Crack Initiation Assessment of Wearing Course Asphalt Mixtures Using Aggregate Gradation Characteristic

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Abstract. At normal service temperatures, wearing course asphalt mixtures may have ductile cracking. Aggregate gradation characteristic is important to avoid the premature cracking. The present study discusses a relationship between the characteristic of aggregate gradation and crack resistance of wearing course mixtures. Asphalt mixture specimens were prepared using different types of aggregate gradation. The Bailey method was employed in order to recognize the characteristic of aggregate gradations. Notched semi circular bending test was conducted to obtain the critical J integral (J_c). The coarse aggregate (CA) ratio and the fine graded fine aggregate coarse (FG FA_c) ratio defined by the Bailey method were introduced to recognize the effect of aggregate gradation type on J_c. The result was decreasing the J_c value with increasing the CA ratio and FG FA_c ratio. Satisfying the current Bailey criterion on the CA ratio for stone mastic asphalt mixtures and setting FG FA_c of fine graded HMA mixtures near 0.4 seem useful in order to obtain HMA mixtures with a high J_c. The present study also discusses spherical aggregates assembly models as an aid to illustrate development of the aggregates interlocking, which influences to the cracking.

Keywords: *asphalt mixtures; cracking; aggregate gradation; critical J integral.*

1 Introduction

At normal service temperatures, wearing course asphalt mixtures may have ductile cracking [1]. Mobasher et al [2] separated the cracking development within hot mix asphalt (HMA) into two stages, namely cracking initiation and cracking propagation. Asphalt researchers have suggested the critical J integral (J_c) as a cracking potential indicator. The property of J_c illustrates the accumulated energy necessary to develop a new crack in HMA mixture. A greater J_c value indicates a higher resistance to the cracking [3]. However, fracture scientists usually use J_c in order to mainly evaluate initiation of ductile cracking [4].

Interlocking of aggregates is one of possible factors delaying the cracking development within asphalt mixtures [2]. Aggregates interlocking can be achieved when the backbone aggregates contact each other. Stone and coarse sand particles may act individually or cooperatively as the backbone aggregates supporting traffic loads. It means that aggregates interlocking depend on aggregate gradation. Hence, it is necessary to discuss a relationship between aggregate gradation characteristic and cracking resistance of asphalt mixtures. The relationship should be useful to obtain a simple criterion for a stable aggregate gradation with adequate crack resistance.

This study aims to discuss a relationship between aggregate gradation characteristic and cracking resistance of wearing course mixtures. HMA specimens were prepared with six types of aggregate gradation. The notched semi circular bending (SCB) beam test was carried out to obtain J_c. The Bailey method was introduced to evaluate characteristics of each aggregate gradation. This study introduced the spherical aggregates models as an aid to understand the effect of aggregates gradation on aggregate interlocking of the HMA mixture, which considerably influences to the cracking. This study proposed simple criteria from the aggregate gradation characteristic for indicating crack resistance of HMA mixtures. The criteria can be useful to early identify crack potential of wearing course mixtures in asphalt pavements.

2 Relevant Particulars on The Study

Both asphalt and aggregates characteristics affect crack resistance of HMA mixture. Many researchers investigated influence of asphalt types on cracking resistance of HMA mixture. Generally, use of additives in asphalt is positive to increase crack resistance of HMA mixtures [2, 3, 5, 6]. On the other hand, influence of aggregate gradation characteristics have been investigated by only few researchers. Alshamsi reported that the coarser aggregate gradation, the higher crack resistance could be obtained [7]. However, fine gradation may improve tensile strength of HMA mixture which is very important to prevent crack failure of the mixture [8]. It seems that the mechanism on how aggregate gradation characteristics affecting crack resistance of HMA mixture is still unclear.

Van de Ven et al. [9] classified HMA mixtures into four groups based on aggregate skeleton types, namely real stone skeleton, stone-sand skeleton, sand-stone skeleton and real sand skeleton. The stone skeleton mixture empirically requires stone content not less than 75% by total aggregate weight [10]. Van de Ven et al. [9] illustrated that stone particles in a stone-sand skeleton type could contact each other, and the space between stone particles was occupied by sand particles. Stone particles in a sand-stone skeleton type didn’t contact each other, but they floated in the sand matrix.

An asphalt mixture is an assembly of bitumen bound aggregates. Compressive stress (F_N) and tensile stress (F_T) are developed among the aggregates, when the asphalt layer is subjected to traffic loading [11]. The F_N makes adjacent aggregate particles to contact each other. On the other hand, the F_T may work to separate the particles away. When two contacting aggregates are completely separated away, a crack appears in the interface between those aggregates.

The present study assumes that spherical aggregates assembly models can illustrate structure of aggregate gradation and interlocking of aggregate particles. Figure 1 illustrates a micro-structural assembly of spherical aggregates, including F_N and F_T. Geometrical structure of the spherical aggregates determines the aggregates interlocking and configuration both F_N and F_T. The figure shows that small θ has a long interlocking length and a low F_T. The energy, which is required to create a new surface in the interface between two contacting aggregates, increases as the interlocking length is longer [12].

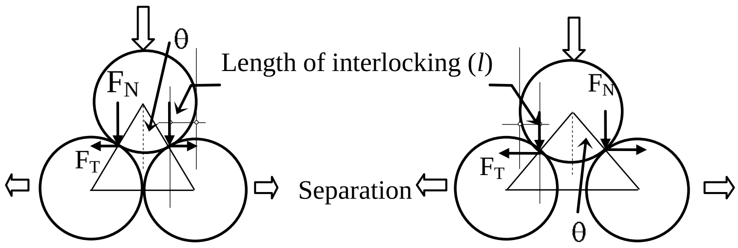


Figure 1 Microstructure of the spherical aggregates assembly [12].

Traffic load shall generate high tensile stress at the edge of a pneumatic tire in an asphalt surface [8]. HMA mixture contains air voids and flaws due to improper the material compaction. These defects are the crack tip having stress concentration when asphalt surface is subjected to the traffic load. A plastic deformation, which is a zone of degradation, appears ahead the crack tip due to the stress. The plastic deformation may be possibly formed by matrix deformation and micro cracking [13]. Micro cracks in the zone of degradation may coalesce and grow as macro-crack. Macro crack indicates that the weakening of the material takes place over a certain area. Further loads reduce the stiffness of HMA mixture, so the mixture towards having a structural failure [14]. Micro cracks increases, as the size of aggregates within HMA mixture is finer [15].

3 Characterizing Aggregate Gradation Using the Bailey Method

The Bailey method provides a rational guideline to analyze the characteristics of aggregate gradation for HMA mixtures. The Bailey method classifies aggregate particles within HMA mixtures into four types, namely stone, interceptor, coarse sand, and fine sand. Stone or coarse sand particles may act as the backbone aggregates supporting traffic loads. Primary control size (PCS) is used to recognize stone and coarse sand particles. Secondary control size (SCS) is used to recognize coarse sand and fine sand particles. Tertiary control size (TCS) is used to break fine sand particles into the coarser and the finer particles. Half size (HS) is used to recognize stone particles and interceptor. Interceptor is too large to fit into the voids created by the larger coarse aggregate particles. The Bailey method categorizes HMA mixtures into three types, stone mastic asphalt (SMA), coarse-graded, and fine-graded. Stone particles are the backbone aggregates for SMA and coarse graded mixtures. Coarse sand particles are the backbone aggregates for fine graded mixture. Gradation types of HMA mixtures can be evaluated using the Bailey criteria of CA, FA_c, and FA_f ratios. Here, CA is the coarse aggregate ratio, FA_c is the fine aggregate coarse ratio, and FA_f is the fine aggregate fine ratio. These ratios can be determined from HS, PCS, SCS, and TCS. The Bailey method provides the suggested range of the Bailey ratios, or called in the present study as the Bailey criteria, for each type of HMA mixture. The criterion for the CA ratio facilitates tight packing of stone particles. The criterion for the FA_c ratio facilitates tight packing of coarse sand particles and fitting of gaps among the stone particles. The criterion for the FA_f ratio avoids excessively fine sand particles. An aggregate gradation having the Bailey ratios outside the Bailey criteria may have excessive interceptors and/or fine sands. These excessive interceptors and/or fine sands may reduce the packing of backbone aggregates [16].

4 Experimental Works

Aggregate gradations used in the experimental work were designed by following the Indonesian standards and by considering the Bailey criteria [16] and the aggregate skeleton criteria [9]. Figure 2 illustrates the aggregate gradation curves, the Fuller curve, the restricted zone and the control points. A high quality coarse aggregate source was used to produce the aggregate gradations, i.e., it has angularity of 100/98, flakiness and elongation of 0.1%, Los Angeles abrasion value of 13.6%, and soundness of 1.7%. Table 1 shows the design properties of the HMA mixtures. Gradations 1 and 6 remained outside the control points. Both gradations were developed as new Indonesian wearing course mixtures in the present study. Gradation 6 contained a large fraction of manufactured sand. The blend consisted of 18% of crushed stone, 73% of screening, 5% of coarse sand, 2% of fine sand, and 2% of filler sources. Each reference number of the HMA mixtures indicates the corresponding number of the aggregate gradation.

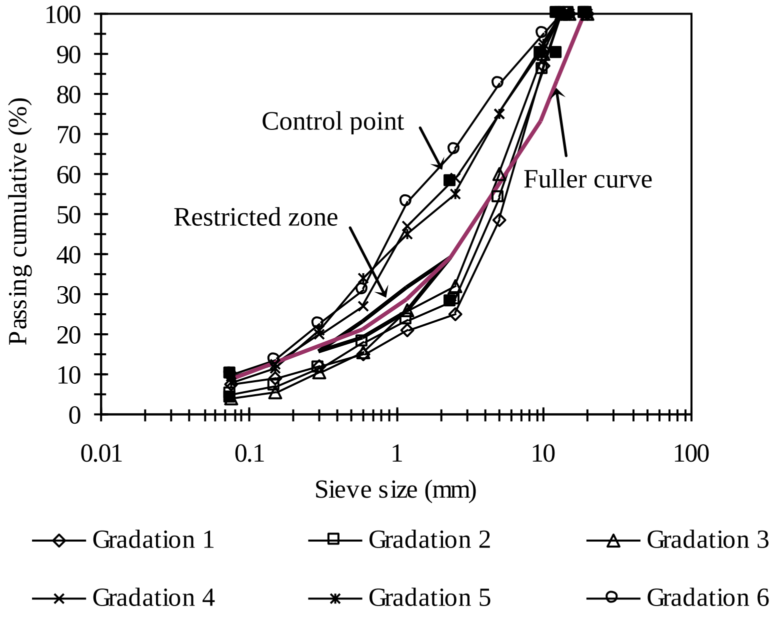


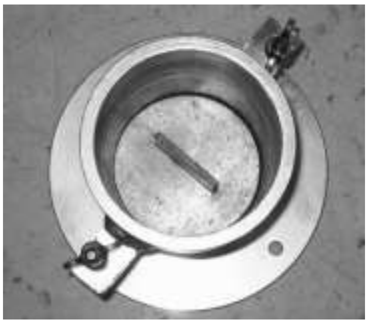
Figure 2 Aggregate gradations used in the present study.

Table 1 Properties of aggregate gradation and HMA mix design results.

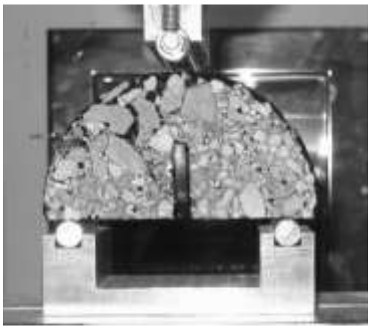
Mix	Stone content	Values of Bailey ratios			OAC[c]	Remarks
		CA	FA_c	FA_f	%	
1	75%	0.40	0.61	0.61	5.34	Full SMA stone skeleton
2	72%	0.48[a]	0.64[a]	0.38	5.83	Partial coarse graded stone-sand skeleton
3	68%	0.61	0.50	0.36	5.31	Full coarse graded stone-sand skeleton
4	41%	0.59	0.46	0.47	5.41	Full coarse graded sand-stone skeleton
5	45%	0.69[a]	0.63[a]	0.34	5.62	Partial coarse graded sand-stone skeleton
		FG CA[b]	FG FA_c[b]	FG FA_f[b]		
6	34%	1.67[a]	0.43	Not defined	5.37	Partial fine graded sand-stone skeleton

[a] Value of the Bailey ratio does not satisfy the Bailey criteria cited in [16]. [b] FG CA is CA ratio for fine dense graded mix, FG FA_c is FA_c ratio for fine dense graded mix, FG FA_f is FA_f ratio for fine dense graded mix [16]. [c] OAC is optimum asphalt content. In order to decide OAC, both the ordinary Marshall method and the modified Marshall method were employed. Following the Indonesian standard, the modified Marshall method is carried out by compacting each side of HMA specimens as many as 400 blows, in order the specimen reaches it's the ultimate air void [17].

Gradation 1 contained a high stone fraction (> 75%) and completely followed the Bailey criteria for SMA mixtures. As aforementioned, minimum stone content in stone skeleton mixtures is 75% [10]. Therefore, Gradation 1 was classified as a full SMA stone skeleton. The fraction of stone was higher than that of sand in Gradations 2 and 3, but Gradation 2 partially satisfied the Bailey criteria for coarse-graded stone-sand skeletons, while Gradation 3 fully satisfied the criteria. Therefore, Gradations 2 and 3 were classified as partial and full coarse-graded stone-sand skeletons, respectively. The fraction of sand was higher than that of stone in Gradations 4, 5, and 6. Gradation 4 fully met the Bailey criteria for coarse-graded stone-sand skeletons, while Gradation 5 partially satisfied the criteria. Gradations 4 and 5 were classified as full and partial coarse-graded sand-stone skeletons, respectively. Since Gradation 6 partially satisfied the Bailey criteria for fine-graded mixture, it could be classified as a partial fine-graded sand-stone skeleton.



(a) Marshall mould with the plate to create a notch



(b) The notched SCB test specimen and testing jig

Figure 3 Marshall mould with the plate to create a notch and a notched SCB HMA specimen set on the testing jig. [12]

Gradation 6 was comprised of a particularly large amount of manufactured sands, which included screenings and coarse sand. The screening and coarse sand appeared to become backbone aggregates, and the stone particles floated within the screening and coarse sand. The packing quality of the screening and coarse sand mostly affected the performance of Gradation 6. Since their packing could be evaluated by FG FA_c, satisfying only the FG FA_c requirement was adequate for Gradation 6 to obtain a good packing.

The notched SCB beam test was performed in order to measure J_c. The temperature and deformation rate of the test were selected at 30.0°C and 0.04 mm/s, respectively. The notched SCB HMA specimen was prepared using a Marshall mould with the special plate on the base. Two depths of notch (a), 15 mm (= a_1) and 22.5 mm (= a_2), were used in the test. Each specimen had 150 blows on the topside. The compacted specimen was split into two pieces by saw cutting. Figure 3 shows the Marshall mould with the plate to create a notch, and the notched SCB test specimen on the testing jig.

5 Data Analysis and Discussion

The following equation was used to calculate J_c [5].

$$J_c = \left(\frac{U_1}{b_1} - \frac{U_2}{b_2} \right) \frac{1}{a_2 - a_1} \tag{1}$$

where,

J_c : critical J integral (kJ/m^2).

U_1, U_2 : strain energy values (N.mm or 10^{-3} J) at failure obtained from a load deflection curve, for the specimens with the notch depth a_1 (mm) and a_2 (mm). The strain energy values are calculated from the beginning of the notched SCB beam test until the load reaches the peak value.

b_1, b_2 : thicknesses of the specimen (mm).

Table 2 shows the J_c properties of the HMA mixtures with six aggregate gradations. Figure 4 illustrates the relationship between the aggregate gradation characteristic and J_c. The present study uses CA ratio for recognizing the characteristic of SMA mixture and coarse graded mixtures, i.e., Mixtures 1 to 5. FG FA_c ratio is used to represent the characteristic of Mixture 6 as a fine graded HMA mixture. A tendency, namely decreasing J_c with increasing the CA ratio and the FG FA_c ratio, agrees with the one reported by previous researcher [7]. The high value of coefficient of determination (R^2) may indicate a strong correlation between the aggregate gradation characteristic, i.e., the values of CA ratio and FG FA_c ratio, and J_c. It means that the CA ratio can be effective to recognize J_c of the SMA mixture and the coarse graded HMA mixtures.

Table 2 Table 2 Values of J_c.

Specimen label	U_i^a (J)	b_i (mm)	$\frac{U_i}{b_i}$ (J/m)	Average of $\frac{U_i}{b_i}$ (J/m)	$J_c{}^b$ (kJ/m^2)
1Aa_1	0.316	45.6	6.80	9.22	0.761
1Ba_1	0.535	45.0	11.64		
1Aa_2	0.153	43.3	3.47	3.51	
1Ba_2	0.161	44.5	3.55		
2Aa_1	0.520	47.1	10.81	8.02	0.599
2Ba_1	0.252	47.2	5.22		
2Aa_2	0.145	45.6	3.12	3.52	
2Ba_2	0.181	45.2	3.92		
3Aa_1	0.193	43.6	4.35	5.13	0.229
3Ba_1	0.265	43.8	5.92		
3B$a_2{}^c$	0.155	44.5	3.42	3.42	
4Aa_1	0.505	44.6	11.09	7.89	0.232
4Ba_1	0.210	43.9	4.69		
4Aa_2	0.283	46.0	5.61	5.70	
4Ba_2	0.286	44.6	5.79		
5Aa_1	0.227	46.2	4.81	7.11	0.133
5Ba_1	0.399	41.5	9.41		
5Aa_2	0.167	46.0	3.55	6.11	
5Ba_2	0.365	41.2	8.68		
6Aa_1	0.369	41.6	8.68	9.25	0.760
6Ba_1	0.396	39.5	9.82		
6Aa_2	0.188	45.7	4.02	3.55	
6Ba_2	0.141	44.7	3.08		

[a] i is an index of which refers to the notch depth. [b] J_c was calculated using equation (1). [c] The testing on a specimen with 3Aa_2 label failed. The computer did not store the load-deflection data of the specimen.

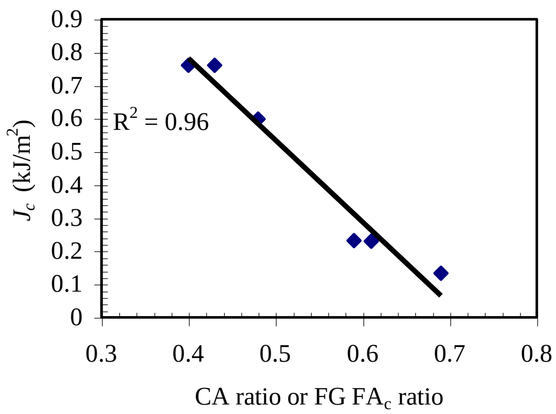


Figure 4 Relationship between aggregate gradation characteristics, i.e. CA ratio and FG FA$_c$ ratio, and J_c.

Figure 5 illustrates various models of spherical aggregates assembly for the aggregate gradations structure shown in Figure 2. Those models are introduced only as an aid to understand the effect of aggregate gradations on the aggregates interlocking. Figure 5 also shows the θ of each spherical aggregates assembly model.

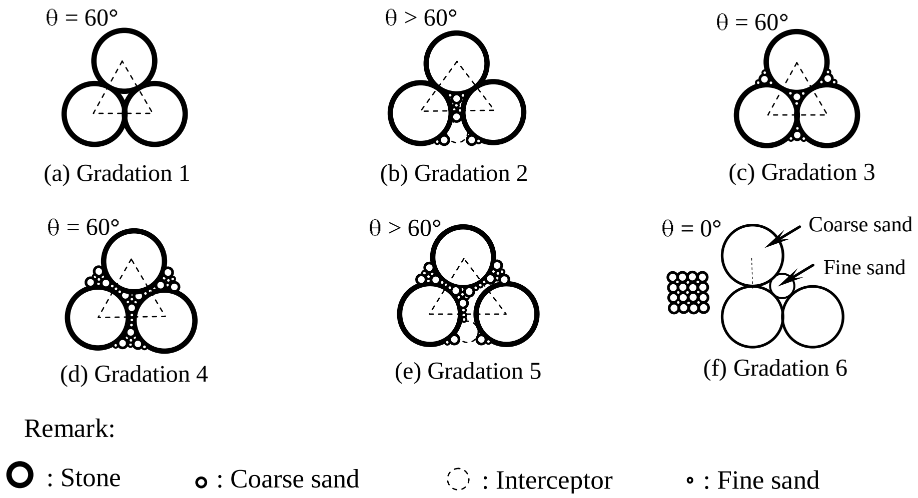


Figure 5 Spherical aggregates assembly models of the aggregate gradations.

Table 1 illustrated that the fraction of stone within Gradation 1 was higher than that of sand, and Gradation 1 satisfied the Bailey criteria. They mean that stone particles within the gradation were packed well. The present study selects tetrahedral packing for simply illustrating a tight packing of stone particles within Gradation 1. The tetrahedral packing has θ of 60°.

Table 1 illustrated that Gradation 3 had the fraction of stone was higher than that of sand, and satisfied the Bailey criteria. Therefore, stone particles within Gradation 3 also might be simply modeled using tetrahedral packing having θ of 60°. Since the sand content of Gradation 3 was higher than that of Gradation 1, the present study assumes that that there are more spaces being filled by sand particles between the stone particles in Gradation 3. The present study introduces the following assumption on the sand particles. In the tetrahedral packing, a space between spherical particles with individual spherical diameter (D) can be occupied by a smaller spherical particle with the maximum diameter (d_{max}) of 0.155D [18]. In the case of spherical aggregate assembly with D = 12.5 mm, the space can be occupied by a spherical aggregate with d_{max} = 1.94 mm. The present study assumes the d_{max} value of 1.94 mm is close enough to 2.36 mm, which is the PCS defined in the Bailey method for HMA mixture with

NMAS 12.5 mm. As stated in the Bailey method, PCS is a criterion to separate coarse aggregate and fine aggregate.

Table 1 illustrated that Gradation 2 had the fraction of stone was higher than that of sand. Basically, stone particles within Gradation 2 can be packed with touching each other. Gradation 2 did not satisfy the Bailey criterion for CA Ratio. It means that Gradation 2 contained some interceptors, which occupied the spaces between stone particles. The interceptors created additional voids, so packing of stone particles were disturbed. Figure 5.b illustrates that, due to the interceptor between the stone particles, the packing model of Gradation 2 has a larger θ than 60°.

Table 1 illustrated that Gradation 4 satisfied the Bailey criteria. It means that both stone and sand particles within Gradation 4 were tightly packed, and the θ value might be 60°. The table also illustrated that the fraction of sand within Gradation 4 was higher than that of stone. This study selects the model of densest packing with three-sized spherical particles suggested by Hecht [19], to illustrate the aggregate structure of Gradation 4. Sand particles might separate the stone particles in Gradation 4 away.

Table 1 illustrated that Gradation 5 had the fraction of sand was higher than that of stone. Sand particles might separate the stone particles in Gradation 5 away. Gradation 5 did not satisfy the Bailey criterion for CA Ratio. It means that Gradation contained some interceptors, which occupied the spaces between stone particles. The interceptors create additional voids. Figure 5.e illustrates that, due to the interceptor, the packing model of Gradation 5 has a larger θ than 60°.

Gradation 6 contained a large amount of manufactured sands that was about 78 %. Those sand particles might isolate stone particles, so the stone particles could not play the role of backbone aggregates. As stated previously, the coarse sand and screening particles within Gradation 6 were well packed, since Gradation 6 matched the Bailey criterion for FG FA_c. The present study modeled Gradation 6 as a simple cubic spherical aggregates assembly. The simple cubical spherical aggregates assembly model permits fine sand particles occupying the space between coarse sand particles. This stands on the following assumption. In the simple cubic packing, a space between spherical particles with D of individual spherical can be occupied by a smaller spherical particle with the maximum diameter (d_{max}) of 0.414D [18]. In the case of spherical particle assembly with D = 1.94 mm, the space can be occupied by a smaller spherical particle with d_{max} = 0.8 mm. This study assumes that the d_{max} value of 0.80 mm is sufficiently close 0.6 mm, which is SCS defined in the Bailey method for HMA mixtures with NMAS 12.5 mm. The Bailey method uses SCS as the criterion to recognize coarse sand and fine sand. Figure 5.f shows that the simple cubic spherical aggregates assembly of Gradation 6 has very small θ, which is close to 0°.

Mixture 1 was a SMA mixture with the CA ratio of 0.4, and had the highest J_c. Mixtures 2 to 5, which were the coarse-graded HMA mixtures, had the CA ratio that were larger than 0.4. Most of the coarse-graded HMA mixtures, i.e. Mixtures 3 to 5, had low J_c. The Bailey method uses the CA ratio to illustrate packing of stone particles in SMA and coarse graded HMA mixtures. As the CA ratio increases, the numbers of interceptors and/or fine aggregates in the aggregate gradation also increases. Both of them may reduce or eliminate contacts between the stone particles [16]. As the result, interlocking of the stone particles decreases, so cracking can be initiated easier in the HMA mixture. From Figure 4, satisfying the current Bailey criterion on the CA ratio for SMA mixture, i.e., 0.35 – 0.4, seem useful in order to obtain HMA mixtures with a high J_c.

Mixtures 1 to 5 are the SMA or coarse-graded mixtures. Interlocking of stone particles is a main factor to avoid cracking in those HMA mixtures. Figure 5 shows that θ of Gradations 1 $\approx$ 3 < θ of Gradation 2, θ of Gradation 4 < θ of Gradation 5. Gradations 4 and 5 have some sand layers between stone particles. Therefore, it can be expected that stone interlocking of Gradation 1 $\approx$ 3 > stone interlocking of Gradation 2 > stone interlocking of Gradation 4 > stone interlocking of Gradation 5. The tendency of stone interlocking is almost same as that of J_c values for Mixtures 1 to 5, while the J_c of Mixture 2 was higher than that of Mixture 3. Fraction of aggregates larger than 2.36 mm in Gradation 2 is higher than that in Gradation 3, so it is possible that the stone interlocking of Gradation 2 is higher than that of Gradation 3. From the description abovementioned, it seems that small θ and high stone fraction are positive to enhance aggregate interlocking of coarse graded HMA mixture, so cracking resistance of the mixture can be improved.

However, the models of Gradations 2 and 3 can not identify amount of stone fraction and sand fraction in both gradations. Fraction of sand in Gradation 3 was higher than that in Gradation 2. Figure 6 illustrates that sand layers may separate some stone particles within Gradation 3. The F_T may develop micro cracks among the sand layers. Number of micro cracks in the degraded sand layers increases, as the F_T increases. Later, the micro-cracks coalesce forming macro-crack. Due to the macro crack, stiffness of the HMA mixture is reduced so the mixture has severe cracks easier.

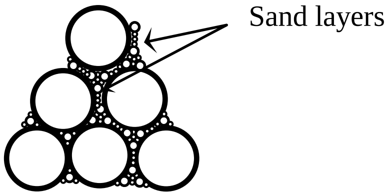


Figure 6 Sand layers separate some stone particles within Gradation 3.

Figure 4 shows that most of coarse graded mixtures examined in the present study, Mixtures 3 to 5, have small J_c. Figure 4 implies that satisfying the current Bailey criterion on the CA ratio for coarse graded HMA mixtures, i.e., 0.5 – 0.65, can be unsuitable in order to obtain HMA mixtures with a high J_c. Unfortunately, these mixtures are very common being used for wearing course in Indonesia since these mixtures stay inside the control points defined in the Indonesian standard. Obviously, these mixtures may become a serious problem for maintaining Indonesian asphalt pavement performance, since the increase of heavy vehicle traffic and high temperatures has promoted cracking of the asphalt surface layers in Indonesian pavements. Therefore, further study is required to seek values of CA ratio belongs the coarse graded HMA mixture, which can result appropriate J_c.

Mixture 6 was composed of a large amount of manufactured sand, that is, about 78 % of total mineral aggregates. The texture of the manufactured sand particles is generally rough, and a large number of the sand particles has a large surface area. Both the rough texture and the large surface area are effective to adhere asphalt binder, and enhance the adhesion between the manufactured sand and asphalt binder. Since θ value of Gradation 6 is very small (i.e. 0°), the F_T might be very limited and cannot separate the contacting spherical aggregates. The adhesion between the manufactured sand and asphalt binder, and the small F_T may be positive in order to arrest the crack development within Mixture 6. As the result, development of micro cracks within Mixture 6 may not be severe. In fact, the J_c value of Mixture 6 is higher than that of Mixtures 2 to 5.

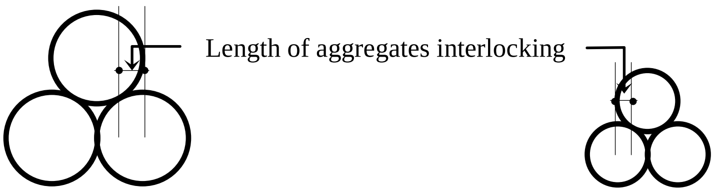


Figure 7 Effect of aggregate size on length of aggregates interlocking.

Figure 7 illustrates that the use of larger aggregate size lengthens the length of aggregates interlocking. As mentioned above, the length of aggregates interlocking may affect the J_c value of HMA mixtures. The implication of the model is according with a study conducted by Wu et al [20] that J_c values were fairly sensitive to changes in aggregates size of HMA mixtures. The implication is also in line with the past studies conducted by some concrete researchers that the use of larger aggregate size within concrete mixture improved toughness of the mixtures [21, 22].

6 Conclusion

The conclusions of the present study are summarized as follows.

1. The present study discusses the relationship between the aggregate gradation characteristic and cracking of wearing course mixture induced by a traffic load.
2. The notched SCB beam test was conducted in order to obtain J_c. The result shows that the CA ratio and the FG FA_c ratio defined by the Bailey method may recognize the effect of aggregate gradation type on J_c. A tendency, that J_c decreases with increasing CA ratio and FG FA_c ratio, agrees with the one reported by previous researcher [7].
3. Satisfying the current Bailey criterion on the CA ratio for SMA mixtures and setting FG FA_c of fine graded HMA mixtures near 0.4 seem useful in order to obtain HMA mixtures with a high J_c. On the other hand, satisfying the current Bailey criterion on the CA ratio for coarse graded HMA mixtures, i.e., 0.5 – 0.65, seems unsuitable in order to obtain HMA mixtures with a high J_c.
4. The present study discusses the spherical aggregates models as an aid to illustrate interlocking of backbone aggregates. Small θ and high stone fraction are positive to enhance aggregate interlocking of coarse graded HMA mixture. Small θ and high coarse sand fraction are positive to enhance adhesion of fine graded HMA and to arrest crack development within the mixture. In both cases, crack resistance of HMA mixtures can be improved.

Further research is still required. In particular, the following items should be investigated: values of CA ratio is required to obtain suitable J_c for coarse graded HMA mixture and effect of environment or aging on cracking resistance of HMA mixtures.

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