EFFECT OF THE BAILEY RATIOS IN SUPERPAVE GRADATION DESIGN FOR TOKYO INTERNATIONAL AIRPORT PAVEMENT

Teck Shang Goh[1]✉, Osamu Takahashi[2], Ryota Maekawa[3]

[1, 2]*Dept of Civil and Environmental Engineering, Nagaoka University of Technology,*
1603-1 Kamitomiokamachi, Nagaoka, Niigata, Japan
[3]*Port and Airport Research Institute, Airport Research Center,*
3-1-1 Nagase, Yokosuka, 239-0826, Japan
E-mails: [1]tsgoh@yahoo.com; [2]roadman@vos.nagaokaut.ac.jp; [3]maekawa-r28a@pari.go.jp

Abstract. This paper discusses the use of the Bailey method in Superpave mixture design for Tokyo International Airport (HND) pavements. The objective of this study is to determine whether the fine graded gradations with 70% of loose unit weight of coarse aggregate will produce the mixtures that meet the Superpave requirements and provide high rutting resistance compared to the current HND Marshall mixture. Ten gradations with the recommended upper and lower limits of the Bailey ratios were designed. The effect of the Bailey ratios on voids in mineral aggregate (VMA) and rutting resistance of the mixture was examined. Rutting resistance of each specimen was evaluated by Asphalt Pavement Analyzer (APA). The experimental results showed that the current Bailey recommended limits have to be adjusted to a narrow range. The mixture with the mean values of the Bailey recommended limits had adequate VMA and better resistance to rutting.

Keywords: airfield pavement, asphalt mixture, Superpave, aggregate gradation, Bailey method, rut test.

1. Introduction and objective

Rutting is the most commonly occurring distress on asphalt pavement in Tokyo International Airport (HND). The occurrence of rutting in some of the taxiways was just after a short service period of one year. It seems that the current 19 mm fine graded Marshall mixture cannot withstand the traffic operations. To explore ways of resolving the matter, the authors had conducted a research to investigate whether the Superpave mixture could perform better than the current Marshall mixture in the earlier study (Goh *et al.* 2011a). The same gradation of HND Marshall mixture was used to make the Superpave specimens. The specimens were compacted by Superpave gyratory compactor (SGC) with the equivalent compaction to Marshall compaction effort. The experimental results showed that the HND Superpave mixture could not meet the voids in mineral aggregate (VMA) requirement even though it was within the Superpave control points. It is difficult for mixture designer to determine an appropriate gradation for Superpave mixture, especially for the case in HND, because the Marshall mix design method is still widely being practiced and insufficient information regarding the Superpave mixture for airfield pavements.

In the earlier study, the Bailey method was deployed to develop the gradations. The Bailey method is chosen because it relates the aggregate gradation and VMA. The Bailey method uses the percentage of loose unit weight of coarse aggregate (CALUW) and aggregate ratios to control the air voids and VMA. Eight gradations from fine to coarse within the Superpave control points were designed. The CALUW was ranged from 60% to 105% to investigate the level of aggregate interlock in the mixture. The experimental results showed that all mixtures met the VMA requirement and had rut depth ranging from 3.0 mm to 6.5 mm. The fine graded mixture with 70% of CALUW was slightly better performed than the other mixtures. The mixture was finer than the current HND Marshall mixture. Hence, it is important to determine whether all the fine gradations with 70% of CALUW will meet the Superpave criteria and produce better-performed mixture than the current HND Marshall mixture.

This study is a follow up to the earlier study. The objectives are to further investigate: 1) the performance of the fine graded mixtures with 70% of CALUW within the Bailey recommended limits. The 70% of CALUW is chosen because it is the upper limit of the Japanese preferred job mix gradation bands; 2) to examine the effect of the Bailey ratios on VMA, because it was not exam-

ined in detailed in earlier study. An analysis of the HND mixture was also carried out to better know the packing characteristic of HND aggregates. It is expected that the information obtained in this study is a useful reference for establishing the Japanese Superpave job mix formula gradation.

2. Overview of Bailey method

The overview of Bailey method is described as follows so that the reader is familiar with the terminology. In 2002, a *Transportation Research Board* (TRB) issued a circular on a method of gradation design and analysis called the Bailey method (Vavrik *et al.* 2002). It is used to design and evaluate the aggregate interlock and packing characteristics of a gradation based on VMA. The Bailey method has 4 control sieves to split the aggregates into coarse and fine aggregates, namely half sieve (HS), primary control sieve (PCS), secondary control sieve (SCS) and tertiary control sieve (TSC). The method determines coarse aggregate as those particles that create voids and fine aggregate as those particles that fit into the voids created by the coarse aggregates. The definition of coarse and fine aggregates is based on primary control sieve (PCS) and is dependent on the nominal max particle size (NMPS) of the mixture. The PCS is estimated as the closest sieve to the result of $0.22 \times$ NMPS. The value of 0.22 was determined from a two-dimensional and three-dimensional analysis of the packing of different shaped particles. The Bailey method uses 0.22 to further separate the fine fraction. The SCS is defined the sieve closest to 0.22 of the PCS. It splits the fine aggregates into coarse sand and fine sand. The TCS is defined as the sieve closest to 0.22 of the SCS. The TCS splits the fine part of the fine fraction similarly.

A gradation curve is controlled by the aggregate ratios which are also referred as the Bailey ratios. These ratios are calculated using the above mentioned four designated control sieves. For a coarse graded gradation, three aggregate ratios, namely coarse aggregate ratio (*CA*), fine aggregate ratio of coarse portion (*FA_c*) and fine aggregate ratio of the fine portion (*FA_f*), are given to analyze the packing of the combined aggregates. The *CA* ratio is used to design and evaluate the packing of the coarse fraction and the resulting voids structure. FA_c ratio and FA_f ratio are used to design and evaluate coarse part of fine fraction (below PCS) and the fine part of fine fraction respectively. In a fine graded mixture, the coarse aggregates are regarded as floating between the fine aggregates. New *CA* and new *FA* ratios are used to evaluate the fine gradation curve.

To govern the volumetric data, a mixture is evaluated based on volume. The Bailey method uses three governing unit weights to determine the volumetric data at specific voids structure. Three unit weights, namely 1) the loose unit weight (LUW); 2) the rodded unit weight (RUW) and 3) the chosen unit weight of coarse aggregate (CACUW). LUW represents a state of the aggregate when no compaction effort has been applied. RUW represents a state of the aggregate with some compaction effort. CACUW indicates the volume of coarse aggregates in the blend. As the CACUW increases, the blend becomes coarser and vice versa. Therefore, the CACUW determines the types of mixture and the level of the aggregate interlock. For a dense graded mixture, the CACUW refers to a percentage of loose unit weight of coarse aggregate (CALUW). In a coarse graded mixture, coarse aggregate interlock plays a significant role in resisting deformation. The lower limit of the aggregate interlock is at 100% of CALUW (coarse graded) and the upper limit of the aggregate interlock is at 110% of CALUW. In a fine graded mixture, the fine aggregates play the role in resisting the deformation. For a fine graded mixture, the CALUW is less than 90%.

The effects of these parameters on the VMA value are showed in Table 1. To increase the VMA of the mixture, the designer can increase the volume of coarse aggregate, to increase the *CA* ratio or to decrease the *FA* ratios. According to Bailey principles, each parameter acts individually to change the VMA. If one of the parameters causes the changes in opposite direction, the result may have the net effect. It is a general understanding that decrease the VMA in the mixture, which in turn will decrease air voids, may lead to reduce the effective asphalt content and consequently rutting will be reduced.

The TRB circular has provided the recommended Bailey ratios for each NMPS. However the recommended ranges are mainly based on the aggregate source in US. Furthermore, the recommended ranges for fine graded mixture are uncertain. Thus, some studies are required to determine the parameters based on the local aggregates for local application.

3. Analysis of HND mixture

Table 2 shows the job mix gradation limits for 19 mm NMPS and the sieve size distributions of the HND Marshall mixture. The Superpave mixture using the same HND gradation and same compaction effort had a low VMA of 12.8%. To better know how to increase the VMA based on the same compaction effort, the authors reviewed the mixture design using the Bailey method. Since the HND mixture is a fine graded, the evaluation consists two parts: 1) to evaluate the blend based on original *CA* and *FA* ratios and 2) to evaluate the combined blend below the original PCS as an entire blend by itself with new *CA* and *FA* ratios. The CALUW for the job mix control envelopes of Japanese Marshall Specification ranges between 70% and 80%. The CALUW of current HND mixture was at 71%. Table 3 summarizes the recommended limits of Bailey ratio for 19 mm NMPS and the Bailey ratios of the HND mixture.

In the Bailey method, particles retained on half sieve (HS) are called plugger. Particles passing through HS but retained on PCS are referred to as interceptors.

Table 1. The effects of Bailey principles on VMA

Parameters	To increase VMA	To decrease VMA
CALUW	Increase (for coarse graded mixture) Decrease (for fine graded mixture)	Decrease (for coarse graded mixture) Increase (for fine graded mixture)
CA / New CA	Increase ratio	Decrease ratio
FA_c / New FA_c	Decrease ratio	Increase ratio
FA_f / New FA_f	Decrease ratio	Increase ratio

Table 2. The job mix gradation limits for 19 mm NMPS and the sieve size distributions of the HND mixture

Sieve	Percent of passing by weight, %								
	25.0 mm	19.0 mm	13.0 mm	4.75 mm	2.36 mm	600 μm	300 μm	150 μm	75 μm
19 mm NMPS	100	100–95	90–75	65–45	50–35	30–18	21–10	16–6	8–4
HND	100	97.3	78.9	55.5	39.9	28.4	16.6	8.3	5.7

Table 3. The Bailey ratios of the HND mixture

Bailey items	% CALUW	PCS	CA	FA_c	FA_f	New CA	New FA_c	New FA_f
Recommended limits	N/A	N/A	0.60–0.75	0.35–0.50	0.35–0.50	0.60–1.00	0.35–0.50	0.35–0.50
HND	71	55.5	0.48	0.60	0.50	0.44	0.50	0.34

Note: N/A – not applicable.

The interceptor-sized particles increase voids in the mixture because they are too large to fit into the voids created by the plugger-sized particles. They also prevent the plugger particles both from packing together and from packing the fine fraction. The ratio of the percent passing of interceptor to plugger is defined as the *CA* ratio (Vavrik *et al.* 2002). Based on the Bailey calculation, the HND mixture had 44.5% of the aggregate structure retained on the original PCS (4.75 mm). The 44.5% of the aggregates was split into 14.5% of interceptor-sized particles and 30% of plugger-sized particles. The *CA* ratio was calculated at 0.48. According to the literature a balance in the coarse portion of aggregate structure will have a *CA* ratio of 0.40 to 0.80 (Vavrik *et al.* 2001). This indicated that the HND mixture has an almost balance coarse aggregate structure although it is not within the recommended range of *CA* ratio (Vavrik *et al.* 2002).

Evaluation of the coarse portion of the fine aggregate within the aggregate structure was carried out using the SCS. The ratio of the coarse portion of the fine aggregate to the total fine fraction is determined to as *FA_c* ratio. The *FA_c* ratio was 0.60 which was not within the recommended range. It indicated that the mixture contained an excessive amount of fine portion of the fine aggregate (Vavrik *et al.* 2002). The volume of the fine aggregates passing over new PCS (1.18 mm) was greater than the volume of voids that exist between the new coarse fraction between 4.75 mm and 1.18 mm. The gradation curve had a hump in the fine portion (1.18 mm) which could be a potentially tender mixture. The fine portion of the fine aggregate within the structure was evaluated using the TCS. The ratio of the fine portion of the fine aggregate to the total fine fraction is determined by the *FA_f* ratio. The *FA_f* ratio was calculated at 0.50, which was within the upper limit of the recommended range. The slightly low *CA* ratio and both high *FA* ratios indicated the mixture would have a low VMA.

The new *CA* ratio only dealt with 22.8% of the total fraction (below the PCS). The new *CA* ratio was calculated at 0.44 which was falling outside of recommended range. The low new *CA* ratio indicated fewer interceptors and would result in a low VMA. The high new *FA_c* ratio of 0.50 was the upper limit of the recommended range and the low new *FA_f* ratio of 0.34 was slightly lower than the recommended range of 0.35. According to the literature, high new *FA_c* ratio works well with the low new *FA_f* ratio (Vavrik *et al.* 2002). Therefore the low VMA might be a bit mitigated. Based on the evaluation, the VMA of HND mixture can be increased by decreasing the *FA* ratios.

4. Experimental work

To ascertain the application of Bailey method for gradation design in Superpave mixture design with the local HND aggregates. This study examines: 1) whether the current recommended Bailey limits can be adopted directly without any adjustment with local aggregates; if not, 2) what is the recommended ranges and 3) the accuracy of the Bailey estimate to predict the VMA. An experiment was set up to carry out the following tasks: 1) to develop a series of aggregates blends varying within the limits of the recommended Bailey ratios; 2) to decide the design asphalt content of the Superpave Specimens at 4% of air voids and to compact the mix-

ture using Superpave gyratory compactor (SGC) with the N_{des} of 105 (Goh *et al.* 2011a); 3) to evaluate the mixture performance of Superpave specimens with APA. The testing temperature of APA was 60 °C, which is the standard testing temperature for rutting potential of the Japanese conventional method.

Fig. 1 shows the workflow of the experimental work. An excel worksheet was used to calculate Bailey ratios for each mixture. The sieve distribution data, bulk and apparent specific gravity, the LUW and RUW of each aggregate were input in the excel worksheet. The chosen unit weight of coarse aggregate (CACUW) was set at 70% of loose unit weight of coarse aggregate (CALUW). The first step was to calculate the voids created by each coarse aggregate and the amount of each fine aggregate to fill the voids for each blend. The volume of coarse and fine aggregates was adjusted in order to obtain the desired Bailey ratios. After obtaining the desired Bailey ratios, the final aggregate percent passing the sieve sizes could be calculated. Then, the air voids and VMA of mixture was estimated based on the first initial specimen. In this case, the data of mixture F3 that had 70% of CALUW in the earlier study was used as the initial specimen for calculating the estimated asphalt content (AC), air voids and VMA (Goh *et al.* 2011a, 2011b). The asphalt content of each specimen was determined based on the estimated air voids at 4%. The procedure to decide the initial asphalt content has slightly deviated from the conventional trial and error Superpave procedure. After that, specimens were made and the density of the specimens was measured. The actual air voids and VMA of the specimens were calculated.

To cover all the recommended upper and lower limits of the 6 Bailey ratios, there were $2 \times 2 \times 2 \times 2 \times 2 \times 2 = 64$, possible blend combinations could be considered. Some blends were eliminated for practical reasons considering the findings in the past studies (Vavrik *et al.* 2002). For example, the combined blend with low values for both *FA* ratios is avoided, as it may produce instability mixture. It shows a belly curve in the 0.45 power chart. *S* shaped gradation with high *CA* ratio in Superpave is also avoided, because it may be difficult to compact in the field. The blends were reduced to 10 aggregate gradations. Table 4 tabulates the size distributions of the blends, their Bailey ratios and the estimated values of VMA. Since all the blends are fine graded, the evaluation on the change of the Bailey ratios was firstly focused on the new *CA* ratio and new *FA* ratios. Most of the gradation curves were designed at the upper limits of new FA_c ratios (0.50) except M9 and M10. This was considered as the worst-case scenario. Mixture with high new FA_c ratio is expected to have low VMA. In this study, the new FA_c ratio was so happen to be the same value as the FA_f ratio. All gradations are plotted on the standard 0.45 power chart as shown in Fig. 2.
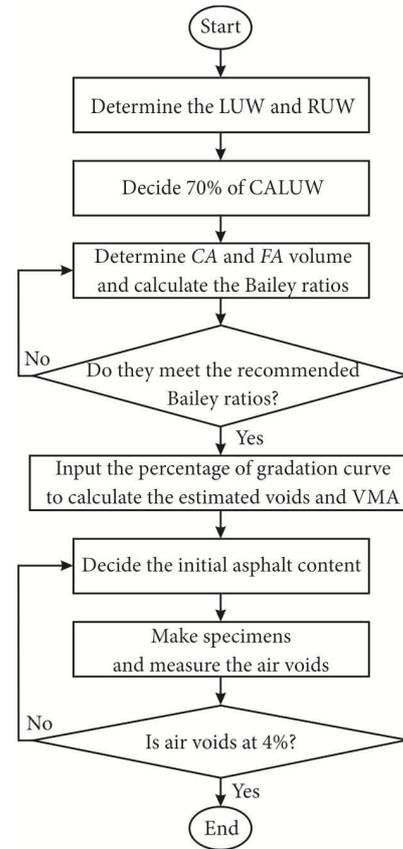

Fig. 1. The workflow of the experiment

It is important to determine whether the changes in VMA of HND aggregates will follow the direction of Bailey principles. Thus, M1, the baseline blend was designed with the lower limit of *CA* ratio with upper limit of *FA* ratios and lower limit of new *CA* ratio with upper limits of new *FA* ratios in a way that the mixture would have the lowest VMA in this study. The Bailey ratios for the subsequent mixtures were changed from M1. M2 and M3 had the same values of the *CA* ratio and *FA* ratios. The difference between the M1 and M2 was the change of new FA_f ratio from 0.50 to 0.35. The difference between M1 and M2 was the change of the new *CA* ratio from 0.60 to 1.02 and the new FA_f ratio from 0.50 to 0.35. The difference between M1 and M4 was the change of FA_c ratio from 0.50 to 0.47. The difference between M1 and M5 was the change of FA_c ratio from 0.50 to 0.39 and the new FA_f ratio from 0.50 to 0.41. The difference between M1 and M6 was the change of *CA* ratio from 0.60 to 0.75. The difference between M1 and M7 was the *CA* ratio from 0.60 to 0.75 and new *CA* ratio from 0.60 to 1.01. The difference between M1 and M8 was the *CA* ratio of 0.60 to 0.75 and FA_c ratio from 0.50 to 0.38. M9 and M10 were the blends with change of all ratios. M10 had the mid values of the six Bailey recommended limits. With this arrangement, the changes in VMA of each mixture could be seen clearly.
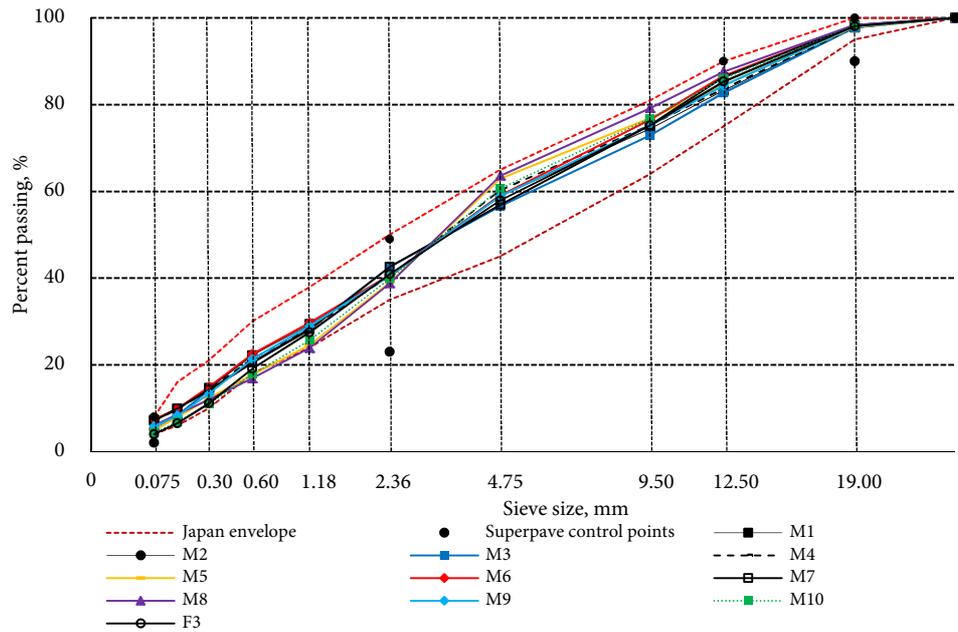
Fig. 2. The gradation curves of the mixtures in this study

Table 4. The size distributions of the blends, their Bailey ratios and the estimated values of VMA

Sample	F3	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
19.0 mm	98.1	97.8	97.8	97.7	97.8	97.9	98.3	98.3	98.4	98.0	98.2
12.5 mm	85.3	83.2	83.3	82.7	83.7	84.5	86.6	86.3	87.6	84.4	86.0
9.5 mm	75.2	74.5	74.4	72.9	75.3	76.9	76.5	75.3	79.2	75.2	76.8
4.75 mm	57.9	59.2	58.9	56.6	60.3	62.9	59	56.9	63.6	58.9	60.6
2.36 mm	40.9	40.6	40.4	42.6	40.5	39.0	40.7	42.6	38.8	40.6	39.9
1.18 mm	27.5	29.4	29.2	28.3	28.5	24.6	29.7	28.2	23.9	28.9	25.7
0.600 mm	19.1	22.2	22.2	20.6	21.4	17.7	22.5	20.5	16.9	21.3	17.8
0.300 mm	11.1	14.7	14.5	14.1	14.3	12.3	14.9	14.2	12.0	13.3	11.0
0.150 mm	6.5	9.8	8.1	8.3	9.7	7.9	9.9	9.9	8.6	8.2	6.8
0.075 mm	4.0	7.3	5.1	5.0	7.2	5.0	7.4	7.1	6.0	5.8	4.3
CA (0.60–0.75)	0.70	0.60	0.61	0.60	0.61	0.61	0.75	0.75	0.75	0.66	0.70
FA_c (0.35–0.50)	0.48	0.50	0.50	0.50	0.47	0.39	0.50	0.50	0.38	0.49	0.42
FA_f (0.35–0.50)	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.46	0.43
New CA (0.60–1.00)	0.79	0.60	0.61	1.02	0.61	0.60	0.60	1.01	0.60	0.64	0.69
New FA_c (0.35–0.50)	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.46	0.43
New FA_f (0.35–0.50)	0.36	0.50	0.35	0.35	0.50	0.41	0.50	0.50	0.50	0.44	0.39
Change in PCS	0.0	0.2	0.2	−0.2	0.4	0.8	0.2	−0.2	1.0	0.2	0.5
Change in new CA	0.0	−0.5	−0.5	0.7	−0.5	−0.5	−0.5	0.6	−0.5	−0.4	−0.3
Change in new FA_c	0.0	−1.9	−1.9	−1.9	−2.0	−1.9	−2.0	−2.0	−2.0	−1.1	−0.5
Change in new FA_f	0.0	−2.7	0.2	0.1	−2.9	−0.9	−2.7	−2.8	−2.8	−1.5	−0.6
Total changes	0.0	−5.0	−2.0	−1.3	−4.9	−2.5	−5.0	−4.3	−4.3	−2.9	−0.9
Estimated VMA, %	14.0	9.0	12.0	12.7	9.1	11.5	9.0	9.7	9.7	11.1	13.1

The estimated VMA of M1 was predicted from the VMA of F3. F3 was the mixture design with 70% CALUW in the earlier study (Goh *et al.* 2011a, 2011b). The TRB circular has suggested some percents to affect 1% change in VMA for a coarse graded mixture; however no information is given for a fine graded mixture. The study used the suggested percents by past researchers, Aurilio *et al.* (2005) and Gierhart (2007). Both suggested the same percents to affect 1% change in VMA for the fine graded mixture. The percents for each parameter are as follows:

1. 6.00% changes in the original PCS affects 1% change in VMA;

2. 0.35 change in the new CA ratio affects 1% change in VMA;

3. 0.05 change in the new FA_c ratio affects 1% change in VMA;

4. 0.05 change in the new FA_f ratio affects 1% change in VMA.

The Eqs (1)–(4) was the calculations to estimate the change due to the PCS and each new ratio of each mixture compared with F3. The change in PCS and each new Bailey ratio of each mixture was divided by the above percents. Below is the sample calculation to show how to estimate the VMA of M1.

Change in PCS

$$= \frac{M1(4.75 \text{ mm}) - F3(4.75 \text{ mm})}{6\%}, \qquad (1)$$

where M1 (4.75 mm) and F3 (4.75 mm) – the percent passing the 4.75 mm sieve size of M1 and F3 respectively.

Change in new CA

$$= \frac{M1(\text{new } CA) - F3(\text{new } CA)}{0.35}, \qquad (2)$$

where M1 (new CA) and F3 (new CA) – the new CA ratio of M1 and F3 respectively.

Change in new FA_c

$$= \frac{M1(\text{new } FA_c) - F3(\text{new } FA_c)}{0.05}, \qquad (3)$$

where $M1$ (new FA_c) and F3 (new FA_c) – the new FA_c ratio of M1 and F3 respectively.

Change in new FA_f

$$= \frac{M1(\text{new } FA_f) - F3(\text{new } FA_f)}{0.05}, \qquad (4)$$

where M1 (new FA_f) and F3 (new FA_f) – the new FA_f ratio of M1 and F3 respectively.

Compared M1 with F3, increase in the percent passing the PCS increased the VMA. Decrease in the CA ratio and new CA ratio decreased the VMA. Increase in

the FA ratios and new FA ratios also decreased the VMA, therefore the net change was – 5%. The estimated VMA of M1 was equal to the actual VMA of F3 plus the net change. Thus, the estimated VMA was 9%. According to the estimation, all mixtures could not meet the VMA requirement except M10. It means that the current recommended upper and lower limits of the Bailey ratios are not appropriate for the HND aggregates. It was noted that M6 had the same estimated value of VMA as M1. The change in CA ratio was not captured in the estimation.

5. Results and discussion

Table 5 shows the volumetric properties and the rut depths of the compacted specimens for all blends. The VMA values ranged from 10.8% to 14.8% and the rut depth ranged from 2.72 mm to 4.39 mm. M10 was the only blend that satisfied all the Superpave requirements. M10 had a VMA value of 14.3% and a rut depth of 2.88 mm. It means that the selection for the best possible blend could be at the mid values of recommended ranges for all six Bailey ratios. M6 had the lowest VMA value. The mixture had the upper limit of CA ratio, FA ratios, lower limit of new CA and upper limit of new FA ratios. This combination is not recommended as it has low CA and low VMA. High FA ratios and new FA ratios indicate that an increase in volume of the fine portion of fine aggregates. As these ratios increase, the fine aggregates packed together tighter and increased the packing density. This condition caused a decrease in the voids in overall structure. Compared M6 with M1, M6 with a higher CA ratio had the gradation curve of coarse aggregate portion finer than M1. It contained less large plugger-size particles and more interceptor-sized particles than that in M1. Therefore, its VMA was slightly lower than M1. According to the Bailey principles, an increase in the CA ratio will increase the VMA (Vavrik *et al.* 2002). It deviated from the general Bailey principles, in which an increase in the CA ratio caused a slight decrease in VMA. The designers need to be noted especially for designing the fine graded mixture with 70% of CALUW.

Table 5. The properties of Superpave mixtures and APA results

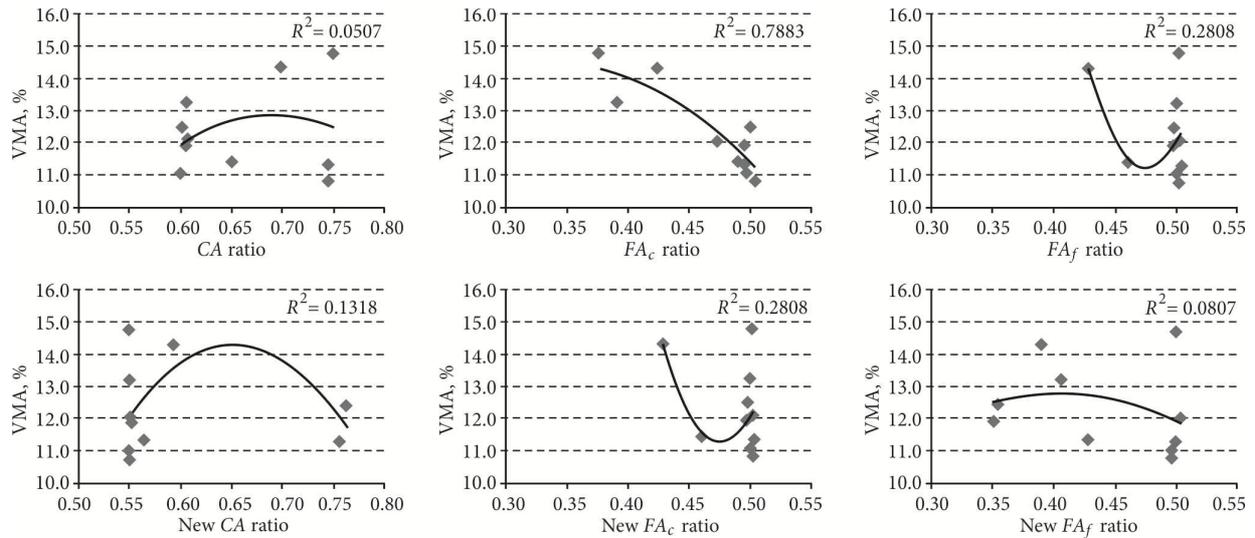| Blend	OAC, %	Gmb, g/cm³	VMA, %	VFA, %	D/B ratio	Compliance with Superpave	Rut, mm
M1	3.9	2.453	11.0	64.9	2.4	No	3.08
M2	4.4	2.438	11.9	67.9	1.5	No	3.16
M3	4.8	2.429	12.5	66.5	1.4	No	4.33
M4	4.4	2.438	12.0	66.0	2.1	No	3.08
M5	4.9	2.418	13.2	69.1	1.3	No	3.16
M6	3.7	2.455	10.8	62.0	2.6	No	2.95
M7	4.1	2.448	11.3	64.6	2.3	No	2.41
M8	5.7	2.397	14.8	71.3	1.3	No	4.39
M9	4.0	2.442	11.4	64.5	1.8	No	2.72
M10	5.5	2.400	14.3	73.1	0.9	Yes	2.88

Fig. 3. The Bailey ratios versus VMA

Table 6. The difference in VMA due to change in the new Bailey ratios and percent passing the PCS

Difference between blends	M1-M2	M1-M3	M1-M4	M1-M5	M1-M6	M1-M7	M1-M8	M1-M9	M1-M10	M2-M3	M6-M7	M6-M8
Difference in PCS	−0.30	−2.60	1.10	3.70	−0.20	−2.30	4.40	−0.30	1.40	−2.30	−2.10	4.60
Difference in new CA	0.00	0.42	0.00	0.00	0.00	0.41	0.00	0.04	0.08	0.42	0.41	0.00
Difference in new FA_c	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.07	0.00	0.00	0.00
Difference in new FA_f	0.15	0.15	0.00	0.09	0.00	0.00	0.00	0.06	0.11	0.00	0.00	0.00
Change in PCS	−0.05	−0.43	0.18	0.62	−0.03	−0.38	0.73	−0.05	0.23	−0.38	−0.35	0.77
Change in new CA	0.01	1.20	0.01	0.00	0.00	1.16	0.00	0.11	0.24	1.19	1.16	0.00
Change in new FA_c	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80	1.44	0.00	0.00	0.00
Change in new FA_f	2.90	2.94	0.00	1.80	0.00	0.00	0.00	1.22	2.12	0.00	0.00	0.00
Total net change	2.86	3.70	0.19	2.42	−0.04	0.77	0.73	2.08	4.03	0.81	0.81	0.77
VMA of blend M1/M2/M6 (A)	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.9	10.8	10.8
VMA of other blends (B)	11.9	12.5	12.0	13.2	10.8	11.3	14.8	11.4	14.3	12.5	11.3	14.8
Difference in VMA, %, (B–A)	0.90	1.50	1.00	2.20	−0.20	0.30	3.80	0.40	3.30	0.60	0.50	4.00
Change in a predicted direction	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The results indicated that the mixtures with the recommended upper and lower limits of Bailey ratios could not meet the Superpave requirements although they did produce better rutting resistance mixtures than the original HND Marshall mixture. The present Bailey recommended limits have to be adjusted to a narrow range in order to meet Superpave requirements. Fig. 3 illustrates the effect of the six Bailey ratios on VMA. Based on the charts, to have 13% of VMA, the tendency for the CA ratio, FA_f, FA_f, new CA, new FA_c and new FA_f should be selected from 0.60 to 0.70, 0.35 to 0.45, 0.35 to 0.44, 0.70 to 0.90, 0.35 to 0.44, and 0.38 to 0.43 respectively.

The FA_c ratio had the highest correlation with VMA even though the mixtures were fine graded. The trend indicated that the VMA decreased with an increase in the FA_c ratio. This is in the agreement with the Bailey principle. Most of the FA_f ratio or new FA_c ratio were prefixed at 0.5, thus the trend line for FA_f ratio lower than 0.4 could not be seen. The new CA ratio chart indicated that once the new CA ratio increased beyond 0.8, VMA began

to decrease. It means that as the new CA value exceeds 0.8, the interceptors-size particles of fine aggregate start to dominate the coarse fraction of fine aggregate portion and caused a decrease in VMA. The CA ratio was expected to have the lowest correlation with VMA, because the coarse particles floated in fine aggregates.

This study also examined whether the change of the actual VMA follows the direction predicted by the Bailey principles. Each mixture was compared with M1 respectively. M3 was further compared with M2; M7 and M8 were further compared with M6. Table 6 tabulates the difference in percent passing the PCS, each new Bailey ratio and the change in VMA values. In general, the VMA changes were in the predicted direction of each Bailey principles except for M6. However, with fine graded mixture, the change of each original Bailey ratio is not included in the calculation; it only captures the change by PCS. Therefore, the changes cannot be seen based on present evaluation method. The authors are of the opinion that the change of each original Bailey ratio should be included for more accurate estimation.

Table 7. The difference between an estimated VMA and the actual VMA

Blend	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Actual VMA	11.0	11.9	12.5	12.0	13.2	10.8	11.3	14.8	11.4	14.3
Estimated VMA	9.0	12.0	12.7	9.1	11.5	9.0	9.7	9.7	11.1	13.1
Difference in VMA	2.0	–0.1	–0.2	2.9	1.7	1.8	1.6	5.1	0.3	1.2
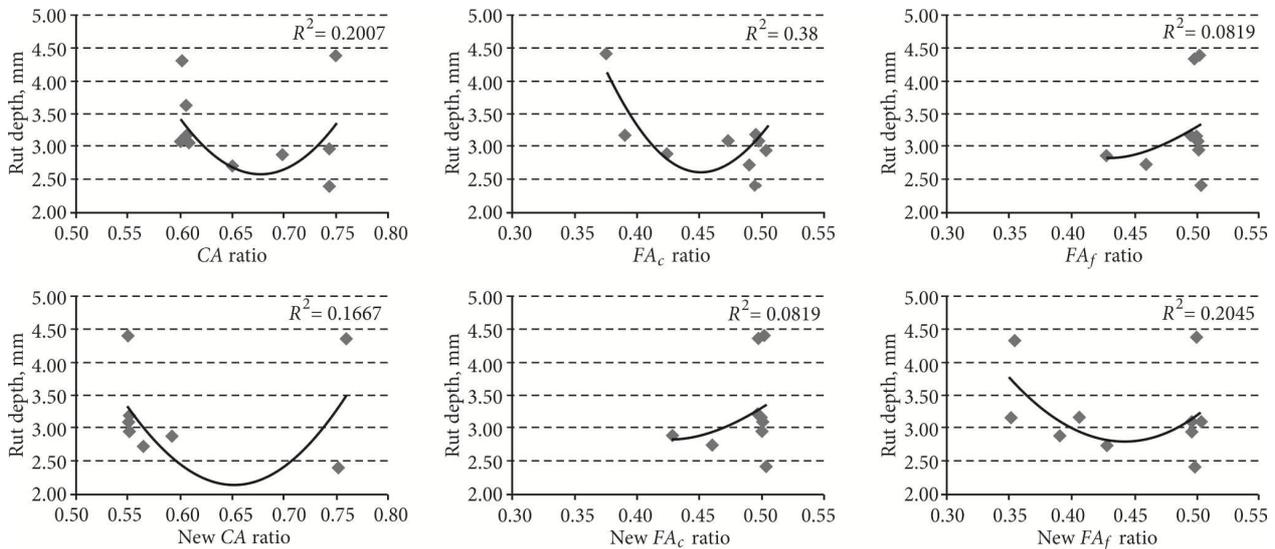
Fig. 4. The Bailey ratios versus rut depths

It was observed that when the *CA* ratio and the *FA* ratios were kept constant (M1–M3), the total change in the new Bailey ratios and percent passing the PCS of 3.70 only affected 1.5% in VMA. In vice versa, when the new *CA* and new *FA* ratios were kept in constant (M6–M8), the total change in original *CA* and *FA* ratios and PCS of 0.77 affected 4.0% change in VMA. It means that although the mixtures are fine graded, the original Bailey ratios seem to be a strong indicator for VMA evaluation instead of the new Bailey ratios. Based on the differences in VMA between M1 and M2, M2 and M3 and M1 and M3, the change by altering the new *CA* ratio (M1–M2), the new FA_f ratio (M2–M3) and both *CA* and FA_f ratio (M1–M3) were insufficient to obtain the desired VMA.

To evaluate the accuracy of the Bailey estimation on VMA based on an initial trial sample, the comparison between the actual and estimated VMA for each mixture was made. The difference is given in Table 7. The variance is from –0.2% to 5.1%. Three mixtures namely, M2, M3 and M9 had accurate estimation. The estimated VMA values of other mixtures were out. Two reasons that might be affecting the estimation: 1) the suggested percent to change 1% of VMA was not appropriate for HND aggregates. It indicates that the suggested factors need adjustment to reflect the actual source of HND; 2) the change of each original Bailey ratio was not captured in the calculation. This is potentially subject for future study. Shen and Yu (2011) and Yu (2012) developed a model for simulating the angularity properties of

aggregate particles using the Bailey method. Their studies showed that the actual VMA values were very close to estimated VMA values.

Fig. 4 shows the analysis of each Bailey ratios on rut depth. The data was analyzed to compare with the six Bailey ratios. In general, all the data did not show a high correlation with rutting. Among these ratios, the FA_c ratio had the highest correlation with rut depth. The rut depth decreased with an increased in FA_c ratio. FA_f ratio was the second highest correlation with rut depth. A hyperbolic relationship was obtained and the lowest rut depth could be seen between the ranges of 0.65 to 0.70. The new *CA* ratio and new *FA* ratios showed less sensitive on the rutting resistance. The curve was almost flat. This indicates the original Bailey ratios have strong influence on rut depth.
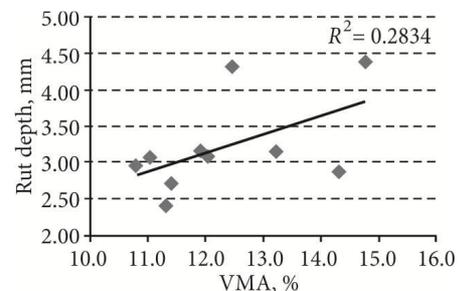

Fig. 5. The VMA versus rut depth

Fig. 5 illustrates the conventional method to evaluate the relationship between VMA and the rut depth for this

study. The rut depth increased with an increase in VMA. However, it showed a moderate correlation between the VMA and rut depth. Comparing the correlation of the Bailey ratios versus VMA with the Bailey ratios versus rut depth, it seems that the Bailey ratios have more effect on the VMA rather than that on rut depth. The selection of Bailey ratios significantly controls the VMA but less influence on the performance of mixture. One reason is that the mixtures are in the same CALUW and only have minimal changes on the degree of aggregate interlock.

6. Conclusions

This study has proven that the Bailey method is a useful tool to alter the VMA of a mixture. The gradation design process with the Bailey method allows mix designer to control the gradation curve and make a rational decision to enhance the desired VMA of the mixture. The results of the study have shown that that the gradation close to the recommended Bailey limits could not meet the Superpave requirements. The conclusions of this study are summarized as follows:

1. With 70% of CALUW, the current recommended upper and lower limits of the Bailey ratios are not appropriate for the HND aggregates. Adjusting the recommended limits to a narrow range is required. In order to comply with the Superpave VMA requirement, the suggested range for CA ratio is 0.60–0.70 and that for the FA_c ratio and FA_f ratio are from 0.35 to 0.45 and 0.35 to 0.44, respectively. The new CA ratio should be selected from 0.70 to 0.90 and that for the new FA_c ratio and new FA_f ratio are from 0.35 to 0.44 and 0.38 to 0.43, respectively.

2. The best possible range of aggregate gradation is recommended to design at the mid values of the recommended limits of the Bailey ratios because it will have more continuous gradation curve to produce adequate VMA and low rut depth mixture.

3. The results showed that although they were fine graded mixtures, the CA ratio and FA ratios had more influence on the VMA and rut depth. Therefore, the alteration of VMA by changing the new CA ratio and new FA ratios is inadequate to obtain the desired volumetric properties.

4. In this study, the vary of VMA is 4.8% at the same CALUW, however the vary of rutting resistance is less than 2 mm. Therefore, the Bailey ratios have more effect on VMA rather than that on performance.

5. The accuracy of Bailey estimation to predict the VMA is poor especially for those blends involving some changes in CA ratio and FA ratios. Further study is needed to determine a method for estimating the change. The changes in CA ratio and FA ratios are recommended to be included as part of the calculation.

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