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Prithvi S. Kandhal
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Prithvi S. Kandhal
Associate Director
National Center for Asphalt Technology
Auburn University, Alabama

Kee Y. Foo
Assistant Professor
Bradley University, Peoria, Illinois

and

Rajib B. Mallick
Senior Research Associate
National Center for Asphalt Technology
Auburn University, Alabama

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Prithvi S. Kandhal, Kee Y. Foo and Rajib B. Mallick[1]

ABSTRACT

Reports of increased difficulties in meeting the minimum voids in mineral aggregate (VMA) requirements have surfaced with the recent use of Superpave volumetric mix design. The low VMA of Superpave mixes can generally be contributed to the increased compactive effort by Superpave gyratory compactor. This has led to the increased use of coarser asphalt mixes (gradations near the lower control points). However, the minimum VMA requirements in Superpave volumetric mix design for these coarse mixes are the same as those developed for the dense mixes designed by the Marshall method.

Literature review has indicated that the rationale behind the minimum VMA requirement was to incorporate at least a minimum permissible asphalt content into the mix in order to ensure its durability. Studies have shown that asphalt mix durability is directly related to asphalt film thickness. Therefore, the minimum VMA should be based on the minimum desirable asphalt film thickness rather than a minimum asphalt content because the latter will be different for mixes with different gradations. Mixes with coarse gradation (and, therefore, low surface area) have difficulty meeting the minimum VMA requirement based on minimum asphalt content in spite of thick asphalt films.

A rational approach based on a minimum asphalt film thickness has been proposed and validated. The film thickness approach represents a more direct, equitable, and appropriate method of ensuring asphalt mix durability and encompasses various mix gradations.

[1] Respectively, Associate Director, National Center for Asphalt Technology, Auburn University, Alabama; Assistant Professor, Bradley University, Peoria, Illinois; and Senior Research Associate, National Center for Asphalt Technology, Auburn University, Alabama.

A CRITICAL REVIEW OF VMA REQUIREMENTS IN SUPERPAVE

INTRODUCTION

One of the problems encountered by highway agencies implementing Superpave volumetric mix design is the difficulty in meeting the minimum voids in mineral aggregate (VMA) requirement. The low VMA of these mixtures can often be attributed to the increased compactive effort by the Superpave gyratory compactor and the increased use of coarser asphalt mixes (gradations below restricted zone).

A vast majority of conventional asphalt mixes in the U.S. have gradations above the maximum density line (1). Many highway agencies have made their asphalt mixes coarser than those conventionally used in order to meet the Superpave VMA requirements. Superpave also recommends the use of aggregate gradations below the maximum density line especially for high volume roads. Even then, it is not always possible to meet the VMA requirement.

Literature review has indicated that the rationale behind the minimum VMA requirement for conventional asphalt mixes was to incorporate a minimum desirable asphalt content into the mix to ensure its durability. Studies have shown that asphalt mix durability is directly related to asphalt film thickness. Therefore, the minimum VMA should be based on the minimum desirable asphalt film thickness rather than a minimum asphalt content because the latter will be different for mixes with different gradations. Mixes with a coarse gradation (and, therefore, low surface area) have difficulty meeting the minimum VMA requirement based on minimum asphalt content in spite of thick asphalt films. A critical review of the minimum VMA requirement is, therefore, needed.

BACKGROUND ON DEVELOPMENT OF VMA CRITERIA

In a paper presented to the Highway Research board in 1956 (2), McLeod pointed out that the basic criteria for both the design and analysis of asphalt paving mixtures should be on a volumetric basis and not on the basis of weight. Most specifications in those days tended to specify a range of asphalt content by weight along with grading bands or limits for the aggregate, which in effect required a design on the basis of weight.

McLeod (2) illustrated the volumetric relationship between the total asphalt binder, air voids between the coated aggregate particles, and the total aggregate in a compacted paving mixture. He developed the volumetric criteria such as VMA based on specimens compacted with a Marshall hammer with 75 blows on each side of the specimen. He recommended that the VMA, which is the volume of voids between the aggregate particles, should be restricted to a minimum value of 15%, the volume of the air voids (within the VMA) should lie between 3 and 5%, which in turn restricted the volume of asphalt cement binder in the compacted mixture to a permissible minimum of 10% by volume. Therefore, his proposal for a specification of a minimum 15% VMA, along with 5% air voids, automatically established a minimum asphalt content of about 4.5% by weight (10% by volume).

McLeod's calculations were based upon a bulk specific gravity of 2.65 for the aggregate and 1.01 for the asphalt cement. No asphalt absorption was considered in the volumetric analysis.

Another paper presented by McLeod in 1959 (3) to the American Society of Testing and Materials, advocated the use of bulk specific gravity of the aggregate for calculating both the VMA and the air voids. Absorption of the asphalt cement into the aggregate was also taken into account in the volumetric analysis. McLeod recommended again that the lowest permissible asphalt content in a hot mix asphalt (HMA) mix should be 4.5% by weight, to ensure mix durability. This amounts to about 10% asphalt cement by volume. No HMA performance data were presented to support the minimum asphalt content of 4.5% on which the minimum VMA requirement was based. In this paper, McLeod also proposed a relationship between the minimum VMA and the nominal maximum particle size of the aggregate, which was adopted by the Asphalt Institute in 1964 (4). He based this relationship upon the bulk specific gravity of the aggregate and an air voids content of 5% for the compacted mix. However, the background data for relating the minimum VMA requirements to the nominal maximum size of the aggregate was not given (3).

During the last 30 years or so, most asphalt paving technologists did not realize that these minimum VMA requirements were based on 5% air void content (and not 4% air void content generally used for mix design) and 75-blow Marshall compaction. Obviously, the minimum VMA requirements corresponding to 4% air void content would be 1% lower than those recommended in earlier editions of Asphalt Institute MS-2 (4). This was recognized in 1993 and the Asphalt Institute MS-2 was revised (5) to give minimum VMA requirements corresponding to 3, 4, and 5% air void contents. These revised minimum VMA requirements have also been incorporated in the Superpave mix design procedures.

ASPHALT BINDER FILM THICKNESS IN DURABILITY CONSIDERATIONS

It is generally agreed that high permeability, high air voids, and thin asphalt coatings on the aggregate particles are the primary causes of excessive aging of the asphalt binder which contributes to the lack of durability of the HMA mixes often encountered in the field. However, the concept of an "average film thickness" for dense-graded asphalt mixtures is not easily understood. How much validity can be assigned to a film thickness, calculated simply by dividing the total surface area of the aggregate (obtained from its gradation) by the effective asphalt content? It is highly unlikely that all the particles in a mix have the same film thickness of asphalt coating. Fine aggregate particles may have a much thicker coating as compared to the coarse aggregate particles, and in fact, for all practical purposes, some very fine particles might simply be embedded in the asphalt cement/filler mortar system. Therefore, the term "film thickness" is elusive and difficult to define. However, for the purpose of calculation later in this paper, we shall assume that the concept of the "average film thickness" is indeed valid, and proceed with the calculations. Surface area will be calculated using the procedure outlined in the Asphalt Institute's MS-2 (5).

Campen, Smith, Erickson and Mertz (6) presented the relationship between voids, surface area, film thickness and stability for dense graded HMA. The authors recognized that thicker asphalt binder films produced mixes which were flexible and durable, while thin films produced mixes which were brittle, tended to crack and ravel excessively, retarded pavement performance, and reduced its useful service life. On the basis of the data they analyzed, average film thicknesses ranging from 6 to 8 microns were found to have provided the most desirable pavement mixtures. They also concluded that the film thickness decreases as the surface area of the aggregate is increased. However, the asphalt binder requirement of a mix is not directly proportional to its surface area. The asphalt binder requirement was found to increase as the surface area was increased, but at a rate much lower than that guided by a relationship of direct proportionality (6).

Goode and Lufsey (7) also did some significant work in relating asphalt hardening to voids, permeability, and film thickness. They recognized that the hardening of the asphalt binder in a mix was a function of air voids, film thickness, temperature, and time. On the basis of their work they concluded that a minimum value of 0.00123 for 'bitumen index' (which corresponds to a value of 6 microns for the average film thickness) could be included as a criterion in all mix design procedures. The 'bitumen index' was defined as pounds of asphalt cement per square foot of surface area. They used the concept of bitumen index to avoid the implication that all particles were coated with the same uniform thickness of asphalt cement. Their study indicated that a combined factor of the ratio of the air void to the bitumen index could be satisfactorily related to the asphalt binder hardening characteristics in the HMA mixture. They suggested that the Marshall method of mix design could be improved by incorporating a maximum value of voids-bitumen index ratio in place of a maximum value of air voids alone, and suggested a value of 4 as the maximum for this ratio, to ensure reasonable resistance to aging.

Kumar and Goetz (8) studied the asphalt binder hardening as related to HMA permeability and asphalt film thickness. They stated that the best procedure for predicting the resistance of hardening of asphalt binder in a single-sized HMA mix was to calculate the ratio of the film thickness factor to permeability. The film thickness factor was defined as the ratio of the percent asphalt content available for coating the aggregate to the surface area of the aggregate.

RATIONAL APPROACH BASED ON ASPHALT FILM THICKNESS

Rather than specifying a minimum VMA requirement based on minimum asphalt content as recommended by McLeod and adopted by Superpave, a more rational approach is to directly specify a minimum, average asphalt film thickness to ensure the durability of asphalt mixtures.

For dense graded mixtures, Campen, Smith, Erickson and Mertz (6) recommend an average film thickness ranging from 6 to 8 microns. Kandhal and Chakraborty (9) quantified the relationship between various asphalt film thicknesses (ranging from 4 to 13 microns) and the aging characteristics of a dense-graded HMA mix so that an optimum average asphalt film thickness desirable for satisfactory mix durability could be established. They used the Strategic Highway Research Program (SHRP) aging procedures to simulate both short and long term aging of HMA mixtures. An optimum film thickness of 9-10 microns was indicated in this study, below which the HMA mix (compacted to 8% air voids content to facilitate aging) aged at an accelerated rate. Obviously, the optimum film thickness for HMA compacted to 4-5 % air voids content in service should be somewhat lower than 9 - 10 microns because the rate of aging would be considerably lower at 4 - 5 % air voids compared to 8 % air voids. Based on the past research experience, an average asphalt film thickness of 8 microns is recommended and has been used in this paper.

Effect of Aggregate Gradation on VMA

The minimum desirable VMA for different aggregate gradations were calculated for an average film thickness of 8 microns at 4% air voids. An example of such calculation follows. The surface area calculation (5) is given in Table 1.

Table 1. Calculating Surface Area From Given Aggregate Gradation

Sieve Size, mm	Percent Passing	Surface Area Factor (m^2/kg)	Surface Area (m^2/kg)
25	100	0.41	0.41
19	95		
12.5	78		
9.5	66		
4.75	51	0.41	0.2091
2.36	35	0.82	0.28372
1.18	25	1.64	0.41492
0.6	19	2.87	0.53669
0.3	14	6.14	0.84118
0.15	9	12.29	1.1061
0.075	5	32.77	1.6385
			$\sum = 5.44021$

Example 1

Assuming specific gravity of asphalt is 1.02 and bulk specific gravity of aggregate = 2.70

$$\text{Weight of effective asphalt binder} = 5.44021 \frac{m^2}{kg\ of\ aggregate}\ x\ 8\ x\ 10^{-6}\ m\ x\ 1.02\ x\ 1000\ \frac{kg}{m^3}$$

$$= 0.044392 \frac{kg}{kg\ of\ aggregate}$$

$$\text{Asphalt content by weight of total mix} = \left[\frac{0.044392}{(1 + 0.044392)}\right] x\ 100$$

$$= 4.25\ \%$$

$$(REFER\ TO\ FIGURE\ 1)$$

$$Volume\ of\ asphalt\ binder = \frac{4.25\ kg}{1.02\ x\ 1000\ \frac{kg}{m^3}} = 0.004167\ m^3$$

$$Volume\ of\ aggregate = \frac{95.75\ kg}{2.7\ x\ 1000\ \frac{kg}{m^3}} = 0.035463\ m^3$$

$$Total\ volume\ of\ mix\ with\ 4\%\ air\ voids = \frac{(0.004167 + 0.035463)}{96}\ x\ 100 = 0.041281\ m^3$$

$$Since,\ volume\ of\ air = total\ volume\ of\ mix - volume\ of\ effective\ asphalt - volume\ of\ aggregate$$

$$Volume\ of\ air = 0.041281 - 0.004167 - 0.035463 = 0.001651\ m^3$$

$$VMA = \frac{(0.001651 + 0.004167)}{0.041281}\ x\ 100 = 14.09\ \%$$

Two HMA mixtures with nominal maximum sizes of 19 mm and 12.5 mm have been considered. The aggregate gradations: above the Superpave restricted zone (ARZ), through the restricted zone (TRZ), and below the restricted zone (BRZ) have been considered for each mix (Table 2 and Figures 2 and 3). The VMA for the various mix aggregate gradations were calculated and the results tabulated in Table 3 for film thickness of 6, 7, and 8 microns. Table 3 shows that for a constant film thickness, the aggregate gradation does change the minimum desirable VMA. The gradations below the restricted zone (BRZ) which represent a coarse mix have the lowest VMA in both mixes with 12.5 mm and 19 mm nominal maximum size. This illustrates the shortcoming of the current Superpave minimum VMA requirement based on McLeod's work. By specifying a minimum VMA, Superpave has generally penalized coarse mixes (those below the restricted zone) which represent a majority of Superpave mixes that are currently being placed.

The current Superpave minimum VMA requirement for 19 mm nominal maximum size

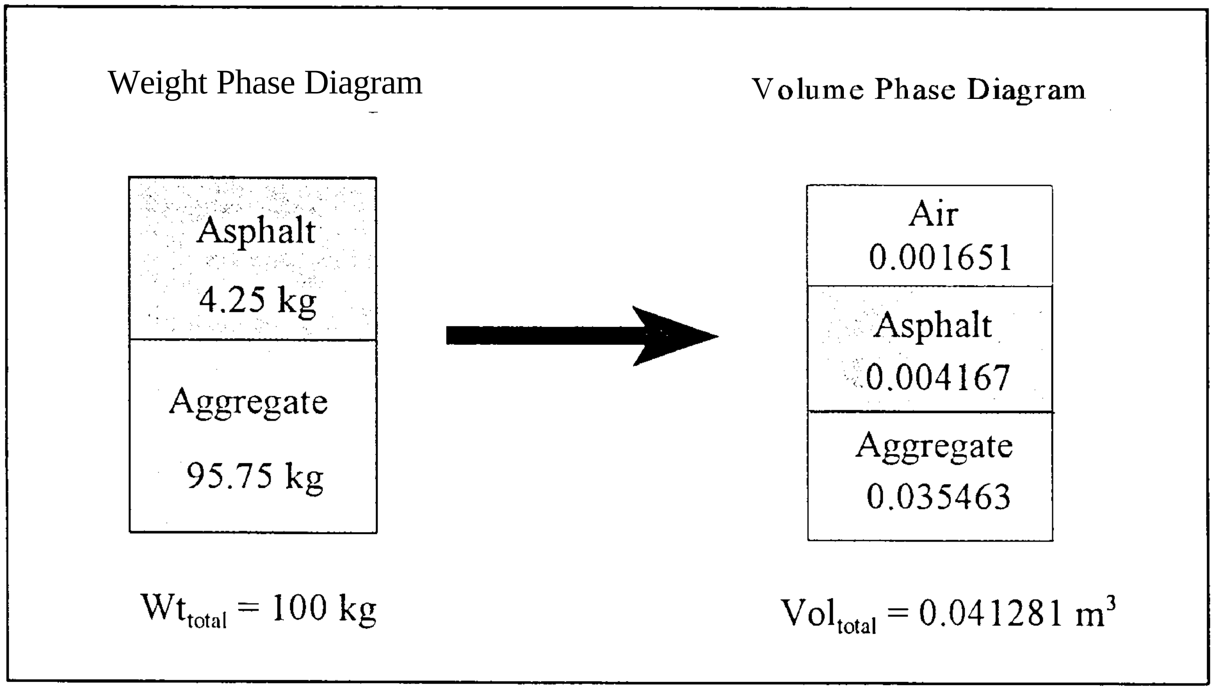

Figure 1. Weight and Volume Phase Diagram for Compacted HMA

Table 2. Aggregate Gradations Considered

Sieve Size, mm	Percent Passing					
	19 mm Nominal Maximum Size			12.5 mm Nominal Maximum Size		
	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ
25	100	100	100			
19	100	95	90	100	100	100
12.5	88	78	67	100	96	90
9.5	79	66	52	89	83	76
4.75	65	51	36	73	60	47
2.36	49	35	23	55	39	30
1.18	38	25	17	35	28	23
0.6	28	19	14	25	21	17
0.3	19	14	10	20	16	10
0.15	11	9	7	11	9	7
0.075	5	5	5	5	5	5

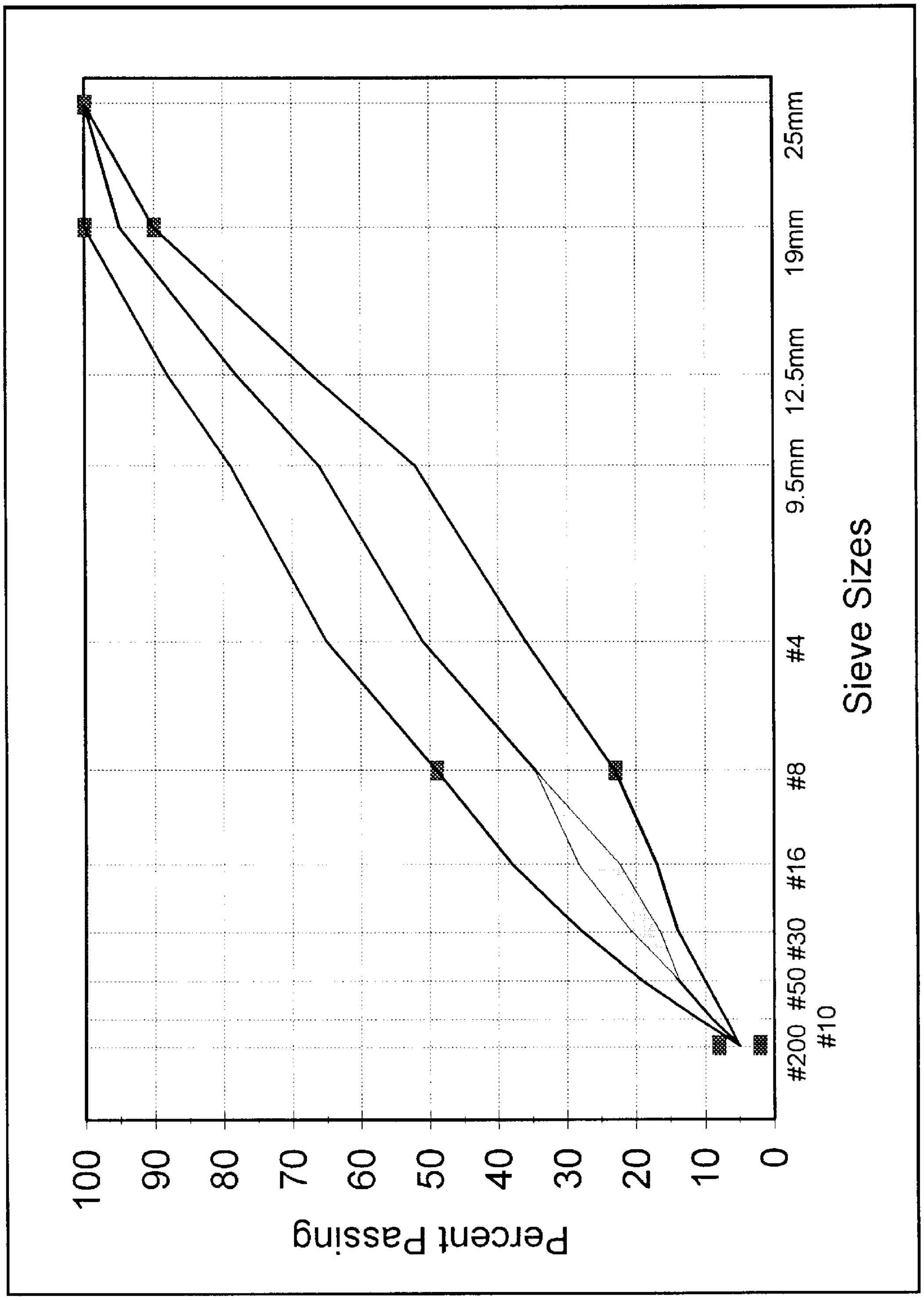

Figure 2. Aggregate Gradation for 19 mm Nominal Size

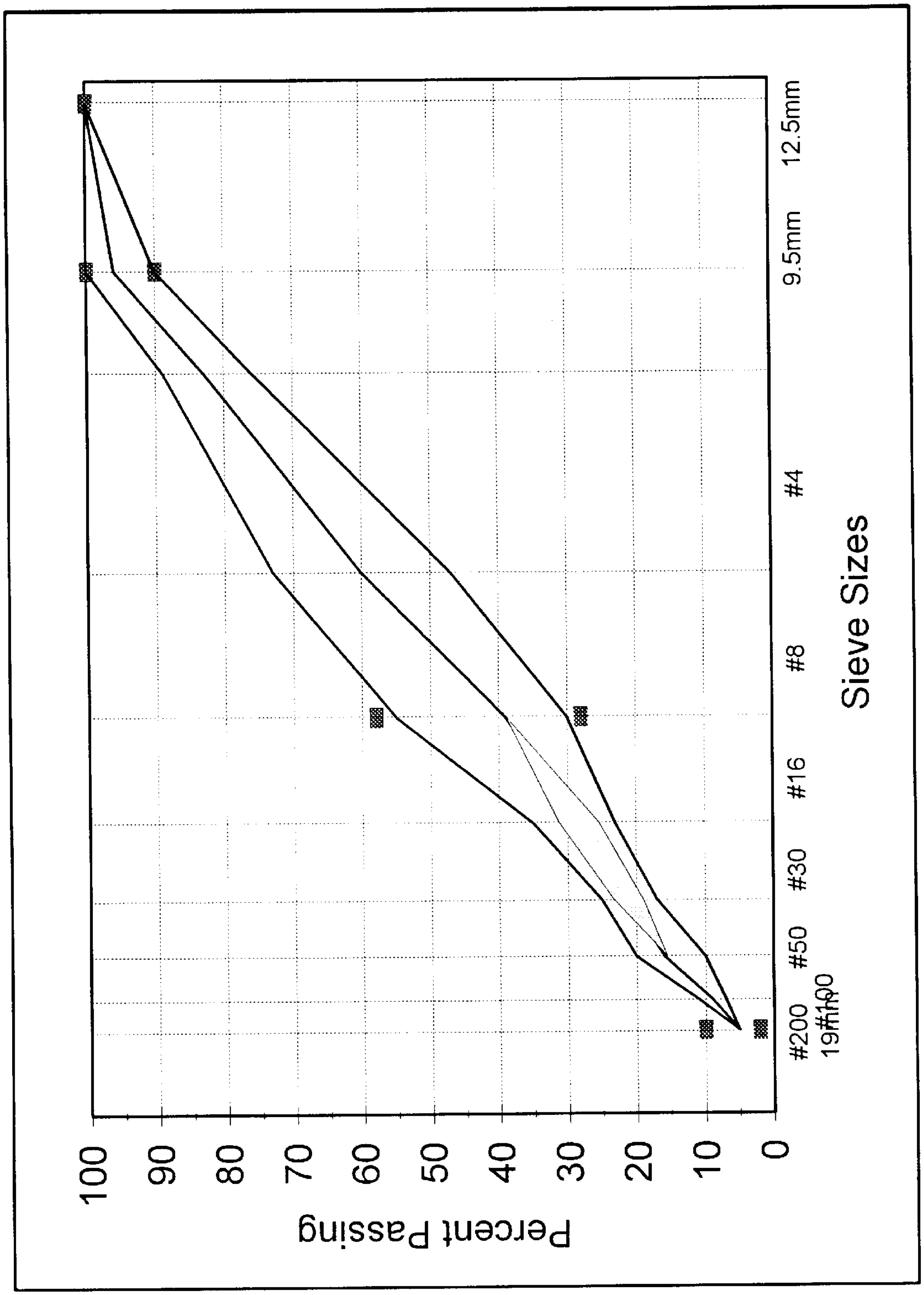

Figure 3. Aggregate Gradation for 12.5 mm Nominal Maximum Size

Table 3. Calculated VMA Based on Film Thickness

Film Thickness (Micron)	19 mm Nominal Maximum Size			12.5 mm Nominal Maximum Size		
	ARZ	TRZ	BRZ	ARZ	TRZ	BRZ
6	13.35	11.78	10.58	13.36	12.20	10.96
7	14.73	12.95	11.59	14.75	13.43	12.03
8	16.07	14.09	12.57	16.09	14.63	13.06
Avg	14.72	12.94	11.58	14.73	13.42	12.02

mix is 13%. If that VMA requirement is assumed to be based on gradation through the restricted zone, then the minimum VMA requirement for a coarser gradation (below the restricted zone and near the lower control points) should be lowered by a “gradation factor” of approximately 1.2 to 1.5 percent depending on the film thickness used (Table 3). It should be noted, however, that the gradation on which the current VMA requirements are based is not available in the literature.

The adjustment of the current Superpave VMA requirement with a “gradation factor” for gradation below the restricted zone is at best a temporary, quick fix solution. Table 4 shows the “gradation factors” for different nominal maximum aggregate sizes corresponding to a film thickness of 8 microns.

A better and equitable solution to ensure mix durability is to specify the minimum average asphalt film thickness. An average film thickness of 8 microns is recommended at this

Table 4. Gradation Factors

Nominal Maximum Size				
37.5 mm	25 mm	19 mm	12.5 mm	9.5 mm
0.5	1.0	1.5	1.5	2.0

time based on past research. Therefore, the final step in the Superpave volumetric mix design should be to calculate the average asphalt film thickness, and if the average asphalt film thickness is equal to or greater than 8 microns then the mix design can be approved.

VALIDATION OF ASPHALT FILM THICKNESS APPROACH

Superpave volumetric mix designs were conducted on six different mixes. Of these, three mixes consisted of 100% crushed granite aggregate, and the other three consisted of 80% crushed granite and 20% natural sand. The properties of the aggregate used in the mixes are shown in Table 5. A 3-10 million ESALs traffic level was selected for compaction. The design parameters are shown in Table 6. The $N_{initial}$, N_{design} and $N_{maximum}$ values were 8, 96, and 152, respectively. A PG 64-22 grade asphalt cement was used in all mixtures.

Table 5. Properties of Aggregates Used in the Laboratory Validation Study

Property	Granite Coarse Aggregate	Granite Fine Aggregate	Natural Sand	Blend of Granite, Fine Aggregate, and Natural Sand
Bulk Specific Gravity	2.688	2.712	2.618	2.693
Uncompacted voids (AASHTO T304, method A)	---	49.4	40	47.9

Table 6. Design Parameters and Superpave Criteria

Traffic, ESALs	$N_{initial}$	N_{design}	$N_{maximum}$	VMA, % (minimum)	VFA
3-10 million	8	96	152	14	65-75

The mix with 100% crushed aggregate (CR) and the mix containing 20% natural sand (NS) were made with the three following different aggregate gradations: (1) above the restricted zone (ARZ), (2) through the restricted zone (TRZ), and (3) below the restricted zone (BRZ). The gradations are shown in Table 7 and Figure 4. The gradations are different only around the restricted zone for these mixes of 12.5 mm nominal maximum size. In other regions the gradations were kept the same. Mix designs were conducted for each of the mixes with the Superpave gyratory compactor.

Table 7. Gradation of Aggregates Used in the Laboratory Validation Study

	Percent Passing		
Sieve Size (mm)	ARZ	TRZ	BRZ [a]
19	100	100	100
12.5	96	96	96
9.5	83	83	83
4.75	60	60	60
2.36	55	39	30
1.18	35	28	23
0.6	25	21	17
0.3	20	16	10
0.15	7	7	7
0.075	5	5	5

[a] ARZ - Above Restricted Zone
TRZ - Through Restricted Zone
BRZ - Below Restricted Zone

The Superpave volumetric mix design results for the six mixes are shown in Table 8. At the optimum asphalt content, all of the mixes except (TRZ-NS) and (BRZ-NS) meet the VMA criteria (>14.0%). The BRZ- NS mix barely fails the VMA criteria (VMA = 13.9). The average

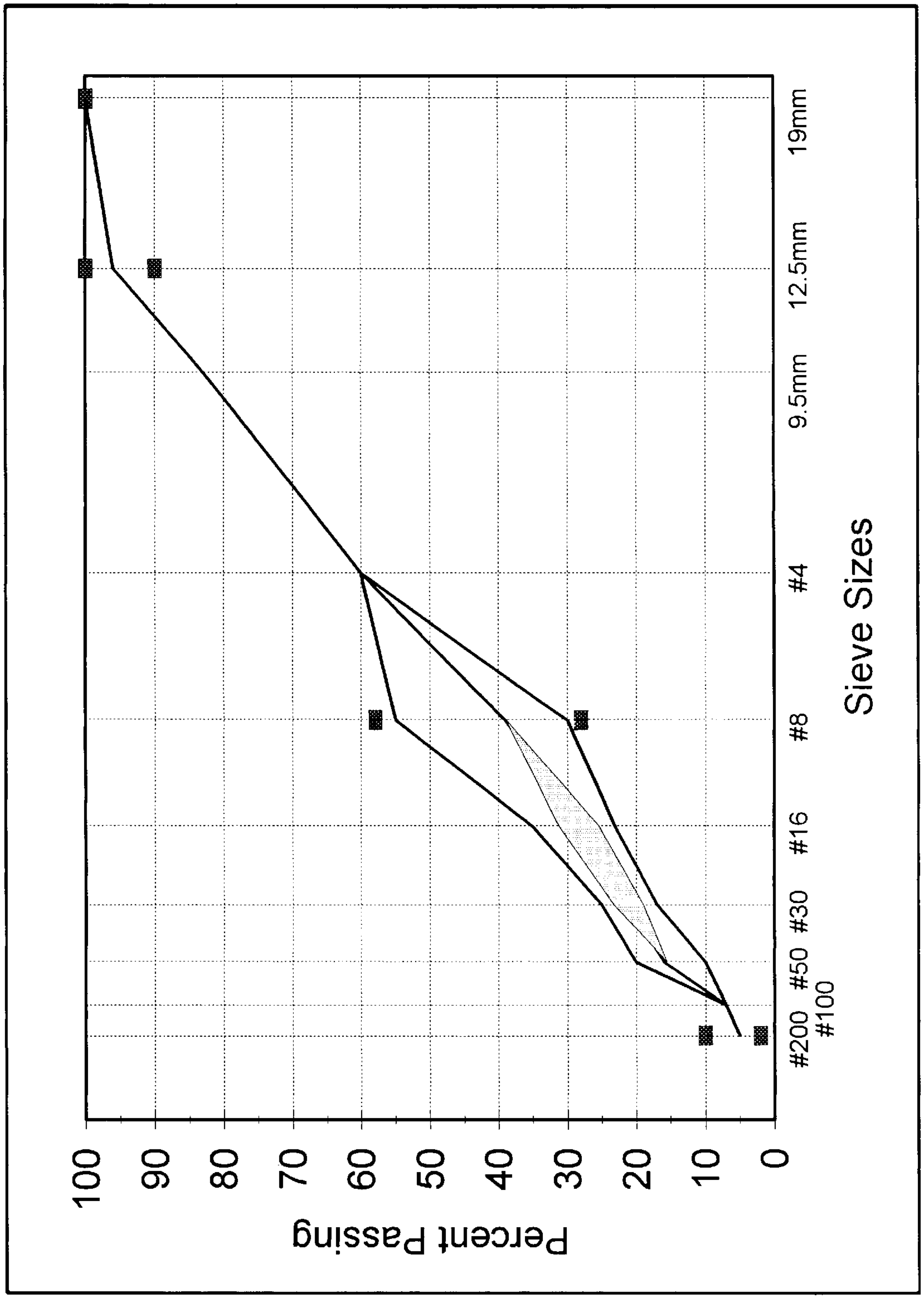

Figure 4. Gradations of Laboratory Validation Mixes

Table 8. Mix Design Results

Mix[a]	Properties			
	AC Content, %	VTM, %	VMA, %[b]	Avg. Film Thickness, µm
ARZ-CR	5.1	4.0	15.2	8.6
TRZ-CR	4.7	4.0	14.4	8.8
BRZ-CR	4.9	4.0	14.9	10.4
ARZ-NS	4.6	4.0	14.0	7.7
TRZ-NS	4.1	4.0	13.0	7.6
BRZ-NS	4.5	4.0	13.9	9.5

[a] ARZ-CR - Above Restricted Zone, All Crushed
TRZ-CR - Through Restricted Zone, All Crushed
BRZ-CR - Below Restricted Zone, All Crushed
ARZ-NS - Above Restricted Zone, 20 Percent Natural Sand
TRZ-CR - Through Restricted Zone, 20 Percent Natural Sand
BRZ-NS - Below Restricted Zone, 20 Percent Natural Sand
[b] Minimum VMA Requirement = 14.0

asphalt film thickness for each mix was calculated from the mix design results based on the optimum asphalt content and surface area. Following is an example of how the average asphalt film thickness for ARZ-CR mix was calculated.

Example 2

The aggregate surface area was calculated from the aggregate gradation. This calculation is shown in Table 9.

Specific gravity of asphalt = 1.02

From Table 8, the following is given for ARZ-CR mix:

VMA = 15.2% VTM=4.0% Optimum asphalt content = 5.1%

$$Volume\ of\ asphalt\ binder\ =\ 15.2\ -\ 4.0\ =\ 11.2\ \%$$

$$Weight\ of\ asphalt\ binder\ =\ 0.112\ m^3\ x\ 1000\ \frac{kg}{m^3}\ x\ 1.02\ =\ 114.24\ kg$$

$$Weight\ of\ aggregate\ =\ \frac{114.24}{5.1}\ x\ (100\ -\ 5.1)\ =\ 2125.76\ kg$$

$$Weight\ of\ asphalt\ per\ kilogram\ of\ aggregate\ =\ \frac{114.24}{2125.76}\ =\ 0.053741\ kg$$

$$Asphalt\ Film\ Thickness\ =\ \frac{0.053741}{6.1253\ \frac{m^2}{kg}\ x\ 1000\ \frac{kg}{m^3}\ x\ 1.02}\ =\ 8.6\ \mu m$$

Table 9. Calculating Surface Area From Aggregate Gradation of ARZ-CR Mix

Sieve Size, mm	Percent Passing	Surface Area Factor (m^2/kg)	Surface Area (m^2/kg)
19	100	0.41	0.41
12.5	96		
9.5	83		
4.75	60	0.41	0.2460
2.36	55	0.82	0.4510
1.18	35	1.64	0.5740
0.6	25	2.87	0.7175
0.3	20	6.14	1.2280
0.15	7	12.29	0.8603
0.075	5	32.77	1.6385
			∑ = 6.1253

All mixes except ARZ-NS and BRZ-NS have more than 8 microns average asphalt film thickness. As expected, mixes containing natural sand generally have lower VMA compared to mixes containing 100% crushed aggregate. The major observation is that mix BRZ-NS failed to meet the minimum VMA requirement of 14.0% but does have an average asphalt film thickness greater than 8 microns (9.5 microns). The BRZ-NS mix should be significantly more durable with a film thickness of 9.5 microns than the ARZ-NS mix with a film thickness of 7.7 microns, although both have comparable VMA values. If a minimum asphalt film thickness of 8.0 microns is specified then two mixes: ARZ-NS and TRZ-NS will be unacceptable, which is logical. As expected, the VMA requirement unfairly penalizes coarser mixes (those with gradation below the restricted zone).

If the minimum VMA requirement was based on a minimum average asphalt film thickness of 8 microns, it would vary depending on the gradation as shown in Table 10. All mixes except ARZ-NS and TRZ-NS meet the minimum VMA requirements based on an average asphalt film thickness of 8 microns.

Table 10. VMA Requirements and Actual Values

Mix	VMA		
	Minimum Required by Superpave	Minimum Based on 8 Micron Film Thickness	Actual Obtained in Mix Design
ARZ-CR	14.0	15.2	15.2
TRZ-CR	14.0	14.2	14.4
BRZ-CR	14.0	13.2	14.9
ARZ-NS	14.0	15.2	14.0
TRZ-NS	14.0	14.2	13.0
BRZ-NS	14.0	13.2	13.9

CONCLUSIONS AND RECOMMENDATION

The minimum VMA requirement currently adopted by Superpave to ensure mix durability is inadequate. It is not equitable to mixes with different gradations. The requirement penalizes mixes with coarse gradations (those below the Superpave restricted zone) which may have low VMA but have increased asphalt film thickness. Various studies have shown that the asphalt mix durability is directly related to film thickness.

It is recommended that minimum average asphalt film thickness be used to ensure mix durability instead of minimum VMA. A minimum average thickness of 8 microns is recommended at this time. The film thickness can be calculated from the asphalt content and surface area of the aggregate as shown in an example in this paper.

The current method of calculating aggregate surface area uses surface area factors as given in the Asphalt Institute Manual Series 2 (5). The background research data for these surface area factors could not be found in the literature. Further research is needed to verify these surface area factors. However, the current surface area factors can be used at this time to calculate the "average" asphalt film thickness because (a) the optimum film thicknesses (such as 8 microns) recommended in the literature are based on these factors, and (b) they are considered adequate for comparison purposes.

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