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DISCLAIMER

ABSTRACT

The use of Stone Matrix Asphalt (SMA) has continued to rise in the United States due to its ability to withstand heavy traffic without rutting. This ability is derived from a stone-on-stone coarse aggregate skeleton. While this coarse aggregate skeleton is imperative for SMA to perform, there is currently no quantitative method to measure when it exists. This paper reports on the development of such a method.

A method for determining when stone-on-stone contact exists is presented. The proposed method first determines the voids in the coarse aggregate (VCA) for the coarse aggregate only fraction of the SMA mixture. Secondly, the VCA for the entire SMA mixture is determined. When the two VCA values are compared, the VCA of the SMA mixture should be less than or equal to the VCA of the coarse aggregate only fraction to ensure that stone-on-stone contact exists in the mixture.

Five different methods for determining the VCA of the coarse aggregate only fraction were used to see which performed best and was most practical. The aggregate degradation produced by each of the five methods was also determined and compared to the coarse aggregate breakdown produced in an SMA mixture compacted with 50 blows of a Marshall hammer. The results indicate that the Superpave Gyratory Compactor and dry-rodded methods produced the best results. Both of these methods are recommended for further testing.

KEY WORDS: aggregate skeleton, voids in the coarse aggregate, aggregate degradation

A METHOD TO ENSURE STONE-ON-STONE CONTACT IN STONE MATRIX ASPHALT PAVING MIXTURES

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INTRODUCTION

Stone Matrix Asphalt (SMA) is a type of hot mix asphalt (HMA) that has been used in Europe for over 20 years to resist studded tire wear and to provide better rutting resistance. SMA consists of two parts, a coarse aggregate skeleton and a high binder content mortar. The coarse aggregate skeleton provides the mixture with stone-on-stone contact, giving it strength, while the high binder content mortar adds durability. The mortar is typically composed of fine aggregate, mineral filler, asphalt binder and a stabilizing additive. This stabilizing additive acts to hold the asphalt binder in the mixture during the high temperatures of production and placement.

Since the strength of SMA relies heavily on the stone-on-stone aggregate skeleton, it is imperative that the mixture be designed and placed with a strong coarse aggregate skeleton. Within the last five years the use of SMA in the United States has continued to grow. However, no testing has been performed on a routine basis during design and/or production to ensure that SMA mixtures have an adequate coarse aggregate skeleton. The work reported in this paper details the development of a method to establish when a stone-on-stone coarse aggregate skeleton exists in SMA mixtures.

OBJECTIVE

The primary objective of this research was to develop a quantitative method to measure when coarse aggregate stone-on-stone contact exists in an SMA mixture. Constraints placed upon the method are that it should be relatively simple, and be applicable to different aggregate types.

LITERATURE REVIEW

There is agreement in the SMA literature that in order for SMA to work properly, stone-on-stone contact of the coarse aggregate must be developed. However, a quantitative method for establishing when this condition exists is lacking. Traditionally, the SMA gradation specification has been used to help ensure an adequate coarse aggregate skeleton. For example, in Sweden where SMA has been used successfully for many years, the specifications (*1*) generally follow what has become known as the “30-20-10 rule.” This rule suggests that an SMA should have approximately 30 percent passing the 4.75-mm (No. 4) sieve, 20 percent passing the 2.36-mm (No. 8) sieve, and 10 percent passing the 0.075-mm (No. 200) sieve. The first major use of SMA in the United States was designed following this rule (*2*). The SMA gradation most widely used in the United States can be found in the guide prepared by the Federal Highway Administration (FHWA) sponsored SMA Technical Working Group and published by the National Asphalt Pavement Association (*3*).

The use of quantitative test procedures to determine when coarse aggregate stone-on-stone contact is achieved in SMA was discussed by Haddock, et al. (*4*). In their paper about the Indiana SMA project, the authors note the importance of a coarse aggregate skeleton and present a method for determining if an SMA mixture has an adequate skeleton. Their method involves compacting the coarse aggregate only fraction of the mixture using 50 blows of the flat-faced, static base, mechanical Marshall hammer, and determining its density. Two percent asphalt cement by mass of total mixture is used to aid in the compaction process. After SMA mixture specimens have been compacted and their densities determined, the density of the coarse aggregate skeleton in the total SMA mixture is calculated. This skeleton density is then compared to the density of the coarse aggregate only fraction previously determined. If the SMA coarse aggregate skeleton density is greater than or equal to the coarse aggregate only fraction density, the SMA mixture has a stone-on-stone coarse aggregate skeleton.

Brown and Mallick (*5*) discuss a similar method for determining when coarse aggregate stone-on-stone contact exists in an SMA mixture. Their method is based on the relationship between voids in the coarse aggregate (VCA) and the percent fine aggregate (material passing the 4.75-mm (No. 4) sieve) in the mixture. By compacting a series of mixtures containing a range of 15 to 50 percent fine aggregate and calculating the VCA of the mixtures, Brown and Mallick were able to clearly show that as the percent fine aggregate in a mixture decreases, the VCA decreases. This approximately linear relationship persists until the percent fine aggregate reaches about 30 percent. At this point, the VCA becomes more or less constant. The point at which the VCA ceases to decrease with a further decrease in percent fine aggregate was interpreted to be the point at which coarse aggregate stone-on-stone contact exists.

Based on their findings, Brown and Mallick suggest using the dry-rodded unit weight apparatus (AASHTO T 19) to determine when coarse aggregate stone-on-stone contact exists in an SMA mixture. To use this approach, the coarse aggregate only fraction of the SMA mixture is placed in the unit weight bucket and its density determined. The density is used to calculate the VCA for the coarse aggregate only fraction. In this state, coarse aggregate stone-on-stone contact obviously exists since only the coarse aggregate is present. The entire SMA mixture is then compacted using normal methods and the density of the mixture determined. From this information, the VCA of the SMA aggregate skeleton can be calculated. If the SMA aggregate skeleton has a VCA less than or equal to the coarse aggregate only fraction VCA, the SMA mixture is judged to have stone-on-stone contact.

TEST PLAN

To develop a method of determining when stone-on-stone contact exists in an SMA mixture, five different compaction methods were used in combination with five different aggregate types. The five compaction methods were the Marshall hammer, the dry-rodded method (AASHTO T19), a vibrating table, the Superpave Gyratory Compactor (SGC), and the British vibrating hammer. Three replicates were used for each combination of aggregate type and compaction method. With the exception of Florida limestone, each of the coarse aggregate fractions had the same gradation. These gradations are shown in Table 1. For the Florida limestone, the percent passing the 9.5-mm sieve was reduced to 20 in an attempt to raise the VMA of the mixture.

Table 1. Coarse Aggregate Gradation

Sieve Size (mm)	Percent Passing
19.0 (3/4-inch)	100
12.5 (1/2-inch)	87
9.5 (3/8-inch)	40*
4.75 (No. 4)	0

*20 percent for Florida limestone

After the VCA of the coarse aggregate only fraction was determined using each of the five methods, a mixture design was completed for each of the aggregate types using 50 blows per specimen face of a flat-face, static base, mechanical Marshall hammer to compact the specimens. The VCA of each of these mixtures was calculated and compared to the VCA of the coarse aggregate only fraction. In addition, an extraction (if necessary) and a gradation were performed on each of the coarse aggregate only VCA replicates to determine the amount of aggregate breakdown that occurred. Extractions and gradations were also performed on SMA mixture samples after compaction with the Marshall hammer. These gradations were compared to those of the VCA replicates in an attempt to determine if the coarse aggregate degradation is similar for both.

MATERIALS AND TESTING PROCEDURES

Coarse Aggregate Test Results

Five aggregate types were selected for use in this study: traprock, granite, limestone, Florida limestone, and silicious gravel. These aggregates were selected because they provide a range of qualities from excellent to marginal. Traprock and silicious gravel are very hard materials while Florida limestone is very soft. Limestone and granite are somewhere between these two extremes. The surface textures, absorption characteristics, and shapes are also significantly different for each of the aggregates.

Each of the five coarse aggregates was tested to evaluate its basic properties. The results are provided in Table 2. The data shows that, with the exception of the Florida limestone, the coarse aggregates were non-absorptive. The Florida limestone had a water absorption value of 3.7 %, while the absorption values of the other coarse aggregates were 1.2% or less.

Table 2. Properties of the Coarse Aggregates

		AGGREGATE TYPE				
Property	**Test Method**	**Granite**	**FL Limestone**	**Gravel**	**Limestone**	**Traprock**
Bulk Specific Gravity	AASHTO T85	2.644	2.373	2.565	2.725	2.932
Apparent Specific Gravity	AASHTO T85	2.713	2.602	2.643	2.755	3.024
Absorption, %	AASHTO T85	1.0	3.7	1.2	0.4	1.0
Los Angeles Abrasion, % Loss	AASHTO T96	37.0	36.0	17.0	24.0	17.0
Flat & Elongated, %	ASTM D4791					
3 to 1		0.6	0.3	1.8	5.9	1.6
5 to 1		0	0	0	1.0	0
Soundless (5 Cycles), % Loss Sodium Sulfate	AASHTO T104	0.3	12	3.3	0.2	1.1
Crushed Content, %						
One Face		100	100	100	100	100
Two Faces		100	100	67	100	100

The Los Angeles abrasion values for all the aggregates were below 40 percent. Although the Florida limestone showed high degradation during mixture compaction, it has a reasonably low abrasion value of 36 percent. The traprock and gravel had measured abrasion values below 20 percent. These two aggregates had less degradation during compaction than did the others. It appears that the Los Angeles abrasion test seems to predict trends in aggregate quality, but may not be an accurate measure of the breakdown potential for aggregates.

Coarse Aggregate VCA Determination

The VCA of the coarse aggregate only fraction was determined using five different methods. These methods are described below. For each of the methods, three replicates of each aggregate type were batched such that their gradations matched the gradation in Table 1. The three replicates were densified according to the given method and the VCA determined. After the VCA was determined, the asphalt cement was extracted from each of the replicates produced using the Marshall hammer, SGC, and vibrating hammer. The gradations of these replicates, along with the gradations of the densified aggregate from the two remaining methods were then determined according to AASHTO T 11 and T 27.

Marshall Hammer Method

The Marshall hammer method employs 50 blows per specimen face of a flat-face, static base, mechanical Marshall hammer; 100 mm (4 inch) diameter molds were used. The replicates had 2 percent AC-20 asphalt cement added by total specimen mass to aid in the compaction process. When the compacted samples had cooled sufficiently, they were extracted from the molds and their bulk specific gravities determined according to AASHTO T 269, section 6.2. The VCA for each was calculated using equation 1.

$$VCA = 100 - \left[100 \left(\frac{G_{mb}}{G_{sca}} \times (1 - P_b) \right) \right] \qquad (1)$$

where,

G_{sca} - bulk specific gravity of the coarse aggregate,
G_{mb} - bulk specific gravity of the compacted specimen, and
P_b - percent asphalt binder in the mixture (by total mixture mass).

Dry-Rodded Method

The dry-rodded method was performed according to AASHTO T 19, Unit Weight and Voids in Aggregate. A 3 liter (0.1 ft^3) capacity metal container was used. The VCA in the dry-rodded condition (VCA_{DRC}) can be calculated using equation 2.

$$VCA_{DRC} = \frac{G_{sb}\gamma_w - \gamma_s}{G_{sb}\gamma_w} \times 100 \qquad (2)$$

where,

G_{sb} - bulk specific gravity of the coarse aggregate,
γ_w - density of water (999kg/m^3), and
γ_s - unit weight of the aggregate in the dry-rodded condition (kg/m^3).

Vibrating Table Method

Using the vibrating table, the replicates were compacted in the same metal container used for the dry-rodded method. The container was fixed to a vibrating table capable of vibrating at 50 Hz and charged with approximately one-third of the aggregate sample. The sample was vibrated for one minute and then vibration stopped. More of the aggregate sample was added until the container was approximately two-thirds full. It was then vibrated for an additional minute and stopped. Finally, the container was filled to overflowing with the remainder of the sample and mounded on top. The sample was again vibrated for one minute. At the end, the container was removed from the vibrating table, the excess aggregate struck off, and the unit weight of the aggregate determined according to AASHTO T 19. No rodding was used at any time. The VCA of the aggregate for this method was calculated using equation 2.

Superpave Gyratory Method

The Superpave gyratory method employed 100 revolutions of the SGC. The selection of 100 revolutions was made in consultation with some of the states currently using SMA. These states indicated that 100 revolutions of the SGC produced an SMA laboratory density similar to the density experienced in the field. The replicates had 2 percent AC-20 asphalt cement added by total specimen mass to aid the compaction process. The specimens were produced in 100-mm (4 inch) diameter molds. The 100-mm (4-inch) molds were used so as to match the mold size used in the Marshall method of compaction. When they had cooled sufficiently, they were extracted from the molds and their bulk specific gravities determined according to AASHTO T 269, section 6.2. The VCA of the specimens was obtained using equation 1.

Vibrating Hammer Method

The vibrating hammer method used the British Kango hammer to compact the replicates and followed the protocol outlined by the Asphalt Institute for the design of Open Graded Friction Courses (*6*). The molds were 150-mm (6 inches) in diameter and the hammer was attached to a compaction frame; 100-mm molds were not available. Two percent AC-20 asphalt cement by total specimen mass was added to each aggregate sample and the mixture placed in the mold. The mold and hammer were then placed in position and two 4.54-kg (10 lbs.) weights were attached to the hammer. The hammer was vibrated on the sample for 15 seconds and then removed. A dial gauge was used to determine the height of the sample after compaction. Using this height, the bulk specific gravity was determined according to AASHTO T 269, section 6.2. The VCA values for the specimens were obtained using equation 1.

TEST RESULTS

The results of the VCA for the coarse aggregate only fraction are shown in Table 3. The test results show very little variability between VCA replicates or between the different methods. For each aggregate, the Marshall hammer and the SGC provided the lowest VCA. The vibrating table and dry-rodded method provided approximately equal VCA for all aggregates. The vibrating hammer always provided the highest VCA and therefore the lowest coarse aggregate density. In the case of the vibrating table and dry-rodded methods, the VCA for all aggregates was within the range of 37 to 42 percent. A two-way analysis of variance F-test (α = 0.05) indicates that while at least one of the means is different by method type, there is no difference in the means by aggregate type, nor is there interaction between aggregate type and method. This seems to indicate that different types of coarse aggregates having the same gradation will provide similar VCA values when compacted using the same method.

Table 3. Voids in the Coarse Aggregate Test Results for the Coarse Aggregate Only Fraction

		VOIDS IN THE COARSE AGGREGATES, %				
Method	**No.**	**GRN**	**FL LMS**	**GRA**	**LMS**	**TRP**
Marshall Hammer	1	32.7	26.9	33.3	30.3	35.0
	2	31.6	27.4	33.8	29.4	36.2
	3	32.1	26.4	33.2	29.9	-
	Avg	32.1	26.9	33.4	29.9	35.6
	S D	0.55	0.50	0.32	0.45	0.85
Superpave Gyratory Compactor	1	36.0	29.8	37.6	36.4	39.5
	2	33.4	29.9	36.8	36.9	38.7
	3	34.7	31.3	37.2	36.6	39.3
	Avg	34.7	30.3	37.2	36.6	39.2
	S D	1.30	0.84	0.40	0.25	0.42
Dry-Rodded	1	39.1	39.8	37.3	42.5	40.9
	2	39.3	38.8	37.6	42.8	40.7
	3	39.1	38.0	37.3	42.2	40.8
	Avg	39.2	38.9	37.4	42.5	40.8
	S D	0.12	0.90	0.17	0.30	0.10
Vibrating Table	1	40.2	40.6	37.8	41.6	40.7
	2	39.8	39.9	37.9	41.6	41.0
	3	40.1	39.0	37.6	41.7	40.6
	Avg	40.0	39.8	37.8	41.6	40.8
	S D	0.21	0.80	0.15	0.06	0.21
Vibrating Hammer	1	48.2	43.7	45.5	47.2	48.5
	2	47.2	44.1	45.0	47.6	48.0
	3	47.1	44.4	45.8	47.7	49.2
	Avg	47.5	44.1	45.4	47.5	48.6
	S D	0.61	0.35	0.40	0.26	0.60

SD = Standard Deviation, GRN = Granite, FL LMS = Florida Limestone, GRA = Gravel, LMS = Limestone, TRP = Traprock

As previously mentioned, one concern is the breakdown of coarse aggregate in the compaction process. A test method is needed to force the aggregate particles together without excessively breaking them. After compaction of the coarse aggregate, a gradation analysis was conducted on each sample to evaluate the amount of breakdown. The test results are presented in Tables 4-8 for the granite, Florida limestone, gravel, limestone, and traprock, respectively. Breakdown is defined as the change in the amount of material passing the 4.75-mm (No. 4) sieve from the original gradation to the after compaction gradation.

Table 4 shows that there is significant breakdown with both the 50-blow Marshall hammer and with the SGC for the granite aggregate. The percent passing the 4.75-mm (No. 4) sieve increased by 11-14 percent for these two methods. The other three compaction methods show very little breakdown. Florida limestone (Table 5) had more breakdown than the granite aggregate. The percent passing the 4.75-mm (No. 4) sieve increased by 15-22 percent for the Marshall and SGC compactors. The other three methods produced very little breakdown. The gravel (Table 6) shows much less breakdown with the SGC than with Marshall hammer (13 percent for Marshall and 5 percent for the SGC). The other three methods show very little breakdown of the gravel. Limestone shows a very high breakdown when compacted with the Marshall hammer (25 percent) as well as a significant amount of breakdown (11 percent) with the SGC (Table 7). There is very little breakdown of the limestone with the other three methods. The compaction of traprock shows the same general trend as that for gravel (Table 8). The Marshall hammer produced the most breakdown (13 percent), the SGC was second (6 percent) and the other three methods produced little breakdown. In general, the Marshall hammer produced about twice as much breakdown as the SGC while the remaining three methods produced no significant breakdown.

Table 4. Gradations Before and After VCA Determinations for Granite

	PERCENT PASSING					
Sieve Size (mm)	**Original Gradation**	**50-Blow Marshall**	**Dry-Rodded Test**	**Vibratory Table**	**Superpave Gyratory**	**Vibrating Hammer**
19.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	87.0	89.8	87.2	88.6	87.9	88.1
9.5	40.0	56.3	44.7	42.9	52.4	41.5
4.75	0.0	14.2	2.5	1.4	11.2	2.5
2.36	0.0	7.0	0.7	0.4	5.1	1.0
1.18	0.0	5.0	0.6	0.4	3.4	0.9
0.60	0.0	3.8	0.5	0.4	2.4	0.8
0.30	0.0	2.7	0.5	0.3	1.6	0.8
0.15	0.0	1.8	0.4	0.3	0.9	0.7
0.075	0.0	1.2	0.3	0.2	0.4	0.6

Table 5. Gradation Before and After VCA Determinations for Florida Limestone

	PERCENT PASSING					
Sieve Size (mm)	**Original Gradation**	**50-Blow Marshall**	**Dry-Rodded Test**	**Vibratory Table**	**Superpave Gyratory**	**Vibrating Hammer**
19.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	87.0	91.3	86.2	88.8	88.9	90.0
9.5	20.0	57.4	39.3	42.3	48.4	46.1
4.75	0.0	21.9	2.5	2.4	14.8	1.3
2.36	0.0	10.0	0.8	1.0	6.6	0.8
1.18	0.0	6.6	0.7	0.9	4.6	0.7
0.60	0.0	4.7	0.7	0.9	3.5	0.7
0.30	0.0	3.7	0.7	0.9	2.8	0.6
0.15	0.0	2.9	0.6	0.8	2.3	0.5
0.075	0.0	2.4	0.4	0.6	2.0	0.4

Table 6. Gradations Before and After VCA Determinations for Gravel

Sieve Size (mm)	PERCENT PASSING					
	Original Gradation	**50-Blow Marshall**	**Dry-Rodded Test**	**Vibratory Table**	**Superpave Gyratory**	**Vibrating Hammer**
19.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	87.0	90.8	88.5	89.0	89.2	88.4
9.5	40.0	58.3	45.0	43.1	49.2	42.8
4.75	0.0	13.4	2.7	2.3	5.4	2.4
2.36	0.0	5.3	0.4	0.5	1.8	0.4
1.18	0.0	3.1	0.4	0.4	1.1	0.4
0.60	0.0	1.9	0.4	0.4	0.7	0.3
0.30	0.0	1.1	0.4	0.4	0.5	0.2
0.15	0.0	0.6	0.5	0.4	0.3	0.2
0.075	0.0	0.2	0.3	0.3	0.1	0.1

Table 7. Gradations Before and After VCA Determinations for Limestone

Sieve Size (mm)	PERCENT PASSING					
	Original Gradation	**50-blow Marshall**	**Dry-Rodded Test**	**Vibratory Table**	**Superpave Gyratory**	**Vibrating Hammer**
19.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	87.0	91.7	88.9	85.9	88.6	86.7
9.5	40.0	66.8	44.2	41.6	52.8	43.7
4.75	0.0	24.5	1.5	1.4	10.8	1.6
2.36	0.0	12.4	0.5	0.4	5.7	0.7
1.18	0.0	7.0	0.4	0.3	3.5	0.5
0.60	0.0	4.2	0.3	0.3	2.2	.04
0.30	0.0	2.8	0.3	0.3	1.5	0.4
0.15	0.0	1.9	0.3	0.2	1.1	0.3
0.075	0.0	1.5	0.3	0.2	0.9	0.3

Table 8. Gradations Before and After VCA Determinations for Traprock

	PERCENT PASSING					
Sieve Size (mm)	**Original Gradation**	**50-blow Marshall**	**Dry-Rodded Test**	**Vibratory Table**	**Superpave Gyratory**	**Vibrating Hammer**
19.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	87.0	88.6	87.5	86.6	86.8	86.6
9.5	40.0	51.1	43.4	42.2	47.6	40.6
4.75	0.0	12.9	1.6	1.5	6.0	3.6
2.36	0.0	4.5	0.3	0.4	2.1	0.4
1.18	0.0	2.6	0.3	0.4	1.3	0.4
0.60	0.0	1.8	0.3	0.4	1.0	0.3
0.30	0.0	1.3	0.2	0.4	0.8	0.3
0.15	0.0	0.9	0.2	0.3	0.6	0.3
0.075	0.0	0.7	0.2	0.3	0.5	0.2

After looking at the change in the 4.75-mm (No. 4) sieve data for the various aggregates and densification methods, it is concluded that the reason for the lower VCA with the Marshall hammer and the SGC is aggregate breakdown. If this breakdown is representative of aggregate breakdown during construction, then it is acceptable. However, if this breakdown is significantly different than what occurs during production, placement, and compaction, then it is not acceptable and will produce some error in the measurement of coarse aggregate stone-on-stone contact. An analysis of the data shows that the difference in VCA produced by the various methods is a direct result of aggregate breakdown (Figure 1). The method ultimately selected to measure coarse aggregate stone-on-stone contact should result in breakdown similar to that which occurs during construction.

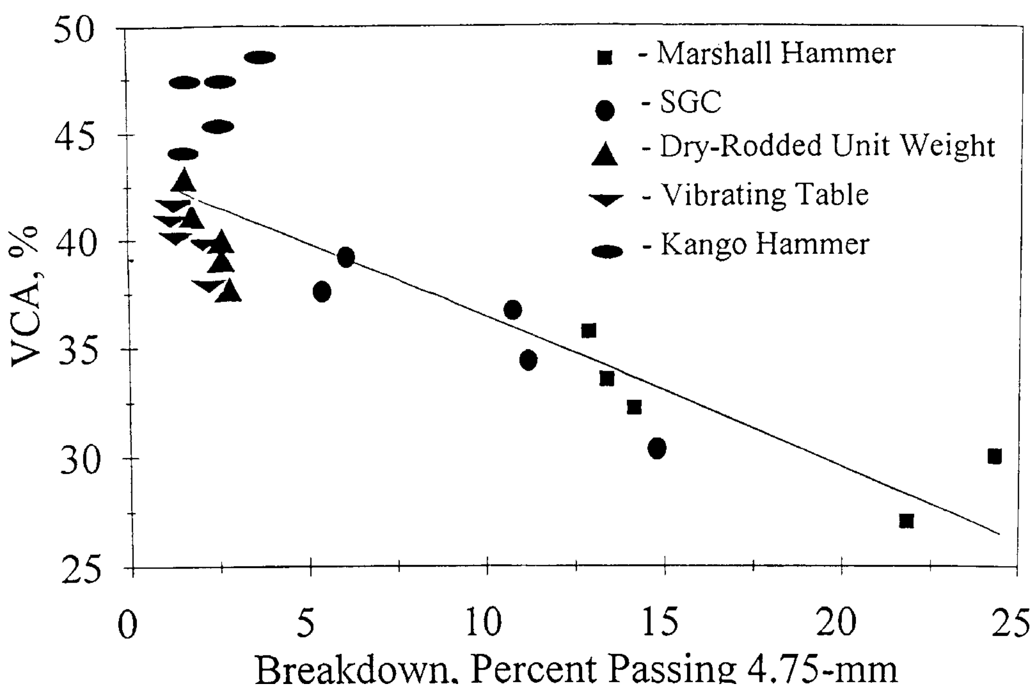

Figure 1. Effect of Aggregate Breakdown on VCA

Coarse aggregate breakdown in SMA mixtures is important because of its effect on the VCA of the mixture. Recent research (*7*) has shown that as the percent of aggregate passing the 4.75-mm (No. 4) sieve increases in an SMA mixture, the VCA also increases. When the mixture VCA increases beyond the VCA of the coarse aggregate only fraction, coarse aggregate stone-on-stone contact is lost in the mixture. Thus, the amount of coarse aggregate breakdown in an SMA mixture directly affects the stability of the mixture's coarse aggregate skeleton.

Samples of SMA mixtures compacted in the laboratory with the Marshall hammer were extracted to evaluate the amount of breakdown in the total SMA mixture. The extracted gradation results are provided in Table 9. The aggregate breakdown in compacted SMA mixtures was very similar to the aggregate breakdown of the coarse aggregate only fraction (Tables 4-8) when compacted with the SGC. Compaction of the coarse aggregate only fraction with the Marshall hammer tended to produce more degradation than is experienced by the total SMA mixture. The remaining three methods for densifying the coarse aggregate only fraction resulted in much less coarse aggregate degradation than that experienced by the total SMA mixture.

Table 9. Gradation Results for the SMA Mixtures Containing the Five Aggregates After Compaction with the Marshall Hammer

Sieve Size (mm)	Original Gradation	Extracted Aggregate Gradations				
		Granite	FL Limestone	Gravel	Limestone	Traprock
19.0	100	100.0	100.0	100.0	100.0	100.0
12.5	90	92.8	92.2	91.3	93.5	90.8
9.5	55*	66.2	60.0	67.0	69.7	63.7
4.75	25	40.8	36.2	31.0	35.1	32.4
2.36	20	27.2	27.9	22.9	25.8	23.9
1.18	17	22.4	23.1	19.0	19.8	19.7
0.60	14	18.8	19.7	15.7	16.0	16.6
0.30	13	16.0	17.7	14.1	14.0	14.6
0.15	11	13.3	15.6	12.5	12.1	12.7
0.075	10	11.3	13.6	11.0	10.5	11.1

*The original gradation for Florida limestone had only 40 percent passing the 9.5-mm sieve

CONCLUSIONS AND RECOMMENDATIONS

Five methods were evaluated to determine when coarse aggregate stone-on-stone contact occurs in SMA mixtures. The five methods were Marshall hammer, SGC, dry-rodded test, vibrating table, and vibrating hammer. Each of the methods produced repeatable results and similar VCA values. In general, the Marshall hammer and SGC produced the lowest VCA values while the vibrating hammer gave the highest. The dry-rodded and vibrating table methods produced VCA values that were approximately equal and between the high and low extremes. The results also seem to indicate that for a given compaction method and aggregate gradation combination, the coarse aggregate only fraction produces approximately the same VCA regardless of aggregate type.

A comparison of coarse aggregate degradation caused by each of the five methods was also completed. The SGC appears to duplicate the coarse aggregate breakdown found in an SMA mixture compacted with 50 blows of the Marshall hammer. The Marshall hammer method tends to degrade the aggregate too much while the other methods show very little degradation. It appears that aggregate breakdown is at least partially responsible for the lower VCA values produced by the Marshall hammer and SGC methods.

After studying the results, the following recommendations can be made:

1. The vibrating hammer did not do an adequate job of compacting the samples. This, coupled with the complexity of the method serve to make it an unattractive method for VCA determination.
2. The Marshall hammer appears to degrade the coarse aggregate excessively during compaction of the coarse aggregate only fraction. It therefore may not be the best option for determining VCA.
3. The SGC seems to give reasonable results and should therefore be pursued as a viable method.
4. The dry-rodded and vibrating table methods produce nearly identical results. Since the dry-rodded test is the easiest of the two to perform, it deserves further consideration.
5. The amount of aggregate breakdown that occurs during construction should be quantified to determine if it is similar to that produced by the 50-blow Marshall hammer and SGC methods during the SMA mixture design.
6. Both the SGC and dry-rodded methods should be studied further and the amount of aggregate breakdown they produce compared to the aggregate degradation that occurs in SMA mixtures during mixture design, as well as during production and placement.

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