ISSN 1822-427X print
ISSN 1822-4288 online

THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

http://www.bjrbe.vgtu.lt

2007, Vol II, No 1, 21–28

EFFECT OF AGGREGATE GRADATION ON WORKABILITY OF HOT MIX ASPHALT MIXTURES

Iman Haryanto[1], Osamu Takahashi[2]

[1]*Highway Engineering Laboratory, Dept of Civil and Environmental Engineering, Nagaoka University of Technology, 1603-1 Kamitomiokamachi, Nagaoka, Niigata, Japan*
E-mail: [1]hary@stn.nagaokaut.ac.jp
[2]*Dept of Civil and Environmental Engineering, Nagaoka University of Technology, 1603-1 Kamitomiokamachi, Nagaoka, Niigata, Japan*
E-mail: [2]roadman@vos.nagaokaut.ac.jp

Abstract. The ease of hot mix asphalt (HMA) mixture for compacting describes workability of the HMA mixture. This study developed a simple workability index (*WI*) and applied it to investigate effect of aggregate gradation on workability of HMA mixtures. Such mixture specimens were prepared with 6 types of aggregate gradation. The Marshall compactor and the steel roller compactor were employed to fabricate the specimens. The index was applied to identify workability of HMA specimens, even though they were fabricated with different compactors. *WI* of HMA mixture was low, when the fraction of stone or sand within the HMA mixture was high. Interlocking makes the aggregates difficult to displacement by compaction. *WI* of HMA mixture can be high, when the mixture uses aggregate gradation falling slightly above the Fuller curve. Sand particles within the aggregate gradation, contacts disappear between stone particles, so interlocking of stone particles is weak. As a result, the stone particles are easily shifted by the compaction load.

Keywords: workability, index, HMA mixture, compaction, aggregate gradation, interlocking, aggregates packing.

1. Introduction

Workability is a property describing the ease of hot mix asphalt (HMA) mixtures for constructing [1]. If HMA mixture is less workable, it cannot be compacted properly. As a result, performance of a HMA mixture may be poor. A very workable HMA mixture should be avoided, since it may deform easier under a repeated traffic load. The illustrations confirm that workability is an important property, since the properties affect performance of HMA in the field [2].

Past researchers introduced some methods for the workability assessment. The methods employed some devices like torque-meter [1], gyratory compactor [3] and modified roller compactor [4]. However, standards of HMA mixtures in many countries still employ the Marshall compactor as a basis to fabricate HMA mixture specimens; and workability evaluation generally has not yet been included in the standards. Asphalt industries in some countries generally have not adopted the methods to evaluate workability of HMA mixture yet. Therefore development of a simple method for workability assessment applicable for any type of HMA mixture compactor can be useful.

Aggregate gradation is one of the factors affecting workability of HMA mixture [2]. Aggregate gradation fitting the maximum density line will be typically the easiest to be compacted. Aggregate gradation with strong interlocking was difficult to displacement by the compaction [5]. Aggregate gradation passing above the restricted zone could be less workable than that passing below the restricted zone [1]. However, none of those studies has identified the basic characteristic of aggregate gradation affecting workability of a HMA mixture.

The Bailey method provides a rational guideline to evaluate aggregates packing within HMA mixtures. It assumes that a HMA mixture is composed of stone, interceptor, coarse sand and fine sand particles. Stone or coarse sand particles act as backbone aggregates supporting traffic load. Fine sands fill-in the spaces between backbone aggregates. Interceptors are too large to fit in the voids created by larger coarse aggregate particles. Excessive interceptors and fine sands reduce packing of backbone aggregates. The Bailey method categorises HMA mixtures into 3 kinds: stone mastic asphalt (SMA), coarse graded and fine graded. Gradation of those HMA mixtures can be evaluated by the Bailey criteria. For satisfying the Bailey criteria it is important to achieve dense packing of backbone aggregates within the HMA mixtures. Aggregates packing affects the mechanical properties of the HMA mixture [6]. However, the effect of aggregates packing on workability of HMA mixture has not been clarified yet.

This study is aimed to develop a simple workability index (*WI*) and to apply the index for studying the effect of aggregate gradation on workability of HMA mixtures. Such mixture specimens were prepared with 6 aggregate gradations. The Marshall compactor and the steel roller compactor were employed to fabricate the specimens. The index developed in this study could be employed to evaluate workability of HMA specimens, even though the specimens were compacted by different compactors. Spherical aggregates assembly models were employed in this study as an aid to understand the effect of aggregates gradation and aggregates packing on workability of HMA mixture.

2. Development of *WI*

In this study, a loose HMA mixture is assumed as a mixture of aggregates coated by a very thin asphalt film. Initial porosity of the loose HMA mixture should be relatively high, since the coated aggregate particles are just in contact without any outside compaction effort being applied or with a very minimum compaction effort applied. During compaction, stone and sand particles in HMA mixture are continuously re-oriented, and porosity of the HMA mixture gradually reduces. Asphalt films are lubricants for aggregates. Sand particles occupy spaces between stone particles or are mixed with asphalt and fillers forming an asphalt mastic. Due to compaction energy, aggregates are quickly re-oriented and porosity of the HMA mixture greatly reduced. A compacted HMA mixture is assumed as a dense-aggregates mixture with asphalt and voids. Fig 1 illustrates simple models of the aggregates mixture and the compacted HMA mixture.

A workable HMA mixture can be compacted easier than an unworkable HMA mixture. Under the same compaction energy, porosity of the workable HMA mixture decreases more than that of the unworkable HMA mixture [3, 4]. Use of high asphalt content generally enhances workability of HMA mixtures [5, 7]. From the past researches it can be assumed that porosity reduction and asphalt content are the factors affecting workability of HMA mixtures. This study employs parameters of (*VIG*-*VIM*) and V_{be} shown in Fig 1 to describe the porosity reduction and the volume of effective asphalt, respectively.

Fig 2 illustrates the contact situations of three bonded spherical particles. Top spherical aggregate is trapped between bottom spherical aggregates, so the top spherical aggregate is interlocked between the bottom ones. This mechanical interlocking governs the strength of the spherical aggregates assembly against displacement. Fig 2 shows

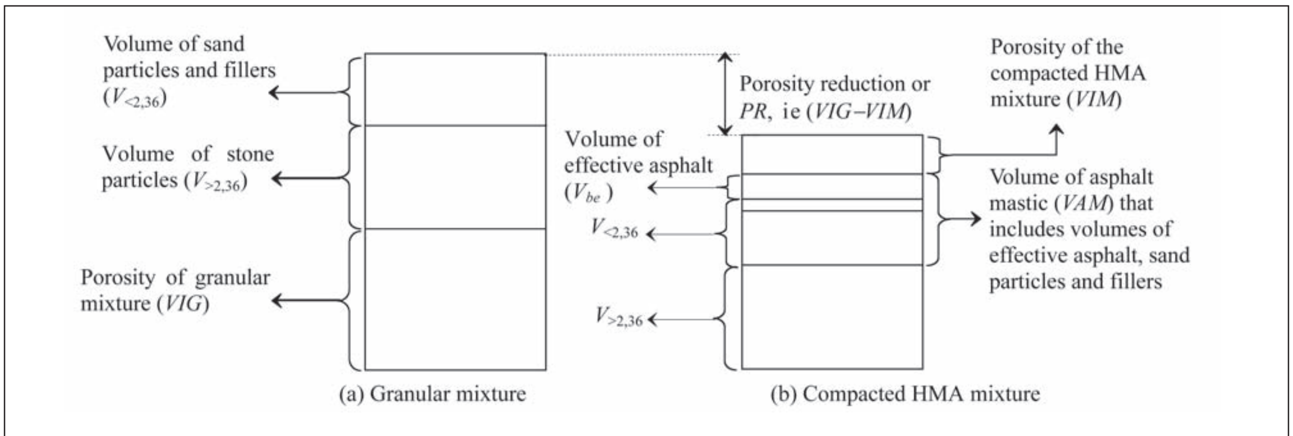

Fig 1. Model of aggregates mixture and compacted HMA mixture

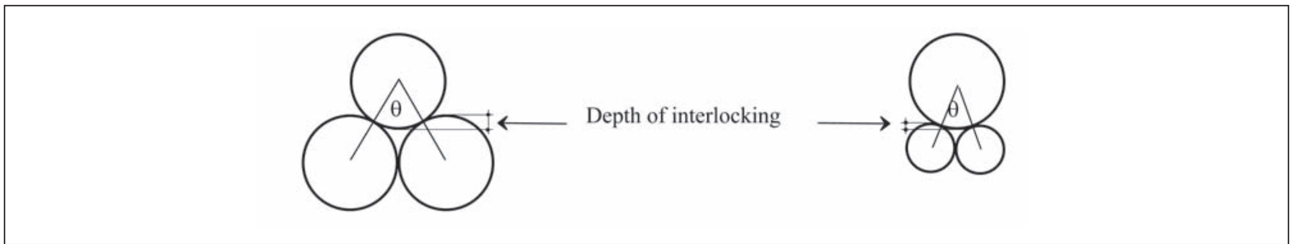

Fig 2. Effect of diameter size on θ and interlocking depth of spherical aggregate assemblies

that contact angle (θ) determines the spatial configuration of spherical aggregates in the assembly. Fig 2 also illustrated that diameter size of spherical particles affects θ. Spherical particles with the same diameter size construct an assembly with θ larger than that constructed in a spherical particles assembly with different size of diameter [8]. Greater θ is positive to obtain a greater mechanical interlocking. Greater θ creates a spherical aggregates assembly with deeper interlocking depth on the top spherical aggregates. Since the top spherical aggregate is trapped in a deeper location, the spherical aggregates assembly has stronger interlocking against the load. Consequently, interlocking of single-size spherical aggregates assembly is stronger than that of multi-size spherical aggregates assembly. Past research indicated that aggregates interlocking affected workability of HMA mixture [5]. This study employs the interlocking model of spherical aggregates assembly as a basis to introduce aggregates interlocking component of *WI*.

The backbone aggregates is a main source for developing the aggregates interlocking in HMA mixture. Either stone skeleton or sand skeleton can be a source of aggregates interlocking within HMA mixture. Sand particles are a major fraction in HMA mixture with sand skeleton. Stone particles are a major fraction in HMA mixture with stone skeleton [9]. This study assumes that proportion of stone fraction and sand fraction in HMA mixture can indicate which aggregates are more dominant as the backbone aggregates. Volume of the backbone aggregates (*BAV*) is volume of aggregates fraction with a higher proportion. Volume of minor aggregates (*MAV*) is volume of aggregates fraction with a lower proportion. A parameter of (*MAV/BAV*) may illustrate heterogeneity of aggregates in HMA mixture. When *MAV/BAV* is near to 1, volume proportion between stone fraction and sand fraction is towards a balance. When the proportion between stone fraction and sand fraction is almost same, the aggregates mixture is considered in this study as the multi-size spherical aggregates assembly. When *BAV* is significantly more than *MAV*, then *MAV/BAV* is small. In this case, one of aggregate fractions, whether stone fraction or sand fraction, is very dominant within the aggregate mixture. This study considered the aggregates mixture as the single-size spherical aggregates assembly. Since aggregates interlocking in the single-size spherical aggregates assembly is different with that of the multi-size spherical aggregates assembly and the parameter of (*MAV/BAV*) may identify the type of spherical aggregates assembly, this study employs (*MAV/BAV*) to represent aggregates interlocking component of *WI*.

The models of spherical assembly simplify the aggregate particles in HMA mixture as spherical particles. In fact, real aggregates used in HMA mixture do not always fit the assumption. The real stone particles may be angular. Angularity increases aggregates interlocking of HMA mixture with stone skeleton. On the other hand, the HMA mixture

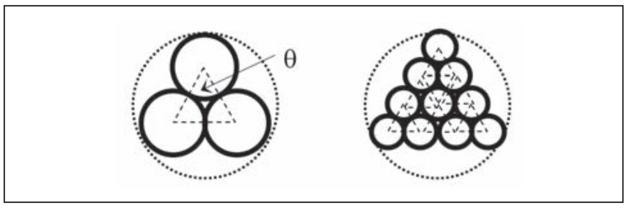

Fig 3. Spherical aggregates assemblies with small and large spherical aggregates occupying the same room

with sand skeleton comprises large numbers of sand particles. If the single size spherical aggregates assembly presented in Fig 2 is considered as a unit of spherical aggregates assembly, sand particles within the sand skeleton of HMA mixture construct large units of spherical aggregates assembly. Fig 3 compares structures of aggregates interlocking in the assemblies with small and large spherical aggregates occupying the same room. Fig 3 shows the assembly with small spherical particles creates large numbers of aggregates interlocking than that in the assembly with large spherical particles. Enlargement of aggregates interlocking due to the nature of real stone skeleton or sand skeleton of HMA mixture is also considered when developing *WI*.

WI includes (*VIG-VIM*), V_{be}, and aggregates interlocking. Both (*MAV/BAV*) and the enlargement effect, either created by angularity of stone particle or by large numbers of sand particles, illustrate aggregates interlocking characteristic, and both of them simultaneously affect workability of HMA mixture. The equations (1) to (4) present *WI* formulation and other associated variables.

$$WI = (VIG - VIM) \cdot V_{be} \cdot \left(\frac{MAV}{BAV}\right) \cdot \left(\frac{1}{f}\right), \quad (1)$$

$$V_{be} = VMA - VIM, \quad (2)$$

$$V_{>2,36} = (1 - VMA) \cdot P_{>2,36}, \quad (3)$$

$$V_{<2,36} = (1 - VMA) \cdot P_{<2,36}, \quad (4)$$

where *BAV* — volume of aggregate fraction with a higher proportion (%); either $V_{<2,36}$ or $V_{>2,36}$ may be as *BAV* depending on which volume of aggregates fraction is larger; *MAV* – volume of aggregate fraction with lower proportion; *f* – the enlargement factor; *VMA* – voids in mineral aggregates; $P_{>2,36}$ – aggregates are retained the sieve size 2,36 mm, %; $P_{<2,36}$ – aggregates are passing the sieve size 2,36 mm, %.

Value of *f* for a HMA mixture with $V_{>2,36} > V_{<2,36}$ is decided as follows. Douglas (2002) investigated the effect of angularity on friction angle of rock-fill granular mixtures at several normal stresses, namely low stress (0,1 MPa), medium stress (0,5 MPa) and high stress (1 MPa). The study showed that the rock-fill granular mixtures with round to sub-angular rock-fill particles had almost the same friction angles, namely 46,7°, 42,2° and 40,3° at the low, medium and high normal stresses, respectively.

On the other hand, the rock-fill granular mixtures with angular particles had larger friction angles, namely 48,8°, 44,4° and 42,6° at the low, medium and high normal stresses, respectively [10]. From the Douglas's study (2002), angularity increased friction angles of rock-fill granular mixtures about 4–6 % higher. The authors assume that increase of friction angle may indicate increase of aggregates interlocking as many as 5 % in HMA mixture with $V_{>2,36} > V_{<2,36}$ and uses the crushed stone. Therefore, *f* of the HMA mixture is taken as 1,05 in this study.

No study has been reported to quantify effect of sand particles on the aggregates interlocking associated with workability of HMA mixture. For a HMA mixture has $V_{<2,36} > V_{>2,36}$, fraction of sand particles is higher than that of stone fraction, and the sand particles in the HMA mixture are relatively more dominant acting as the backbone aggregates in the HMA mixture. Since the use of large sand in HMA mixture with sand skeleton potentially increases aggregates interlocking significantly, in this preliminary study the authors discuss the use of $V_{<2,36}/V_{>2,36}$ as *f* for the HMA mixture with $V_{<2,36} > V_{>2,36}$.

3. Experimental work

3.1. HMA materials and aggregate blends evaluation

Mineral aggregates and straight asphalt of Pen 60/80 used in this study are produced in Japan. Coarse and medium aggregates, screening, and coarse and fine sand were involved as mineral aggregates. Table 1 presents individual porosity of the mineral aggregates sources. The rodding procedure outlined in AASHTO T-19 was applied to obtain an individual porosity of the mineral aggregates sources.

Six aggregate gradations were prepared by combined mineral aggregates and filler sources. Table 2 presents proportion of the mineral aggregates sources for each aggregate blend with their *VIG*. Equation (5) was employed to calculate *VIG*.

$$VIG = \frac{\sum_{i=1}^{n} P_i \cdot W_i}{\sum_{i=1}^{n} W_i}, \quad (5)$$

where P_i — individual porosity of the mineral aggregates source; W_i — proportion of the mineral aggregates sources used to develop aggregate blending (as in Table 2).

Fig 4 illustrates the gradation curves, the Fuller curve, the control points and the restricted zone specified by the Indonesian specification of wearing course mixture. Gradations 1 and 6 stay slightly outside the control points. Table 3 presents the size distributions. The Bailey method was applied to evaluate aggregates packing of the six gradations. Table 4 illustrates results of the evaluation.

Table 1. Individual porosity of the mineral aggregates sources

	CA6	CA7	Sc	CS	FS
Porosity (%)	42,3	43,1	30,4	36,0	40,2

Note: CA6 and CA7 are categories of the coarse aggregates and medium aggregates in Japan. Sc, CS and FS are abbreviations of mineral screenings, coarse sand and fine sand sources.

Table 2. Proportion of the mineral aggregates and filler sources for each gradation

Gradation	CA6 (%)	CA7 (%)	Sc (%)	CS (%)	FS (%)	Filler (%)	VIG (%)
1	49	23	15	7	–	6	40,14
2	42	30	–	23	1	4	41,03
3	36,9	23,6	35,4	–	3,7	0,4	38,19
4	24,9	–	72,5	0,3	0,5	1,8	33,49
5	22	23	–	0,47	2	6	39,32
6	18	–	73	5	2	2	33,08

Table 3. Size distributions of the aggregates gradations

Sieve size (mm)	Gradation					
	1	2	3	4	5	6
13	100	100	100	100	100	100
10	87,1	86,0	90,2	91,7	92,7	95,2
5	48,4	53,9	60,2	75,2	74,8	82,3
2,5	25,0	28,4	32,0	59,3	55,2	66,0
1,2	20,9	23,5	25,9	47,2	45,2	53,0
0,6	15,0	17,8	15,6	26,9	34,1	31,2
0,3	11,8	11,3	10,7	19,9	20,9	22,3
0,15	9,1	6,8	5,6	12,6	11,7	13,5
0,075	7,7	4,9	4,2	9,6	7,9	10,1
Stone content ($P_{>2,36}$)	75,0	71,6	68,0	40,8	44,9	34,0
Sand and filler content ($P_{<2,36}$)	25,0	28,4	32,0	59,3	55,2	66,0

Table 4. Results of gradation evaluation by the Bailey method

Gradation	Values of Bailey ratios		
	CA[a]	FA_c[a]	FA_f[a]
1	0,40 (0,25–0,4)[b]	0,61 (0,6–0,85)	0,61 (0,6–0,85)
2	0,48 (0,5–0,65)	0,64 (0,35–0,50)	0,38 (0,35–0,50)
3	0,61 (0,5–0,65)	0,50 (0,35–0,50)	0,36 (0,35–0,50)
4	0,59 (0,5–0,65)	0,46 (0,35–0,50)	0,47 (0,35–0,50)
5	0,69 (0,5–0,65)	0,63 (0,35–0,50)	0,34 (0,35–0,50)
	FG CA[c]	FG FA_c[c]	FG FA_f[c]
6	1,67 (0,6–1,0)	0,43 (0,35–0,5)	Not defined

[a]CA – coarse aggregate ratio. FA_c – fine aggregate coarse ratio. FA_f – fine aggregate fine ratio. [b]Numbers in round brackets are the Bailey criteria, ie suggested values of the Bailey ratios for each HMA type aforementioned in 1 [6]. [c] FG CA – CA ratio for fine dense graded mixture, FG FA_c – FA_c ratio for fine dense graded mixture, FG FA_f – FA_f ratio for fine dense graded mixture.

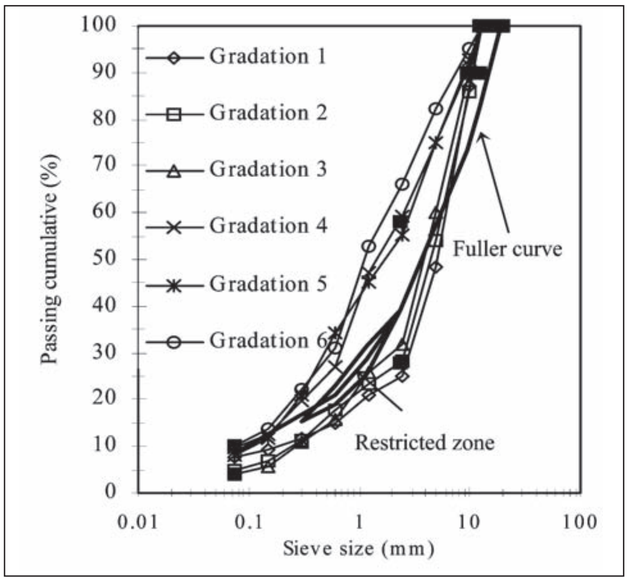

Fig 4. Aggregate gradations used in this research

3.2. HMA mixture design procedure and the results

The following procedures were carried out to design HMA mixtures in this study.

1. Prepare and examine aggregates, sand, filler and asphalt binder.
2. Fabricate Marshall briquettes with 6 asphalt contents. Every sample was subjected by 75 blows of each side.
3. Measure and determine design properties, ie volumetric parameters, stability and flow, with each sample.
4. Determine the 3 asphalt contents to conduct the refusal density compaction. The first asphalt content was initially determined so that the air voids of compacted sample approximately corresponded to 6 %. After that, the other asphalt contents were decided as 0,5 % lower and 0,5% higher than the first asphalt content. The duplicate specimens were made for each asphalt content.
5. Prepare and examine aggregates, sand, filler and asphalt binder.
6. Determine air voids of the samples fabricated by the refusal density compaction.
7. Perform comprehensive evaluation of the asphalt mixture properties to obtain an acceptable range of asphalt content based on the specified requirements as presented in Table 5.
8. Determine the optimum asphalt content (OAC), namely the median of satisfactory asphalt contents range obtained from step 7.

Table 6 presents results of the HMA mixture design. Then the Marshall cylindrical specimen was fabricated at respective OAC of the 6 HMA mixtures for the workability assessment. Each specimen had 75 blows on each side. The specimens were prepared as a triplicate for each type of HMA mixture. Table 6 also illustrated pertinent properties of the Marshall cylindrical specimens. Each value of the properties was an average value from 3 specimens. Each reference number of the mixture is the same as the number of aggregate gradation.

Table 5. Performance requirements of Indonesian wearing course mixture [11]

The properties of asphalt mixture	Specified values
Voids in mineral aggregates (VMA), %	15
Voids in the mixture (VIM) after 2 × 75 blows, %	4,9–5,9
Voids filled with asphalt (VFA), %	65
VIM at refusal density	2,5
Stability, kN	8
Flow, mm	2
Marshall Quotient, kN/mm	2
Retained stability index, %[a]	85
Asphalt absorption, %	1,2

[a]Retained stability index in comparison with the stabilities after the specimens were soaked for 24 h and 30 min.

Table 6. Results of HMA were mixture design and pertinent properties of the Marshall cylindrical specimens

Mixture	OAC, %	*VMA*, %	*VIM*, %	V_{be}, %	$V_{>2,36}$, %	$V_{<2,36}$, %
1	5,34	15,25	4,59	10,66	63,58	21,17
2	5,83	16,87	5,56	11,31	59,55	23,58
3	5,31	16,93	5,94	11,00	56,51	26,56
4	5,41	17,78	5,95	11,83	33,51	48,72
5	5,62	15,32	5,17	10,15	37,98	46,70
6	5,37	17,46	5,86	11,60	28,10	54,44

Table 7. Pertinent properties of the slab specimens

Mixture	*VMA*, %	*VIM*, %	V_{be}, %	$V_{>2,36}$, %	$V_{<2,36}$, %
1	15,1	4,4	10,7	67,0	22,3
	15,7	5,1	10,6	67,0	22,3
2	17,0	6,1	10,9	63,9	25,3
	16,1	5,1	11,0	63,8	25,3
3	18,5	8,0	10,5	60,9	28,6
	17,3	6,7	10,7	60,8	28,6
4	16,3	4,4	11,9	36,0	52,2
	17,6	5,9	11,8	35,9	52,3
5	16,5	6,3	10,3	40,3	49,5
	16,6	6,3	10,3	40,3	49,5
6	19,7	8,4	11,3	30,2	58,5
	20,4	9,1	11,2	30,2	58,6

3.3. Compaction of the slab HMA mixture specimen

A laboratory steel roller compactor was used to fabricate a slab specimen with the dimension of 300 × 300 × 50 mm. The following settings of the steel roller compactor were commonly applied in Japan to pro-

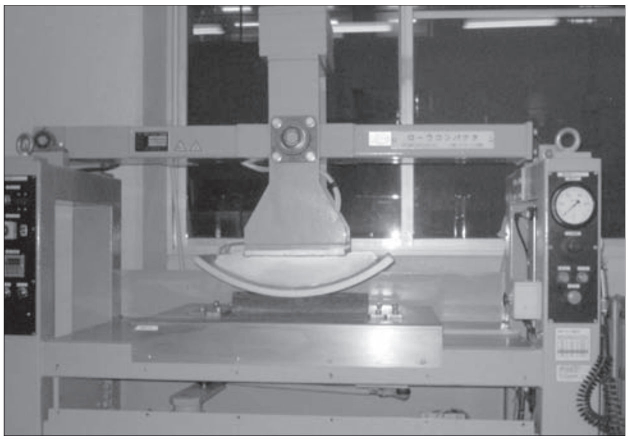

Fig 5. A steel roller compactor

duce a slab HMA mixture specimen with straight asphalt of Pen 60/80, namely a temperature of 120,0 °C, a pressure of 0,475 MPa and a passing number of 25 times. Fig 5 shows the steel roller compactor.

The slab specimens were prepared as a duplicate for each type of HMA mixture. The specimens were prepared at respective OAC of the six HMA mixtures mentioned in Table 6. Table 7 illustrates pertinent properties of all slab specimens.

4. Data analysis and discussion

Table 8 illustrates *WI* values. The *WI* values were calculated by equation (1) and considered values of *VIG*, *VIM*, V_{be}, $V_{>2,36}$ and $V_{<2,36}$ illustrated in Tables 2, 6 and 7.

Fig 6 illustrates a comparison between *WI* values of the Marshall cylindrical specimens and those of the slab specimens. The relationship has a high coefficient of determination (R^2). Fig 6 indicates that *WI* consistently identifies workability property of the six HMA mixtures for the Marshall cylindrical specimens and those of the slab specimens. It seems that the index is applicable to identify workability of HMA specimens, even though the specimens are fabricated with different compactors.

Fig 7 illustrates a relationship between stone content and *WI* values. *WI* of HMA mixtures were low when the fraction of stone or sand within the HMA mixture was high. Interlocking between aggregates makes the aggregates being difficult to displacement by the compaction. Alternatively, for mixture 6 with sand fraction 66 %, a high sand content increases viscosity of asphalt mastic, As a result, the mixture may be difficult to compact.

A past research reported that a blend of aggregates following the maximum density line would be the easiest to compact because individual aggregates particles all "fit together" properly [5]. The specification of wearing course mixture in Indonesia employs the Fuller curve as the gradation with a maximum density. Fig 7 predicts that *WI* value

Table 8. *WI* values

Mixture	*WI* (,10^{-2})	
	Marshall cylindrical specimen	Slab specimen[a]
1	1,20	1,18, 1,21 (1,20)
2	1,51	1,43, 1,49 (1,46)
3	1,59	1,42, 1,50 (1,46)
4	1,54	1,22, 1,21 (1,22)
5	2,29	1,97, 1,97 (1,97)
6	0,84	0,66, 0,65 (0,66)

[a] Numbers in round brackets are the average value.

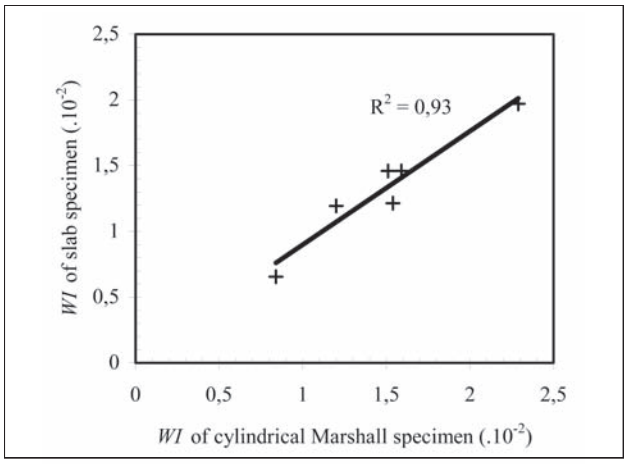

Fig 6. A comparison between *WI* values of the Marshall cylindrical specimens and those of the slab specimens

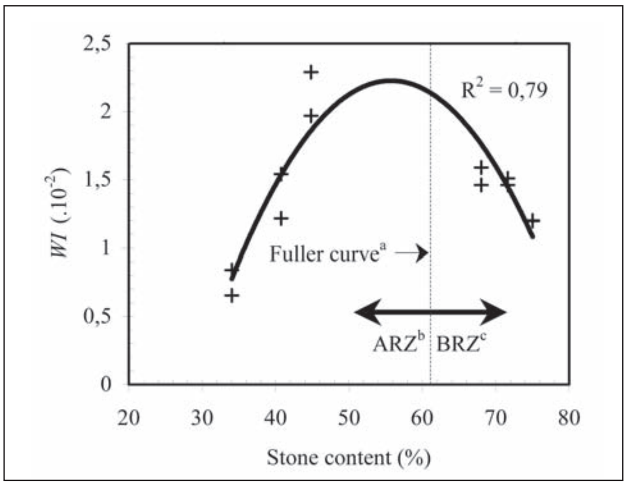

Fig 7. A relationship between stone content and *WI*

[a] The standard of wearing course mixture in Indonesia defines that, in the Fuller curve, 61 % of mineral aggregates are retained by sieve size 2,36 mm. [b] ARZ is above the restricted zone. [c] BRZ is below the restricted zone

can be high when HMA mixture uses aggregate gradation falling slightly above the Fuller curve. Sand fraction in the aggregate gradation is slightly more than stone fraction. Fig 8 illustrates a simple model of the aggregate gradation structure employing spherical aggregates assembly. Sand particles within the aggregate gradation loose contacts be-

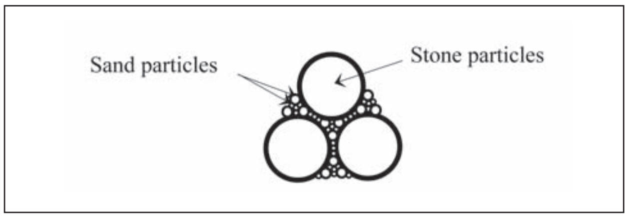

Fig 8. Sand layers reduce interlocking of stone particles

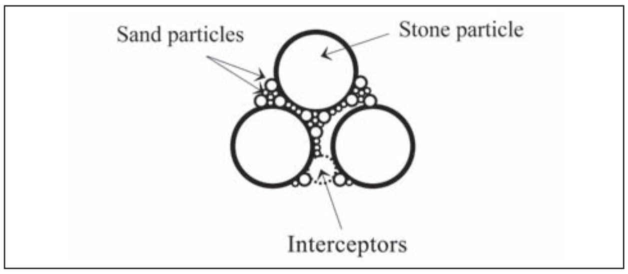

Fig 9. Interceptors reduce aggregates packing

tween stone particles, so interlocking of stone particles is weak and, as a result, the stone particles are easily shifted by the compaction load. Alternatively, the sand particles give a ball-bearing effect, so stone particles are easily shifted by compaction load. In both cases workability of HMA mixture can be improved.

Mixtures 4 and 5 were above the restricted zone. Stone fraction of mixture 5 was higher than that of mixture 4. However, mixture 5 had *WI* higher than that of mixture 4. Table 4 illustrates that gradation 5 did not satisfy the Bailey criterion for CA ratio. When the CA ratio stays outside the recommended values, the Bailey method testifies that there are too much interceptors and/or fine sand in the gradation. Fig 9 illustrates how the interceptors reduce the densest packing of backbone aggregates and create additional voids. The extra voids in aggregate gradation structure may be occupied by asphalt. As illustrated in Table 6, OAC of mixture 5 was slightly higher that that of mixture 4. Since mixture 5 had higher OAC and stone particles within the mixture could be separated by sand layers, thus it could be possible that workability of mixture 5 was higher than that of mixture 4.

Past researchers reported that HMA mixtures employing aggregate gradation passing above the restricted zone could be less workable than those employing aggregate gradation passing below the restricted zone [1]. *WI* values of mixture 6 shown in Table 8 and Fig 7 confirm the past finding.

5. Conclusions

Conclusions of this study can be summarised as follows:

1. This study has developed a dimensionless index of *WI* to evaluate workability of HMA mixtures, *WI* employs *VIG*, *VIM*, V_{be}, (*MAV*/*BAV*), and *f* simultaneously illustrates the workability of HMA mixture.

2. *WI* consistently evaluates workability property of the six HMA mixtures for the Marshall cylindrical specimens and those of the slab specimen. It seems that the index is applicable to identify workability of HMA specimens, even though the specimens are fabricated with different compactors.

3. *WI* of HMA mixture was low when the fraction of stone or sand within the HMA mixture was high. Interlocking of aggregates makes the aggregates difficult to be displaced by compaction. *WI* of HMA mixture can be high, when the HMA mixture uses aggregate gradation falling slightly above the Fuller curve. Sand particles within the aggregate gradation loose contacts with stone particles, so interlocking between stone particles is weak and, as a result, stone particles are easily shifted by the compaction load.

4. Interceptors reduce the densest packing of backbone aggregates and create additional voids. The extra voids in aggregate gradation structure may be occupied by asphalt. When the asphalt content is larger and the sand layers separate stone particles, workability of HMA mixture employing aggregate gradations above the restricted zone may increase.

Acknowledgement. The authors express their gratitude to Fukuda Road Construction Company for their assistance in providing the aggregates and asphalt binder source. The authors also thank the Toa Road Construction Company for providing the screening material.

References

1. GUDIMETTLA, J. M.; COOLEY, L. A.; BROWN, E. R. *Workability of Hot Mix Asphalt*: NCAT Report 03-03, Auburn, Alabama, 2003. 66 p.
2. CHATTERJEE, S.; WHITE, R. P.; SMIT, A.; PROZZI, J.; PROZZI, J. A. *Development of Mix Design and Testing Procedures for Cold Patching Mixtures*. Center for Transportation Research, The University of Texas at Austin, Jan 2006, p. 1–2.
3. CHADBOURN, B. A.; NEWCOMB, D. E.; VOLLER, V. R.; DESOMBRE, R. A.; LUOMA, J. A.; TIMM, D. H. *An Asphalt Paving Tools for Adverse Conditions*. University of Minnesota and Minnesota Dept of Transportation, 1998.
4. OLIVER, J.; ALDERSON, A. *Development of An Asphalt Workability Index*: Pilot Study, Austroads Inc., Sydney, 2006.
5. VON QUINTUS, H. L.; SCHEROCMAN, J. A.; HUGHES, C. S.; KENNEDY, T. W. *Asphalt-Aggregate Mixture Analysis System AAMAS*: NCHRP Report 338, Transportation Research Board, Washington DC, 1991, p. 72–73.
6. VAVRIK, W. R.; HUBER, G.; PINE, J. W.; CARPENTER, S. H.; BAILEY, R. *Bailey Method for Gradation Selection in HMA Mixture Design*: TR Circular Number E-C044, Transportation Research Board, Washington DC, Oct 2002.

7. PUTRA, S.; ISMANTO, B. I.; WIDODO, P. Workability Assessment of Asphalt Concrete Mixture at Various Gyratory Compaction (Penilaian Workability Campuran Beton Aspal dengan Berbagai Variasi Pemadatan Gyratory). In *4th Symposium Forum of Transportation Studies Inter Universities*, Nov 8, 2001, Electronic Edition, Denpasar, Indonesia, p. 8 (in Indonesian).
8. SUNG, I. H.; LEE, H-S.; KIM, D. E. Effect of Surface Topography on the Frictional Behavior at the Micro/nano-scale, *Wear*, 2003, Vol, 254, p. 1091–1031.
9. POTGIEITER, C. J. Bitumen Rubber Asphalt: Year 2003. Design and Construction Procedure in South Africa. In: *8th Conference on Asphalt Pavements for Southern Africa (CAPSA '04)*, Sept 12-16, 2004, Sun City, South Africa, p. 15, http://asac.csir.co.za/capsa/Documents/015.pdf accessed on Dec 5, 2006.
10. DOUGLAS, K. J. *The Shear Strength of Rock Masses*, PhD dissertation, The University of New South Wales, Sydney, Australia, Dec 2002, p. 4.58, http: http://www.library.unsw.edu.au/~thesis/adt-NUN/public/adt-NUN20040107.094847/index.html accessed on Dec 5, 2006.
11. DIRECTORATE GENERAL OF HIGHWAY – REPUBLIC OF INDONESIA. Indonesian National Standard of Road Pavement (Standar Nasional Indonesia Mengenai Perkerasan Jalan), Jakarta, 2002 (in Indonesian).

Submitted 9 Jan, 2007; accepted 20 Feb, 2007