VMA as a Design Parameter in Hot-Mix Asphalt

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Current research at Iowa State University on behalf of the Iowa Department of Transportation has focused on the volumetric state of hot-mix asphalt (HMA) mixtures as they transition from stable to unstable configurations. This has traditionally been addressed during mix design by a minimum voids in the mineral aggregate (VMA) requirement, based solely upon the nominal maximum aggregate size. The current research addresses three maximum aggregate sizes (19mm, 12.5mm, and 9.5mm), three gradations (coarse, fine, and dense), and combinations of natural and manufactured coarse and fine aggregates. Specimens are compacted using the Superpave Gyratory Compactor (SGC), conventionally tested for bulk and maximum theoretical specific gravities, and physically tested using the Nottingham Asphalt Tester (NAT) under a repeated load confined configuration. The results clearly demonstrate that the volumetric conditions of an HMA mixture at the stable/unstable threshold are influenced by the maximum aggregate size, gradation and aggregate shape and texture. The currently defined VMA criterion, while significant, is seen to be insufficient by itself to correctly differentiate sound from unsound mixtures. Under current specifications, many otherwise sound mixtures are subject to rejection solely on the basis of failing to meet the VMA requirement. The results of the current research project suggest a new set of volumetric design parameters that explicitly take into account such factors as aggregate gradation, shape, and texture.

INTRODUCTION

In Superpave, the volumetric design of asphalt mixtures requires consideration of air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). The percent air voids is used as the basis for selecting the asphalt binder content. VMA is defined as the sum of the volumes of the air voids and the unabsorbed binder in the compacted specimen. VFA is the percentage of VMA containing asphalt binder. It is widely accepted that these volumetric properties are useful in predicting hot-mix asphalt pavement performance. Excessive air voids or VFA and inadequate VMA suggest potential durability problems. Insufficient air voids or excessive VFA indicate potential rutting problems.

Over the years, mix designers have established standards of maximum and/or minimum limits on these volumetric properties to exclude poor performing asphalt mixes. The current Superpave guidelines are shown in Tables 1 and 2. The VFA requirements originated with the Corps of Engineers in the late 1940s (*1*). The VMA requirements date back to 1959, when Dr. Norman W. McLeod first proposed a relationship between "critical" minimum VMA and nominal maximum aggregate size for dense graded mixtures (*2*). In 1962, the Asphalt Institute dropped the VFA requirements in favor of a minimum VMA requirement in their Marshall mix design guidelines (*3*). The Asphalt Institute reinstated a VFA requirement in 1994 in conjunction with the minimum VMA requirement (*4*).

In Superpave, meeting McLeod's minimum VMA requirement is a deciding factor on whether or not an aggregate blend can be used. In recent years, some researchers have presented concerns that these minimum VMA requirements are too restrictive and may rule out economical mixes with acceptable performance properties (*5*). Others point out that evaluating and selecting the aggregate gradation to achieve VMA is the most difficult and time-consuming step in the Superpave mix design process (*6*). Others suggest it is not applicable to all asphalt mixtures and propose refinements to it (*7*).

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TABLE 1 Superpave VMA Requirements

Nominal Maximum Aggregate Size	Minimum VMA, %
9.5 mm	15.0
12.5 mm	14.0
19 mm	13.0
25 mm	12.0
37.5 mm	11.0

TABLE 2 Superpave VFA Requirements

Traffic, ESALs	Design VFA, %
$< 3 \times 10^5$	70–80
$< 1 \times 10^6$	65–78
$< 3 \times 10^6$	65–78
$< 1 \times 10^7$	65–75
$< 3 \times 10^7$	65–75
$< 1 \times 10^8$	65–75
$< 3 \times 10^8$	65–75

RESEARCH OBJECTIVES

The research objective was to determine the validity of the minimum VMA requirement vs. nominal maximum aggregate size required in Superpave volumetric mix design. The project sought to fulfill three specific objectives:

1. To establish a laboratory method by which the transition of an asphalt paving mixture from sound to unsound behavior may be credibly identified and measured.
2. To use that method to identify and evaluate statistically the effects of aggregate-related factors on the critical state of such mixtures.
3. To derive a predictive relationship relating critical state (e.g., critical VMA) to aggregate-related properties such as nominal maximum aggregate size, gradation, shape, and texture.

This paper presents the results of objectives 1 and 2. Work is in progress on objective 3.

TABLE 3 Experimental Matrix

		Nominal Maximum Aggregate Size								
		9.5 mm			12.5 mm			19.0 mm		
CA	FA	Fine	Dense	Coarse	Fine	Dense	Coarse	Fine	Dense	Coarse
Crushed	Manufactured	x	x	x	x	x	x	x	x	x
Natural	Manufactured	x	x	x	x	x	x	x	x	x
50/50	50/50	x	x	x	x	x	x	x	x	x
Gravel	Natural	x	x	x	x	x	x	x	x	x

EXPERIMENTAL TEST PROGRAM

Experimental Design

The test matrix used in the study is presented in Table 3. As shown, a total of 36 blends were studied; nine gradations comprised of four different aggregate blends. The four blends selected were:

1. Manufactured: Each gradation is 100 percent crushed material.
2. 50-50 Blend: Each gradation is a blend of 50 percent crushed and 50 percent natural material on each sieve size.
3. Manufactured Fine-Natural Coarse (MFNC): The material passing the #4 sieve was 100 percent crushed and the material retained 100 percent natural. The coarse (natural) aggregate was washed to make sure the P200 (75 mm) material was entirely from the crushed aggregates.
4. Natural: Each gradation is 100 percent natural material.

Comparing these four blends should distinguish the effects of gradation and shape for both the fine and coarse aggregates. For example, comparing the manufactured with the MFNC would emphasize the effects of the coarse aggregate shape and texture. Comparing the MFNC with the natural blends would examine the shape and texture effects of the fine aggregate to be examined.

For each blend, two specimens at 4, 5,6,7, and 8% asphalt content were fabricated and tested to determine the critical state volumetric properties. These properties were then compared with the values shown in Tables 1 and 2 to "validate" the Superpave guidelines.

Materials

Asphalt Binder

While the binder was not intended to be a variable in the study, it was important that it be of a typical performance grade used in Iowa. Jebro, Inc., of Sioux City, Iowa supplied ten 5-gallon pails of a conventional PG58-28 binder. The binder test results and specification requirements are listed in Table 4.

Table 4 Superpave Test Properties of Asphalt Binder used in Laboratory Testing.

	Test Results	Specification Requirements
Original Properties		
Flash Point Temperature °C	230+	230 minimum
Rotational Viscosity, 135 °C	0.247	3.0 maximum
Dynamic Shear, @ 10 rad/s kPa	1.024@58 °C	1.0 minimum
Rolling Thin Film Oven (RTFO) Residue Properties		
Mass Loss, %	O.248	1.0 maximum
Dynamic Shear @ 10 rad/s kPa	2.515@58°C	2.2 minimum
Pressure Aging Vessel (PAV) Residue Properties		
Dynamic Shear, @ 10 rad/s kPa	4253@ 19°C	5000 maximum
Creep Stiffness @ 60 s, Mpa	239@-18 °C	300 maximum
m-value	0.303@-18 °C	0.300 minimum

Aggregates

It was essential to differentiate the aggregates in as many ways as possible to determine what properties contribute to critical VMA. Ideally, it would have been desirable to select aggregates based on specific (measured) test properties for comparison, but this is easier said than done. Since gravel is not commonly used in asphalt mixtures, it was difficult to locate a source of natural coarse aggregates. Automated Sand and Gravel of Fort Dodge, IA provided both the coarse and fine natural aggregates used in the study. Martin-Marietta Aggregates of Ames, IA supplied the manufactured aggregates used in the study.

TABLE 5 Aggregate Gradations

Sieve Number (mm)	Percent Passing 9.5 mm NMS Fine	Dense	Coarse	12.5 mm NMS Fine	Dense	Coarse	19.0 mm NMS Fine	Dense	Coarse
19.0	100	100	100	100	100	100	100	100	100
12.5	100	100	100	95	95	95	87	74	65
9.5	95	95	95	86	73	65	78	65	55
4.75	80	65	55	65	54	45	59	47	40
2.36	60	47	36	50	39	32	45	34	28
1.18	45	34	25	37	29	22	33	25	20
0.600	32	26	17	27	21	15	25	18	14
0.300	22	19	12	18	15	10	18	13	10
0.150	9	9	9	9	9	9	9	9	9
0.075	4	4	4	4	4	4	4	4	4

Once the aggregates were selected and sufficient quantities were obtained, each aggregate needed to be characterized using conventional tests. The aggregates were dried and sieved prior to testing. Once this was done, the aggregate gradations used in the study could be selected. For the project, three nominal maximum aggregate sizes (19mm, 12.5mm, and 9.5mm) were used. For each nominal maximum aggregate size, fine, dense, and coarse gradations were carefully blended in the laboratory. The gradations used in the study are shown in Table 5.

LABORATORY TESTING

Specimen Preparation

For the most part, Superpave mix design procedures (AASHTO TP4-93) and applicable British testing standards for the Nottingham asphalt tester (NAT) were followed. However, to expedite testing and conserve materials, two important changes were made.

1. Specimen size: The NAT equipment limits specimen height to approximately 115–120 mm in height, which would seem adequate for normal SGC specimens of 4500–4700 g. The Transport Research Laboratory (TRL) researchers who worked with the NAT used specimen heights of 60 mm and 90 mm (*8*). The Superpave specimens are considerably larger than these and would require some care in mounting the linear variable displacement transducers (LVDTs) used to measure axial deformation. Once the decision was made to use smaller specimens, it was decided to target a specimen height of 80 mm, which would also conserve asphalt and aggregates. It was found that a batch weight of 3375 g would provide the right specimen geometry and optimize materials.
2. Unsawn/polished specimen ends: The TRL researchers recommend cutting and polishing the specimen ends prior to testing in the NAT, as they will reduce end effects and can be specified and reproduced by independent laboratories. However, since the same specimens would be used to determine the theoretical maximum specific gravity, it was determined that cutting and polishing would be omitted. The SGC compacted specimens were examined for levelness and seemed adequate. Of course, prior to testing they were liberally coated with a silicon-teflon grease to mitigate end effects.

Mixing and compaction temperatures of 147°C and 135 °C were used throughout the study. A two-hour short-term aging period was used prior to compaction. All specimen tested were compacted to N_{design} = 109, which corresponds to the heaviest traffic levels used in Iowa.

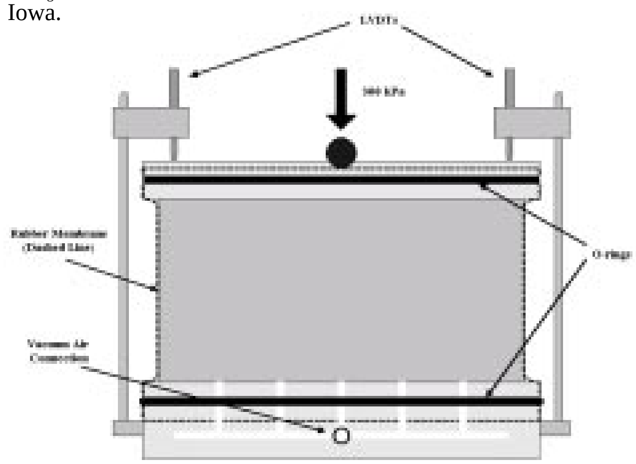

FIGURE 1 Schematic of NAT triaxial apparatus

Testing Procedures

Repeated load triaxial tests were conducted using the Nottingham asphalt tester (NAT). The NAT is widely used in Europe for testing asphalt mixtures—most commonly in a repeated load axial configuration. It has recently been modified to apply a confining stress; this is done through a vacuum as shown in Figure 1(*8, 9*). All tests were conducted at 45 °C.

The NAT repeated load triaxial test procedures are summarized as follows:

1. Place specimen in environmental test chamber 130 minutes prior to test to consistent test temperature.

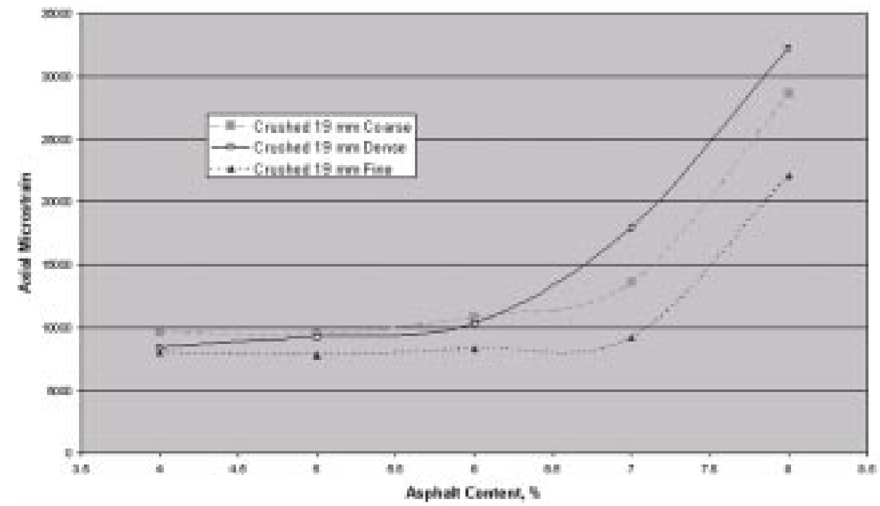

FIGURE 2 NAT results used for determining critical transition

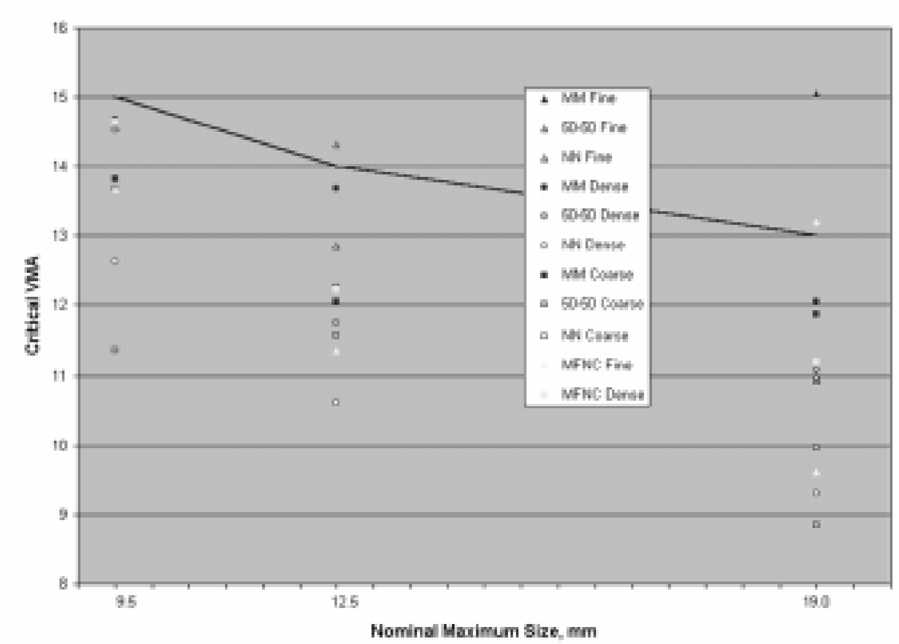

FIGURE 3 Critical VMA vs. nominal maximum aggregate size

2. Grease top and base platen with silicon-teflon grease.
3. Place HMA specimen on base, slide rubber membrane over it, and secure with O-ring.
4. Place top platen on specimen, roll membrane up over edge, and secure with O-ring.
5. Place in center of load frame and lower load cell onto the ball seating.
6. Place the LVDTs on the support arms and zero them out.
7. Enter in appropriate test data (e.g. specimen height, name, etc.) and start test.
8. Begin the test after a two minute conditioning—1800 cycles (one second load duration, one second recovery) taking one hour at 300 kPa axial load, 17 kPa confining stress.

The repeated load triaxial test provides realistic loading conditions in that it simulates traffic and confines the HMA laterally. Recent improvements and innovations (such as the NAT equipment) have made it user-friendly, expedient, and easily adaptable into a Superpave based mix design program.

ANALYSIS OF RESULTS

The first step of the analysis was to determine the critical transition asphalt content of the compacted HMA mixture based on a visual analysis of the NAT results. To show how this was done, the test results for the three 19 mm NMS crushed aggregate blends is shown in Figure 2. Examining the plot the critical asphalt content of the three mixes was estimated as 6.6 for the coarse, 6.3 for the dense, and 6.9 for the fine-graded mix. Five of the mixes did not become unsound over the range of asphalt contents used in the study. For each of the 31 mixes that became plastic, the volumetric properties were calculated at the critical point. Whereas McLeod specified VMA at 5 percent air voids and Superpave at 4 percent air voids, the critical VMA was defined at whatever air content the mix became unstable.

TABLE 6 Comparison of Observed Critical VMA Values with Superpave Requirements

Nominal Maximum Aggregate Size	Observed VMA, Average Value	Observed VMA, Standard Deviation	Minimum Required VMA
9.5 mm	13.5	1.5	15
12.5 mm	12.3	1.1	14
19 mm	11.2	1.7	13

VMA & Nominal Maximum Size

The critical VMA values where the mixtures became unsound are plotted in Figure 3. Table 6 compares the average values with Superpave's minimum VMA requirements. As can be seen, the minimum VMA requirements based on nominal maximum aggregate size appear to fit the data trend reasonably well, however it is seen that the measured values are typically less than the Superpave criteria.

Therefore, from a practical viewpoint, this gives credence to the complaints that the VMA requirements are too restrictive, as is shown in Figure 3, where only three mixes meet the Superpave VMA requirements. Given the difficulties in achieving Superpave's minimum VMA requirements, it is worth examining how other aggregate properties, e.g., gradation and surface texture, effect critical VMA. This involves using analysis of variance (ANOVA) to identify the significant aggregate-related effects upon critical VMA.

In selecting what factors to include in the ANOVA analysis, it was hypothesized that critical VMA would be determined not only by nominal maximum aggregate size, but also by crushed coarse aggregate content, crushed fine aggregate content, and some indicator of the gradation curve. For the latter, the fineness modulus (ASTM C-136), was selected.

TABLE 7 ANOVA Results

Source	Type 1 Sum of Squares	df	Mean Square
Corrected Model	73.245	11	6.659
Intercept	4184.617	1	4184.617
Fineness Modulus	51.150	8	6.394
Crushed Coarse Aggregate Content	12.993	2	6.496
Crushed Fine Aggregate Content	9.103	1	9.103
Nominal Maximum Aggregate Size	0	0	
Error	2.887	16	0.180
Total	4260.75	28	
Corrected Total	76.133	27	

The ANOVA results are presented in Table 7 and show that nominal maximum aggregate size becomes insignificant when the fineness modulus of the aggregate blend is included as a factor. This makes sense as the fineness modulus encodes information about the nominal maximum aggregate size of the blend.

Other Volumetric Properties

Air Voids

In Superpave, the design asphalt content is determined at 4 percent air voids (N_{design}). Prior to Superpave, Marshall mix design allowed a range of 3–5 % air voids. For the mixes tested, the results suggest a lower limit of 2.6 % air voids (S.D. = 0.65) at the critical state.

Voids Filled with Asphalt

The mixes studied were compacted to N_{design} = 109 gyrations, which, under Superpave (Table 2), corresponds to a traffic level of 3–10 million ESALs. Following Table 2, this limits VFA to 65–75 percent. For the mixes tested, the critical VFA appears to occur at about 78 percent (S.D. = 5.8).

CONCLUSIONS

The results presented here are of a preliminary nature and based on performance testing equipment that is still in the developmental stage. Work is ongoing to develop an equation relating critical VMA to aggregate properties to refine the Superpave requirements. Based on the results achieved so far the following conclusions are presented:

1. Specifying a minimum VMA requirement for asphalt paving mixtures based on nominal maximum aggregate size may be unrealistic.
2. Fineness modulus (shape of gradation) and crushed coarse and fine aggregate content (surface texture) appear to be much more robust indicators of critical VMA.
3. Current minimum VMA requirements may rule out mixtures that perform satisfactorily as some have suggested.

FURTHER WORK

The next step in the research is to analyze the results statistically to develop an equation
$VMA_{crit} = f(\text{FM (Gradation)},\%\text{ crushed coarse},\%\text{ crushed fine}) + \varepsilon$.

This equation will then need to be applied to field and laboratory data, for both well and poorly performing mixes for validation.

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