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Resilient modulus model of asphalt mixture using steel slag

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Keywords: bitumen modulus, resilient modulus, reclaimed asphalt pavement, slag materials.

Abstract. The use of waste materials from road scrapping, called reclaimed asphalt pavement (RAP) and steel slag aggregates becomes more and more popular in road maintenance and road reconstruction. Those materials can replace and reduce the amount of virgin materials needed in the mixing process. In this research, the optimum bitumen content (OBC) of Marshall specimens has to be determined firstly, before the samples for resilient modulus test were prepared. The UMATTA equipment was used to determine the resilient modulus of each sample, which consist of: original mixture i.e., without slag and RAP materials, and the mixture with RAP and slag. The results showed that the mixture with RAP and slag materials has the higher resilient modulus, compared to the original mixture, and the most impactful parameters for the results are bitumen modulus, percentage of RAP materials, slag materials and void in mixture.

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1. Introduction

In recent decades, the repair and reuse of waste materials from industrial activities and the construction sector have become very important to reduce the use of raw materials for road construction. For example, the use of Reclaimed Asphalt Pavement (RAP) plays an important role, because in addition to providing economic benefits, the environmental impact is also reduced [1–2]. Similarly, slag materials can also overcome the limited availability of rocks. The RAP material is obtained when the asphalt layer is removed for reconstruction, restoration of the surface layer and pavement removal due to utility installation, whereas the slag is a residue from the steel-making process. In the pavement rehabilitation, those materials were used in hot mix conditions and refer to the Indonesian specifications. Accordingly, the use of RAP [3] or slag materials [4–6] in hot-mix condition have given a good result compared to the conventional asphalt mixture.

Several studies show that the addition of RAP in the asphalt mixture indicates the changes in the physical behaviour of the mixture that affects its durability and structural performance [3, 7–8]. The use of 40–60 % RAP in hot mix asphalt can increase its Stiffness and Indirect Tensile Strength (ITS) value, and can produce the pavement which is resistant to rutting but prone to cracking and fatigue. It gives also a generally higher variability of hot-mix asphalt mixtures using RAP materials [3, 8]. Based on some study, the EAF slag on Stone Mastic Asphalt (SMA) mixture can increase its Stability value and its Marshall Quotient, which are indicators of high stiffness, resistance to permanent deformation, and higher durability [9–10]. The EAF slag also give better mechanical properties compared to the natural aggregates, considering that it is recommended as a reliable road material [11–13]. Meanwhile, another study shows a decreasing value of the Marshall Stability [14]. This inconsistency can be attributed to the different test temperatures, size and percentage of slag [15].

The RAP material has significantly aged, which causing a reduction in the bonding between the aggregate and asphalt. The use of slag as an aggregate is expected to reduce the occurrence of this, due to the characteristic of slag material which has a high bonding with asphalt [16]. Based on a study of the resistance of asphalt mixture to fatigue, which using a combination of RAP and slag, the result shows that the asphalt mixture can increase its fatigue life and the damage is insignificant, in a mixture that containing RAP and slag than the control mixture [17]. Other results showed, that the asphalt mixture using slag and RAP without any rejuvenating material, can improve the overall performance of the mixture, compared to the control mixture [15]. The steel slag is more effective in improving the performance of asphalt mixtures, because one of the properties of steel slag is having the capacity to store heat, which causes higher energy consumption during the production of Hot Mix Asphalt (HMA), compared to the natural aggregate. Alternatively, the transportation of slag with RAP requires a longer time, starting from the production site to the layering site [18]. The time needed to increase the traffic, after completing the construction until it can be used, is around 5 to 10 minutes.

One important parameter in pavement design is the Stiffness Modulus, which represents the behaviour of mechanical properties that making possible to analyse structures with stress and strain distribution under wheel loads. Stiffness Modulus is a fundamental mechanical parameter that expresses synthetically the structural properties of asphalt mixtures, determined through non-destructive tests (NDT), and it is very useful for conducting statistical evaluations of the effects of one or more components in the mechanical response of a mixture [19]. Stiffness Modulus test on asphalt mixture is carried out by the Universal Material Testing Apparatus (UMATTA) test, where the main factors that need to be considered in the Stiffness Modulus testing are temperature and load frequency [20].

In general, the aims of this research are to determine the optimum performance and Stiffness Modulus of asphalt mixtures using RAP and Slag materials, with the target results are its Stiffness Modulus value that is greater than the original hot-mix asphalt mixture, which using the bitumen penetration (Pen) 60 / 70 and natural aggregates.

2. Experimental Methods

2.1. Materials

There are three aggregate materials used in this study: natural aggregate, RAP and steel slag. The natural aggregates were obtained from crushed stones from PT KADI International located in Klari, Karawang, Indonesia. While the RAP aggregate was from raking the National Road in Karawang, Indonesia. There are two types of steel slag that are commonly used in asphalt mixtures. The first one is Basic Oxygen Furnace (BOF), a steel-making process using converted furnace, and the second one is Electric Arc Furnace (EAF), a steel-melting process with electric arc [21]. In this study, the EAF slag type was used as a steel waste from steel-melting process. The tests result of physical and mechanical properties of the aggregates can be seen in Table 1.

Table 1. Physical and mechanical properties of aggregates and steel slag.

Test Type	Natural Aggregate	RAP Aggregate	Steel Slag
Coarse Aggregate Specific Gravity	2.642	2.496	3.488
Fine Aggregate Specific Gravity	2.614	2.442	3.086
with LA Machine	21.17	32.30	13.01
Sand Equivalent Value	76.35%	*	88.62%

Note: *) no measurement

The reference gradation used was the Asphalt Concrete – Binder Course (AC-BC) gradation which refers to the Indonesian General Specifications of Roads and Bridges [22], Meanwhile, the RAP aggregate gradation was laid within the upper and lower limits of the reference gradation. The determination of the slag aggregate gradation was the same as the reference aggregate gradation, because all filter sizes were available for slag aggregate. This curve can be seen in Fig. 1.

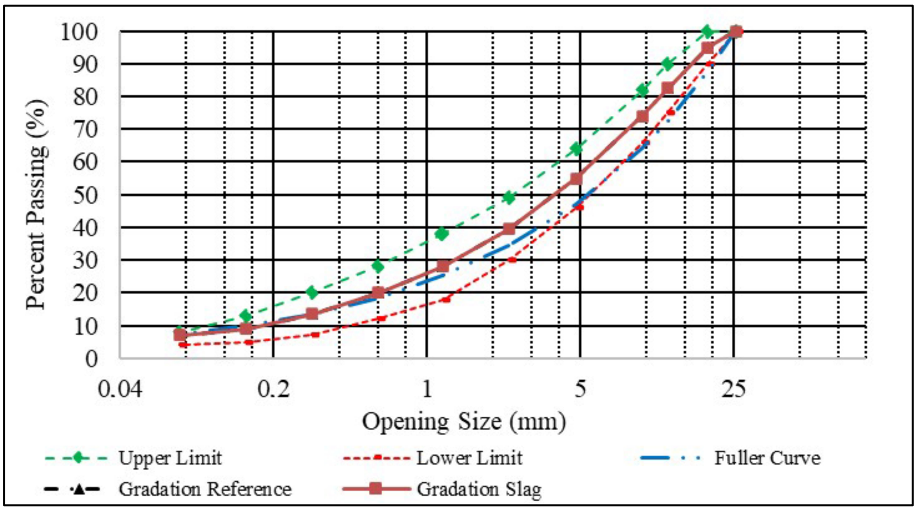
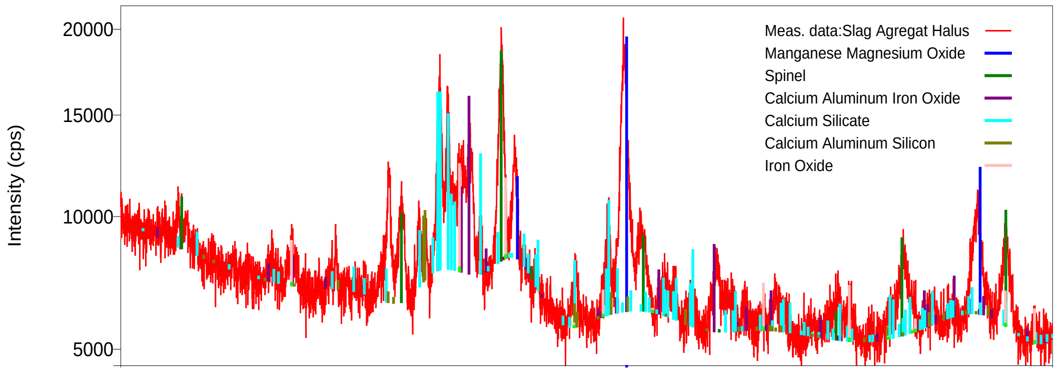


Figure. 1. Aggregate gradation of AC-BC mixture with RAP and slag.

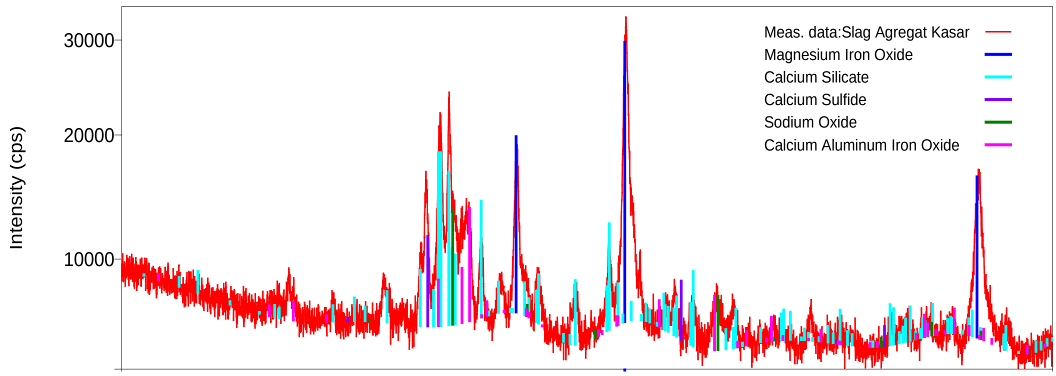
The asphalt material used in this study was the oil asphalt Pen 60/70 produced by PT. Pertamina. Regarding the mixtures that using Pen 60/70, the results are more durable than that using the Pen 80/100 and RAP asphalt which obtained from extraction test using an evaporator with Tricholore Ethylene (TCE) fluid [25]. In order to make the characteristics of RAP asphalt close to control asphalt Penetration grade 60/70, a rejuvenating agent, namely Reclamite® of 23 %, was used to be mixed with the RAP asphalt [23–24]. The test results can be seen in Table 2.

Table 2. Asphalt and RAP asphalt characteristics.

Test	Pen60/70	RAP	RAP-Reclamite
Asphalt Level	–	5.15	–
Penetration	64.7	10	62.04
Softening Point	51	80	53
Ductility	100	38	100



a. Fine slag aggregate



b. Coarse slag aggregate

Figure 2. XRD spectrum test results for fine and coarse slag aggregates.

Slag material has a mineral and chemical composition characteristic that are different from other materials, so it needs to be tested by the X-ray fluorescence spectrometry (XRF) and X-ray diffraction (XRD). The working principle of this XRD is to use X-ray fraction scattered by the angle of the crystal being tested, so that the pattern that appears in the XRD pattern, represents a plane of crystal that has a certain orientation. The test results of XRD for fine and coarse aggregates can be seen in Fig. 2.

Based on the XRD test results it can be seen that for fine slag aggregate there are 4 dominant crystals, namely Manganese Magnesium Oxide (MGOMnO), Calcium Aluminium Iron Oxide (Ca2Fe140Al060O5), Calcium Silicate (Ca2SiO4), and Calcium Aluminium Silicon (Ca3Al2Si2), and for the coarse slag aggregate there are 3 dominant crystals: Calcium Silicate (Ca2SiO4), Sodium Oxide (NaO2) and Calcium Aluminum Iron Oxide (Ca2Fe140Al060O5). The Ca or Si ratio contained in fine and coarse slag aggregates is an indication of substantially alkaline, where this property affects the adhesion properties of slag aggregates in asphalt mixtures [25].

Meanwhile, the XRF is based on the identification and enumeration of X-ray characteristics that occur due to the photoelectric effect that can be analysed for the element content in slag material. The results can be seen in Table 3.

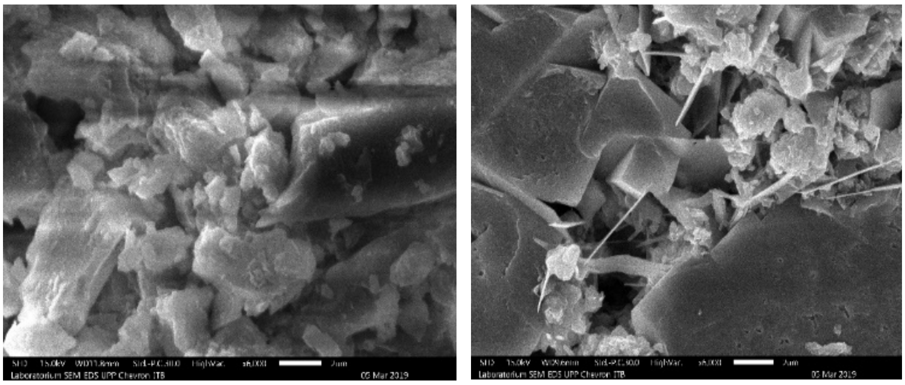
Table 3. Chemical composition of slag aggregate based on XRF test.

Slag Aggregate	**Oxide Content (%)**															
	Mg	Al	Si	P	S	Cl	K	Ca	Ti	MN	Fe	Sr	Zr	Na	V	Cr
Coarse	2.7	5.2	9.3	0.3	0.08	0.02	0.1	35.2	0.95	2.34	43.6	0.1	0.01			
Fine	3.0	5.8	7.7	0.3	0.1	0.02	0.1	30.8	0.8	2.9	47.3	0.1	0.1	0.08	0.6	0.3

Based on the Table 3, for fine slag aggregates and coarse slag aggregates, the most important elements are Fe, Ca, Si and Al. The content of aluminium oxide together with other metal elements in the slag result in a resistance to abrasion, while the Na element has a small percentage in the coarse slag aggregate (<12 %). So according to ASTM D5106-15, it is still permissible to use it in the asphalt mixtures up to 100 % use.

2.2. Morphology Characteristic

The Scanning Electron Microscope (SEM) is an equipment to evaluate and to compare the surface characteristics of the material, its pore dimensions and its crystal structure of natural slags and aggregates [26]. The SEM test was carried out with ± 0.5 cm test specimen, and then it was enlarged up to 6000 times. This result can be seen in Fig. 3.



a. Natural Aggregate **b. Slag Aggregate**

Figure. 3. Morphology of aggregate characteristics.

2.3. Asphalt Rheology

Mechanical asphalt rheology test (G^* and δ) was carried out using a DSR tool referring to AASHTO T315 with a test frequency of 10 rad/s and test temperature referring to the temperature range contained in the PG AASHTO M320 asphalt specification table. This test was carried out on three asphalt conditions: original, RTFOT and PAVT [24]. Based on these conditions, the asphalt stiffness modulus was obtained using the following formula:

$$S_{bit} = 2(1+\mu)\cdot G^*, \qquad (1)$$

where S_{bit} is asphalt stiffness modulus, μ is Poisson ratio and G^* is complex shear modulus.

The DSR temperature sweep test is usually conducted to verify the grade of asphalt in the PG system, related to the mechanical behaviour of asphalt, the SUPERPAVE sets limits on the amount of G^* and δ on the flow parameters and the fatigue crack parameters, which are listed in Table 4.

Table 4. Performance grade of asphalt pen 60/70, RAP asphalt and RAP asphalt with reclamite.

Condition	**SUPERPAVE Criteria**	**Test Result °C**		
		Asphalt Pen 60/70	RAP Asphalt	RAP Asphalt (Reclamite)
Original Binder	Rutting	65.3	110.7	68.7
RTFOT	Rutting	63.6	120.2	68.9
PAVT	Fatigue	23.7	52.8	25.4

Based on Table 4, the performance grade can be determined based on the value of G^*/sin δ under the original conditions. The PG value is 64 for asphalt Pen 60/70, the PG value for RAP asphalt is 106, while the PG value for the RAP asphalt added with Reclamite rejuvenating materials is 64. The change in PG value on RAP asphalt with the addition of rejuvenating material shows a decrease in PG value, resulting in the same PG value with that of asphalt Pen 60/70. This indicates that there has been a good rejuvenation process in the RAP asphalt mixed with Reclamite.

2.4. Mixture Design

The resilient modulus test in the laboratory was carried out by the Indirect Tensile Modulus test, using the UMATTA equipment and referring to ASTM (1997) D4123-82, with a loading pulse width of 250 ms, and pulse repetition period of 3000 ms. It was carried out on the temperature variations with respect to fluctuations in temperature at the pavement, which were 35 °C and 45 °C. This type of test was a test that cannot damage the test specimen, because the load given was relatively small and it used a cylindrical specimens of the same size as the Marshall test specimen. The test specimens were loaded with a haversine or triangular pattern on its vertical diametrical plane through a loading bar.

The mixture design method uses Marshall method that referring to ASTM D6927 in order to obtain the value of Optimum Asphalt Content (OAC) that could be used for subsequent Resilient Modulus tests. The further discussion on the determination of OAC can be seen in another paper [27].

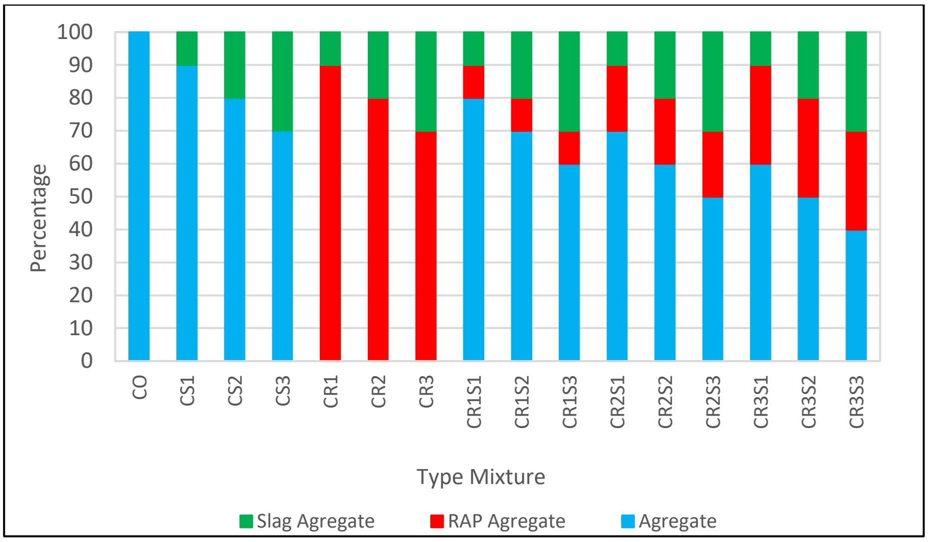


Figure. 4. The Combinations of Mixture Types.

This research used 16 combinations of mixture, in which there were variations of the percentage of slag and RAP materials. All variations can be seen in Fig. 4, with one mixture as a control mixture that using a natural aggregate and asphalt Pen 60/70 as a basic material.

3. Results and Discussion

3.1. Asphalt Stiffness Modulus

The value of asphalt stiffness modulus based on the results of the laboratory test using the DSR equipment, derived from the complex modulus $\left(G^*\right)$ value by using the equations (1), can be seen in Fig. 5.

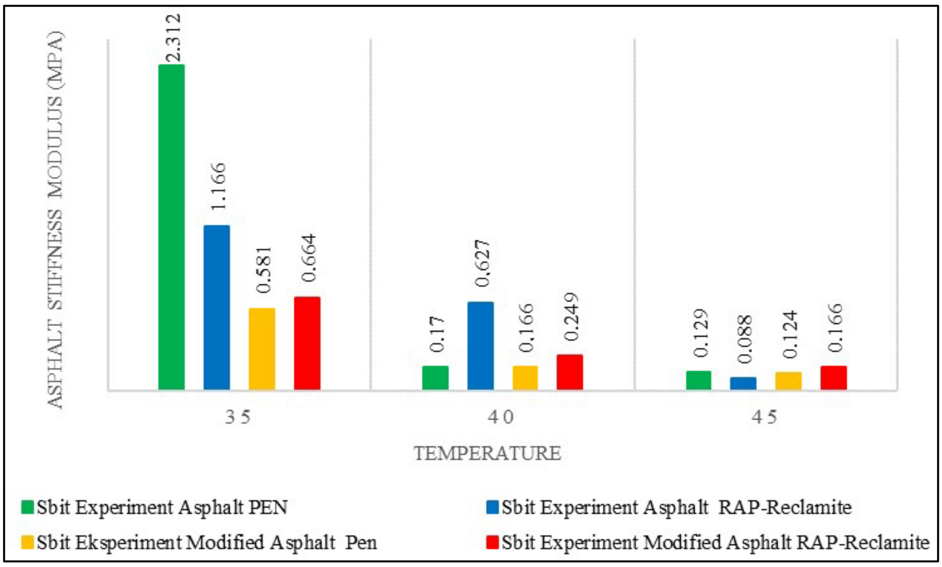


Figure. 5. Asphalt stiffness modulus.

Based on Fig. 5, the asphalt stiffness modulus value resulted from the DSR test, for asphalt penetration grade 60/70, is higher than that of RAP asphalt with Reclamite-added. Basically, this is due to the characteristics of the rejuvenating material that could make the condition of RAP asphalt returns into an original asphalt that is more “fresh” and liquid. The experimental testing makes it possible to use modified asphalt, where a calibration factor was needed. By using the statistical calculations, a calibration factor of 0.83 was obtained to apply the modified experimental Asphalt Stiffness Modulus.

3.2. Mixture Stiffness Modulus

Resilient modulus test of asphalt mixtures was carried out at 35 °C and 45 °C, based on an acceptable mean annual pavement temperature (MAPT) of 41 °C for the Indonesian climate. This test was carried out with the highest temperature, which was 45 °C, because at that temperature the asphalt has behaved like a viscous liquid with a little ability to return to normal condition. An increase in the test temperature affects the value of resilient modulus, where the higher the temperature the lower the modulus value. This is because at high temperatures, the asphalt will become a viscous material.

Based on Fig. 6, it can be seen that the asphalt mixture using RAP materials (CR1, CR2 and CR3) gives the largest modulus value while for the basic mixture, without slag and RAP (C0), the modulus value is the smallest. The aging process that occurs in the mixture can increase the modulus value of the mixture. This is shown in the mixture with RAP material, namely CR1, CR2 and CR3 mixtures. This is because the mixture contains aging RAP material was stiff, resulting in a higher modulus value. This phenomenon can be correlated to the increasing percentage of RAP in the mixture, with the higher asphalt aging rate, will increase the modulus value of the mixture at either 35 °C or 45 °C. The volumetric value will also affects the resilient modulus, where the void in mixture (VIM) value of CR3 mix is higher than that of CR1 mix, so that the increasing value of VIM will increase also the modulus value in the mixture.

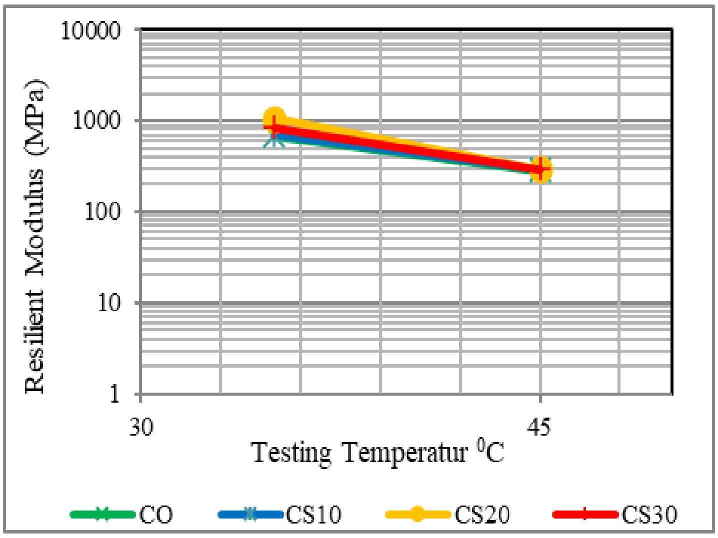
Figure. 6. Mixture Resilient Modulus.

The comparison of mixtures using slag (CS1, CS2, and CS3) shows that the increase in the percentage of slag will increase the resilient modulus value when it is related to the volumetric condition where the VIM value is greater on CR3 so the void mineral agregrate (VMA) CR3 value is smaller than the VMA CR1 so that the value increases VIM and reduced VMA values cause an increase in resilient modulus. This is also related to the surface roughness of the slag aggregate so that it gives a larger resilient modulus value. The results for the combination of slag mixtures with the addition of RAP (CR1S1, CR1S2, CR1S3, CR2S1, CR2S2, CR2S3, CR3S1, CR3S2, and CR3S3) showed an increase in the resilient modulus value seen from the higher VIM volumetric with the increase in the percentage of RAP in the mixture.

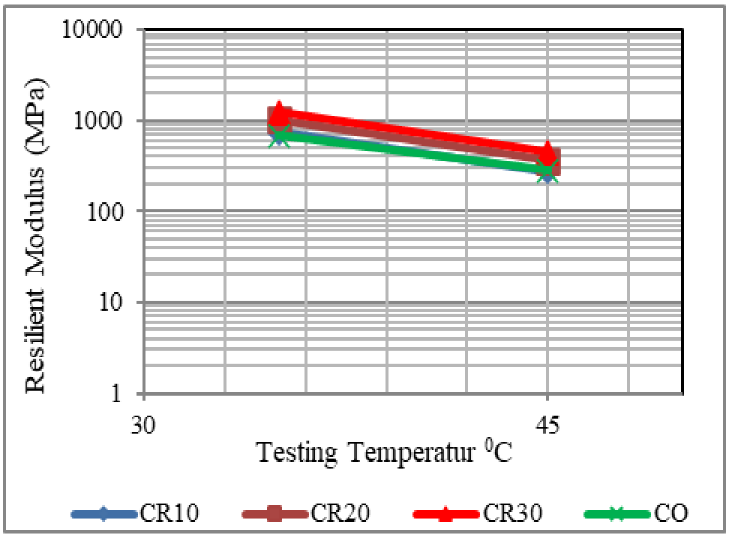
Value was found in the 30 % RAP mixture (CR3). This might be due to the asphalt contained in the RAP material had undergone aging at 35 °C and 45 °C test temperatures, compared to other mixtures, causing a greater mixture stiffness value. Increased stiffness was also seen when slag and RAP was combined. The results are greater when compared to the control mixture (C0). The optimum resilient modulus in the mixture of slag and RAP was in the mixture of RAP30Slag10 (CR3S1), this is shown when the percentage of RAP30 with the addition of slag indicates a smaller modulus value. In contrast, the smaller percentage of RAP with increasing slag causes a greater resilient modulus value. This is due to the high volumetric characteristics of the void in mix (VIM) with an increase in percentage of slag in the mixture.

3.3. Sensitivity of Resilient Modulus to Temperature Changes

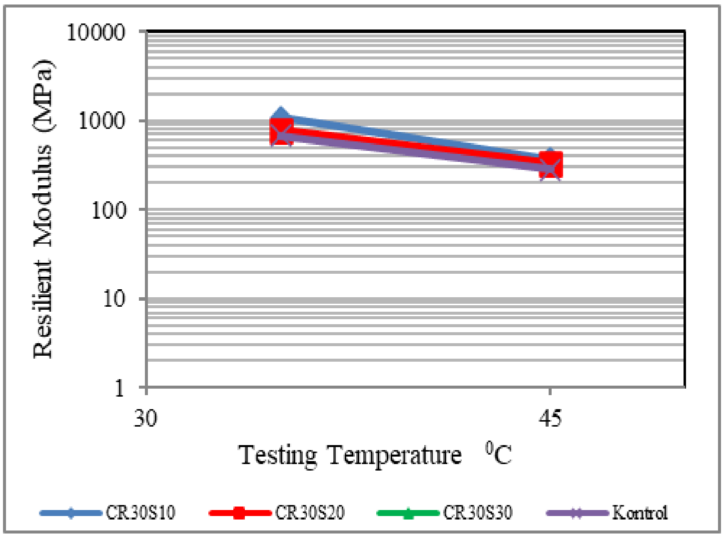
Resilient modulus is very dependent on temperature, so it is necessary to analyse how the temperature sensitivity of Moduli at high temperatures (35 °C and 45 °C), where the asphalt characteristic are in viscous or visco-elastic conditions, as shown in Fig. 7 below.



a. RAP mixture



b. Slag mixture



c. Combination of RAP and slag

Figure 7. Temperature sensitivity of resilient modulus.

Based on Fig. 7a, at high temperatures (35 °C to 45 °C) and the increase in RAP percentage, it is shown that the line of the asphalt mixture using RAP is getting steep but almost coincide at one point. This presents that an increase in the RAP percentage at high temperatures tends to be insensitive to temperature changes. Meanwhile on Fig. 7b, the Modulus test with slag aggregate at same temperature of 35 °C to 45 °C, the increase in slag percentage shows a steeper slope, means the increasing sensitivity to temperature changes, compared to the control mixture without slag, where less sensitive to changes in temperature.

For overall combination in Fig. 7c, it can be seen that the addition of RAP in the slag mixture can reduce the sensitivity to temperature changes, especially at high-temperature conditions (35 °C – 45 °C). This condition can overcome the weakness of the slag aggregate which is sensitive to temperature changes. On the other hand, adversely the presence of RAP can increase the Stiffness Modulus using slag only.

3.4. Model of Mixture Resilient Modulus

The model of resilient modulus was developed based on tests conducted in the laboratory, under viscous conditions. The proposed regression models require another tests to determine whether the independent variables have an influence to the dependent variables. In this case, the classic assumption test was used cooperated with another several tests, such as multi-collinearity test, heteroscedasticity test, normality test, auto-correlation test and linearity test [28–30].

In this research, the proposed prediction model selected was a multi-linier regression model, composed with several models including some dependent variables and a combination of some independent variables, such as model of the Nottingham University [31] and the Shell Model [32]. Table 6 presents the results of the model in viscous conditions for mixtures using RAP and slag, where the dependent variable is the Resilient Modulus of mixed (S_{mix}) and the independent variables are the Modulus of asphalt (S_{bit}), the void in mixture (VIM), and the percentage of RAP and slag materials.

Table 5. Analysis prediction resilient modulus model.

Test	Variable	Coefficient	DF	F	t	sig
Resilient modulus (Smix)	Constant	–112.603	4	69.336	–1.066	0.291
	S_{bit}	1140.587			16.320	0.000
	RAP	0.798			0.523	0.603
	Slag	0.555			0.347	0.729
	VIM	65.286			2.646	0.010
	R Square	0.825	R-Sq(adj)	0.813		

Based on the VIM Model, the value of R^2 is 0.825. This value is closed to 1.00, meaning that the independent variables provide almost all the requirement needed to predict the dependent variables. Based on the results of "one-way analysis of variance" (ANOVA), include with the F-test with a confidence level of 95 % (α = 0.05), it is obtained that the F-statistic value is greater than the F-value representing the relationship between independent variables. This is consistent with a p-value less than 0.05, which means that the resulted model is significant, and all regression coefficients significantly affect the Resilient Modulus of the mixture.

The VIM Model shows also that the dependent variable has a positive effect on Resilient Modulus. With the increasing value of Asphalt Modulus and the percentage of RAP, the Mixture Modulus becomes higher. This phenomenon can be related to aging process that occurs inside the asphalt of RAP. Meanwhile, the increase in percentage of slag contributes to an increase in the Resilient Modulus of mixture. This is due to the rough characteristic of the slag surface. Moreover, the selected model of Resilient Modulus needs to be validated, and compared with the value of Resilient Modulus measured in the laboratory. This correlation can be shown in Fig. 8.

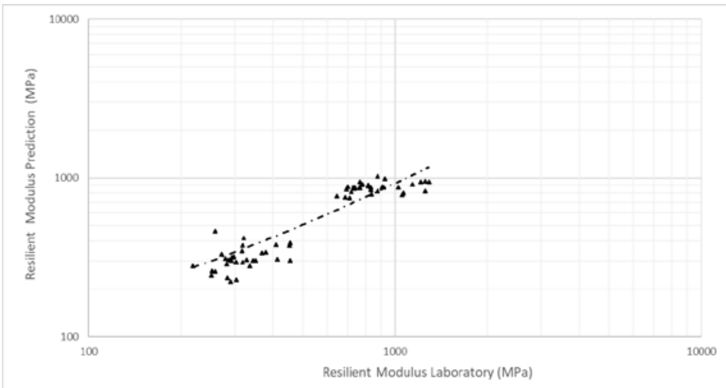


Figure 8. Comparison of laboratory and prediction model.

Based on Fig. 8, the "E" prediction model of resilient modulus, was selected, because besides that model can fulfilling all the classic assumption tests, it gave also a value of average ratio closed to 1.00. This condition concludes that the results of the prediction model of resilient modulus were closed to the results of the direct measurement using the UMATTA equipment.

4. Conclusion

Based on the analysis of the previous discussion, the following conclusions were obtained:

1. The morphology characteristics of slag aggregates used in this research, which is measured by using the XRD test, showed that the most important elements are Fe, Ca, Si and Al. Those elements in the slag will result in a resistance to abrasion.

2. The pen grade and softening point values of RAP asphalt with reclamite nearly same with that of the original pen grade asphalt 60/70. This condition approves the positive role of reclamite on the RAP asphalt only.

3. The value of stiffness modulus of RAP asphalt with reclamite, measured by DSR test at temperature of 35 °C and 45 °C, was nearly same with than that of asphalt modified pen 60/70. This condition approves also the positive role of reclamite on the RAP asphalt.

4. The maximum value of resilient modulus of asphalt mixture was obtained by a RAP percentage of 30 % (CR3), at both temperatures of 35 °C and 45 °C, whereas its optimum value was resulted from the combination mixture by 30 % RAP and 10 % slag (CR3S1).

5. The increase percentage of RAP in the asphalt mixture shows an insensitive trend with the increase of temperature, while the sensitive trend was obtained in the RAP mixture with slag. This combination of RAP and slag will obviously give an advantage in temperature sensitivity of the asphalt mixture.

6. The development of a resilient modulus model using RAP and slag materials under viscous conditions gives the optimum result of: SMix =1140,587 Sbit + 65,286 VIM +0.798 RAP + 0.555 slag - 122.603, where this equation was obtained by the combination of theoretical model from Shell and Nottingham.

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