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STRUCTURAL ANALYSIS OF AGGREGATE BLENDS USING THE SHRP GYRATORY COMPACTOR

by
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and
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and
Jennifer Ries

Final Report
for
Iowa DOT
Research Project MLR-95-8

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Iowa Department
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TABLE OF CONTENTS

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ABSTRACT

The Iowa Department of Transportation (IDOT) received a SHRP gyratory compactor in December of 1994. Since then the IDOT has been studying the ability of the compactor to analyze fundamental properties of aggregates such as shape, texture, and gradation, by studying the volumetrics of the aggregate blends under a standard load using the SHRP gyratory compactor. This method of analyzing the volumetrics of aggregate blends is similar to SHRP's fine aggregate angularity procedure, which analyzes void levels in noncompacted aggregate blends, which in turn can be used to evaluate the texture and/or shape of aggregates, what SHRP refers to as *angularity*. Research is showing that by splitting the aggregate blend on the 2.36 mm (#8) sieve and analyzing the volumetrics or *angularity* of the separated blend, important fundamental properties can be determined. Most important is structure (the degree and location of aggregate interlock). In addition, analysis of the volumes of the coarse and fine portions can predict the voids in the mineral aggregate (VMA), and the desired asphalt content. By predicting these properties it can be determined whether or not the combined aggregate blend, when mixed with asphalt cement, will produce a mix with structural adequacy to carry the designed traffic load.

INTRODUCTION

In recent years there has been growing interest and controversy concerning voids in the mineral aggregate (VMA) levels in hot mix asphalt (HMA). A vast amount of research evaluating and testing both aggregates and HMAs has been conducted to quantify the proper gradation and level of VMA in asphalt mixes to ensure maximum performance levels of both the aggregate and the asphalt binder. Designing mixes to achieve a minimum VMA specification with completely different aggregate gradation blends can produce mixes with varying physical and performance characteristics. The Strategic Highway Research Program (SHRP) recognizes the relationship between gradation, VMA, and performance and has implemented a restricted zone that controls the gradation by limiting the amount of fine material (passing the 2.36 mm (#8) sieve) and a fine aggregate angularity test. These specifications help to improve aggregate structure and mix performance, however, since aggregates vary in shape, texture and specific gravity, when different aggregates are combined they produce many variations in structure and VMA. Designing an aggregate blend to produce the desired VMA and structure for a particular traffic level is very difficult because of this variability. In addition, to verify that the desired aggregate structure has been achieved, the mix must be compacted and a specimen sawed in half and visually inspected.

To eliminate some of the uncertainty in designing asphalt mixtures, a method for determining aggregate structure in HMAs before mixing the aggregate and asphalt binder was developed using the gyratory compactor. This method can be used to determine an initial asphalt content to bracket for the desired void level for the eventual mixing of asphalt binder and aggregate, and to predict the VMA for the HMA at the designed traffic level.

Development of this procedure was inspired by the research paper, "An Evaluation of Stone-on-Stone Contact in Stone Matrix Asphalt" by E.R. Brown and Rajib Basu Mallick from the National Center for Asphalt Technology and by the paper, "Minimum VMA in HMA Based on Gradation and Volumetric Properties" by John Hinrichsen and John Heggen of the Iowa Department of Transportation (IDOT).

SHRP AC MIXTURE DESIGN PROCEDURE

The SHRP SUPERPAVE Mix Design manual gives guidelines on testing with the gyratory compactor. Research has shown that testing with the compactor gives very similar results to construction compaction. According to the SUPERPAVE manual the gyratory compactor has several benefits, including simulating density and aggregate orientation. SHRP specifications require that asphalt mixes have certain densification characteristics during compaction in the gyratory compactor. There are three points, or gyrations, along the compaction curve which evaluate the mix for rut resistance (N-initial), design voids (N-design), and resistance to plasticity (N-max). Comparisons to the Volumetric Analysis were made at these three points. Test results show that there is surplus VMA at N-design in the HMA ranging from 1.0% to 2.5% for mixes one thru five. This indicates that these five mixes could be designed with more fines, unless the aggregates are susceptible to aggregate breakdown. The surplus VMA would allow for the increase of fine material and still yield adequate stone-on-stone contact. There also appears to be a close relationship between the surplus VMA and the voids filled with asphalt (VFA) in the compacted specimens.

SHRP GYRATORY COMPACTOR

A Troxler, model 4140, gyratory compactor was used for the research. It was received by the Iowa Department of Transportation on December 20, 1994 and has been used to test more than two hundred samples.

MATERIALS

Various mixes were used for the research, ranging from a three aggregate blend to a five aggregate blend. The types of aggregates composed in the various mixes ranged from natural sand to manufactured sand, while the coarse and intermediate aggregate was composed of a crushed carbonate, crushed quartzite, or slag (Table 1).

AGGREGATE STRUCTURE

For this method of evaluating the aggregate structure and the VMA in the combined aggregate blends, the coarse aggregate is considered to be everything retained on the 2.36 mm (#8) sieve and the fine aggregate is everything passing the 2.36 mm (#8) sieve. A coarse mix is characterized by stone-on-stone contact; the fine aggregate can fill the voids in the coarse aggregate, but not so much as to affect the stone-on-stone contact of the coarse aggregate. In this type of mix the coarse aggregate is the load bearing structure and it controls the densification and VMA during compaction, until the point where the voids in the coarse aggregate are filled with fine aggregate. A mix is considered fine when the total -2.36 mm (-#8) volume, the volume passing through the 2.36 mm sieve, is more than the voids in the consolidated coarse aggregate. In this type of mix the fine aggregate becomes the load bearing structure and sole controller of densification and VMA. Figures 1-3 show how an ideal coarse mix would fit together.

PROCEDURE

Dry aggregate was analyzed with no asphalt binder to determine the volumetric properties of the aggregate design. The coarse and fine portions of a combined aggregate blend were obtained by splitting the aggregate blend on the 2.36 mm (#8) sieve. This can be accomplished more accurately by sieving all the individual aggregate components down through the 2.36 mm (#8) sieve and building the coarse and fine portions of the aggregate design separately. Each portion was then evaluated in the gyratory compactor. The coarse aggregate was placed in a splitting pan and worked until homogeneous. The aggregate was then poured into a 150 mm gyratory mold, dry rodded ten times after adding each 1000-1200 grams, and the final weight of the sample was recorded. The charged mold was then placed in the compactor and, after a 600 kPa load was applied, the height was recorded. Initially in an attempt to analyze the VMA collapse, or degree of aggregate interlocking, the coarse fraction was subjected to ten to twenty gyrations. However, excessive aggregate breakdown was detected beyond about five gyrations so the use of gyrations in this research was abandoned in favor of applying a standard load, and using the data from the compacted hot mix asphalt (HMA) to analyze the degree and location of aggregate interlocking. The fine aggregate was subjected to the same steps as the coarse aggregate, but due to the resulting height of smaller samples the distance the ram in the compactor had to travel was beyond manufacturers recommendation, so a 25 mm slug was placed in the mold before testing, and the 25 mm was simply subtracted from the displayed height on the compactor.

VOLUMETRICS OF THE COARSE FRACTION

The total volume of the coarse portion of the aggregate blend (Vtc) was calculated by squaring the radius of the mold and multiplying by the height of the sample and pi (3.14)(Vtc = $\Pi r^2 h$). The volume occupied by the coarse aggregate (Vc) was computed by dividing the weight of the coarse portion (W) by the coarse aggregate (+2.36 mm (+#8)), bulk specific gravity (Gsb), (Vc = W/Gsb). The volume of the voids in the coarse fraction (Vvca) was calculated by subtracting the volume of the coarse aggregate from the total volume (Vvca = Vtc-Vc). The percent of voids in the coarse portion (%VCA) was also calculated by dividing volume of the voids by total volume (%VCA = 100(Vtc-Vc)/Vtc). Tables 2-9 show the calculated values for the coarse portion of each mix tested.

VOLUMETRICS OF THE FINE FRACTION

Analysis of the fine aggregate was similar to that of the coarse aggregate. Total volume (Vtf), volume of aggregate (Vf), volume of voids (Vvfa), and percent of voids (%VFA) were calculated as above using the fine (-2.36 mm (-#8)) sample weight and Gsb instead of the coarse (+2.36 mm (+#8)) values.

COMPOSITE VOLUMES

The culmination of the coarse and fine volumetric data comprise the three composite volumes which are used in this research. The first is the maximum volume, which is the total volume of coarse aggregate at a 600 kPa load, if the total fine volume is less than the volume of coarse aggregate voids. In the case where the total fine volume is more than the volume of the coarse aggregate voids, the maximum volume would be equal to the second composite volume, which is the consolidated volume. The consolidated volume is the total volume of fine aggregate at a 600 kPa load plus the volume of the coarse aggregate. The last composite volume used is the same as the consolidated volume, except that the minimum volume is based on the fine aggregate having a void level of 26% (Tables 2-9). Preliminary research is showing a close relationship between voids in the fine material and film thickness, especially in fine mixes. To ensure adequate film thickness it is believed that the minimum voids in the fine aggregate must be at least 24-26%, but further research is necessary to verify this estimate.

VMA OF COMPOSITE VOLUMES

After computing the volumetrics of the coarse and fine fractions and the composite volumes, VMA was calculated at each of the composite volumes. The VMA levels were computed by dividing the sum of the volume of aggregate in the coarse and fine portions by the various composite volumes. Calculations are shown in Tables 2-9. Comparisons to HMA data are shown on Table 11.

ASPHALT CONTENT

Asphalt content was computed for each aggregated blend by first establishing if it was a coarse aggregate blend or a fine aggregate blend. For coarse blends the consolidated VMA was used, and for fine aggregate blends the minimum VMA was used. This allowed for some densification of aggregate to occur to establish a more accurate calculated percent asphalt content. Calculations for this are shown on Tables 2-9.

ANALYSIS OF AGGREGATE STRUCTURE

Results from this aspect of the research is very encouraging. Analysis clearly shows that when the combined gradation runs below SHRP's restricted zone (34.6% on the 2.36 mm sieve for a 19 mm mix) coarse aggregate contact is achieved. The lower the percent passing the 2.36 mm sieve the greater the difference between the coarse aggregate void volume and the total volume of fines (Table 10). This indicated greater aggregate interlocking occurring in the coarse aggregate. The percent passing the 2.36 mm sieve on Mix #1 is equal to the lower limit on the 2.36 mm sieve for a 19 mm mix. Comparisons of the VMA levels in the HMA and the Volumetric Analysis of Mix #1 indicate that when the percent passing is that low the coarse aggregate has reached its limit of consolidation. This can be seen from the difference in the VMA at N-Design and the VMA at the consolidated volume. When the percent passing the 2.36 mm sieve rises above 34% the coarse aggregate does not contribute significantly to the aggregate structure because the greater volume of fine aggregate spreads the coarse aggregate apart. The aggregate interlocking is occurring in the fine portion and the coarse aggregate thus becomes VMA reducer. Preliminary research is also showing a close relationship between the

Volumetric Analysis using the gyratory compactor and SHRP's Angularity test method C.

ANALYSIS OF VMA

Comparisons of VMA levels in the HMA and the Volumetric Analysis show some promise of predicting VMA. The coarse mixes lined up well at N-Design and at consolidated VMA when the percent passing the 2.36 mm sieve was in the middle of the gradation tolerance (23-34%) (Table 11). When the percent passing was close to the gradation limits the predicted VMA was not as close. The VMA of the fine mixes (#6, #7, and #8) lined up closer to N-Design when using the Volumetric Analysis's minimum VMA.

ANALYSIS OF CALCULATED ASPHALT CONTENT

This aspect of predicting the asphalt content was not as successful as the prediction and evaluation of the aggregate structure and VMA (Table 12). The results of the Volumetric Analysis were in the ball park, but were no more accurate than a good educated guess. Further research may be able to increase this accuracy.

CONCLUSIONS

Structural characteristics of aggregate combinations relating to coarse (+2.36 mm (+#8)) aggregate interlock, shape, and texture can be assessed using the SHRP Gyratory Compactor. By separating the aggregate into two size fractions and measuring the volumetric properties under a standard load in the SHRP gyratory compactor, the fundamental properties of the aggregate combination can be determined. Degree of coarse aggregate interlocking, VMA, and asphalt content can be accurately predicted by testing the aggregate alone, without mixing it with asphalt binder. The method appears to be independent of the type of structure desired and should work equally well for dense-graded, open-graded and stone mastic asphalt (SMA) mixes. Further research may indicate the possibility of analyzing the volumetrics when split on a different sieve or varying the load to more accurately predict and evaluate these important fundamental properties of asphalt mix designs.

ACKNOWLEDGMENTS

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TABLE TITLES

TABLE 1 Combined Aggregate Data

	Combined Gradation - % Passing Each Sieve									
	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.60 mm	0.30 mm	0.15 mm	0.075 mm
Mix #1	100.0	92.0	80.0	51.0	23.0	17.0	12.0	5.9	4.0	3.0
Mix #2	100.0	85.0	66.0	43.0	27.0	17.0	12.0	7.5	5.7	4.5
Mix #3	100.0	88.0	67.0	37.0	27.0	20.0	14.0	6.9	3.7	3.1
Mix #4	100.0	89.0	64.0	38.0	27.0	18.0	12.0	6.4	4.2	3.4
Mix #5	100.0	92.0	80.0	42.0	27.0	19.0	13.0	6.3	3.2	2.5
Mix #6	100.0	94.0	87.0	65.0	34.0	21.0	13.0	7.7	4.7	3.7
Mix #7	100.0	90.0	76.0	60.0	49.0	36.0	24.0	12.0	7.0	5.2
Mix #8	100.0	92.0	82.0	65.0	52.0	41.0	27.0	11.0	6.2	5.2

Note:
1 millimeter = 0.039 inch

TABLE 2 Volumetric Analysis of Mix #1

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	3709.0		b	1089.0		4798.0
Bulk Specific Gravity (Gsb)	c	2.610		d	2.586		2.605
Total Volume (cc)	e	2309.7	pi * R^2 * H	f	593.8	pi * R^2 * H	
Volume of Aggregate (cc)	g	1421.1	a / c	h	421.1	b / d	
Volume of Voids (cc)	i	888.6	e - g	j	172.7	f - h	
Percent of Voids	k	38.5	(i / e) * 100	l	29.1	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2309.7	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	2014.9	g + f
Minimum Volume (cc)	o	1990.2	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	20.2	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	8.6	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	7.4	100 - [((g + h) / o) * 100]

Asphalt Content @ Consolidated VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.031	
Percent Water Absorbtion by Weight	u	1.3	
Volume of Consolidated VMA (cc)	v	172.7	n - (g + h)
Effective Asphalt Content (%) by volume	w	4.6	q - s
Effective Asphalt Content (%) by weight	x	1.9	[(v-((g+h)/(100-q)*s))*t]/[(a+b)+((g+h)/(100-q)*s)]*100
Calc. Asphalt Content by weight (%)	y	2.5	[(u * 0.50) + x]
VFA (%)	z	53.5	(w /q)*100

Note:

1 gram = 0.035 ounce — H = height

1 cubic centimeter = 0.155 cubic inch — R = radius

TABLE 3 Volumetric Analysis of Mix #2

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	3636.0		b	1161.0		4797.0
Bulk Specific Gravity (Gsb)	c	2.538		d	2.585		2.549
Total Volume (cc)	e	2371.5	pi * R^2 * H	f	664.4	pi * R^2 * H	
Volume of Aggregate (cc)	g	1432.6	a / c	h	449.1	b / d	
Volume of Voids (cc)	i	938.9	e - g	j	215.3	f - h	
Percent of Voids	k	39.6	(i / e) * 100	l	32.4	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2371.5	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	2097.0	g + f
Minimum Volume (cc)	o	2039.5	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	20.7	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	10.3	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	7.7	100 - [((g + h) / o) * 100]

Asphalt Content @ Consolidated VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.024	
Percent Water Absorbtion by Weight	u	1.1	
Volume of Consolidated VMA (cc)	v	215.3	n - (g + h)
Effective Asphalt Content (%) by volume	w	6.3	q - s
Effective Asphalt Content (%) by weight	x	2.6	[(v-((g+h)/(100-q)*s))*t]/[(a+b)+((g+h)/(100-q)*s)]*100
Calc. Asphalt Content by weight (%)	y	3.2	[(u * 0.50) + x]
VFA (%)	z	61.2	(w /q)*100

Note:

1 gram = 0.035 ounce — H = height

1 cubic centimeter = 0.155 cubic inch — R = radius

TABLE 4 Volumetric Analysis of Mix #3

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	3475.0		b	1300.0		4775.0
Bulk Specific Gravity (Gsb)	c	2.630		d	2.595		2.620
Total Volume (cc)	e	2177.1	pi * R^2 * H	f	742.2	pi * R^2 * H	
Volume of Aggregate (cc)	g	1321.3	a / c	h	501.0	b / d	
Volume of Voids (cc)	i	855.8	e - g	j	241.2	f - h	
Percent of Voids	k	39.3	(i / e) * 100	l	32.5	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2177.1	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	2063.5	g + f
Minimum Volume (cc)	o	1998.3	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	16.3	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	11.7	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	8.8	100 - [((g + h) / o) * 100]

Asphalt Content @ Consolidated VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.025	
Percent Water Absorbtion by Weight	u	0.5	
Volume of Consolidated VMA (cc)	v	241.2	n - (g + h)
Effective Asphalt Content (%) by volume	w	7.4	q - s
Effective Asphalt Content (%) by weight	x	3.1	[(v-((g+h)/(100-q)*s))*t]/[(a+b)+((g+h)/(100-q)*s)]*100
Calc. Asphalt Content by weight (%)	y	3.4	[(u * 0.50) + x]
VFA (%)	z	63.2	(w /q)*100

Note:
1 gram = 0.035 ounce — H = height
1 cubic centimeter = 0.155 cubic inch — R = radius

TABLE 5 Volumetric Analysis of Mix #4

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	3488.0		b	1297.0		4785.0
Bulk Specific Gravity (Gsb)	c	2.923		d	2.647		2.843
Total Volume (cc)	e	2009.2	pi * R^2 * H	f	712.2	pi * R^2 * H	
Volume of Aggregate (cc)	g	1193.3	a / c	h	490.0	b / d	
Volume of Voids (cc)	i	815.9	e - g	j	222.2	f - h	
Percent of Voids	k	40.6	(i / e) * 100	l	31.2	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2009.2	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	1905.5	g + f
Minimum Volume (cc)	o	1683.3	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	16.2	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	11.7	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	9.3	100 - [((g + h) / o) * 100]

Asphalt Content @ Consolidated VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.025	
Percent Water Absorbtion by Weight	u	1.9	
Volume of Consolidated VMA (cc)	v	222.2	n - (g + h)
Effective Asphalt Content (%) by volume	w	7.4	q - s
Effective Asphalt Content (%) by weight	x	2.9	[(v-((g+h)/(100-q)*s))*t]/[(a+b)+((g+h)/(100-q)*s)]*100
Calc. Asphalt Content by weight (%)	y	3.8	[(u * 0.50) + x]
VFA (%)	z	63.2	(w /q)*100

Note:

1 gram = 0.035 ounce — H = height

1 cubic centimeter = 0.155 cubic inch — R = radius

TABLE 6 Volumetric Analysis of Mix #5

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	3527.0		b	1271.0		4798.0
Bulk Specific Gravity (Gsb)	c	2.515		d	2.585		2.533
Total Volume (cc)	e	2277.8	pi * R^2 * H	f	749.3	pi * R^2 * H	
Volume of Aggregate (cc)	g	1402.4	a / c	h	491.7	b / d	
Volume of Voids (cc)	i	875.4	e - g	j	257.6	f - h	
Percent of Voids	k	38.4	(i / e) * 100	l	34.4	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2277.8	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	2151.7	g + f
Minimum Volume (cc)	o	2066.8	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	16.8	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	12.0	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	8.4	100 - [((g + h) / o) * 100]

Asphalt Content @ Consolidated VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.031	
Percent Water Absorbtion by Weight	u	2.1	
Volume of Consolidated VMA (cc)	v	257.6	n - (g + h)
Effective Asphalt Content (%) by volume	w	7.7	q - s
Effective Asphalt Content (%) by weight	x	3.4	[(v-((g+h)/(100-q)*s))*t]/[(a+b)+((g+h)/(100-q)*s)]*100
Calc. Asphalt Content by weight (%)	y	4.4	[(u * 0.50) + x]
VFA (%)	z	64.2	(w /q)*100

Note:
1 gram = 0.035 ounce — H = height
1 cubic centimeter = 0.155 cubic inch — R = radius

TABLE 7 Volumetric Analysis of Mix #6

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	3156.0		b	1642.0		4798.0
Bulk Specific Gravity (Gsb)	c	2.549		d	2.528		2.542
Total Volume (cc)	e	1998.6	pi * R^2 * H	f	903.0	pi * R^2 * H	
Volume of Aggregate (cc)	g	1238.1	a / c	h	649.5	b / d	
Volume of Voids (cc)	i	760.5	e - g	j	253.5	f - h	
Percent of Voids	k	38.1	(i / e) * 100	l	28.1	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2141.1	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	2141.1	g + f
Minimum Volume (cc)	o	2115.8	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	11.8	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	11.8	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	10.8	100 - [((g + h) / o) * 100]

Asphalt Content @ Minimum VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.024	
Percent Water Absorbtion by Weight	u	2.5	
Volume of Minimum VMA (cc)	v	228.2	o - (g + h)
Effective Asphalt Content (%) by volume	w	6.8	r - s
Effective Asphalt Content (%) by weight	x	2.9	[(v-((g+h)/(100-r)*s))*t]/[(a+b)+((g+h)/(100-r)*s)]*100
Calc. Asphalt Content by weight (%)	y	4.2	[(u * 0.50) + x]
VFA (%)	z	63.0	(w /r)*100

Note:

1 gram = 0.035 ounce
1 cubic centimeter = 0.155 cubic inch

H = height
R = radius

TABLE 8 Volumetric Analysis of Mix #7

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	2551.0		b	2288.0		4839.0
Bulk Specific Gravity (Gsb)	c	2.674		d	2.630		2.653
Total Volume (cc)	e	1569.2	pi * R^2 * H	f	1325.4	pi * R^2 * H	
Volume of Aggregate (cc)	g	954.0	a / c	h	870.0	b / d	
Volume of Voids (cc)	i	615.2	e - g	j	455.4	f - h	
Percent of Voids	k	39.2	(i / e) * 100	l	34.4	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2279.4	(e) if i > f, (g+f) if i </= f
Consolidated Volume (cc)	n	2279.4	g + f
Minimum Volume (cc)	o	2129.6	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	20.0	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	20.0	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	14.4	100 - [((g + h) / o) * 100]

Asphalt Content @ Minimum VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.031	
Percent Water Absorbtion by Weight	u	2.1	
Volume of Minimum VMA (cc)	v	305.7	o - (g + h)
Effective Asphalt Content (%) by volume	w	10.4	r - s
Effective Asphalt Content (%) by weight	x	4.3	[(v-((g+h)/(100-r)*s))*t]/[(a+b)+((g+h)/(100-r)*s)]*100
Calc. Asphalt Content by weight (%)	y	5.4	[(u * 0.50) + x]
VFA (%)	z	72.2	(w /r)*100

Note:

1 gram = 0.035 ounce H = height

1 cubic centimeter = 0.155 cubic inch R = radius

TABLE 9 Volumetric Analysis of Mix #8

Volumetrics @ 600 kPa		Coarse (+8) Material	Equation		Fine (-8) Material	Equation	Composite Material
Sample Weight (g)	a	2423.0		b	2637.0		5060.0
Bulk Specific Gravity (Gsb)	c	2.552		d	2.627		2.591
Total Volume (cc)	e	1565.7	pi * R^2 * H	f	1452.6	pi * R^2 * H	
Volume of Aggregate (cc)	g	949.5	a / c	h	1003.8	b / d	
Volume of Voids (cc)	i	616.2	e - g	j	448.8	f - h	
Percent of Voids	k	39.4	(i / e) * 100	l	30.9	(j / f) * 100	

Composite Volumes		Result	Equation
Maximum Volume (cc)	m	2402.1	(e) if i > f, (g+f) if i <= f
Consolidated Volume (cc)	n	2402.1	g + f
Minimum Volume (cc)	o	2305.9	(h / 0.74) +g

VMA		Result	Equation
Maximum VMA (%)	p	18.7	100 - [((g + h) / m) * 100]
Consolidated VMA (%)	q	18.7	100 - [((g + h) / n) * 100]
Minimum VMA (%)	r	15.3	100 - [((g + h) / o) * 100]

Asphalt Content @ Minimum VMA		Result	Equation
Specified Target Voids (%)	s	4.0	
Specific Gravity of Asphalt Cement	t	1.031	
Percent Water Absorbtion by Weight	u	1.7	
Volume of Minimum VMA (cc)	v	352.7	o - (g + h)
Effective Asphalt Content (%) by volume	w	11.3	r - s
Effective Asphalt Content (%) by weight	x	4.8	[(v-((g+h)/(100-r)*s))*t]/[(a+b)+((g+h)/(100-r)*s)]*100
Calc. Asphalt Content by weight (%)	y	5.7	[(u * 0.50) + x]
VFA (%)	z	73.8	(w /r)*100

Note:

1 gram = 0.035 ounce — H = height

1 cubic centimeter = 0.155 cubic inch — R = radius

TABLE 10 Volumetric Analysis of Aggregate Structure

Mix #	% Passing 2.36 mm Sieve	Volumes @ 600 kPa: Vol. of Voids in Coarse Agg. (cc)	Volumes @ 600 kPa: Total Volume of Fines (cc)	% Difference[a]
1	23	888.6	593.8	66.8
2	27	938.9	664.4	70.8
3	27	855.8	742.2	86.7
4	27	815.9	712.2	87.3
5	27	875.4	749.3	85.6
6	34	760.5	903.0	118.7
7	49	615.2	1325.4	215.4
8	52	616.2	1452.6	235.7

[a] % Difference = [(Total Volume of Fines) / (Volume of Voids in Coarse Agg.)] * 100

Note:
1 millimeter = 0.039 inch
1 cubic centimeter = 0.155 cubic inch

TABLE 11 Analysis of VMA

Mix #	HMA - % VMA @ N-Initial (8 gyr.)	HMA - % VMA @ N-Design (109 gyr.)	HMA - % VMA @ N- Maximum (174 gyr.)	Volumetric Analysis - % VMA @ Maximum VMA	Volumetric Analysis - % VMA @ Consolidated VMA	Volumetric Analysis - % VMA @ Minimum VMA
1	23.5	13.8	12.4	20.2	8.6	7.4
2	20.9	10.6	8.7	20.7	10.3	7.7
3	20.6	12	10.9	16.3	11.7	8.8
4	22.8	13.1	11.6	16.2	11.7	9.3
5	22.5	12.3	10.6	16.8	12.0	8.4
6	19.8	10.1	8.8	11.8[a]	11.8	10.8
7	19.3	13.4	12.6	20.0[a]	20.0	14.4
8	18.7	13.7	13.1	18.7[a]	18.7	15.3

[a]Voids in the coarse aggregate are too low to hold the total fine volume

TABLE 12 Analysis of Calculated Asphalt Content

	HMA Data[a]		Volumetric Analysis[b]	
Mix #	% AC	% VFA	% AC	% VFA
1	5.1	71.0	2.4	41.5
2	4.6	62.4	3.1	49.2
3	3.9	66.6	3.4	54.2
4	5.0	69.5	3.8	54.1
5	5.2	67.4	4.4	55.1
6	5.1	60.2	4.1[c]	62.9[c]
7	4.7	70.1	5.4[c]	72.1[c]
8	5.3	70.8	5.7[c]	73.8[c]

[a]Asphalt Content (AC) interpolated to 4.0% voids at N-Design using SHRP equations
[b]Asphalt Content calculated at 4.0% voids @ consolidated VMA
[c]Asphalt Content calculated @ minimum VMA

FIGURE CAPTIONS

1. Coarse Aggregate Structure
2. Structure and Void System of Both Coarse and Fine Aggregate
3. Coarse Aggregate Voids Filled with Fine Aggregate Structure

Figure 1
Coarse Aggregate Structure

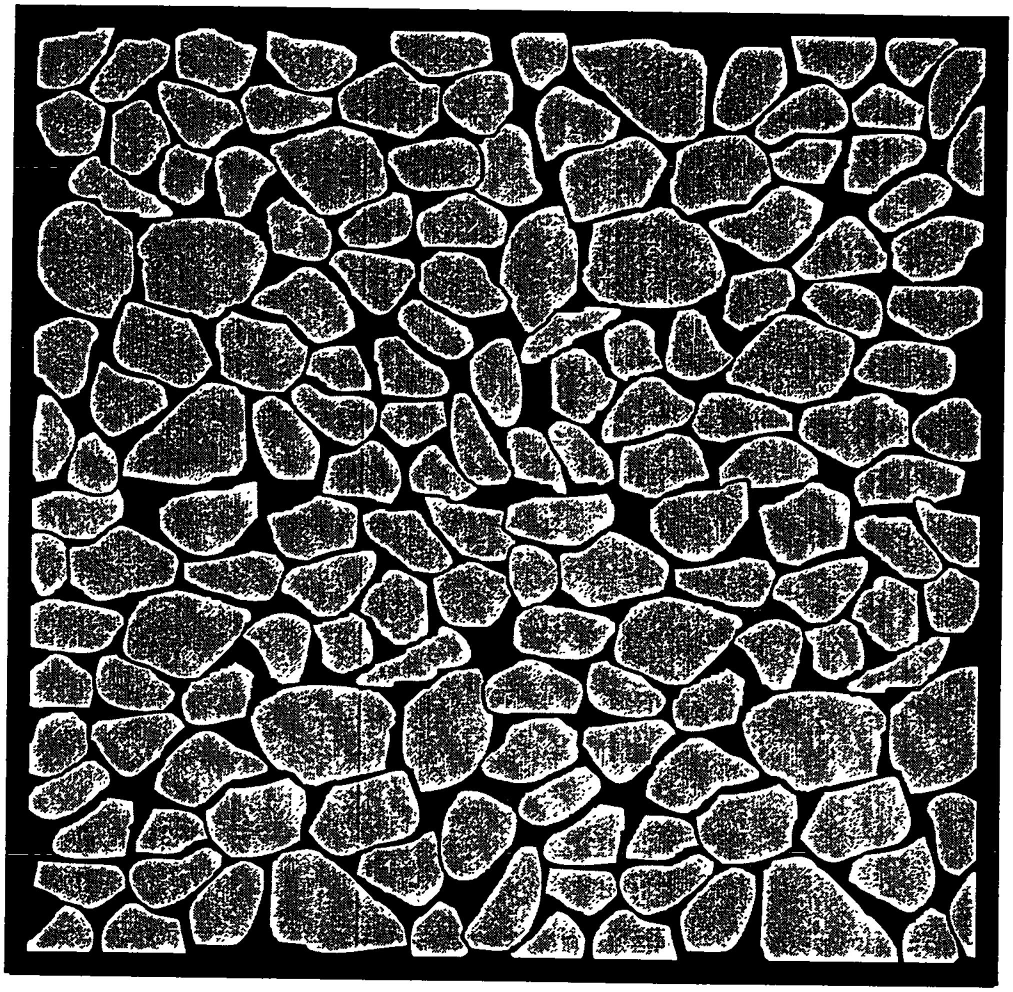

Figure 2
Structure and Void System of Both Coarse and Fine Aggregate

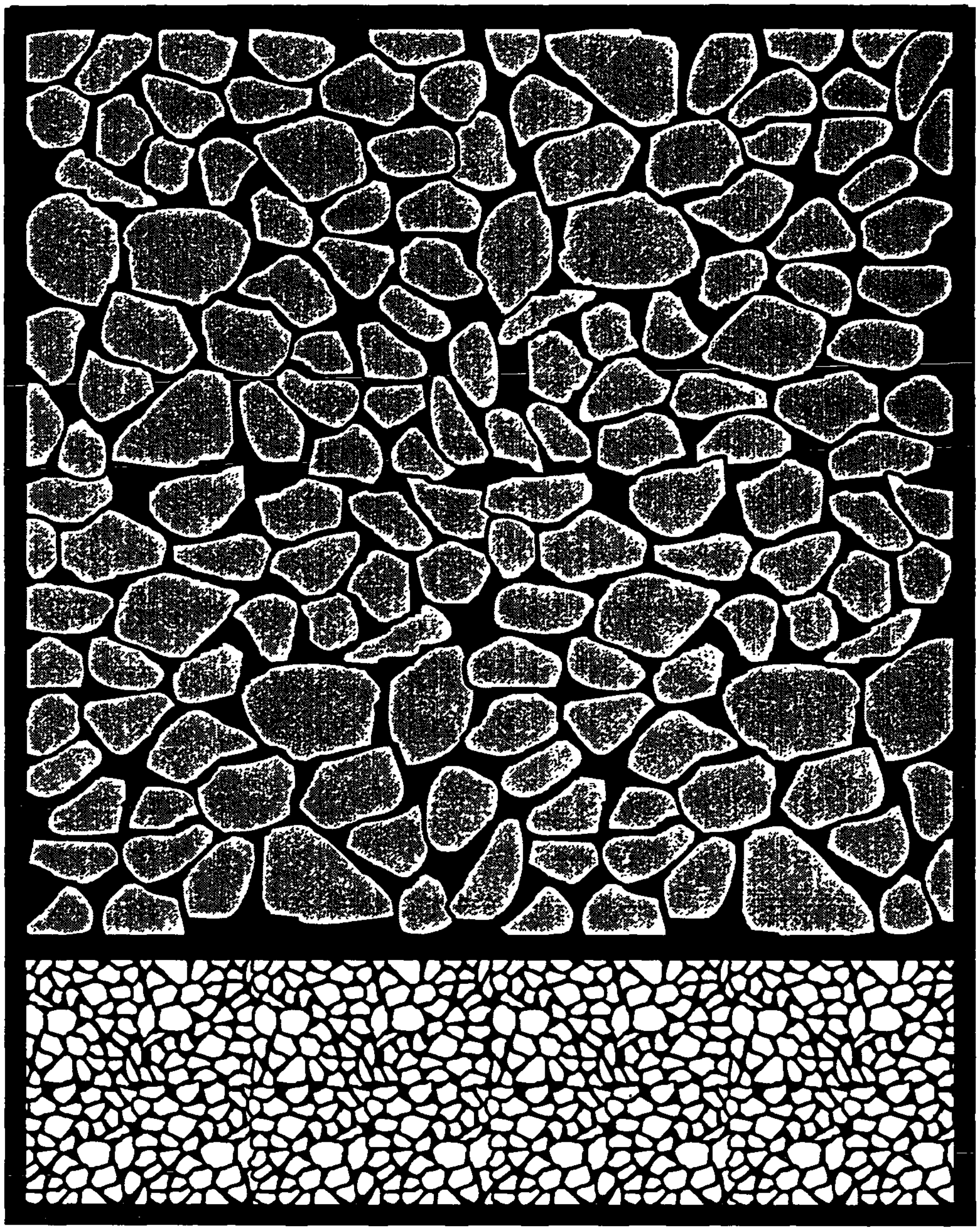

Figure 3
Coarse Aggregate Voids
Filled With Fine Aggregate Structure