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USE OF SECANT SHEAR MODULUS FOR RUTTING POTENTIAL ASSESSMENT OF INDONESIAN WEARING COURSE MIXTURES

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Abstract. Since shear modulus (G) indicates a resistance to shear deformation, the property should be essentially considered to evaluate the rutting potential. This study discusses a criterion of G for Indonesian wearing course mixture (IWCM) design. Simple unconfined compression test was conducted to calculate secant shear modulus (G_s) of IWCM. G_s is a ratio of shear strength (t_s) to shear strain (g).t_s and g were obtained from unconfined compressive strength and the strain transformation law, respectively. Wheel tracking test was conducted to verify validity of G_s as a rutting potential index of IWCM. G_s could rank the laboratory rutting performance of the designed mixtures as well as dynamic stability (DS). A relationship between G_s and DS suggests that over 28 MPa in G_s is equivalent to more than 800 cycles/mm in DS, within the scope of materials sources used in the present study. G_s can be one of rutting potential indicators of IWCM.

Keywords: rutting, secant shear modulus, unconfined compression test, wheel tracking.

1. Introduction

Rutting in wearing course is formed from densification or plastic flow of the hot mix asphalt (HMA) mixture [1]. Densification reduces initial volume of HMA, and physically appears as depressions in the wheel paths. Plastic flow imposes shear deformation of HMA without volume changing, and physically appears as depressions in the wheel path and small upheaval on the side. Despite HMA layers have been properly compacted, large shear stress in the surface of wearing course, due to heavy traffic, can still impose shear deformation. Inadequate shearing resistance of HMA is the primary rutting mechanism rather than densification. Resistance to volume change in HMA is much greater than that to shear deformation in a high temperature [2]. The resistance to volume change obtained from a hydrostatic pressure test was roughly 25 times larger than the resistance to shear deformation obtained by a simple shear creep test [3].

Indonesian road authority has issued a new specification of HMA mixture design in 2002. The standard is practically called Refusal Density Method (RDM). The objective of RDM is to control compacted mixtures so that an ultimate voids in the mixture (VIM) or air voids shall be more than 2,5 % [4]. If the air voids is below the threshold, asphalt mortar acts as a lubricant between the aggregates, and reduces the rutting resistance of mixture [5]. The current Indonesian standard has not yet held any criterion and rational evaluation method concerning shear modulus property, because a reliable manner of measuring shear modulus on HMA mixtures has not been available in Indonesia. On the other hand, the volumetric properties of Indonesia standard cannot completely guarantee early detection of shear deformation in wearing course mixtures. Therefore there is no warranty on which premature rutting will not be formed in wearing course, even if pavement engineers follow the current standard.

Unconfined compression test (UCT) is one of very simple evaluation tests. A specimen of unconfined compression test fails with shear stress. HMA mixture subjected to compressive stress shall adequately have resistance to shear deformation. With an inadequate shear resistance, plastic deformation is developed in HMA mixtures from heavy loading. The plastic deformation is irreversible when the load disappears. In this case, use of elastic shear modulus is unsuitable as an indicator of shape distortion resistance. Shear dynamic/complex modulus (G*) is one of rutting potential indicators in the Superpave mix design [6]. On the other hand, use of secant shear modulus (G_s) obtained from an unconfined compression loading for describing shear distortion resistance seems also appropriate, since G_s represents the average shear modulus during a loading path.

This study aims to obtain the secant shear modulus (G_s) of Indonesian wearing course mixture (IWCM) from UCT, and to verify validity of G_s as a rutting potential index of IWCM, illustrated by dynamic stability (DS) obtained by wheel tracking test (WTT).

2. Determination of G_s by the Marshall type specimen subjected to UCT

The asphalt engineers accept for a large HMA mixture specimen, which has a sufficient height and area of the base in accordance with the maximum aggregate size, is ideal for the compression test. The suggested ratio for unconfined compression test is generally more than 2.0. UCT on the specimen with a lower ratio of height to diameter than the size ratio of 2.0 gives higher values of peak stress and axial strain at peak stress [7].

The Marshall type specimen, which is still employed for the asphalt mixture design in Indonesia, has a ratio of height to diameter on Marshall specimen about 0.6. Since this size ratio is un-ideal for UCT, so asphalt researchers generally omit the use of the Marshall type specimens for determining G_s .

Selvakumar and Narayanasamy [8, 9] performed analysis of the short-sized compacted metallurgy powder specimen subjected to UCT. The ratio of height to diameter was changed as 0.50, 0.75 and 1.00 in their study. Equations (1) to (3) were used to analyse the UCT.

$$\varepsilon_{af} = \ln\left(\frac{h_f}{h_0}\right), \quad \varepsilon_{\theta f} = \ln\left(\frac{D_f}{D_0}\right), \tag{1}$$

$$\varepsilon_{ap} = \ln\left(\frac{h_p}{h_0}\right), \tag{2}$$

$$\alpha = \frac{\varepsilon_{\theta f}}{2\varepsilon_{af}}, \tag{3}$$

where ε_{af}, ε_f – final axial compressive and tangential strains, respectively; ε_{ap} – axial compressive strain at peak stress; h_0, h_f – initial and final heights of specimen, respectively (mm); h_p – heights of the compression test specimen at peak stress (mm); D_f – final diameters of the specimen (mm); α – Poisson ratio.

ε_{ap} and α can be employed to estimate tangential strain at peak stress ($\varepsilon_{\theta p}$) from the Eq

$$\varepsilon_{\theta p} = 2\alpha\varepsilon_{ap}. \tag{4}$$

Shear strain at peak stress (γ) can be obtained from the strain transformation law by considering ε_{ap}, $\varepsilon_{\theta p}$ and volumetric strains (ε_{vp}), namely using the equations

$$\varepsilon_{vp} = \varepsilon_{ap} + 2\varepsilon_{\theta p}, \tag{5}$$

$$\gamma = \varepsilon_{ap} - \tfrac{1}{3}\varepsilon_{vp}. \tag{6}$$

Negative value expresses "compressive" in axial strain. A value of G_s is obtained from the shear strength (τ_s) and γ as follows [10]:

$$G_s = \frac{\tau_s}{|\gamma|}. \tag{7}$$

A value of τ_s can be obtained from the equations [11, 12],

$$\sigma_C = \frac{4P_{\max}}{\pi D_0^2}, \quad \tau_s = \frac{1}{2}\sigma_C, \tag{8}$$

where σ_C – unconfined compressive strength (MPa); P_{max} – maximum applied load (kN); D_0 – initial diameter of specimen (mm).

3. Experimental work

HMA samples were fabricated with seven aggregate gradations. WTT was carried out on the HMA mixtures assessing a rutting susceptibility in the laboratory. An empirical indicator, ie DS, has been established as an index of rutting resistance in Japan. DS is used to verify validity of G_s as an indicator of rutting resistance of HMA mixtures.

3.1. HMA materials sources and mixture design

Mineral aggregates and straight asphalt having pen 60/80 were used in this study. Although both the materials were produced in Japan, they were satisfied with the relevant Indonesian standards. The aggregates were classified as coarse and medium aggregates, screening, coarse sand and fine sand. A high quality coarse aggregate source was used to produce the aggregate gradations, ie it has angularity of 100/98, flakiness and elongation of 0,1 %, Los Angeles abrasion value of 13,6 %, and soundness of 1,7 %.

HMA mixture specimens were prepared with 7 aggregate gradations. Fig 1 illustrates the aggregate gradation curves, the Fuller curve, the control points and the restricted zone.

The RDM was applied to the HMA samples in this study as the typical design procedure for IWCM. In the RDM procedures, a high-energy compaction is applied to asphalt mixtures to reach a state of which a mixture refuses to become any denser, even if further compaction efforts are given. This compaction is superior to an ordinary Marshall compaction procedure for simulating a traffic densification in field asphalt mixtures. Each side of HMA specimen was subjected to 400 blows so that the asphalt mixture specimen reached its ultimate air void content. Air void of the Marshall specimen subjected to the high-energy compaction is one of the considerations to decide the range of acceptable asphalt content and the optimum asphalt content (OAC). A brief description of the RDM procedure may be found elsewhere [13]. Table 1 illustrates results of the mixtures design. Each reference number of the mixture is the same as the number of the corresponding aggregate gradation.

3.2. UCT and WTT

UCT was carried out using the Marshall specimens. The specimen was fabricated following a common Marshall manner used in Indonesian asphalt industry. Each specimen had 75 blows on each side.

This strain limit was arbitrarily chosen from the authors. The computer-controlled testing machine recorded the load and axial displacement during testing. The data of load and axial displacement was directly used to determine σ_C and axial compressive strain. Both ε_{ap} and ε_{af} were also stored in the testing machine. At the end of test, final diameter of the specimen was manually measured in the middle parts of specimen height to obtain $\varepsilon_{\theta f}$.

Prior to the test, specimens were soaked in water at of 30 °C for 14 h. The soaking was a kind of temperature conditioning for HMA specimens. The testing temperature was 20 °C lower than the average highest pavement temperature in Indonesian, namely 50 °C [14], and was also close to the mean monthly pavement temperature, namely 31 °C, for 27 highly populated cities in Indonesia [15]. The testing condition, the deformation rates and the temperature simulates a reasonably slow loading rate and would be rheologically equivalent to traffic loading critical for rutting [16]. However, the deformation rate was slightly lower than that suggested by the previous researchers, because the Marshall specimen was shorter than the specimen used by those researchers.

As previously mentioned, the UCT using an un-ideal size ratio specimen gives higher values of peak stress and axial strain at peak stress than those observed in the UCT using the ideal size ratio specimen. The use of some friction reduction film could ease the effect of this discrepancy [7]. The soap lubricated plastic sheets were inserted between the specimen sides and loading plates. Fig 2 illustrates the arrangement of the plastic sheets, specimen and loading plates.

WTT is one of evaluating tests for rutting potential of HMA mixtures, and is commonly used as a verification test in Japan. The WTT was carried out at a temperature of 60 °C, a wheel speed of 42 pass/min, and a load of 686 N. DS that expresses passage times of the wheel load per 1 mm rut depth has been established as the indicator of rutting potential in the Japanese WTT standard.

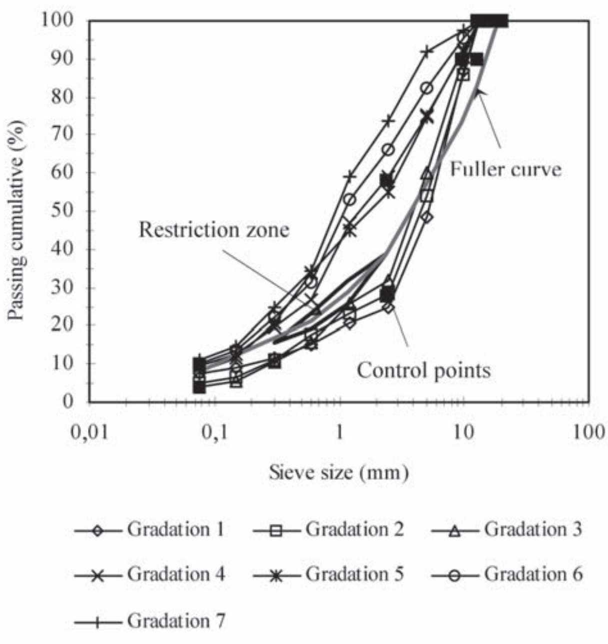

Fig 1. The aggregate gradations used in this study

Table 1. Range of acceptable asphalt content and OAC

Mixture	Range of acceptable asphalt content, %	OAC, %
1	5,25–5,42 (0,17)	5,34
2	5,78–5,88 (0,10)	5,83
3	5,20–5,42 (0,22)	5,31
4	5,20–5,63 (0,43)	5,41
5	5,61–5,62 (0,01)	5,62
6	5,20–5,54 (0,34)	5,37
7	6,60–7,02 (0,42)	6,81

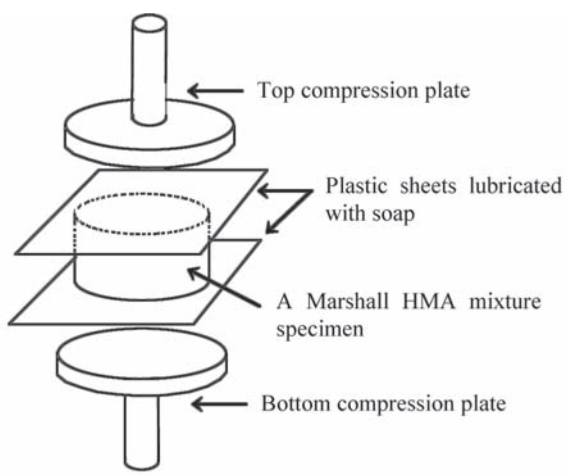

Fig 2. Geometry of UCT

3.3. Correlation analysis method

Both G_s and DS may rank the rutting performance of HMA mixtures used in this study. In order to analyse and compare these properties, this study used the Kendall tau (τ) correlation method, which is one of the quantitative tools for comparing the rankings of two assessment systems [17]. The following equation is used to calculate a coefficient of τ [18].

$$\tau = \frac{4\left|L_X \cap L_Y\right|}{n(n-1)} - 1, \qquad (9)$$

where L_X, L_Y – sets of pairs ranked by the X and Y assessment systems of rankings, respectively; $\left|L_X \cap L_Y\right|$ – number of pairs ranked in the same way by L_X and L_Y; n – number of observed members.

This τ can be determined for a pair of two ranks. The value of τ ranges from –1 to +1, where –1 indicates that the rankings are perfectly inverse each other, and +1 indicates that the rankings are perfectly correlated with each other. A τ value of 0,0 means, that there is absolutely no correlation between the rankings. When a value of τ is ≥ + 0,6 or τ is ≤ –0,6, the rankings of the systems would have a good relationship [17].

4. Test result and evaluation

Table 2 shows the results of ε_{af} and $\varepsilon_{\theta f}$, which are required to calculate α. Table 3 illustrates τ_s, $|\gamma|$ and G_s properties at peak axial load. Table 4 shows the results of DS for each HMA sample on WTT. The standard of Japanese expressways requires more than 800 cycles/mm of DS value for surface mixtures of 13 mm NMAS of dense-graded

Table 2. Strains properties of the HMA specimens at final failure state

Specimen label	h_0, mm	h_f, mm	D_0, mm	D_f, mm	ε_{af}	$\varepsilon_{\theta f}$	α
1a	67,08	55,617	100,73	129,440	–0,187	0,251	0,67
1b	68,29	52,403	101,25	140,650	–0,265	0,329	0,62
2a	68,66	54,520	101,06	141,027	–0,231	0,333	0,72
2b	68,44	56,363	101,16	133,897	–0,194	0,280	0,72
3a	68,78	60,790	101,17	123,437	–0,123	0,199	0,81
3b	67,22	60,187	100,93	121,250	–0,111	0,183	0,83
4a	66,39	62,300	101,31	114,770	–0,064	0,125	0,98
4b	67,37	63,443	101,31	111,653	–0,060	0,097	0,81
5a	66,14	60,687	101,14	117,593	–0,086	0,151	0,88
5b	65,93	60,667	101,11	117,337	–0,083	0,149	0,89
6a	67,23	61,213	101,30	119,303	–0,094	0,164	0,87
6b	67,44	60,567	101,29	121,123	–0,108	0,179	0,83
7a	68,58	64,710	101,06	111,550	–0,058	0,099	0,85
7b	69,45	63,527	101,26	117,810	–0,089	0,151	0,85

Table 3. Values of τ_s, $|\gamma|$, G_s properties at a peak load

Specimen label	σ_c (MPa)	τ_s (MPa)	ε_{ap}	$\varepsilon_{\theta p}$	ε_{vp}	$|\gamma|$	G_s (MPa)	Average G_s (MPa)
1a	3,533	1,767	0,043	0,058	0,072	–0,067	26,3	26,3
1b	2,888	1,444	0,037	0,046	0,054	–0,055	26,3	
2a	2,758	1,379	0,039	0,056	0,073	–0,063	21,9	21,2
2b	3,164	1,582	0,047	0,068	0,090	–0,077	20,5	
3a	3,270	1,635	0,034	0,055	0,076	–0,059	27,5	23,7
3b	4,130	2,065	0,049	0,081	0,114	–0,087	23,7	
4a	5,042	2,521	0,042	0,083	0,123	–0,083	30,3	33,3
4b	5,370	2,685	0,043	0,069	0,095	–0,074	36,2	
5a	4,076	2,038	0,043	0,076	0,109	–0,080	25,6	26,5
5b	4,360	2,180	0,043	0,076	0,110	–0,079	27,5	
6a	4,581	2,291	0,038	0,066	0,094	–0,069	33,1	35,0
6b	5,583	2,792	0,043	0,071	0,099	–0,076	36,9	
7a	4,050	2,025	0,044	0,075	0,106	–0,080	25,4	19,4
7b	4,240	2,120	0,088	0,149	0,211	–0,158	13,4	

Table 4. Values of DS

DS of the slab specimen (in cycles/mm)	Mixture						
	1	2	3	4	5	6	7
Specimen a	853	552	646	1086	7072	1227	258
Specimen b	664	457	705	900	507	1005	387
Average value	759	505	676	993	790	1116	323

mixtures [19]. Each reference number of the specimen label is the same as the number of the corresponding mixture.

Fig 3 illustrates the relationship between G_s and DS. The coefficient of determination is high indicating a good correlative relation. The tendency is increasing DS with increasing G_s. This paper is assuming that DS is a good indicator for field rutting performance of HMA mixtures. Thus G_s can be one of rutting indicators for IWCM. The figure also shows that over 28 MPa in G_s is equivalent to more than 800 cycles/mm in *DS*, within the scope of materials sources used in the present study.

A correlation between G_s and DS, analysed by the Kendall τ method, is presented as follows. Two sets of HMA pairs ranked by G_s and DS properties, denoted by L_{Gs} and L_{DS}, are defined. The criteria, namely greater G_s and DS indicate better performances of HMA, are followed. The comparison analysis gives $|L_{Gs} \cap L_{DS}| = 15$, that is $\{(1,2), (1,3), (3,2), (4,1), (4,2), (4,3), (4,5), (5,1), (5,2), (5,3), (6,1), (6,2), (6,3), (6,4), (6,5)\}$. The value of τ is calculated as + 1 using eq (9). It means that G_s can rank the laboratory rutting performance of the designed mixtures as well as DS.

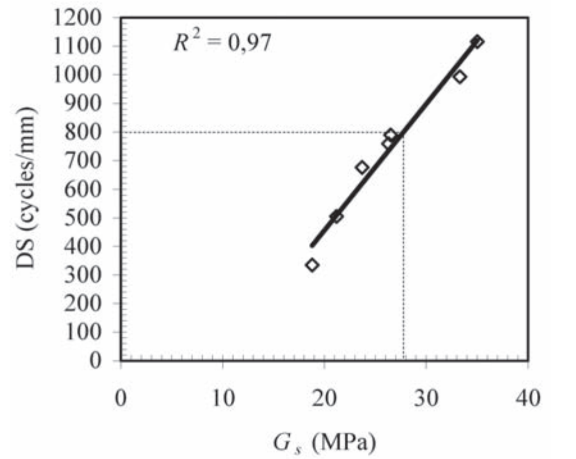

Fig 3. A relationship between averages G_s and DS

5. Conclusion

The present study brings the analysis method of UCT using the short-sized compacted metallurgy powder specimen to obtain G_s of the Marshall type HMA mixture specimen. G_s can rank the laboratory rutting performance of the designed mixtures as well as DS within the scope of mineral aggregates and asphalt binders sources used in the present study. A relationship between G_s and DS suggested that over 28 MPa in G_s is equivalent to more than 800 cycles/mm in *DS*, which is a minimum DS for expressway wearing course in Japan, within the scope of materials sources used in the present study. Further researches are necessary to verify the results of the present study, particularly using wide ranges of mineral aggregates sources and asphalt binder type, and using other rutting testers.

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