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RATIONAL DESIGN METHOD OF HOT MIX ASPHALT BASED ON CALCULATED VMA

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ABSTRACT

VMA (Void in Mineral Aggregate) is an important volumetric factor for design of hot mix asphalt. However, this VMA is usually obtained from laboratory test results of compacted specimen of hot mix asphalt. If VMA would be estimated without preparation of these specimens, design of hot mix asphalt to obtain both an optimum asphalt content and necessary void content would be rational. This paper presents an equation to obtain terminal VMA value for each aggregate gradation curve. This equation was derived from deductive analysis of aggregate mixture tests and is then verified for typical types of asphalt mixture such as dense graded, SMA and porous asphalt. In this method, VMA is calculated and air volume content is decided for aggregate proportions. Binder content to fill the volume of VMA minus air void content is determined. Laboratory test is performed to check the proposed mix design and whether degree of compaction is equal to approximately 98%.

Keywords: mixture design, compaction, density, void, aggregate

1. INTRODUCTION

VMA of hot mix asphalt (hereafter HMA) is known to play as an important role on the performance of HMA. Therefore, VMA as well as air void contents, void filled with asphalt is generally specified in the mix design criteria of each HMA type. Some experimental studies were conducted by changing the proportion of ratio of aggregate for use in HMA in order to get a desirable VMA [1] and also to have maximum density, which was known as the Fuller's curve. Superpave design method has also demonstrated to show VMA of selected aggregate gradation beforehand this compaction test. This calculated method has, however an assumption of asphalt content and air void content and effective aggregate gravity of selected aggregate gradation [2]. Calculation method to obtain VMA only from aggregate gradation (also contains aggregate max. size, shape of aggregate and surface texture of aggregate) of HMA has not been found yet. If VMA calculation method could be introduced, many works of HMA design would be done on the table and HMA design would be rational to obtain both an optimum asphalt content and necessary air void content with minimum experiment. The aim of our study was to formulate an equation to obtain terminal VMA value for each aggregate gradation curve. This equation was derived from deductive analysis of aggregate mixture tests. This equation was verified for natural coarse and fine sand, SMA (NAPA Guideline Example and 7 gradation curves within band) and other HMA types such as dense and porous. From these verification, this equation is valid for acquiring VMA both for aggregate gradation curve and of its HMA. As a result, we proposed a rational mix design method of HMA by using this equation.

2. EXPERIMENTAL

2.1 Experiment of two aggregate mixtures

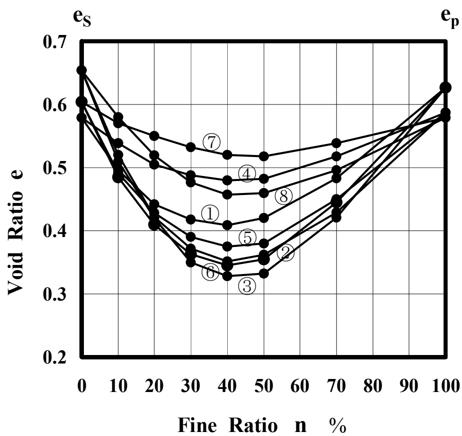
5 kinds of aggregate (ceramic ball) whose mean diameters were 0.6, 1, 3, 7 and 12mm were used. 8 combinations of 2 aggregate size mixtures with different proportion were compacted in 2 liters steal mold by tamping. Test results of each aggregate size were shown in Table 1. Table 2 indicated the blend ratio of each aggregate size for experiment. Test results of 8 combinations were shown in Figure 1. In this figure, Void Ratio; e = Specific Gravity / Unit Mass –1, Fine Ratio n; volumetric proportion of smaller size aggregate in the mixture.

Size (mm)	0.6	1.0	3.0	7.0	12.0	Mean
Specific Gravity	2.498	2.491	2.493	2.532	2.522	2.507
Unit Mass	1.535	1.570	1.579	1.579	1.525	1.558
Void Ratio	0.627	0.587	0.579	0.604	0.654	0.609

Table 1: Aggregate for experiment (ceramic ball).

Particle	Blend Ratio by Mass							
Fine Size %	0	10	20	30	40	50	70	100
Coarse Size %	100	90	80	70	60	50	30	0

Table 2: Blend Ratio of Experimental aggregate.



Size Ratio of 2 aggregates

No.	Coarse / Fine		
①	3.0 / 0.6	=	5.0
②	7.0 / 0.6	=	11.7
③	12.0 / 0.6	=	20.0
④	3.0 / 1.0	=	3.0
⑤	7.0 / 1.0	=	7.0
⑥	12.0 / 1.0	=	12.0
⑦	7.0 / 3.0	=	2.3
⑧	12.0 / 3.0	=	4.0

Figure 1: Void Ratio of 2 Aggregate Mixtures.

2.2 Formulation of void ratio equation for 2 aggregate mixtures

From this test result, void ratio equation can be formulated in the following cubic equation (1)

$$e = e_S + c \cdot n + b \cdot n_2 - a \cdot n_3 \qquad (1)$$

where; Fine ratio (n) is taken as a parameter of the volumetric proportion of smaller size aggregate in the mixture.
e_S = void ratio of coarse unit size aggregate. a, b, c = constant coefficient.
First and second differentiation of equation (1), b = 3a and c = –2a – (e_S–e_p) are obtained, (since, de/dn=0, at n=1, and put b = 3a in equation (1)), where, e_p= void ratio of fine unit size aggregate. Coarse ratio (m) is taken as a parameter of the volumetric proportion of larger size aggregate in the mixture. As m + n = 1, then the equation (1) is transformed into equation (2).

$$\mathbf{e = m \cdot e_S + n \cdot e_P - a \cdot n \cdot (1-n) \cdot (2-n)} \qquad (2)$$

where, a = 0.65•log r (obtained from the above test results.), r = coarse aggregate size / fine aggregate size.

2.3 Inducing void ratio equation in the aggregate gradation

Representative aggregate diameter was introduced in order to extend equation (2) and to induct void ratio equation of more than three kinds of aggregate size, which is aggregate gradation of HMA. Representative aggregate diameter (Sd) is defined in the following equation (3).

$$\mathbf{Sd = (d_r)m \cdot (d_0)n} \qquad (3)$$

Where, d_r = diameter of coarse aggregate, d_0 = diameter of fine aggregate.
Assuming these kinds of aggregate mixture, void ratio could be calculated for the first two kinds of aggregate and then calculated again for the mixture of virtual aggregate with the representative diameter and the rest of the three kinds of aggregates. Equation (3) was verified by mathematical induction method in getting equal void ratio by changing the mixing order of three kinds of aggregates with the same proportion. Therefore, the void ratio of aggregate gradation can be obtained by repeating calculation of void ratio of two aggregate size blends from fine size to maximum size.
Initially, it is necessary to confine both maximum and minimum aggregate size of this gradation, before inducing void ratio equation of aggregate gradation.
2nd: start to calculate void ratio of mixture with minimum aggregate size and next the small size aggregate.
3rd: to calculate representative diameter of first two aggregate size group blend.
4th: continue to calculate void ratio of mixture with obtained virtual aggregate group and third small aggregate group.
5th: to calculate representative diameter of second two aggregate size group mixtures.
6th: continue to calculate void ratio of mixture with obtained 2nd virtual aggregate size group and fourth small size aggregate group.
Continue above calculation until the maximum aggregate size group is done. If we will minimize the difference of diameter between two aggregate sizes group, integration of void ratio component from minimum to maximum aggregate size group, which is indicated in equation (4) will be the void ratio equation of aggregate gradation. Inducing process of this equation in detail was referred to [3].

$$\mathbf{e = m \cdot e_r + n \cdot e_0 - K \cdot m \cdot \log r - 2K \cdot n \cdot \log r - 2K \cdot n \cdot \log n \cdot \log r \cdot n/m - 4K \cdot n \cdot \log n \cdot \log S_d} \qquad (4)$$

where, K=1/(4k), e_r=e_s, e_0=e_p, k: coefficient of aggregate characteristics including shape and surface texture (>1.0), r: size ratio between upper sieve size (d_r) and lower sieve size (d_{r-1}) of coarser aggregate size group.

Sieve	Pass	Mix. Ratio		Diameter				Factor		Member for Culculation				Calculation								
①	②	③	④	Represent		Ratio			⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	⑰	
d_r		Coarse	Fine	D_0	s_0	s_d	r	k	e_r	K				Calculated 6 term of right side in equation(4)							Result	
(mm)	%	m	n			d_r/s_{0-1}	d_r/d_{r-1}			1/4k	log r	log n	log s_d	(1)	(2)	(3)	(4)	(5)	(4 + 5)	(6)	e_0	VMA
25.00	100.0																				0.22	18.2
19.00	97.2	0.03	0.97	21.79	4.37	4.55	1.32	1.05	0.65	0.24	0.12	-0.01	0.66	0.02	0.22	0.00	0.06	-0.02	0.01	0.01	0.22	18.2
12.50	67.3	0.31	0.69	15.41	4.18	5.34	1.52	1.05	0.65	0.24	0.18	-0.16	0.73	0.20	0.16	0.01	0.06	-0.02	0.04	0.08	0.23	18.5
9.50	52.8	0.22	0.78	10.90	2.34	6.20	1.32	1.05	0.65	0.24	0.12	-0.11	0.79	0.14	0.18	0.01	0.04	-0.02	0.03	0.06	0.22	18.3
4.75	21.8	0.59	0.41	6.72	1.53	25.00	2.00	1.05	0.65	0.24	0.30	-0.38	1.40	0.38	0.14	0.04	0.06	-0.02	0.04	0.21	0.23	18.7
2.36	17.8	0.18	0.82	3.35	0.19	24.07	2.01	1.05	0.65	0.24	0.30	-0.09	1.38	0.12	0.41	0.01	0.12	-0.05	0.07	0.09	0.35	26.0
1.18	15.2	0.15	0.85	1.67	0.10	19.54	2.00	1.10	0.70	0.23	0.30	-0.07	1.29	0.10	0.55	0.01	0.12	-0.05	0.07	0.07	0.50	33.5
0.60	13.5	0.11	0.89	0.84	0.06	13.84	1.97	1.10	0.70	0.23	0.29	-0.05	1.14	0.08	0.69	0.01	0.12	-0.05	0.07	0.05	0.64	39.2
0.30	11.9	0.12	0.88	0.42	0.04	9.41	2.00	1.10	0.70	0.23	0.30	-0.05	0.97	0.08	0.82	0.01	0.12	-0.05	0.07	0.04	0.78	43.7
0.15				0.15	0.03		4.00	1.25	0.80	0.20											0.93	48.1
0.075	9.0	0.24	0.76	0.15	0.03	3.87	4.00	1.25	0.80	0.20	0.60	-0.12	0.59	0.19	0.92	0.03	0.18	-0.07	0.11	0.04	0.93	48.1
0.005	0.0	1.00	0.00	0.02	0.02	5.00	15.00	1.60	1.40	0.16	1.18	0.00	0.70	1.40	0.00	0.18	0.00	0.00	0.00	0.00	1.21	54.8

$D_0 = (d_r \cdot d_{r-1})^{0.5}$ ⑩ = ③ * ⑤ ⑫ = ③ * ⑥ * ⑦ ⑭ = 2* ④ * ⑥ * ⑦ * ④ / ③ ⑯ = 4* ④ * ⑥ * ⑧ * ⑨

$s_0 = (D_0)^m \cdot (s_{0-1})^n$ ⑪ = ④ * ⑰(- 1) ⑬ = 2* ④ * ⑥ * ⑦ ⑮ = ⑬ + ⑭ ⑰ = ⑩ + ⑪ - ⑫ - ⑮ - ⑯

Table 3: Example of VMA calculation.

s_0: process value to calculate s_d.
e_r: void ratio of coarser aggregate size group.
e_0: void ratio of fine aggregate size group in the calculated row.

Table 3 shows an example of calculation format for integration of equation (4). This calculation example shows the calculated VMA of **Mix design example of SMA in NAPA** described in paragraph **3.2**. This calculation can be done by computerized software developed by Y.GUNJI.

3. VERIFICATION OF INDUCED VMA EQUATION AND DISCUSSION

3.1 Natural sand

Two types of natural sand were used to verify the induced VMA equation. Physical properties of sands were shown in Table 4. Experiment was conducted by sieving sand using sieve opening of 4.75, 2.36, 0.6, 0.3 and 0.15mm, and necessary properties were tested, shown in Table 5. This table shows that calculated void ratio is almost the same to that of experimental value.

Term	Sand	Coarse Sand	Fine Sand
	Band (mm)	4.75	4.75
		0.15	0.15
	Specific Gravity	2.502	2.320
Passing Percent by Volume	4.750	100.0	100.0
	2.360	80.8	97.5
	0.600	44.5	77.7
	0.300	15.4	27.8
	0.150	0.0	0.0

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Table 4: Sands for experiments.

Sand	Coarse Sand				Fine Sand			
Size Group (mm)	4.75	2.36	0.60	0.30	4.75	2.36	0.60	0.30
	2.36	0.60	0.30	0.150	2.36	0.60	0.30	0.150
Bulk Specific Gravity	2.502	2.502	2.502	2.502	2.320	2.320	2.320	2.320
Total Volume (cm^3)	244.3	244.3	244.3	173.5	244.3	244.3	244.3	244.3
Mass (g)	371.7	365.2	350.3	236.5	347.8	337.1	325.2	305.4
Unit Mass (g/m^3)	1.521	1.495	1.434	1.363	1.424	1.380	1.331	1.250
Measured Void Ratio	0.644	0.674	0.745	0.836	0.630	0.681	0.743	0.856
Diameter Ratio	2.013	3.933	2.000	2.000	2.013	3.933	2.000	2.000
Void Ratio of unit size	0.715	0.806	0.812	0.897	0.700	0.813	0.810	0.917
Mix Ratio	0.192	0.363	0.291	0.154	0.025	0.198	0.499	0.278
Unit Mass (g/cm^3)	1.699				1.550			
Measured Void Ratic	0.473				0.497			
Calculated Void Ratic	0.479				0.492			

Table 5: Voids Ratio of Sand for Experiment and Calculated.

3.2 Mix design example of SMA in NAPA

NAPA published the guideline of SMA to get an appropriate performance results in which mix design example was shown as an Appendix [4]. Table 6 shows composition of aggregate and aggregate gradation of SMA.

Sieve (mm)	#78	#810	M.F	Gradation	G. Band	Coarse	Fine
25.0	100	--	--	100	100	100	--
19.0	96.7	--	--	97.2	90-100	96.4	--
12.7	61.2	100.0	--	67.3	50-74	58.1	--
9.5	44.0	99.8	--	52.8	25-60	39.6	--
4.75	9.0	76.0	--	21.8	20-28	0.0	100
2.36	5.0	65.0	--	17.8	16-24	--	81.5
1.18	3.0	50.2	100.0	15.2	13-21	--	69.7
0.60	2.0	37.6	98.6	13.5	12-18	--	61.9
0.30	2.0	27.5	88.6	11.9	12-15	--	54.6
0.15	--	--	--	--	--	--	--
0.075	1.0	10.0	77.6	9.0	8-10	--	41.0
Specific Gravity	2.704	2.711	2.803	2.715	--	2.704	2.749
Content (%)	84	6	10	100	--	78.2	21.8

Table 6: Composition and Gradation of SMA.

Term	Experiment	Calculate	Difference
Aggregate Density	2.715	2.714	0.001
Specific Gravity	2.468	2.472	-0.004
Asphalt Content %	6.4	6.4	0
Asphalt Volume %	15.1	15.1	0
Fiber Content %	0.3	---	---
Air Voids %	4.0	4.0	0
VMA %	18.1	18.2	-0.1
VMA_{DRC} %	40.8	40.9	-0.1

4.75mm Sieve, Passing Percent by Volume = 21.8 % (Table 6)
Calculate VGA_{DRC} = 21.8 + 15.1 + 4.0 = 40.9 %

Table 7: Comparison of results between laboratory experiment and calculated.
Note: Calculated VMA was shown in Table 3.

According to the laboratory compaction test, Table 7 was a recommended laboratory design mix, which fulfill the standard criteria of air void (=4%), asphalt content (>6%), VMA (>17%) and VCADRC (> asphalt mortar volume). VMA calculated by equation (4) were written in these tables. Table 7 indicated that VMA calculation equation was valid from mix design of HMA in estimating VMA of aggregate mixture.

3.3 Laboratory test of SMA

Compaction test using SHRP gyratory compaction machine were conducted for SMA with four different aggregate grading within gradation band of SMA in order to verify the proposed VMA equation. Table 8 and 9 show the used aggregated properties and mix ratio of component and their aggregate grading respectively. SMA specimens of each aggregate grading with three kinds of asphalt content (including optimum asphalt content and +0.3%) were compacted by 300 rotating numbers. Applications of 300 rotating numbers assume that each SMA will reach at final stage of densification after traffic opening. After compaction was finished, VMA was measured. Figure 2 indicated the comparison of VMA values between measured and calculated from equation (4).
The difference between measure and calculate are considered by existence of bitumen absorption of aggregate. Figure 2 show that VMA calculation equation gives an appropriate estimation of VMA in HMA.

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Sieve size mm	Agg. #6	Agg. #7	Crushed S.	Coarse Sand	Fine Sand	Filler
13.2	100.0					
4.75	0.0	100.0				
2.36		0.0	100.0	100.0	100.0	
0.60			51.1	46.5	68.4	100.0
0.30			32.7	25.1	24.7	99.9
0.15			18.2	15.5	3.7	98.3
0.075			11.7	3.9	1.2	83.7
Specific Gravity	2.680	2.713	2.691	2.694	2.741	2.782

Table 8: Used Aggregate.

Gradation Class		Upper Grading		Upper Middle Grading		Middle Grading		Lower Grading	
Component		Sand only	CS. Mix	Sand only	CS. Mix	Sand only	CS. Mix	Sand only	CS. Mix
Mix Ratio of Component by Mass %	Agg. #6	50.0	50.0	55.0	55.0	60.0	60.0	65.0	65.0
	Agg. #7	15.0	16.0	13.7	14.0	12.5	12.0	11.3	10.5
	Crushed Sand	—	9.0	—	9.0	—	9.0	—	7.5
	Coarse Sand	10.0	7.0	9.0	5.8	8.0	4.5	7.0	4.3
	Fine Sand	10.0	5.0	8.5	4.2	7.0	3.5	5.5	2.7
	Filler	15.0	13.0	13.8	12.0	12.5	11.0	11.2	10.0
Gradation with Passing Percent by Volume %	13.2	100	100	100	100	100	100	100	100
	4.75	49.7	49.7	44.7	44.7	39.7	39.7	34.9	34.8
	2.36	34.7	33.8	31.1	30.8	27.3	27.8	23.5	24.3
	0.60	26.3	24.1	23.6	22.0	20.8	19.9	18.1	17.5
	0.30	19.8	18.8	18.0	17.3	16.1	15.8	14.2	14.1
	0.15	16.5	15.6	15.2	14.4	13.7	13.2	12.2	11.9
	0.075	13.0	12.2	11.9	11.3	10.8	10.4	9.6	9.4
Specific Gravity		2.699	2.696	2.697	2.694	2.695	2.692	2.693	2.691

Table 9: Mix Component and Aggregate Gradation by Volume.

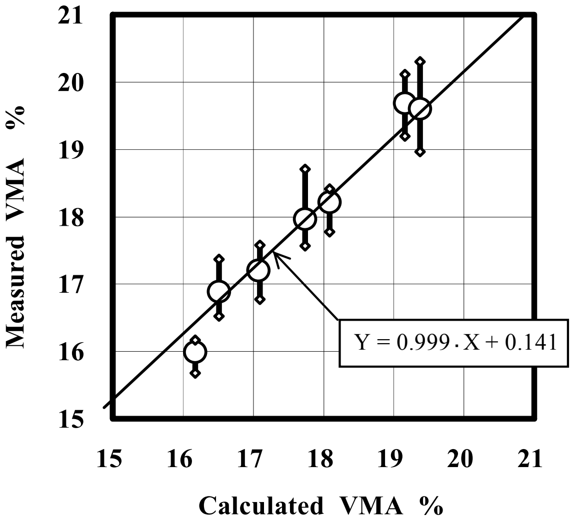

Figure 2: Comparison values of VMA between measured and calculated.

3.4 Job mix design of other types of HMA

VMA of mix design of other types of HMA, which were paved and have had good performance expected for its purpose, was checked by VMA calculation equation. These mix design were done by Marshall tamping method. Marshall tamping numbers of blows on both sides depend on the execution method of HMA type. Job mix design of these HMA was shown in Table 10. Calculated VMA by equation (4) was also included in this table below. From this table calculated VMA demonstrated to have a good coincidence with measured VMA except hydraulic and guss asphalt. Regarding the diversity of these two types of HMA, measured VMA is not a terminal VMA because both of these paving method and of service condition.

Type of HMA		Hydraulic HMA	Guss Asphalt	SMA	Express Way	Dense HMA	Porous HMA
Sieve, Passing Percent by Volume	26.5	100.0	--	--	--	--	--
	19.0	98.5	100.0	--	--	100.0	100.0
	13.2	82.5	98.9	100.0	--	99.3	95.6
	12.7	--	--	--	100.0	--	--
	9.50	--	92.6	--	88.0	--	--
	4.75	67.7	75.0	44.7	64.0	62.5	20.1
	2.36	58.4	53.9	30.8	47.0	42.9	15.1
	0.60	43.8	44.3	22.0	26.0	23.6	11.3
	0.30	33.9	33.4	17.3	16.0	16.7	9.3
	0.15	19.6	28.4	14.4	8.0	9.0	5.8
	0.075	12.4	23.5	11.3	5.7	4.2	4.0
Asphalt	Content %	7.7	8.7	6.2	6.5	5.7	4.8
Theoretical	Specific Gravity	2.366	2.389	2.452	2.410	2.448	2.477
Measured	Density g/cm^3	2.320	2.382	2.393	2.313	2.358	1.981
	VMA %	19.6	18.9	17.0	18.5	17.1	31.6
	Air Void %	1.9	0.3	2.4	4.0	3.7	20.0
Blow	No. of blows	25	50	75	50	75	50
Calculated	VMA %	11.4	10.9	17.1	18.2	16.8	30.1

Table 10: Job mix examples of various types of HMA

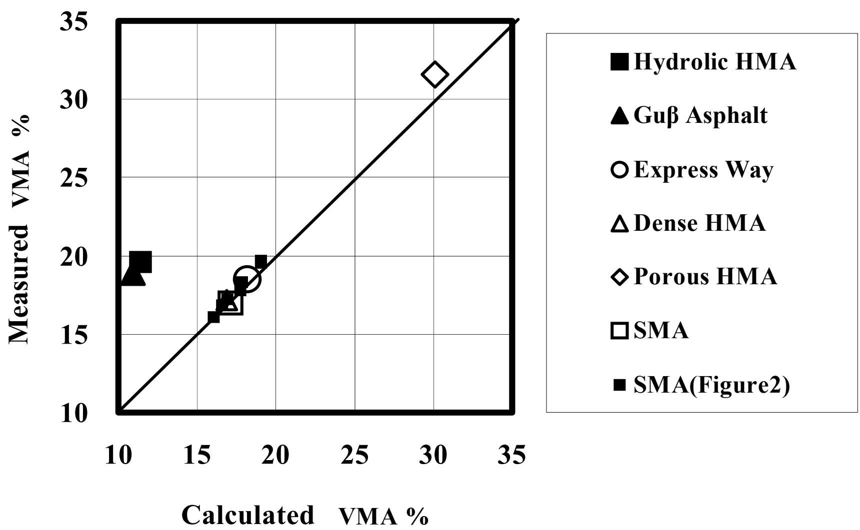

Figure 3: Comparison values of VMA between measured and calculated with Job mix various type examples.

These two types of HMA have the major object of water-tight and it's paving method of like flowing with super plastic consistency. Mix design, therefore, is generally conducted to add 1~4% of asphalt content to measured VMA of combined aggregate. Taking into consideration of this experimental treatment, calculated VMA has also given a good estimation of measured VMA from compacted specimen. Figure 3 show that comparison values of VMA between measured and calculated with Job mix various examples.

4. CONCLUSIONS

If VMA could be estimated at design stage of aggregate gradation, design of HMA would be appropriate to satisfy the standard factors of HMA such as asphalt content, air void ratio, VMA and void filled with asphalt. Our proposed VMA calculation equation on aggregate gradation could be a first proposal in this subject and this equation was verified properly by comparing measured VMA of sand, NAPA's SMA example, laboratory SMA experiment and job mix of various types of HMA. We would like to propose a volumetric design method of HMA by using this equation instead of concluding. This design method could be evaluated to be rational and simple from the following steps.

(a) select an aggregate proportion within gradation band of given HMA type (physical properties of aggregate are measured like conventional method)
(b) calculated VMA of this aggregate gradation
(c) decide necessitates air volume contents. (since, air volume contents at 2.5% is preferred considering the terminal condition of conventional HMA in repair work.)
(d) calculate asphalt content to fill the volume of calculated VMA minus air volume contents
(e) conducts a laboratory compaction test with derived proportion rate of HMA (compaction energy has to be selected properly considering pavement design life.)
(f) check VMA and air void contents of HMA specimen
(g) design is satisfactory when compaction degree of HMA specimen is equal to approximately 98% (since, calculated

VMA is a terminal value, then considering (c) and a sustainable condition of HMA, this 98% value is adequate.).

Table11 shows Software of above design steps [from (a) to (d)] developed for the purpose in case of 2.5% target air void contents. Table 12 shows air void contents with compaction degree from 96% to 100% [design steps from (e) to (g)].

Sieve Size	Component-Percent Passing by Mass								Mix. Gradation %		Gradation Band %	
mm	Cr-6	Cr-7	Crushed S.	C.Sand	F.Sand	Filler			Mass	Volume	Upper	Lower
26.50												
19.00	100.0								100.0	100.0	100	100
13.20	95.9	100.0							98.6	98.6	100	95
9.50												
4.75	2.2	92.9	100.0	100.0	100.0				64.4	64.3	70	55
2.36	0.0	7.0	91.2	92.3	98.9				43.8	43.7	50	35
1.18												
0.60	0.0	1.6	42.8	52.1	90.1				28.1	28.0	30	18
0.30		0.0	26.3	28.2	53.4	100.0			18.4	18.3	21	10
0.15			11.5	5.3	6.0	98.2			8.3	8.3	16	6
0.075			5.7	1.1	1.2	84.9			5.6	5.6	8	4
Gravity	2.677	2.675	2.673	2.688	2.686	2.720			2.680			
Per. Mass	35.0	20.0	20.0	10.0	10.0	5.0			100.0			

ENGLISH

Sieve	Pass	Coarse	Fine	D_0	s_0	s_d	r	k	e_r	K				Calculated 6 term of right side in equation(4)							Result	
d_r	%	m	n			$d_r/s_{0\text{-}1}$	$d_r/d_{r\text{-}1}$			1/4k	log r	log n	log s_d	(1)	(2)	(3)	(4)	(5)	(4+5)	(6)	e_0	VMA
26.5																					0.19	15.97
19.0	100.0	0.00	1.00	22.44	1.66	11.46	1.39	1.05	0.65	0.24	0.14	0.00	1.06	0.00	0.19	0.00	0.07	-0.03	0.00	0.00	0.19	15.97
13.2	98.6	0.01	0.99	15.84	1.66	8.23	1.44	1.05	0.65	0.24	0.16	-0.01	0.92	0.01	0.19	0.00	0.07	-0.03	0.01	0.01	0.19	15.97
9.5				7.92	1.60		2.78	1.05	0.65	0.24											0.20	16.35
4.75	64.3	0.35	0.65	7.92	1.60	6.93	2.78	1.05	0.65	0.24	0.44	-0.19	0.84	0.23	0.19	0.04	0.14	-0.05	0.09	0.10	0.20	16.35
2.36	43.7	0.32	0.68	3.35	0.69	7.28	2.01	1.05	0.65	0.24	0.30	-0.17	0.86	0.21	0.27	0.02	0.10	-0.03	0.06	0.09	0.30	22.84
1.18				1.19	0.32		3.93	1.10	0.70	0.23											0.39	28.26
0.60	28.0	0.36	0.64	1.19	0.32	3.83	3.93	1.10	0.70	0.23	0.59	-0.19	0.58	0.25	0.37	0.05	0.17	-0.06	0.11	0.07	0.39	28.26
0.30	18.3	0.35	0.65	0.42	0.16	3.24	2.00	1.10	0.70	0.23	0.30	-0.18	0.51	0.24	0.47	0.02	0.09	-0.03	0.06	0.06	0.58	36.53
0.15	8.3	0.55	0.45	0.21	0.09	4.43	2.00	1.25	0.80	0.20	0.30	-0.35	0.65	0.44	0.43	0.03	0.05	-0.02	0.04	0.08	0.72	41.82
0.075	5.6	0.33	0.67	0.11	0.03	3.87	2.00	1.25	0.80	0.20	0.30	-0.17	0.59	0.26	0.82	0.02	0.08	-0.03	0.05	0.05	0.96	48.88
0.005	0.0	1.00	0.00	0.02	0.02	5.00	15.00	1.60	1.40	0.16	1.18	0.00	0.70	1.40	0.00	0.18	0.00	0.00	0.00	0.00	1.22	54.98

Mixed Aggregate	Aggregate Spec. Gravity	2.680
	Calculated Void Ratio	0.190
	Calculated VMA %	15.97

Asphalt Mix	Asphalt Content %	5.80
	Theoretical Spec. Gravity	2.452
	Bulk Specific Gravity	2.391
	Void Filled with As. %	84.3
	Calculated Air Voids %	2.50

Table 11: Example of proposed HMA by volumetric design method.

HMA (As. 5.8 %)	Compaction Degree %	96	97	98	99	100
	Bulk Specific Gravity	2.295	2.319	2.343	2.367	2.391
	Void Filled with Asphalt %	67.8	71.3	75.1	79.5	84.3
	Calculated Air Void %	6.40	5.43	4.45	3.48	2.50

Table 12: Examples of various compaction degrees of Table 11 result.

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