 0.3 percent by total mix mass as a stabilizing additive.

Test Methods

During the design of SMA mixes, there are two tests that are not typical of most dense-graded mix designs: voids in coarse aggregate (VCA) and draindown. Each is described in the following paragraphs.

Voids in Coarse Aggregate

The VCA of the coarse aggregate fraction is determined by compacting the aggregate by the dry-rodded technique according to AASHTO T19, Unit Weight and Voids in Aggregate. The acronym VCA_{DRC} indicates the voids in coarse aggregate of the coarse aggregate fraction in the

$$VCA_{DRC} = \frac{G_{ca}\,\gamma_w - \gamma_s}{Gca\,\gamma_w} \; x\ 100$$

dry-rodded condition.

Where,

VCA_{DRC} – voids in coarse aggregate of coarse fraction in dry-rodded condition, %

γ_s – unit weight of the coarse aggregate fraction in dry-rodded condition (kg/m^3)

γ_w – unit weight of water (998 kg/m^3)

G_{ca} – bulk specific gravity of coarse aggregate fraction

The VCA test is used to evaluate the existence of particle-on-particle contact. The VCA_{DRC} is compared to the VCA of a compacted SMA sample (VCA_{MIX}). If the VCA_{MIX} is less than the VCA_{DRC}, then particle-on-particle contact exists.

Draindown Sensitivity

The draindown test measures the potential for asphalt binder to drain from the coarse aggregate structure while the mixture is held at an elevated temperature (e.g., mix storage and transportation). The test is performed in accordance with ASTM D6390, Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures. To run this test, a sample is prepared in the laboratory (during mix design) or obtained during field production. The sample is placed in a wire basket that is placed over a suitable container of known mass (generally a paper plate). The sample, basket, and container are then placed in a forced draft oven for one hour at or above the anticipated production temperature. At the end of the one hour, the mass of the container is obtained. The amount of draindown is then calculated as a percentage of the total mix mass. The maximum allowable draindown for SMA mixes is 0.3 percent.

Asphalt Pavement Analyzer

The Asphalt Pavement Analyzer (APA) is an automated, new generation of the Georgia Loaded Wheel Tester (GLWT). The APA test was conducted in the dry to 8,000 cycles and rut depths were measured continuously. APA testing was conducted on three pairs of specimens compacted at optimum binder content to the design number of gyrations resulting in sample heights being close to mix design height (≈ 115 mm). Testing with the APA was conducted at 64°C. Hose pressure and wheel load were 827 kPa and 534 N (120 psi and 120 lb), respectively.

SMA Mix Design Method

Brown and Cooley (3) presented the steps required to design SMA mixes within a National Cooperative Highway Research Program report. The first step in the mix design process is to select materials that meet SMA specification requirements (Table 2). These requirements are outlined in AASHTO MP-8. Once satisfactory materials have been identified, the optimum aggregate gradation and binder content are selected. This is accomplished by first selecting an appropriate aggregate blend. This blended gradation should provide an aggregate skeleton with stone-on-stone contact and furnish a mixture that meets or exceeds the minimum voids in mineral aggregate (VMA) requirement.

Trial Gradations

The initial trail gradations are selected to be within the master gradation specification ranges with one exception. Table 2 presented the recommended gradation bands for SMA mixes. Recent work at the NCAT has suggested that the percent passing the 0.075 mm sieve for 4.75 mm NMAS SMA mixes can range from 8 to 15 percent (5). SMA gradations are based on percent aggregate volumes passing respective sieves instead of percent mass passing. However, if the bulk specific gravities of the different stockpiles to be used (including mineral filler) do not differ by more than 0.02, gradations based on mass percentages can be used to estimate the gradations based on volumetric percentages. SMA mixtures typically have a large percentage of aggregate retained on each sieve down to a certain sieve after which the percentage of aggregate retained on each sieve is small. The sieve that separates the sieves containing large percentages from sieves with small percentages of aggregates is considered the break point sieve. Break point sieves for different NMAS gradation bands are presented in Table 5. However, it has recently been suggested that rather than having a hard-fast rule of using a predetermined breakpoint sieve dependant upon the NMAS, the slope of the gradation curve should be a factor in selecting the break point sieve (6). A general guideline for determining the critical breakpoint sieve would be to select the finest sieve size for which there is at least 10 percent of the total aggregate retained. This sieve size should also differentiate between the aggregate skeleton and filler materials. For this study, Table 5 was utilized for determining the breakpoint sieve, as these values are in accordance with AASHTO specifications for designing SMA.

Table 5: Break Point Sieves for Differing NMAS Gradations (3)

NMAS Gradation	Break Point Sieve, mm
25.0 mm	4.75
19.0 mm	4.75
12.5 mm	4.75
9.5 mm	2.36
4.75 mm	1.18

Selection of Trial Asphalt Content

The minimum effective asphalt binder content for SMA mixtures is 6 percent by mix mass. It is recommended that the mixture be designed at some amount over 6 percent to allow for adjustments during plant production without falling below the minimum requirement.

Number of Samples

A total of twelve samples are initially required: four samples for each of the three trial gradations. Each sample is mixed at the trial asphalt content and three of the four samples for each trial gradation are compacted to the design compactive effort. The remaining sample of each trial gradation is used to determine the theoretical maximum density according to AASHTO T209.

Sample Compaction

The compaction temperature is determined in accordance with AASHTO T245, section 3.3.2 (temperature-viscosity). However, while this procedure works for neat asphalt binders, the selected temperature may need to be changed for polymer-modified binders. Laboratory samples of SMA are compacted using either 75 or 100 gyrations of the SGC. For aggregates having Los Angeles Abrasion loss values of 30 percent or greater, 75 gyrations should be used. For other aggregates, 100 gyrations should be used for the design compactive effort. More than 100 gyrations should not be used; SMA is relatively easy to compact in the laboratory and exceeding 100 gyrations may lead to excessive breakdown in the aggregate.

Superpave gyratory compactor samples should be 150 mm in diameter and 115±5 mm in height after compaction. Also, the Superpave short term aging should be employed in accordance with AASHTO PP2, Standard Practice for Short and Long Term Aging in Hot Mix Asphalt (HMA).

Selection of Desired Gradation

After trial gradation samples have been compacted and allowed to cool, they are tested to determine bulk specific gravity in accordance with AASHTO T166. The volumetric properties of each compacted sample is then determined. Following are the volumetric calculations of interest for SMA:

$$V_a, \% = 100\ x \left[1 - \frac{G_{mb}}{G_{mm}} \right]$$

$$VCA_{MIX}, \% = 100 - \left(\frac{G_{mb}}{G_{ca}}\ x\ P_{CA} \right)$$

$$VMA, \% = 100 - \left(\frac{G_{mb}}{G_{sb}}\ x\ P_s \right)$$

Where,

V_a – percent air voids in compacted mixture,

VCA_{MIX} – voids in coarse aggregate within compacted mixture,

VMA – voids in mineral aggregates,

G_{mb} – bulk specific gravity of compacted mixture,

G_{mm} – theoretical maximum specific gravity,

P_s – percent of aggregate in the mixture,

P_{CA} – percent of coarse aggregate within the mixture by mass,

G_{sb} – combined bulk specific gravity of the total aggregate, and

G_{ca} – combined bulk specific gravity of the coarse aggregate fraction (retained on breakpoint sieve).

Of the trial blends evaluated, the one with the highest percent passing the break point sieve that meets or exceeds the minimum VMA requirement and has a VCA_{MIX} less than VCA_{DRC} should be selected as the desired gradation. Research has indicated that finer mixes still meeting stone-on-stone contact (VCA_{MIX} less than VCA_{DRC}) performed best (3).

Selection of Optimum Binder Content

Once a trial blend has been selected as the design gradation, it may be necessary to raise or lower the asphalt binder content to obtain the proper amount of air voids in the mixture.

Additional samples are prepared using the design gradation and the binder content varied. The optimum binder content is selected to produce 4 percent air voids in the mix. The SMA mixture should have properties meeting the criteria shown in Table 3.

TEST RESULTS AND ANALYSIS

As discussed previously, a total of sixteen mix designs were conducted. Eight of the designs included the South Mississippi gravel source and eight included the North Mississippi gravel source. Discussion about the different mix designs was separated by the native aggregate source. Following are discussions of the different designs. Throughout this section, five different aggregates will be discussed. A nomenclature was developed for each aggregate as follows:

SMS	South Mississippi Gravel
NMS	North Mississippi Gravel
LMS	Alabama Limestone
ARS	Arkansas Sandstone
NSG	Nova Scotia Granite

South Mississippi Gravel Designs

A total of eight mix designs were conducted with the South Mississippi gravel aggregate source. Mixes included in the designs utilized the following combinations of aggregates: 100 percent SMS, SMS/LMS, SMS/ARS, and SMS/NSG. Mix designs were attempted for each combination of aggregate for 4.75 and 9.5 mm NMAS.

4.75 mm NMAS SMA Designs

A total of four mix designs were conducted utilizing a 4.75 mm NMAS and the SMS aggregate source. Table 6 presents the design properties for each of the aggregate combinations. This table shows that three of the four mix designs could not be successfully completed: the SMS, SMS/LMS, and SMS/NSG combinations. For the SMS design, the property limiting their design was the VMA. For the SMS/LMS and SMS/NSG combinations, the stone-on-stone contact requirements (VCA) could not be achieved. Between 5 and 7 different trial blends were attempted with the stockpiles obtained for these three mixes. For the combination that was successfully designed (SMS/ARS), the optimum binder content was 8.5 percent. This led to an optimum effective binder content above the minimum suggested requirement of 6.0 percent (6.1 percent). The voids in mineral aggregate values for the mix was 17.3 percent. The designed mix also met the requirements for VCA_{MIX} being less than VCA_{DRC}, which indicates the existence of particle-on-particle contact. The result of the draindown test for the 4.75SMS/ARS combination was below the 0.3 percent maximum criteria (0.07 percent). Figure 1 illustrates the design gradation for the 4.75SMS/ARS combination. This figure shows that gradation passed within the control points provided by AASHTO except on the 0.075 mm sieve. However, the gradation does meet the suggested 0.075 mm sieve requirements from NCATs draft report (5). Asphalt Pavement Analyzer rut depths were determined for the mix that was successfully designed. For the 4.75SMS/ARS combination, the measured rut depth was 6.6 mm. This level of rut depth would be considered acceptable and indicates the SMA mix achieved stone-on-stone contact.

Table X: Design Properties for 4.75 mm NMAS SMS Combinations

Combination	Va, %	P_b, %	VMA, %	VFA, %	VCA_{MIX}, %	VCA_{DRC}, %	P_{be}, %	Draindown, %
4.75SMS					Could Not Design			
4.75SMS/LMS					Could Not Design			
4.75SMS/NSG					Could Not Design			
4.75SMS/ARS	4.4	8.5	17.3	74.3	38.7	41.6	6.1	0.07

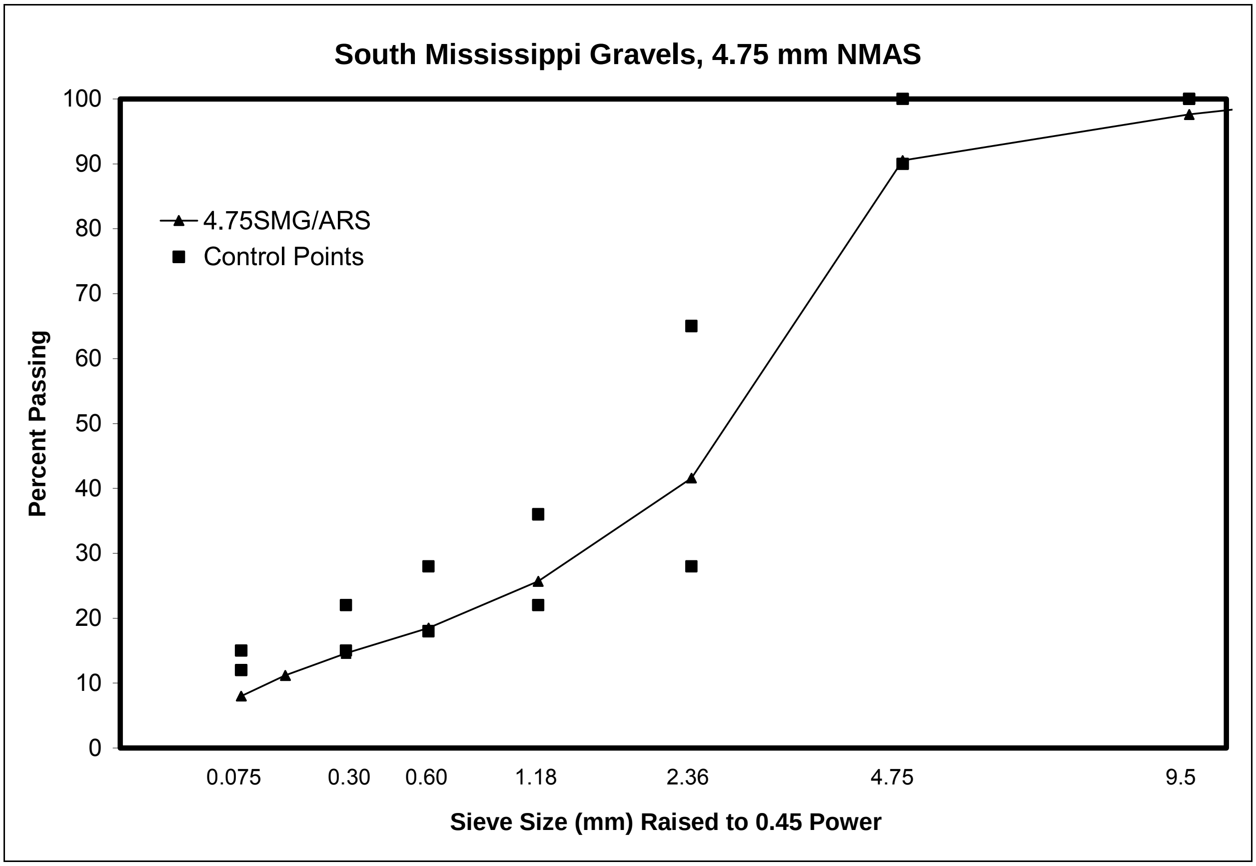

Figure 1: 4.75 mm NMAS SMS Design SMA Gradations

9.5 mm NMAS SMA Designs

A total of four 9.5 mm NMAS mix designs were attempted using the SMS aggregates. Table 7 presents the design properties of the mixes having a 9.5 mm NMAS that were successfully designed with the inclusion of the SMS gravels. This table shows that three of the four mixes were successfully designed. The lone mixture that could not be designed was the 9.5SMS/LMS combination. Five trial blends were attempted for this combination. This combination failed to meet the requirements for stone-on-stone contact (VCA). Figure 2 illustrates the designed gradations for the remaining combinations that were successfully designed. Optimum binder contents ranged from 7.2 to 8.2 percent. Voids in mineral aggregate values ranged from 17.0 to 17.7 percent. All three mixes had VCA_{MIX} values less than VCA_{DRC} values indicating particle-on-particle contact. Effective binder contents were all above the 6.0 percent minimum values. Draindown values determined for the three designed mixes were all below the 0.3 percent criteria established for SMA mixes. Rut susceptibility testing to verify the existence of stone-on-stone contact ranged from a low 7.7 mm for the 9.5SMS/ARS combination to 9.8 mm for the 9.5SMS combination. The 9.8 mm rut depth of the 9.5SMS combination is slightly higher than would be desired; however, this higher value may be related to the aggregate properties of the 100 percent SMS aggregates. Table 4 showed that the SMS aggregates were the least angular of all the aggregate used in this study based upon the fractured face counts, coarse aggregate flow, and fine aggregate angularity results.

Table 7: Design Properties for 9.5 mm NMAS SMS Combinations

Combination	Va, %	P_b, %	VMA, %	VFA, %	VCA_{MIX}, %	VCA_{DRC}, %	P_{be}, %	Draindown, %
9.5SMS	4.2	8.2	17.0	75.6	34.4	37.6	6.1	0.04
9.5SMS/LMS					Could Not Design			
9.5SMS/NSG	4.2	7.2	17.3	76.0	37.0	39.3	6.1	0.00
9.5SMS/ARS	4.6	7.5	17.7	74.2	33.2	40.1	6.2	0.03

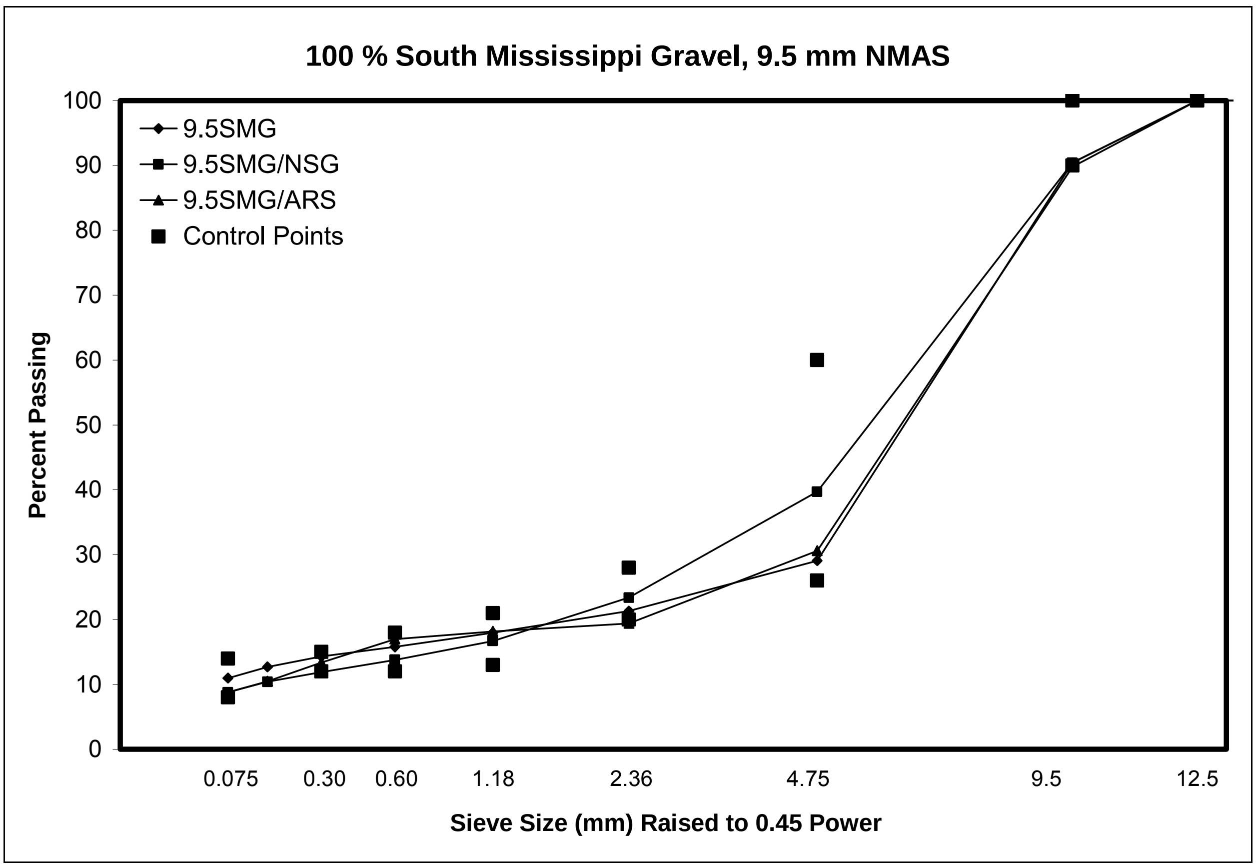

Figure 2: 9.5 mm NMAS SMS Design SMA Gradations

North Mississippi Gravel Designs

A total of eight mix designs were also conducted with the North Mississippi gravel aggregate source. Mixes included in the designs utilized the following combinations of aggregates: 100 percent NMS, NMS/LMS, NMS/ARS, and NMS/NSG. Aggregates other than the North Mississippi gravel source were blended at 30 percent. Mix designs were attempted for each combination of aggregate for 4.75 and 9.5 mm NMAS.

4.75 mm NMAS SMA Designs

Mix designs were attempted for four aggregate combinations utilizing the North Mississippi gravel source and having a 4.75 mm NMAS. Of the four 4.75 mm NMAS mixes utilizing the North Mississippi gravel source, the only combination not successfully designed was the 4.75NMS/LMS combination (Table 8). Six trial blends were attempted for this combination and each trial blend failed to meet the requirements for stone-on-stone contact (VCA). Figure 3 illustrates the gradations of the three combinations that were successfully designed. Optimum binder contents obtained for the three combinations ranged from 7.5 to 7.7 percent. Voids in mineral aggregate values were all above the 17.0 percent minimum requirement. The 4.75NMS/NSG combination had a VMA value above 18 percent. All three combinations met the requirements for VCA. However, the 4.75NMS/NSG combination was very close to failing the requirement as the VCA_{MIX} and VCA_{DRC} were very close (39.4 and 39.5 percent, respectively). Effective binder contents were all above the minimum requirement of 6.0 percent and all three combinations had draindown values less than the 0.3 percent maximum. Rut depths to evaluate stone-on-stone contact ranged from 7.7 to 10.2 mm. The high rut depth of 10.2 mm was for the 4.75NMS/NSG combination, which was also the combination that barely met the VCA requirements. The combination with the lowest rut depth was the 4.75NMS combination. The 4.75NMS/ARS combination had a rut depth of 8.0 mm, which would be considered acceptable.

Table 8: Design Properties for 4.75 mm NMAS NMS Combinations

Combination	Va, %	P_b, %	VMA, %	VFA, %	VCA_{MIX}, %	VCA_{DRC}, %	P_{be}, %	Draindown, %

4.75NMS	4.2	7.5	17.6	76.2	35.7	40.3	6.2	0.14
4.75NMS/LMS				Could Not Design				
4.75NMS/NSG	4.0	7.7	18.1	77.8	39.4	39.5	6.5	0.07
4.75NMS/ARS	4.0	7.7	17.4	76.7	37.6	40.7	6.1	0.07

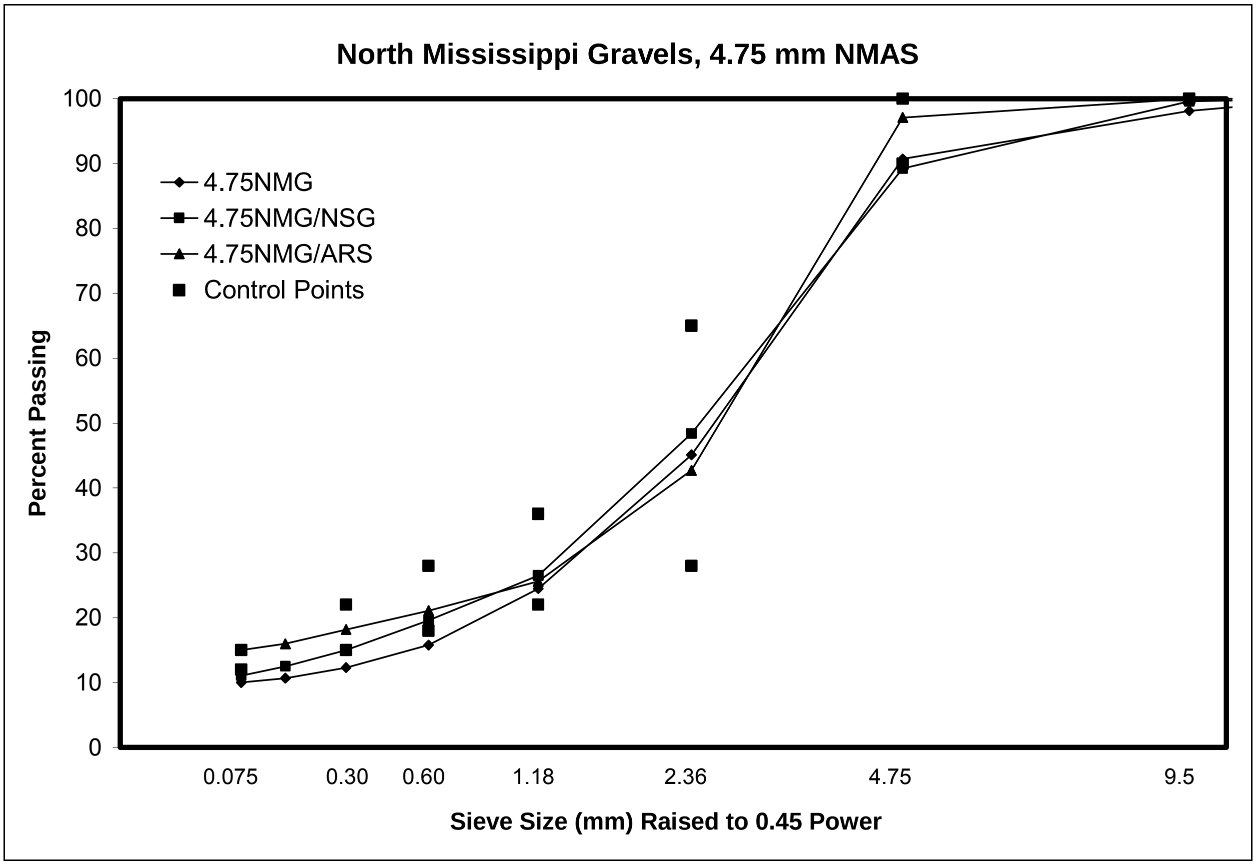

Figure 3: 4.75 mm NMAS NMS Design SMA Gradations

9.5 mm NMAS SMA Designs

A total of four 9.5 mm NMAS mix designs were attempted using the NMS aggregates. Table 9 presents the design properties of the mixes having a 9.5 mm NMAS that were successfully designed. This table shows that all four mixes were successfully designed. Figure 4 illustrates the gradations of the designed 9.5 mm NMAS SMA mixes. Optimum binder contents ranged from 7.5 to 7.8 percent. Voids in mineral aggregate values ranged from a low of 17.0 percent to a high of 18.7 percent. All four combinations met requirements for stone-on-stone contact (VCA); however, the VCA_{MIX} and VCA_{DRC} for the 9.5NMS/NSG combination were very close. All four combinations also had draindown values less than the 0.3 percent maximum criteria. Rut depths obtained for the four designed combinations ranged from a low of 7.8 mm to a high of 12.3 mm. The 9.5NMS and 9.5NMS/ARS combinations had acceptable rut depths at 7.8 and 8.1 mm, respectively. The 9.5NMS/LMS and 9.5NMS/NSG had rut depths of 12.3 and 12.1 mm, respectively, and are higher than would normally be acceptable. Interestingly, the 9.5NMS/LMS and 9.5NMS combinations had the same effective binder contents and met VCA requirements, but provided the highest and lowest rut depths, respectively. The 9.5NMS/NSG combination provided a high rut depth, but the VCA_{MIX} and VCA_{DRC} were very similar (38.9 and 39.2 percent, respectively).

Table 9: Design Properties for 4.75 mm NMAS NMS Combinations

Combination	Va, %	P_b, %	VMA, %	VFA, %	VCA_{MIX}, %	VCA_{DRC}, %	P_{be}, %	Draindown, %
9.5NMS	3.9	7.8	18.4	79.0	37.8	40.0	6.7	0.08
9.5NMS/LMS	4.0	7.8	18.7	78.8	37.8	41.9	6.7	0.10
9.5NMS/NSG	4.1	7.7	18.1	77.3	38.9	39.2	6.4	0.08
9.5NMS/ARS	3.8	7.5	17.0	77.4	37.7	41.1	6.1	0.07

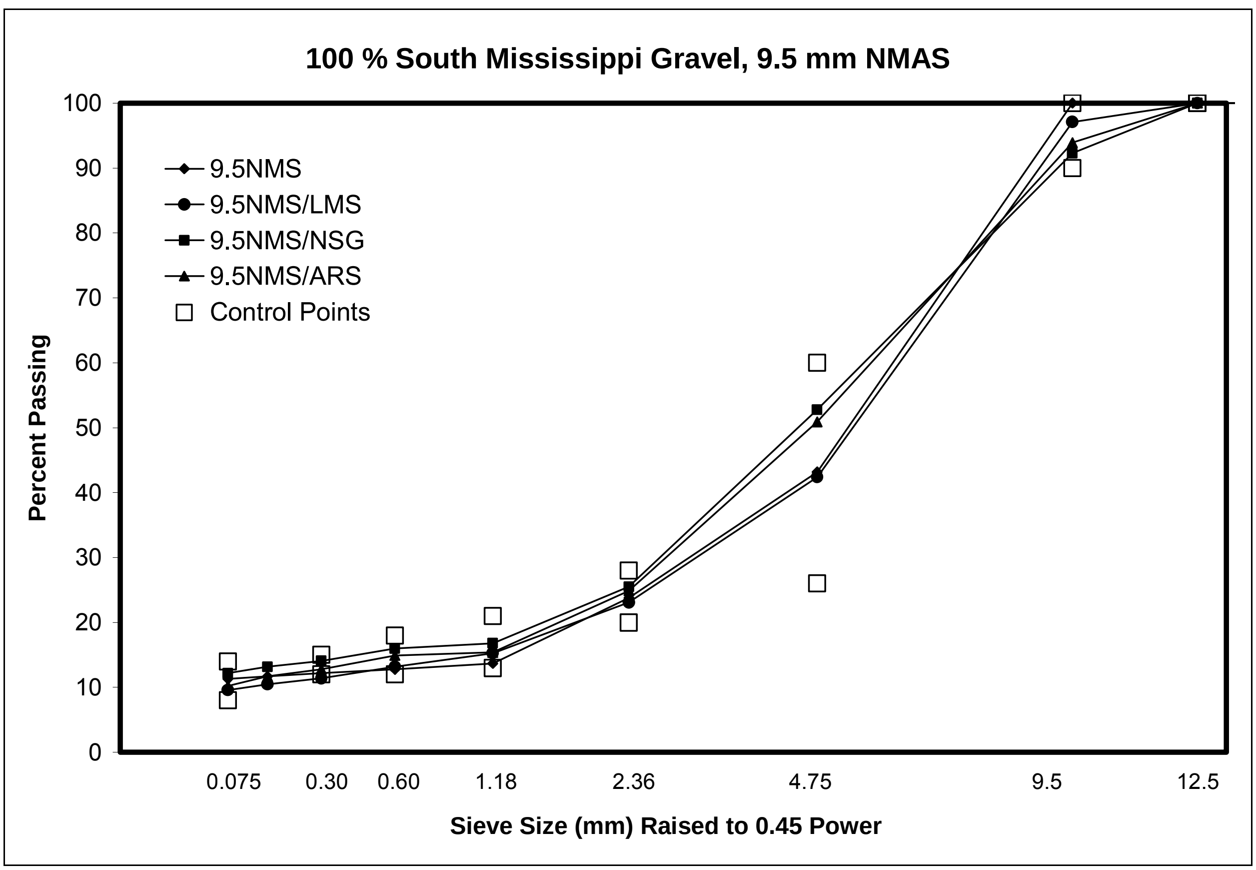

Figure 4: 9.5 mm NMAS NMS Design SMA Gradations

DISCUSSION

The results of the sixteen mix designs suggest that SMA mixes can be successfully designed using native Mississippi gravels. However, after conclusion of the mix designs there are several issues that need to be discussed.

First, the objective of this study was to design SMA mixes having gradations that met either a 4.75 or 9.5 mm NMAS. In doing so, stockpiles had to be modified in order to achieve the gap-grading required for SMA mixes. The modification was achieved by breaking, or separating, a given stockpile over a certain sieve. For mixes having a 4.75 mm NMAS, the sieve used for separating a stockpile was generally the 2.36 mm sieve. The two fractions (particles coarser than 2.36 mm sieve and particles finer than 2.36 mm sieve) were then utilized as separate stockpiles. Similar types of stockpile modifications were necessary for some 9.5 mm NMAS mixes. These types of modifications can be conducted in the field using high frequency screen decks; however, stockpile modifications will add to the mixture cost.

Second, there was a definite effect of native gravel source on the design of the SMA mixes. Designs conducted with the South Mississippi gravels were more difficult, and in more instances, not possible. Based upon the properties of the aggregates presented in Table 4, the South Mississippi gravel source were not as angular as the North Mississippi gravel source. The less angularity of these South Mississippi gravel source likely led to the difficulty in providing the required VMA and particle-on-particle contact required for SMA mixes. Of interest from the coarse aggregate properties (Table 4) was that the percent with two fractured faces for the South Mississippi gravels was 80 percent or less. By contrast, both of the North Mississippi coarse aggregate stockpiles used in this study had approximately 85 percent with two fractured faces. Therefore, designing SMA mixes may not be possible for all Mississippi gravel sources.

The third issue for discussion also deals with the angularity of the native gravels. During the rut testing of successfully designed mixes to verify the existence of particle-on-particle contact, there were rut depths higher than would be desired. The fractured face counts measured on the South Mississippi gravel coarse aggregates were 90/80 percent (one fractured face/two fractured faces) for the -3/4 in. stockpile and 97/72 percent for the -1/2 in. stockpile. For the North Mississippi coarse aggregates, the 5/8 in. stockpile had a fractured face count of 100/85 percent and the 1/2 in. stockpile was 95/84 percent. To ensure the internal shear strength and, thus, rut resistance of SMA mixes utilized in Mississippi, the fractured face counts should most likely be higher than was used in this study. No specific recommendations can be provided because the research approach was not developed to evaluate specific aggregate properties, but rather to determine whether SMA mixes could be designed utilizing native Mississippi materials. Based upon the experiences of the principle author of this report, the requirements for coarse aggregate angularity (fractured face count) of aggregates to be used for SMA in Mississippi should be at least 98/90 percent. An alternative method would be to require a minimum coarse aggregate flow value (AASHTO TP56-03, Method B) of 46 percent (7, 8).

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to evaluate whether native Mississippi materials can be used to successfully design rut resistant stone matrix asphalt mixtures. Based upon the laboratory testing and analysis of test results to carry out the project objectives, the following are concluded:

1. Stone matrix asphalt mixtures having either a 4.75 mm or 9.5 mm NMAS can be successfully designed in the laboratory using native Mississippi gravels. Mixes utilizing 100 percent native Mississippi gravels were successfully designed. Also, some mixes fabricated at 70 percent native gravel and 30 percent non-native aggregate blends were successfully designed.
2. Based upon the native gravel sources obtained for this study and a 4.75 mm or 9.5 mm NMAS gradation, some stockpile modification will likely be required. This would entail separating stockpiles on a particular screen and utilizing the separated fractions as separate stockpiles within the blend. The exact sieve required to separate a stockpile will likely be dependant upon the NMAS of the gradation and the gradation of the stockpile.
3. Mix designs attempted with the South Mississippi gravel source were not as

successful as those attempted with the North Mississippi gravel source. However, this conclusion only pertains to the source of gravel and not geographic location.

4. Mixes having a 4.75 mm NMAS were more difficult to design than mixes having a 9.5 mm NMAS. Four of the eight 4.75 mm NMAS designs were successfully completed, while seven of the eight 9.5 mm NMAS designs were successfully completed.
5. All four combinations (2 NMAS * 2 native gravel sources) containing the Arkansas sandstone were successfully designed and yielded relatively low rut depths signifying the existence of particle-on-particle contact. This was likely due to the uniform grading of the sandstone "chips".

The results of this study were encouraging in that SMA mixes were successfully designed in the laboratory. This study was an initial step in being able to include SMA within the HMA mix selection process within Mississippi. Further work is recommended to refine the constituent properties for SMA mixes fabricated with materials common in Mississippi. Test sections also need to be placed and monitored to further evaluate the effectiveness of SMA mixes in Mississippi. Because of the success in Alabama, it is also recommended that SMA be considered for problematic intersections.

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