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MINIMUM VMA IN HMA BASED ON GRADATION AND VOLUMETRIC PROPERTIES

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and
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Iowa Department
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DISCLAIMER

ABSTRACT

The use of voids in the mineral aggregate (VMA) criteria for proper mix design of hot mix asphalt (HMA) mixtures is a time honored and fairly successful tool. Recent developments in the field of asphalt mix design have encouraged the use of mixtures with a coarse aggregate structure to resist the affect of heavy traffic loads. By using the equations presented, which account for both aggregate gradation and the volumetric properties of the materials, the mix designer is able to judge the proper VMA requirement for each unique blend of materials. By applying the new equations, the most economical mix may be selected without great risk of reduced durability. Supporting data from field application is presented to illustrate the use of the equations.

KEY WORDS: VMA, mix design, economics

INTRODUCTION

The design of dense graded HMA using a single VMA specification for a wide variety of materials within the limits of a defined gradation band has been in use in Iowa and many other states for several decades. Since McLeod (1) first proposed the concept 40 years ago, a great deal of research has verified the importance of having sufficient VMA in the mix to obtain durable pavements. Over the years, however, the definition of "sufficient VMA" has become a matter of controversy. For example, a 19 mm (3/4 in.) mix was originally recommended to have a minimum VMA of 15 (percent by volume), the FHWA (2) later recommended 14, and recently the SHRP Delphi group and the Asphalt Institute (3) recommended 13. Some of this difference can be explained by differences in the definition of nominal maximum size. For example, Iowa defines nominal maximum size as the first sieve which is allowed to retain any aggregate while the SUPERPAVE definition is one sieve size larger than the first sieve to retain more than 10 percent of the aggregate. Some mixes would not be the same size designation under both definitions. Regardless of the definition used, there is still no general agreement concerning what is the proper minimum VMA. It is generally agreed, however, that as mixes become coarser the required VMA should be less. This is why a 25 mm (1 in.) mix normally has a lower minimum VMA requirement than a 19 mm (3/4 in.) mix which has a lower requirement than a 12.5 mm (1/2 in.) mix.

The VMA values assigned to each mix size are a compromise based on what is considered typical. The assumption that the bulk dry specific gravity of the aggregate is 2.65, for example, is inherent in the specified value. It is generally recognized that this assumption allows for a range of specific gravities of 2.5 to 2.8 and any materials outside this range may require that the specified VMA be adjusted. The problem has always been that there was no method to determine what the acceptable VMA was for each unique combined aggregate.

DERIVATION OF THE EQUATIONS

There is a method which may allow the calculation of the minimum percent VMA required in a particular aggregate combination based on the volumetrics of the components and the required air voids and film thickness. To accomplish this, the film thickness equation is modified so that a minimum film thickness is assumed and the equation is then solved for the percent asphalt (P_b). The result, then, is the minimum percent asphalt required to achieve the minimum film thickness. This result is then substituted into the minimum percent asphalt equation provided by Dr. Richard W. Smith (4) and the equation is solved for VMA. The resulting figure, then, is the minimum VMA required to achieve both the proper coating (film thickness) and air voids needed to produce durable asphalt cement concrete (ACC) pavements.

The following equations are the result: Equation 1 is the English version of the minimum asphalt calculation where the surface area (SA) is provided in ft^2/lb. Equation 2 is the metric equation where SA is provided in m^2/Kg.

$$P_{bm}=100\frac{100(SA)(FT)+4870(P_{ba})}{4870(100+P_{ba})} \quad (1)$$

$$P_{bm}=\frac{10(SA)(FT)+100(P_{ba})}{100+P_{ba}} \quad (2)$$

P_{bm} is the minimum percent asphalt by weight of total mix.
SA is the calculated surface area.
FT is the minimum film thickness needed in microns.
P_{ba} is the percent asphalt absorption aggregate basis.

The surface area coefficients recommended by the Asphalt Institute in MS-2(3) were used for all calculations combined with the following equation which has been used in Iowa for many years to determine film thickness.

$$FT=\frac{(P_{be})(10)}{(SA)}$$

P_{be} = Effective percent asphalt by weight of total mix.

The above equation using SA in m^2/kg is combined with the absorbed asphalt as follows:

$$P_{be}=P_b-\frac{(P_{ba})(100-P_b)}{(100)}$$

P_b = Total percent asphalt by weight of total mix.
The result is equation 2 when solved for P_b.

If the asphalt absorption is not known, as would be the case before any actual trial mixing is done, a percentage of the water absorption may be used to estimate the asphalt absorption. Asphalt absorption is normally 50 to 80 percent of the water absorption. If any historical data is available for the materials, this percentage can be determined with acceptable accuracy. Once the minimum asphalt content has been determined, whether by the film thickness method above or any other valid method, it can be entered into the following equation to determine the minimum VMA which is required to allow sufficient space for that amount of asphalt and the correct air void level.

(3)

$$Min.\,VMA=\frac{100(P_{bm})(G_{se})(G_{sb})+(100-P_{bm})(G_b)(G_{se})(V_t)-100(100-P_{bm})(G_b)(G_{se}-G_{sb})}{(100-P_{bm})(G_b)(G_{sb})+(P_{bm})(G_{se})(G_{sb})}$$

P_{bm} is the minimum percent asphalt by weight of total mix.

G_{se} is the effective specific gravity of the aggregate.

G_{sb} is the bulk dry specific gravity of the aggregate.

G_b is the specific gravity of the asphalt cement.

V_t is the target percent air voids.

The aggregate effective specific gravity is normally calculated from the results of the maximum specific gravity tests on the mixture. However, it can also be estimated by substituting an assumed percentage of the water absorption for the asphalt absorption (P_{ba}) in the following equation:

$$G_{se} = \frac{100}{\frac{100}{G_{sb}} - \frac{P_{ba}}{G_b}} \qquad (6)$$

A system to establish a reasonable VMA requirement based on the volumetric properties of the materials has been sought by researchers for many years. The above equations provide a means for comparing material combinations in a new way and could change how specifications and mix designing have traditionally been viewed.

APPLICATION OF THE EQUATIONS

One of the interesting results associated with equation 3 is the effect of the bulk dry specific gravity of the aggregate. Like the Hveem procedure, the VMA criteria currently in use appear to be derived from materials with a specific gravity of 2.65. By holding all the other variables constant and changing only the G_{sb} (and G_{se} in relation to the absorption which is held constant) it can be shown that the VMA required to allow space for the amount of asphalt needed changes more than 1% over the range of specific gravities of 2.5 to 2.8 which are the limits normally associated with the VMA criteria. Aggregate bulk dry specific gravities used in the examples were determined using the Iowa method of vacuum saturation except for the data in Table III, which was determined by the technicians at the Asphalt Institute using the AASHTO methods.

Another aspect of these equations is that they can be calibrated to fit the particular materials used. That is, a mix design can be produced using traditional methods with a specified minimum VMA and then the mix can be adjusted to the most economical blend by applying these equations and using the result of the original design to establish the minimum film thickness. To illustrate this point, consider Figure One. The four mixes plotted in Figure One were designed for a research project concerning the effect of gradation on the durability of surface mixes. Mix B was the standard mix which had been used on other projects containing 5.3 percent asphalt cement (AC) which yielded a film thickness of 9.1. Using mix B as a baseline and calculating the minimum VMA required for the other three designs (assuming a minimum film thickness of 9) yields the data in Table I.

Mix A was used as the fine research mix since it met the specified minimum VMA of 14.5. Analyses using equations 2 and 3, however, demonstrates that this mix should have been rejected because it did not have enough room for sufficient asphalt, and, in fact, this mix showed significant check cracking behind the finish roller indicating it was too tender and contained too little asphalt. Mix C, also fell below the minimum VMA calculated but was never used as the coarse research mix on the project. Mix D was chosen as the coarse research mix based on an educated guess that the minimum VMA for such a coarse mix should be about 12.0. The calculations validate that guess by yielding a minimum VMA of 12.1 for mix D.

In another example, in Figure Two, a mix design for an Interstate pavement overlay was submitted by the contractor and accepted by the agency as meeting all the criteria. This was a fine gradation, however, near the top of the specified band similar to mix B. The surface area was 4.92 m^2/kg (24.03 ft^2/lb) which results in a calculated film thickness of 9 at the recommended asphalt content of 5.4 percent. By using 9, then, as an assumed minimum and evaluating other blends of these materials, the equations, as expected, show that finer blends require more asphalt and more VMA and coarser mixes require less.

In fact, mixes D and E did not meet the specified minimum VMA of 13.5, but, by applying the equations, it can be shown that they did not, in fact, need that much (Table II). Mix E falls outside the range of gradations normally associated with dense-graded HMA, so the assumption of 9 as the minimum film thickness is probably not correct. Mix D, however, is within the range of dense-graded mixes and the calculated minimum VMA is 12.1 while the actual measured VMA is 12.6. Mix D, then, should have been an acceptable mix and may have been a more economical choice since the required asphalt content to achieve 4 percent air voids was nearly 1 percent less than the selected design.

This example clearly demonstrates the problem associated with using an inflated VMA requirement as the method of achieving sufficient coating with a safety margin. The more inflated the VMA requirement (or the greater the safety margin) the finer the mix will often need to be and the higher the asphalt content will need to be to coat the finer mix. While this traditional approach to designing and controlling HMA has worked fairly well, it may be placing unnecessary restrictions on the contractor and may be costing the agency (and the taxpayers) money. The contractor, if required to maintain VMA in the plant produced mix, will add clean sand. If the agency has a crushed particle or angularity specification which must be met, manufactured (crushed) sand may be required. This type of material increases VMA more than adding natural sand or clean coarse material but is a premium priced product. Yet, by adding fine material to increase VMA, the film thickness is being reduced. Since the purpose of VMA in the first place is to assure that there is room for sufficient asphalt coating and voids, the addition of fine material to increase VMA can be self defeating in the sense that it may increase the voids while at the same time reducing the asphalt coating.

DISCUSSION OF FILM THICKNESS

The inaccuracies of the film thickness determination are widely recognized, however, historical data can be analyzed to determine a best fit criteria based on the surface area coefficients commonly used, so the question of the accuracy of those coefficients is less important. In other words, it makes little difference if the result of the equation is exactly correct as long as that result can be correlated with some measure of performance. There is a substantial amount of evidence on file to support the use of the film thickness equation as an empirical measure of the proper volume of asphalt. Therefore, the only assumption made in the calculation of minimum VMA is what minimum film thickness value should be used in the equations. Preliminary results of a review of the mixes used in Iowa in 1994 indicates that a minimum film thickness of 9 microns corresponds to the current requirements for VMA and gradation better than the 7.5 to 8 microns currently specified as the minimum in Iowa.

Criticism of the film thickness equations is often based on the difference in surface area between a sphere and a cube (5). While this argument is interesting and technically correct, it has nothing to do with the actual shape of aggregate particles. Close examination of aggregates reveals that all aggregates are composed of a variety of different shapes, particularly the combined aggregates usually used in HMA. Evidence that surface area does not vary greatly between aggregates can be seen in the fine aggregate angularity test used in the SUPERPAVE mix design system. The relatively narrow range of test results indicates that volumes and, therefore, surface areas of a standard gradation are similar for most aggregates.

DISCUSSION OF VMA

It has been known for many years that the required VMA decreases as the aggregate gradation becomes coarser. This is directly related to surface area, not to the fact that there may be a 2 percent difference in the amount of top size aggregate in the mix. Yet, most agencies use the nominal maximum size as the basis to decide what the proper minimum VMA should be. For example, in Iowa, a 50 blow 19 mm (3/4 in.) mix is required to have 14.5 VMA while a 12.5 mm (1/2 in.) mix requires 15.0 VMA, but the gradation bands for these two mix sizes overlap on every screen. The reasoning for this is that the 19 mm (3/4 in.) mix is allowed to be coarser and, therefore, MAY require less VMA. It is also clear that coarser mixes tend to require less asphalt to maintain the level of coating needed for durability. Once again, this is a function of the surface area.

Until the adoption of the minimum percent asphalt equation provided by Dr. Richard W. Smith (4), the volumetric control of plant produced mix in Iowa was limited to the control of air voids in both lab compacted and field compacted test specimens, VMA was seldom examined in the field. A limited review of the history files on HMA projects indicates that 25 to 30 percent of the mixes used in the 1980's did not contain the specified VMA in the plant produced mix. There is no corresponding evidence of premature pavement failures that would indicate that most of these mixes were, in fact, unacceptable. Field technicians have indicated that mix designs which have performed well for many years are suddenly not passing, usually due to low VMA which results in recommended asphalt contents below the minimum percent asphalt. One conclusion which can be drawn from these observations is that the VMA criteria being applied may not be correct for all the possible aggregate combinations which will produce acceptable mixes.

Criticism of the VMA criteria proposed by both the SHRP Delphi group and the Asphalt Institute (3) has been leveled by those who hold to the theory that only VMA and voids are meaningful criteria for use in the design and control of HMA. This criticism is based on the traditional values for VMA of 14 to 15 (for a 19 mm (3/4 in.) mix) as recommended by McLeod (1) and the FHWA (2). Reducing the VMA to 13 for 19 mm (3/4 in.) mixes, as recommended, has caused concerns that the resulting asphalt contents will be too low to produce the film thickness needed for durability. This criticism would be valid if the mixes were typically graded near the extreme fine limits, however, that is not the case. The inclusion of the restricted zone and the definition of nominal maximum size combine to make the typical SUPERPAVE mix design fall on the coarse side, below the restricted zone where the surface area is relatively low and high film thickness is, therefore, easily achieved. It can be demonstrated by use of the equations presented here that a minimum VMA of 13 is indeed a much more reasonable figure for the typical 19 mm (3/4 in.) SUPERPAVE mix, and may, in fact, still be too high for materials with low specific gravities and gradations near the lower limits.

For example, Table III contains data for six material combinations used by the National Asphalt Training Center at the Asphalt Institute for demonstration of the SUPERPAVE level one mix design procedures. The surface area is expressed in m^2/kg and a minimum film thickness of 9.0 is assumed. The minimum VMA calculated for each blend shows that the assumed minimum of 13 is a proper assumption for the intermediate blends (blends 3,4,&6). Blend 5 should be ignored, since it was included only as an example of a mix that plotted above the restricted zone. To achieve this, a value of 7.8 percent passing the .075 mm (#200) sieve was required, which is unrealistic for most materials. Among the realistic mix designs blend 1, the finest, plotted just below the restricted zone, and blend 2, the coarsest, plotted at the lower limits. The average minimum VMA calculated for the five realistic blends is 12.9 which agrees well with the assumed minimum of 13.0.

Table IV contains data for two SUPERPAVE designs used on IA 175 in Hardin County, Iowa. Mix 79 was a 19 mm (3/4 in.) binder course and mix 80 was a 12.5 mm (1/2 in.) surface course using the SUPERPAVE definition of nominal maximum size. The D and F following the mix number designates laboratory mix design (D) or field plant produced (F) mix data. A minimum film thickness of 9 was assumed. The data illustrates two important points. First, that the nominal maximum size may not properly distinguish the minimum VMA requirements for these two mixes. SUPERPAVE would require the 12.5 mm (1/2 in.) mix to have 1 percent more VMA than the 19 mm (3/4 in.) mix (14 vs 13). However, the only difference in the two mixes is approximately a 5 percent difference in gradation on the 9.5 mm (3/8 in.) and 12.5 mm (1/2 in.) sieves. The VMA requirements for the two mixes are actually nearly identical and were treated as such in design and field production. Second, rigidly enforcing a VMA specification without regard for the surface area and volumetric properties of the aggregates can lead to the rejection of high quality mixes. The surface mix would have been rejected if the SUPERPAVE criteria of 14 VMA had been enforced, but the mix was excellent in all respects. In fact, the contractor on the project was so impressed with the ease of production, handling and compaction that the desire to use similar mixes on other projects has been expressed. The lower VMA did not result in too little asphalt, as both designs exhibited coatings superior to the typical fine designs used in Iowa and did not segregate.

Those who hold high VMA requirements as the best way to assure high enough film thickness and air voids often ignore the fact that the calculation of VMA is based on two tests which are well documented to have high variability. Using the ASTM precision statements for the bulk specific gravity of saturated surface dry Marshall specimens (D2726) and the bulk specific gravity of the aggregate (C127 and C128), and applying the procedures in ASTM D4460, assuming an average G_{sb} of 2.65 and an average G_{mb} of 2.35, the precision of the VMA calculation can be determined. The result is then multiplied by 100 to convert it to a percentage, since VMA is expressed as a percentage, yielding a standard deviation for determination of VMA of 1.3%. The D2S% is, therefore, 3.8% which results in a very large range of possible test results. Even if only two standard deviations are allowed, the range is still plus or minus 2.6%. In other words, a contractor's lab may produce a mix design which shows a VMA value of 15 while the agency lab testing the same materials could produce a result of 12 and both values would have to be considered valid since they fall within the testing precision. This fact makes the use of VMA as the only criteria to assure sufficient film thickness a highly questionable and risky proposition, especially as more agencies move to a contractor quality control system where correlation of test results becomes of prime importance. Setting a high VMA requirement may provide a cushion against this variability but has the effect of excluding many acceptable mixes and increasing costs. Of course, the equations presented here suffer from these same cumulative inaccuracies, but are reliable in their ability to compare materials with various gradations and volumetric properties.

POSSIBLE ECONOMIC BENEFITS

Perhaps the greatest value to this new approach is to those agencies that do not pay for the asphalt cement separately. Under this pay system, there is always a significant danger of mixes being produced with too little asphalt because of the contractor's desire to minimize costs. These equations are sensitive to asphalt absorption as well as gradation, and would allow the design of the most economical mix without forcing more asphalt into the mix than is necessary. In a sense, this would allow the custom designing of specifications for each combination of materials which is a completely different way of viewing HMA specifications than the current "one size fits all" specifications. It is not proposed, however, that this system be employed as the exclusive method of determining the acceptability of mix designs or plant produced mix, but it can be used to adjust required criteria in a reasonable manner to allow the use of materials with other than typical gradations and specific gravities. Field (5) demonstrated this same concept based on a visual inspection of the coating characteristics of the mixture. As a result, Ontario adopted a VMA requirement based on both nominal maximum size and the percent passing the 4.75 mm (#4) sieve. The resulting minimum VMA figures agree very closely with those calculated using equations 2 and 3.

FUTURE RESEARCH

Further refinement of these equations is possible. Equations 1 and 2 can be improved by adjusting the surface area by the specific gravity of the aggregate. This is easily accomplished by multiplying the surface area by the ratio of 2.65 to the actual bulk dry specific gravity. Doing so causes the minimum asphalt content to change with aggregate specific gravity, as should be expected, while the minimum VMA remains nearly constant. Some engineers believe that coarser mixes require higher film thickness than finer mixes. If research indicates this to be true, other adjustments to these equations would be possible by applying a factor to the surface area which reflects the gradation of the mix. These equations may also have value in research and in-situ evaluations.

CONCLUSIONS

Setting minimum VMA requirements based solely on the nominal maximum size of the aggregates used in HMA is demonstrated to be too confining. By doing so, an agency often eliminates a significant percentage of aggregate combinations that will produce acceptable HMA. If the minimum VMA is set too high, the result may be mixes with high percentages of sand requiring high asphalt contents. By calculating the surface area and the volumetric properties of the aggregates, the mix designer may realistically adjust VMA requirements and have greater control over the economics of HMA mix design.

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TABLE TITLES

TABLE I

MIX DESIGN DATA - GRADATION RESEARCH PROJECT

MIX	SURFACE AREA	CALC. MIN. VMA	ACTUAL VMA	MIN. %AC
A	6.00	16.0	14.7	6.0
B	5.37	14.7	14.9	5.5
C	4.34	12.8	12.2	4.2
D	4.03	12.1	12.7	3.9

TABLE II

MIX DESIGN DATA - INTERSTATE OVERLAY PROJECT

MIX	SURFACE AREA	CALC. MIN. VMA	ACTUAL VMA	MIN. %AC
A	5.73	16.0	17.8	6.01
B	5.08	14.8	15.9	5.46
C	4.44	13.4	13.7	4.89
D	3.79	12.1	12.6	4.32
E	3.15	10.8	12.9	3.76

TABLE III

MIX DESIGN DATA - NATC\SHRP DESIGNS

BLEND	SURFACE AREA	MIN. VMA	ACTUAL VMA	MIN. %AC
1	5.13	14.8	11.7	5.3
2	3.03	10.6	13.1	3.2
3	4.35	13.2	11.6	4.5
4	4.24	13.0	14.7	4.4
5	6.75	17.8	10.6	6.8
6	4.06	12.7	13.7	4.2

TABLE IV

MIX DATA - SUPERPAVE DESIGNS IA 175

MIX	SURFACE AREA	MIN. VMA	ACTUAL VMA	MIN. %AC
79D	3.09	10.4	13.9	3.98
80D	3.18	10.6	13.3	4.15
79F	4.05	12.2	13.0	4.83
80F	4.00	12.2	13.2	4.87

FIGURE CAPTIONS

FIGURE ONE
GRADATION CHART – GRADATION RESEARCH PROJECT

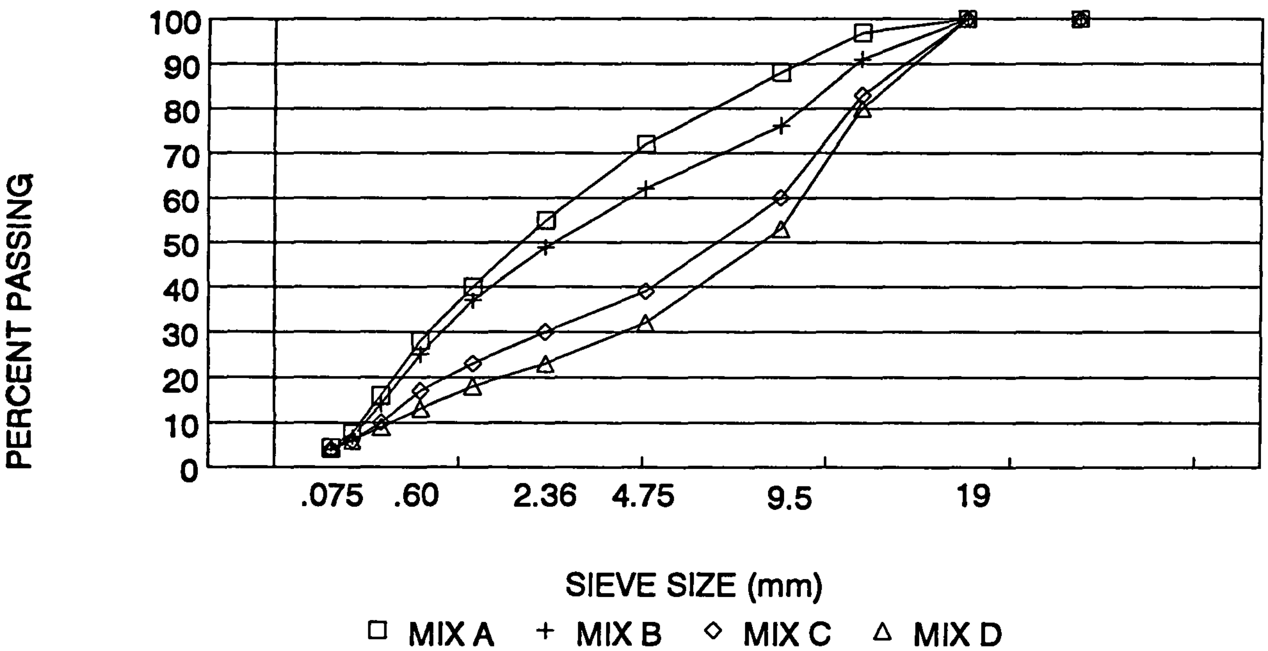

FIGURE TWO
GRADATION CHART – INTERSTATE OVERLAY PROJECT