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INVESTIGATION ON INDICES OF WORKABILITY AND RUTTING RESISTANCE FOR WEARING COURSE MIXTURES

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Abstract. Simple indices easily help to evaluate a performance of hot mix asphalt mixtures. This study aimed to develop a simple workability index and rutting resistance index for wearing course mixtures. Seven aggregate gradations were prepared to investigate dense, coarse, and fine-graded hot mix asphalt mixtures. The study used the Marshall compactor to fabricate specimens. The Superpave Gyratory Compaction was employed to measure the workability of the seven blends, namely the workability energy parameter of asphalt mixtures. The study also conducted Wheel Tracking Test to evaluate rutting resistance of those mixtures. The results showed a strong relationship between the workability index and the workability energy of hot mix asphalt mixtures, namely increasing the workability energy of mixtures with increasing the workability index value. The workability energy value of an asphalt mixture may be high when the area of continuous maximum density for a proportion of stone, which illustrates a degree of far away from the Fuller maximum density line, is low. Moreover, the rutting resistance index correlated well with rutting resistance of the hot mix asphalt mixtures.

Keywords: aggregate gradation, continuous maximum density, hot mix asphalt mixtures, rutting, stone content, Superpave Gyratory Compaction, workability.

1. Introduction

Workability of hot mix asphalt (HMA) illustrates characteristics associated with the construction of the HMA layer, namely being placed, worked by hand, and compacted (Gudimettla *et al.* 2003). An HMA mixture, which has higher workability, can be more easily compacted. Low workability may affect durability and stability of the HMA mixtures in field construction. On the other hand, it is not proper to use an HMA mixture which is very workable, because it may show a poor rutting performance under repeated traffic loads (Haryanto, Takahashi 2007a).

Past researchers pointed out that some compaction equipment such as torque-meter (Gudimettla *et al.* 2003), Superpave gyratory compactor (SGC) (Dessouky *et al.* 2013) and modified roller compactor (Oliver, Alderson 2006) enable to measure workability of HMA mixtures. Moreover, Asphalt Pavement Analyzer and Wheel Tracking Test (WTT) are commonly simulative tests to evaluate rutting resistance of HMA mixtures. Dynamic stability (*DS*) of WTT is a good parameter for assessing rutting potential of HMA mixtures (Haryanto, Takahashi 2007b). However, those devices are expensive and have not been widely available in developing countries. Marshall Compactor is still a basic equipment to fabricate HMA mixtures specimens. Therefore, development of HMA indices obtained by Marshall Compactions and related to workability and rutting resistance of HMA mixtures is required. Those indices will help asphalt designers in the process of choosing an adequate aggregate structure.

Aggregate gradation has a strong effect on the workability of the HMA mixture. If aggregate gradation of an HMA mixture is close to the maximum density line (MDL), the HMA mixture may be compacted properly (Haryanto, Takahashi 2007a). Aggregate gradation passing below the restricted zone could be more workable than that passing above the restricted area (Gudimettla 2003; Haryanto, Takahashi 2007a). HMA mixtures with a high fraction of stone or sand may show a low workability (Haryanto, Takahashi 2007a). However, none of the studies has clearly introduced the relationship between characteristics of an aggregate gradation and workability of an HMA mixture. There are not unique guidelines for designers who do not have enough experience in design of adequate aggregate gradations, which lead to proper workable HMA mixtures.

This study aimed to develop a simple index and applied it to investigate an effect of an aggregate gradation on the workability of 12.5 mm nominal maximum particle

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size (NMPS) wearing course mixtures with different compactors. The study also discussed another simple performance index for assessing rutting resistance of HMA mixtures. SGC was conducted to measure the workability of seven blends, which were following the Vietnamese standard for wearing course HMA mixtures. Moreover, a relationship between the workability and the rutting susceptibility of HMA mixtures was also investigated. The WTT evaluated the rutting resistance of those mixtures.

2. Literature review

SGC gives the vertical pressure and the angle of gyration to an HMA sample during compaction (Asphalt Institute 2001). The computer system automatically measures and records the height of the sample at each gyration. The data is used to evaluate workability of HMA mixtures (Dessouky *et al.* 2013). The researchers used compaction curves to develop two indices associated with field construction. The first index presented workability of an HMA mixture when a volume of the mixture changes from the beginning to 92% of the theoretical maximum specific gravity (G_{mm}). The second index, which was calculated by the change in volume from 92% to 96% of G_{mm}, illustrated the shear strength of an HMA mixture due to interlocking between aggregate particles (Dessouky *et al.* 2013). Based on this idea, two simple indices, namely the workability energy index (*WEI*) and the compact ability energy index (*CEI*), were defined as follows (Dessouky *et al.* 2013):

$$WEI = \frac{\pi d^2}{4} \cdot P \cdot \frac{h_0 - h_{92\%}}{N_{92\%}}, \quad (1)$$

$$CEI = \frac{\pi d^2}{4} \cdot P \cdot \frac{h_{92\%} - h_{f\%}}{N_{des\%} - N_{92\%}}, \quad (2)$$

where d – a diameter of sample, m; P – a compaction pressure of SGC, kN; h_0 – a height of sample before compacting, m; $h_{92\%}$ – a height of sample as air voids of the mixture reach 8%, m; h_f – a height of sample with N_{des}, m; $N_{92\%}$ – a number of gyrations as air voids of the mixture reach 8%; N_{des} – a number of design gyrations.

Designing an adequate aggregate gradation to obtain a proper void in mineral aggregate (VMA) is one of the necessary steps in a design process of HMA mixtures. The past research pointed out that the CMD_{area} parameter has a good relationship with *VMA* (Nhan 2015; Nhat *et al.* 2016). *VMA* of HMA mixtures increases as the value of the CMD_{area} increases. Therefore, the CMD_{area} parameter is useful in controlling a value of *VMA*. Based on the concept of the maximum density gradation (Christopher *et al.* 2011), CMD_{area} parameter is calculated as follows:

$$P_{CMD}(d_i) = \left(\frac{d_{i+1}}{d_i}\right) P\left(d_{i+1}\right), \quad (3)$$

$$P_{dev}(d_i) = P_{CMD}(d_i) - P(d_i), \quad (4)$$

$$CMD_{area} = \sum_{0.075}^{NMPS} A_i, \quad (5)$$

where $P_{CMD}(d_i)$ – percent passing by mass for sieve size d_i on the continuous maximum density (CMD) line, %; d_{i+1} – one sieve larger than d_i, mm; $P(d_{i+1})$ – percent passing by mass for sieve d_{i+1}, %; $P_{dev}(d_i)$ – a deviation from the CMD line to $P(d_i)$ for sieve d_i, %; $P(d_i)$ – percent passing by mass at sieve d_i, %; A_i – an area between $P_{dev}(d_i)$ and $P_{dev}(d_{i+1})$ as shown in Fig. 1. In Fig. 1, a sieve size of the horizontal axis is represented in a logarithmic scale.

3. Development of *WI*

Aggregate gradation plays a major role in determining the workability of the HMA mixture. A fraction of sand and stone at 2.36 mm sieve for 12.5 NMPS mixtures has a great relationship with the workability of the HMA mixture. Workability of an HMA mixture having a high fraction of sand is low (Haryanto, Takahashi 2007a). The CMD pilot illustrates how much the aggregate gradation is far from the Fuller MDL at each sieve (Christopher *et al.* 2011). Past researchers reported that it is easy to compact the HMA mixture in which the aggregate gradation fits the MDL (Haryanto, Takahashi 2007a). The authors of the present study assumed that the area of CMD for stone proportion ($CMD_{area\text{-}stone}$) has a strong relationship with the workability of HMA mixtures. When the $CMD_{area\text{-}stone}$ of an HMA mixture is high, this mixture may not be compacted

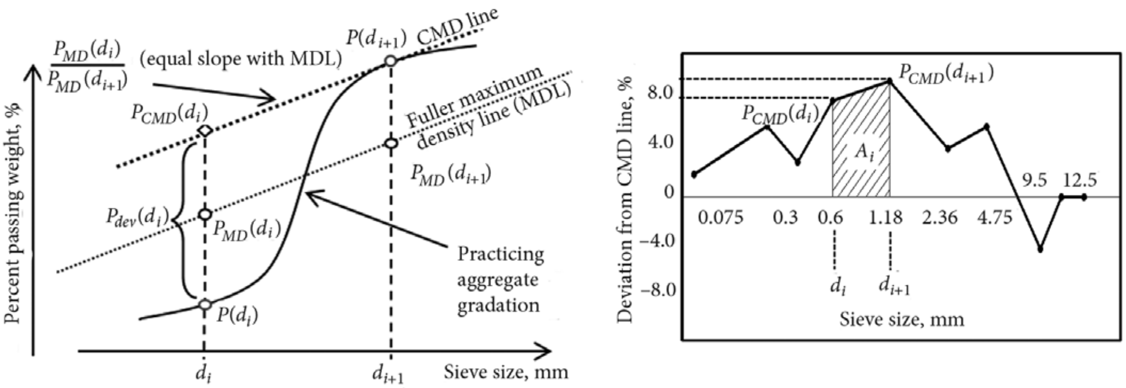


Fig. 1. Concept of CMD and meaning of $P_{CMD}(d_i)$, $P_{dev}(d_i)$ and CMD_{area} (Nhat, Takahashi 2016)

easily. Fig. 2 illustrates the meaning of the $CMD_{area\text{-}stone}$ for an aggregate gradation.

A high workability HMA mixture having a proper apparent film thickness (*AFT*) can easily be compacted. The *AFT* is an average thickness of asphalt binder that coats aggregate particles. An HMA mixture with a higher *AFT* value has higher workability (Christopher *et al.* 2011). When effective asphalt content (V_{be}) increases, the *AFT* of the mixture also increases (Christensen, Bonaquist 2006). Therefore, V_{be} parameter may be a positive factor affecting workability of the HMA mixture (Haryanto, Takahashi 2007a). In addition, a proportion of fine aggregate particles has a strong effect on *AFT*. When a proportion of fine aggregate in a mixture increase, an aggregate specific surface area in the mixture also increases. As a result, the *AFT* value reduces due to asphalt absorption of the fine aggregate. For this reason, workability of the HMA mixture deteriorates.

Too many interceptor particles may disrupt dense packing of the aggregate structure and create additional voids. Asphalt binder may fill the new voids, and workability of the HMA mixture may improve (Haryanto, Takahashi 2007a). No study has investigated to quantify an effect of interceptors on the aggregate interlocking related to the workability of the HMA mixture. This study employed a disruption factor (*DF*) of a dominant aggregate size range (DASR) model as a parameter to illustrate an effect of aggregate interlocking on the workability of HMA mixtures. The DASR is an interactive range of particle sizes that develops aggregate interlocking in the HMA mixture. Coarse particles play the main role in forming a backbone aggregate structure. Aggregate particles smaller than the DASR aggregate along with asphalt binder and fine aggregate (interstitial components (IC)) occupy the air voids created by aggregate particles of the DASR. Aggregate particles larger than the DASR solely float in the DASR aggregate matrix and do not play a major role in the aggregate structure. Aggregate particles interact each other and significantly contribute to friction strength in the HMA mixtures when relative proportions between contiguous size particles in the DASR is lower than 70/30 (Chun *et al.* 2012). The *DF* determines whether fine aggregate disrupts the DASR structure (Chun *et al.* 2012). When a *DF* value is high, fine aggregate reduces the backbone aggregate, and interlocking effect of coarse aggregates is small. As a result, compacted load easily shifts stone particles (Haryanto, Takahashi 2007a). In contrast, if *DF* has a low value, fine aggregate does not take part in transferring loads in the aggregate structures (Chun *et al.* 2012).

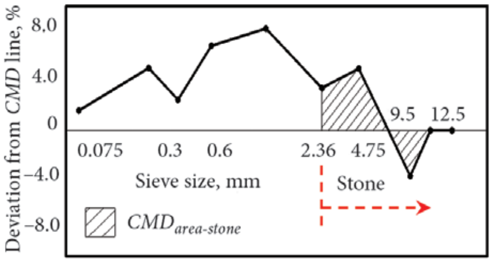


Fig. 2. Meaning of $CMD_{area\text{-}stone}$

In the past research, the smallest sieve of DASR model may be 1.18 mm (Chun *et al.* 2012). In the Bailey method, a secondary control sieve (SCS) splits out coarse sand and fine sand. SCS for 12.5 mm NMPS aggregate gradation is the 0.6 mm sieve (Varik *et al.* 2002). For a coarse sand fraction of 12.5 mm NMPS aggregate gradation, 0.6 mm was the smallest particle size in the DASR (Haryanto, Takahashi 2007c). Therefore, the present study chose 0.6 mm as the smallest particle size of coarse aggregate to calculate *DF* of the DASR for all blends.

Based on the above analysis, the following equation and other associated variables show the process of calculating workability index (*WI*). The present study built a hypothesis that *WEI* increases with increasing *WI*. It is possible to obtain the *WI* value from a stage of mix design procedure.

$$WI = \left(\frac{1}{CMD_{area-stone}}\right)\left(\frac{V_{be}}{S_s}\right) DF, \tag{6}$$

$$S_s = \frac{P_{0.30} + P_{0.15} + P_{0.075}}{5}, \tag{7}$$

$$DF = \frac{\text{Volume of potentially disruptive IC particles}}{\text{Volume of DASR voids}}, \tag{8}$$

where S_s – the area of aggregate specific surface, $m^2 \cdot kg^{-1}$; $P_{0.30}$, $P_{0.15}$, and $P_{0.075}$ – an aggregate content passing 0.30 mm sieve, 0.15 mm sieve and 0.075 mm sieve, percent by total mass of aggregates, %, respectively; V_{be} – effective asphalt content, percent by total volume of a mixture, %. Eq (7) illustrates an effect of fine aggregate on the area of the aggregate specific surface (Christopher *et al.* 2011).

4. Development of rutting resistance index

The past research pointed out that mixture resistivity is an effective parameter to evaluate rutting resistance of HMA mixtures. Resistivity presents the resistance of an aggregate structure to oppose binder flow in the mix. Resistivity also illustrates a contrary characteristic of permeability for an HMA mixture (Christensen, Bonaquist 2006). The resistivity of an asphalt combination derived from S_s, the bulk specific gravity of aggregates (G_{sb}) and *VMA* simultaneously expresses rutting resistance of HMA mixtures (Christensen, Bonaquist 2006). A relationship between mixture resistivity and rutting resistance of HMA mixtures may be explained as follows. The strength of adhesion existing in HMA mixtures increases with increasing S_s. As the sequence, the indirect tensile strength of HMA mixtures increases when the force of adhesion in mixtures increases (Chen *et al.* 2002). The indirect tensile test is a sufficient method to measure cohesion of the mixtures (Christensen *et al.* 2004). Moreover, cohesion has a good relationship with the rutting resistance of HMA mixtures, because this parameter is one of shear strength properties (Haryanto, Takahashi 2007d). Therefore, rutting resistance of HMA mixtures increases with increasing mixture resistivity (Christensen, Bonaquist 2006).

Characteristics of aggregate gradation significantly effect on *VMA* of the mix. The results of past researches showed that *VMA* of the HMA mixture increases as the value of the CMD_{area} increases (Nhan 2015; Nhat *et al.* 2016). Therefore, the CMD_{area} parameter indicates an effect of aggregate gradation on the resistivity of the mixture. When calculating mixture resistivity, the present study used CMD_{area} parameter instead of *VMA*. The mixture resistivity increases with decreasing the CMD_{area} of aggregate gradation.

A volume of effective asphalt is also related to rutting performance of an HMA mixture. Mixes with low V_{be} show high resistivity values (Christensen, Bonaquist 2006). It means that the V_{be} parameter presents a negative effect of asphalt binder on the mixture resistivity. Moreover, a mixture having a high V_{be} value has a high *AFT* value, which reduces rutting resistance of the HMA mixture (Christopher *et al.* 2011).

As mentioned above, when an HMA mixture is highly workable, it may show poor rutting performance under repeated traffic loads (Haryanto, Takahashi 2007a). Eq (9) presents rutting resistance index (*RRI*) formulation. A hypothesis of the present study was that rutting resistance of an HMA mixture increases when *RRI* increases. Eq (10) was based on the equation to calculate resistivity of an HMA mixture (Christensen, Bonaquist 2006). Because Eq (10) was not enough for all the components to calculate mixture resistivity, this equation was only used to determine resistivity index (*RI*), which presents an effect of aggregate gradation on the mixture resistivity.

$$RRI = RI\left(\frac{1}{V_{be}}\right)\left(\frac{1}{WI}\right), \qquad (9)$$

$$RI = \frac{S_s^2\, G_{sb}^2}{CMD_{area}^3}. \qquad (10)$$

5. Experience work

5.1. Preparation of HMA materials

The present study used a straight asphalt of Pen 60/80 and mineral aggregates, which were produced in a local Japanese province, to fabricate HMA samples. Both the materials were satisfied with not only the Japanese requirements but also the Vietnamese criteria. The available aggregates were coarse and medium aggregates, coarse and fine sands.

5.2. Design of aggregate gradation

Seven aggregate gradations were blended to investigate the dense, coarse and fine-graded HMA mixtures. The first group was dense-graded HMA mixtures, namely, from Blends 1 to 3. Blend 3 was a conventional aggregate gradation, and others had a parallel tendency with the mixture 3. The second group was coarse-graded HMA mixtures, namely, Blends 4 and 5. The Blend 4 presented a coarse aggregate gradation near stone matrix asphalt mixture (SMA) for 12.5 mm NMPS (Cooley, Graham 2004). The final group was fine-graded HMA mixtures, namely, Blends 6 and 7. The past research suggested that a percentage of aggregates retaining 2.36 mm sieve or a stone content should be more than 30% (Haryanto, Takahashi 2007d). Therefore, the Blend 7 was prepared to illustrate the fine aggregate gradation, which the stone content in the mixture was slightly over 30%. Fig. 3 shows all gradation curves designed in the study.

5.3. Mix design procedure

According to on the basis of the Marshall method as described in Vietnamese Standard *TCVN 8819–2011 Specification for Construction of Hot Mix Asphalt Concrete Pavement and Acceptance*, all the mixtures were designed in the following steps.

1. Prepare and evaluate the resources, namely aggregates, sand, filler, and asphalt binder.
2. Mix two samples for each blend with a tentative asphalt content (AC) to determine the G_{mm} and the effective specific gravity of aggregate (G_{se}).
3. Fabricate Marshall Briquettes with five ACs. Seventy five blows are applied on each side of the specimens.
4. Measure and determine volumetric parameters, stability, and flow of each sample.
5. Analyse the asphalt mixture properties to obtain an acceptable range of AC based on the specified requirements as presented in Table 1.
6. Determine the design AC, namely a median of the acceptable AC range.
7. Make five specimens at the design AC. Compare the properties with the design criteria for three samples. Determine residual stability index for the rest of two samples.

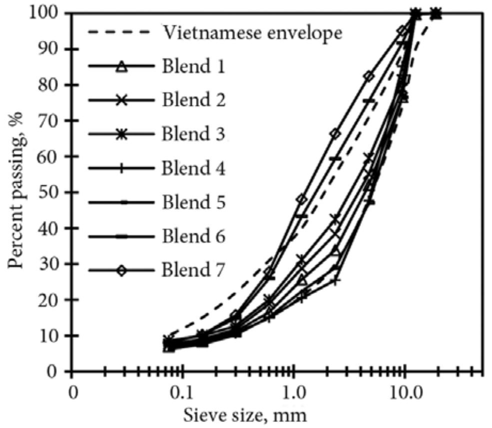


Fig. 3. Aggregate gradations for all the blends

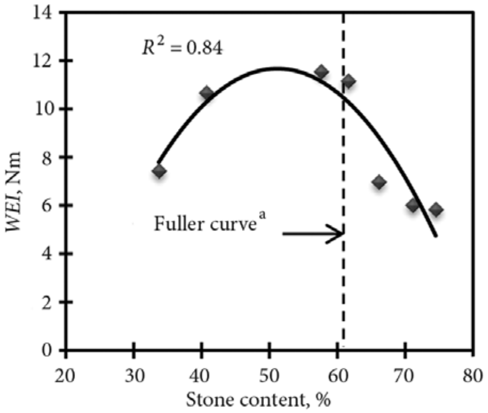
Table 1. Marshall requirements for 12.5 mm NMPS mixtures

Properties of an HMA mixture	Required range
Voids in mineral aggregates (*VMA*)	≥14%
Voids in mixture (*VIM*), after 75·2 blows	3–6%
Stability	≥8.0 kN
Flow	2–4 mm
Residual stability	≥75%

Table 2. Results of properties for Marshall, SCG specimen, and slab-shaped specimen at the design AC

Blend	Marshall specimens				SGC specimens				Slab-shaped specimens		
	Design AC, %	*VIM*, %	*VMA*, %	G_{mb}	N_{des} (gyration)	G_{mb}	*WEI*, Nm	*CEI*, Nm	*VIM*, %	*VMA*, %	G_{mb}
1	4.75	5.3	14.0	2.364	70	2.366	6.99	0.96	7.1	15.6	2.318
2	4.70	4.1	12.7	2.392	48	2.396	11.17	1.61	4.9	13.4	2.372
3	4.60	4.0	12.2	2.398	48	2.394	11.56	1.61	4.5	12.7	2.385
4	6.00	4.0	15.6	2.347	120	2.341	5.84	0.36	6.6	17.9	2.285
5	4.70	5.5	14.3	2.356	70	2.353	6.03	0.95	7.4	16.1	2.307
6	6.00	4.2	15.3	2.339	45	2.335	10.68	1.62	3.6	14.8	2.355
7	6.35	4.3	16.1	2.324	70	2.317	7.45	0.97	5.5	17.2	2.296

Note: Design AC for Blends 2 and 3 was determined as air voids of the HMA mixture were equal to 4.0%.



[a] in the Fuller curve, 61% of mineral aggregates was retained by 2.36 mm sieve size (Haryanto, Takahashi 2007a)

Fig. 4. Effect of stone contents on *WEI*

5.4. Superpave Gyratory Compactor test

SGC data evaluated workability of HMA mixtures. Two specimens with design AC were fabricated using the SGC to determine N_{des} for each blend. The N_{des} was regarded as the number of gyrations where the HMA mixture had the same bulk specific gravity of mixtures (G_{mb}) as that of the Marshall specimen. Other samples were fabricated with the design AC and the N_{des} to check the G_{mb} value of the HMA mixture.

5.5. Wheel tracking test

WTT evaluated rutting resistance for the HMA mixtures investigated in the present study. Slab specimens of the mixtures with the dimension of 300×300×50 mm were prepared for WTT. This study used a laboratory steel roller compactor to fabricate the slab specimen. The process of steel roller compactor in the present study was commonly applied in Japan. The compaction procedure included two stages. The first stage was a passing number of 5 times, without a shield tire. The second stage had a passing number of 20 times by using the shield tire.

The present study conducted the WTT at a temperature of 60 °C. A wheel speed was 42 passes/ min, and a load was 686 N (Haryanto, Takahashi 2007d). A *DS* value illustrates passage times of wheel load per 1 mm rut depth. The *DS* is an evaluation parameter in the Japanese WTT standard for a rutting susceptibility (Haryanto, Takahashi 2007d). The following equation was used to calculate a value of *DS*:

$$DS = 1.5 \cdot \frac{42 \cdot 15}{d_{60} - d_{45}}, \qquad (11)$$

where d_{60} and d_{45} – a rut depth at 60 min and 45 min, mm, respectively.

6. Results and discussions

6.1. Result of mix design

Table 2 shows design ACs and volumetric properties of the seven HMA mixtures fabricated by the Marshall compaction. Each value of the properties was an average value from three specimens. In the process of design, Blends 2 and 3 could not meet the requirement of *VMA* even though AC was changed five times (Nhat, Takahashi 2016).

According to Vietnamese Standard *TCVN 8820–2011*, for dense-graded HMA mixtures, it is possible to determine design AC when air voids of the HMA mixture are equal to 4.0%. Therefore, the authors assumed that design AC for Blends 2 and 3 was established as the AC that gave 4.0% air voids in the mixtures. Each value of the properties illustrated in Table 2 for Marshall specimens was also an average value from three samples.

6.2. Effect of aggregate gradations on workability

Table 2 also shows HMA properties of SGC specimens and results of workability and compactibility for the seven blends. *WEI* and *CEI* were calculated from SGC measured data. Among all the blends, Blend 4 following the SMA aggregate gradation has the smallest *WEI* value. It means that Blend 4 is hard to be compacted. The past research reported that an HMA mixture aggregate gradation of which is close to the MDL is easily compacted because individual aggregate particles easily interlock to fit together and create the densest packing of backbone aggregates (Haryanto, Takahashi 2007a). Fig. 4 illustrates the effect of stone contents or aggregates retaining at 2.36 mm sieve size on the workability of the HMA mixtures. A high correlation

Table 3. *WI* of Marshall, SGC, and slab-shaped specimen

Blend	S_s, m^2/kg	$CMD_{area\text{-}stone}$	*DASR*, mm	*DF*	Marshall and SGC specimens		Slab-shaped specimens	
					V_{be}, %	$WI, \cdot 10^{-2}$	V_{be}, %	$WI, \cdot 10^{-2}$
1	5.32	4.28	9.50–0.60	0.70	8.63	26.52	8.52	26.20
2	5.68	3.00	9.50–0.60	0.89	8.56	44.68	8.54	44.58
3	6.26	1.61	9.50–0.60	0.83	8.18	67.33	8.18	67.29
4	5.14	6.50	4.75–0.60	0.72	11.60	24.99	11.23	24.19
5	4.80	5.98	9.50–0.60	0.75	8.74	22.83	8.62	22.53
6	6.62	3.18	9.50–0.60	0.95	11.11	50.15	11.18	50.47
7	6.78	4.81	4.75–0.60	0.91	11.73	32.72	11.61	32.38

coefficient, namely $R^2 = 0.84$, is obtained between stone contents and *WEI*. The trend line points out that the workability of the HMA mixtures is high if the aggregate gradation is close to the MDL. This result agrees with Haryanto finding (Haryanto, Takahashi 2007a).

Table 3 presents results of parameters to calculate the *WI* of HMA mixtures. The *WI* value of each Marshall specimen is equal to that of the SGC specimen. The *WI* values of the Marshall and SGC samples are also different from that of the slab-shaped samples because of the difference of V_{be}. The Marshall and SGC specimens have the same V_{be}, even though all Marshall specimens have the same compaction energy but SGC specimens individually have the different compaction energy. The V_{be} values of the Marshall and SGC samples are also different to that of the slab-shaped samples. The V_{be} indicates a ratio between the volume of effective asphalt and the total mixture volume. In the period of compaction, with the help of compaction energy, a porosity of an HMA mixture gradually reduces. This process leads to decrease the total mixture volume and to increase the V_{be} and the G_{mb} of the HMA mixture. Therefore, when a mix was fabricated by various devices, the mixture with high G_{mb} has high V_{be}. Table 3 shows that V_{be} changed slightly, so that *WI* values from Marshall, SGC specimens, and slab-shaped specimens are almost same.

Among all the parameters, $CMD_{area\text{-}stone}$ has the best relationship with the *WEI* of HMA mixtures. Fig. 5 shows the effects of $CMD_{area\text{-}stone}$ on *WEI* values for the seven aggregate blends. The correlation coefficient is relatively high, namely $R^2 = 0.89$. The trend line presents that the *WEI* value of HMA mixtures decreases as the $CMD_{area\text{-}stone}$ of the aggregate gradations increases. When an aggregate gradation falls close to the MDL, this aggregate gradation has a low $CMD_{area\text{-}stone}$ and the mixture can be more workable. The shape of trend line between $CMD_{area\text{-}stone}$ and *WEI* values is simpler than that of between the stone content of aggregate gradations and *WEI* values. Those results pointed out that $CMD_{area\text{-}stone}$ is a more suitable parameter than the stone content of aggregate gradations to indicate a degree of the distance between aggregate gradation and the MDL, which strongly affects the workability of HMA mixtures.

Figure 6 illustrates relationships between *WI* values of specimens using various devices and *WEI* values of the SGC specimens for the seven blends. The high correlation coefficient, namely $R^2 = 0.96$, is obtained. The relationship shows the expected tendency, namely increasing the workability of an HMA mixture with increasing the *WI* values. It seems that the index applies to assess workability of HMA mixtures even though the samples are fabricated with the different compaction energy.

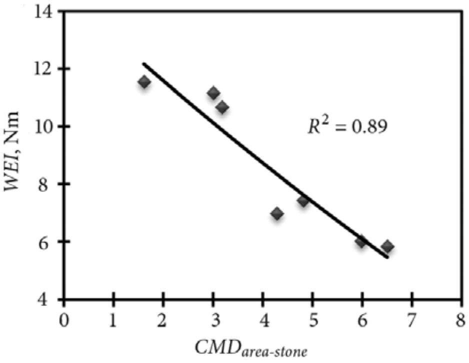


Fig. 5. Effect of $CMD_{area\text{-}stone}$ on *WEI*

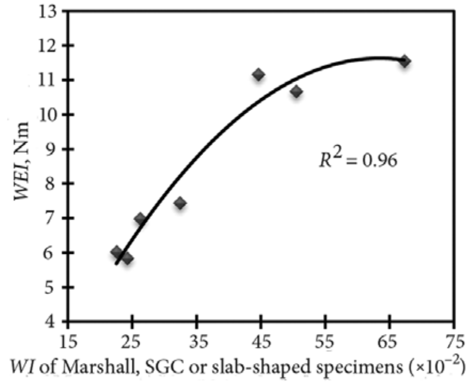


Fig. 6. Relationship between *WI* of Marshall, SGC or slab-shaped specimens and *WEI*

6.3. Evaluation of relationship between rutting resistance index and dynamic stability

Table 4 illustrates *RRI* values of the specimens using various compactors and *DS* values for the seven blends. Because the *WI* values change slightly with different compactions, the *RRI* values of samples compacted with three kinds of compactors are almost same. Fig. 7 shows a relationship between the *RRI* values and the *DS* values. The relationship among the *RRI* values of Marshall, SGC or slab-shaped specimens and the *DS* values shows a reasonable correlation coefficient, namely $R^2 = 0.91$. The trend lines present that rutting resistance of the HMA mixtures increases when *RRI* increases. The results also illustrate that three *RRI* values of the samples fabricated from Marshall, SGC and steel roller compactor may be employed for the same objective, namely assessment of rutting resistance for 12.5 mm NMPS wearing course mixtures. A suitable *DS* value for 12.5 mm NMPS mixtures should be more than 800 cycles/mm (Haryanto, Takahashi 2007d). Based on the Fig. 7, the *RRI* value should be more than 40 ($\cdot 10^{-2}$) for specimens compacted with any kinds of compactors.

Table 4. *RRI* values of Marshall, SGC, and slab-shaped specimens

Blend	*RRI*, $\cdot 10^{-2}$		*DS*, cycles/mm
	Marshall and SGC specimens	Slab-shaped specimens	
1	41.06	42.09	755
2	57.96	58.23	1130
3	119.41	119.58	1168
4	10.94	11.67	422
5	19.37	19.90	667
6	15.38	15.19	340
7	8.59	8.78	284

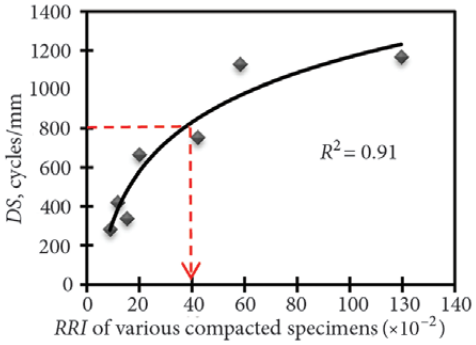


Fig. 7. Relationship between *WI* of Marshall, SGC or slab-shaped specimens and *DS*

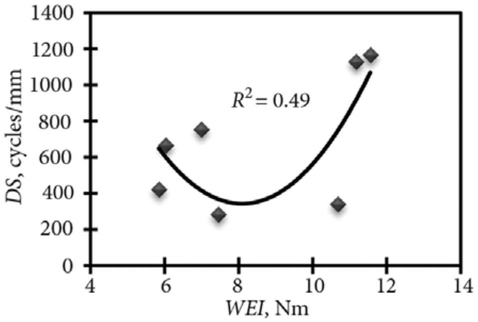


Fig. 8. Relationship between *WEI* and *DS*

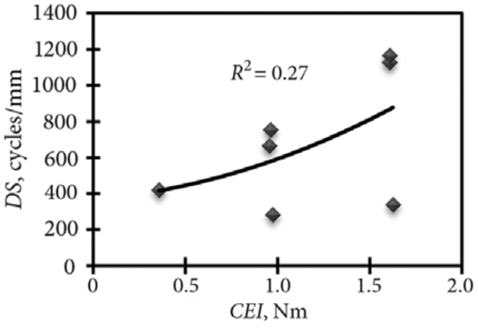


Fig. 9. Relationship between *CEI* and *DS*

6.4. Relationship between workability energy index, compact ability energy index and dynamic stability

Figures 8 and 9 show relationships between the *WEI*, the *CEI* and rutting resistance of the HMA mixtures for the seven aggregate blends. Correlation coefficients between the *WEI*, the *CEI,* and the *DS* are not high. The *WEI* and the *CEI* are not associated with rutting resistance of an HMA mixture. The past research pointed out that the gyration angle, namely 1.25 degree, in SGC is not adequate to evaluate the shear stress that causes rutting in HMA mixtures. This angle should increase to assess rutting potential of HMA mixtures (Anderson *et al.* 2002).

7. Conclusion

The findings of the present study are summarized as follows.

1. This study has developed the workability index for assessing the workability of hot mix asphalt mixtures. The workability index, which consists of aggregate gradation parameters and a mix parameter, can be obtained without any mechanical tests. The workability parameter shows a strong relationship with the workability of mixtures. It means that the index is sufficient to evaluate workability of hot mix asphalt mixtures.

2. The results show that the area of continuous maximum density for a proportion of stone has a high correlation coefficient with workability of mixtures. When this aggregate gradation parameter is low, the mixture shows a proper workability.

3. The relationship between the rutting resistance index values and the dynamic stability values is high. When the rutting resistance index values increase, rutting resistance of hot mix asphalt mixtures also has a tendency to increase. On the Marshall conventional mixture design method, it is easy to calculate this parameter without any mechanical tests. Therefore, the rutting resistance index of Marshall cylindrical specimens sufficiently indicates rutting resistance of wearing course mixtures. Experimental results show that an adequate value of the rutting resistance index for 12.5 mm nominal maximum particle size mixtures is more than 40 ($\cdot 10^{-2}$) for Marshall, Superpave gyratory compactor specimens or slab-shaped specimens.

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