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CHARACTERIZATION OF RECYCLED AGGREGATE FOR USE AS BASE COURSE MATERIAL

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ABSTRACT: This study extensively evaluated the soil water characteristic curve and resilient modulus characteristic of recycled pavement aggregate including recycled concrete aggregate (RCA), recycled asphalt pavement (RPM), and recycled pavement material (RPM) when used as a base course in road structure. The three recycled aggregates with similar gradation were selected for this study. The resilient modulus was determined for each material according to NCHRP 1-28A procedure. The soil-water characteristics curves (SWCC) were determined for each material. The major distresses including longitudinal cracking, alligator cracking, total rutting, and International roughness index (IRI) were predicted from the Mechanistic-Empirical Pavement Design Guide (M-EPDG). The result showed that among recycled aggregates, RPM provided the highest for all distresses while RCA had the lowest distresses. Using recycled pavement aggregates as base course provided lower distress than limestone which was used as a control conventional aggregate. This implied that recycled aggregate had high quality which can use as a base course in road construction.

Keywords: Recycled Pavement Material, Mechanistic Pavement Design, Soil Water Characteristic Curve, IRI, Rutting, Rutting

1. INTRODUCTION

Waste from building and construction (C&D) are generally generated accounted for about half of solid waste around the world. Thus, the reuse of recycled materials from construction and demolition (C&D Waste) as a base course in road construction is one of the best alternatives for reducing virgin aggregates generation. The other benefits of using recycled material are increasing the life cycle of pavement material, reducing energy consumption, and reduce greenhouse gas emissions by on-site reclamation [1], [2], [3].

Three types of recycled materials which have been widely used in the base course application are a recycled concrete aggregate (RCA), recycled asphalt pavement (RAP), and Recycled pavement material (RPM). The RCA is aggregate obtained from the crushing of concrete demolition. The RAP is material derived from recycling asphalt surface while the RPM is generated by striping the old asphalt surface mixed with underling base course. Many types of research indicated that the three recycled materials provided excellent performance suitable for use as a base course or subbase in pavement layer [4], [5], [6], [7].

This article presents the characterizing resilient modulus (M_r) and soil-water characteristic curve (SWCC) of the RCA, RAP, and RPM. Then, the M_r and SWCC were used as input parameters Level I to evaluate pavement performance by using the Mechanistic-Empirical Pavement Design Guide (M-EPDG). The longitudinal cracking, alligator cracking, total rutting, and International Roughness Index (IRI) were predicted over time in order to evaluate pavement distress.

2. REVIEWING THE MECHANISTIC-EMPIRICAL DESIGN GUIDE (M-EPDG)

The M-EPDG is a pavement design methodology, which is based on mechanistic-empirical (M-E) principles. The outputs from the design process are pavement distress and smoothness, not a layer thickness like previous empirical pavement design. The design and analysis procedure calculates the structure response (e.g. stress, strain, and deflection) while the cumulative distress (e.g., fatigue, rutting, or the International Roughness Index (IRI)) can be predicted empirically over time. In addition, the M-EPDG also provides the level of reliability for each of performance indicators [8], [9].

The M-EPDG also provides a more realistic characterization of in-service pavements. The designer can incorporate the effect of traffic volume, climate, subgrade, and existing site conditions. The trial design is evaluated by comparing cumulative pavement performance at the end of design life with design reliability.

The MEPDG software is composed of four models: environmental model, traffic model, material characterization model, and distress prediction model. In addition, the M-EPDG methodology provides three hierarchical levels of design inputs, which allow the designer to match the quality and level of design inputs according to the level of importance of the project follow:

- The input parameters level 1 represents the highest quality level input requiring comprehensive input parameters obtained from direct measurement from the site or in the laboratory such as M_r testing and SWCC for unbound material characterization.
- The input parameters level 2 represents intermediate quality level input, which is determined by the correlations or regression to estimate the parameters from a conventional tested index such as grain size distribution, Atterberg's limits, and CBR for unbound material characterization.
- The input parameters level 3 represents lowest quality level and has the lowest reliability. Input obtained from the user estimate or user experience.

In flexible pavement design, the stress, strain, and displacements within pavement layer due to traffic loads and environment influence are calculated based on elastic theory using finite element method. In the M-EPDG, a variety of structural distresses are considered in the flexible pavement design including, bottom-up fatigue cracking (alligator cracking), surface-down fatigue cracking (Longitudinal cracking), fatigues in chemically stabilization layers, permanent deformation (rutting), and thermal cracking.

3. MATERIALS AND METHODS

3.1 Physical and Engineering Properties of Recycled Aggregate

Tested materials with similar grain-size distribution were collected from a road reconstruction project at different sources across the US under the Pool Fund Project. All recycled aggregates met the standard specification of dense-aggregate base course with maximum particle size 19 mm. The limestone was used as a control base course in order to compare the pavement performance of recycled base course. The soil classification was aggigened according to AASHTO T85. The compaction test followed ASTM D1557. The asphalt content was determined based on ASTM D6307. The Mortar content was obtained by immersing 500 g of RCA in 10% HCL solution for 24 h. The specimens were then sieved to a 5-mm to check mass loss for RCA. Table 1 presents physical and compaction properties of studied materials.

Table 1 Physical and compaction properties of studied materials

Properties	RCA	RAP	RPM	Lime stone
AASHTO designation[1]	A-1-a	A-1-b	A-1-a	A-1-a
Percent gravel	50.6	41.1	59.3	50.5
Percent sand	47.1	44.9	39.1	41.5
Percent fines	2.3	1	0.6	7.8
Specific gravity, G_s	2.63	2.41	2.5	2.58
Maximum dry unit weight[3] (kN/m^3)[2]	20.6	20.3	19.9	20.2
Optimum water content (%)	6	6.4	7.5	8.1
Percent absorption	5	1.3	1.7	2.5
Asphalt[3]/Mortar content	37	4.7	5.3	-

Methods: [1] AASHTO T85, [2] ASTM D1557, [3]ASTM D6307,

3.2 Resilient Modulus and Soil Water - Characteristic Curve Parameters

Resilient modulus (M_r) is input properties for the M-EPDG for measuring pavement response of pavement under traffic loads. M_r is elastic modulus defined as the recoverable strain under repeated load. To characterize M_r of unbound aggregate, varieties of response models have been introduced as a function of stress states.[10],[11],[12]. Among proposed model, the Witczak-Uzan model [12] is well known as a universal equation to provide accuracy prediction which includes bulk stress and octahedron shear stress under repeating loading. Thus, the Witczak-Uzan model was adopted to the MEPDG. The model requires three fitting parameters described as [12]:

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad (1)$$

where θ = bulk stress = $\sigma_1 + 2\sigma_3$ (for cylindrical specimens),
σ_1 = major principal stress,
σ_3 = minor principal stress,
τ_{oct} = octahedron shear stress $= \frac{\sqrt{2}}{3}(\sigma_1 - \sigma_3)$ (for cylindrical specimens),
p_a = atmospheric pressure = 100 kPa, and
k_1, k_2, k_3 = regression parameters

In order to incorporate the effect of moisture on M_r of unbound aggregate, the M-EPDG accounts for the climate effect in pavement response via SWCC modelled by Fredlund and Xing (1994) [13]. The Fredlund and Xing equation provides a sigmoid curve suitable for different type of soil for matric suction from 0 to 1 GPa. The model estimates suction (ψ) and degree of saturation with four fitting parameters as defined by:

$$\theta = C(\psi)\frac{\theta_s}{\{ln[e+(\psi/a_f)^{b_f}]\}^{c_f}} \quad (2)$$

$$C(\psi) = \left[1 - \frac{ln\left(1+\frac{\psi}{h_{rf}}\right)}{ln\left(1+\frac{1\,000\,000}{h_{rf}}\right)}\right] \quad (3)$$

where θ = volumetric water content,
θ_s = saturated volumetric water content,
ψ is suction in kPa, and
a_f (kPa), b_f, c_f and h_{rf} (kPa) = fitting parameters.
$C(\psi)$ = adjusting function used to force θ to zero at 1 GPa.

3.3 The M-EPDG Input Parameters

To evaluate the effect of type of unbound aggregates, conventional pavement structure comprises 11.43 cm asphalt layer, 25.4 cm base course, 50.8 cm subbase, and semi-infinite thickness subgrade was selected for evaluating pavement performance. The traffic input parameters including Average Annual Daily Traffic Truck (AADTT), traffic growth rate, percent of the truck in design lane, and operational speed were assigned as shown in Table 4. The 90% of reliability will be used in the analysis. Other input parameters were assigned to the default value as recommended by the M-EPDG for input parameter level 3.

Table 4 Input for All Variables Used in the Analysis for Studying Impact of Resilient Modulus and Hydraulic Property Input Level in M-EPDG

Input Category	Input Variable
Initial Design Traffic Volume	AADTT 500
Percent Trucks Design Lane	50
Traffic Growth Rate	1.50%
Operation Speed (km/h)	105.6
Asphalt Concrete Layer	PG 58-34, 11.43 cm
Base course	Uniform graded sand, 25.4 cm,
Granular Subbase	Uniform graded sand, 50.8 cm, M_r = 134 MPa
Subgrade	A6 (AASHTO), M_r = 100 MPa

The impact of M_r and hydraulic properties were investigated via longitudinal cracking, alligator cracking, total rutting, and international roughness index (IRI). All distress were calculated monthly for 20 years of service life. As the main objective of this research was to the evaluable quality of recycled materials used for the unbound base course, only properties of base course were changed. The other properties such as climate condition, traffic input, the thickness of pavement structure, and material properties of other were fixed. The failure criteria were defined as 18% of the total area for alligator cracking, 31.6 m/km for longitudinal cracking, 1.9 cm for total rutting, and 253 cm/km for IRI [9].

4. RESULTS AND DISCUSSION

4.1 Resilient Modulus Characteristics

The M_r of studied recycled base course is presented in Fig. 1. According to the NCHRP 1-28A testing protocol, the M_r was characterized by a combination of confining stress and octahedron shear stress with 30 sequences. During the test, test sequences are divided into six loops sequences. For each loop cycle, the confining stress will increase for five load sequences and then drop for a new loop. M_r from each load testing sequence for each material was fitted with the Witczak-Uzan model. As M_r changes with the confining and octahedron shear stress, a summary resilient modulus (SRM) defined as a representative M_r for the pavement material. According to the National Cooperative Highway Research Program (NCHRP), the M_r at confining stress at 208 kPa and the octahedron shear stress of 48.6 kPa was used to represent the M_r of the material [9].

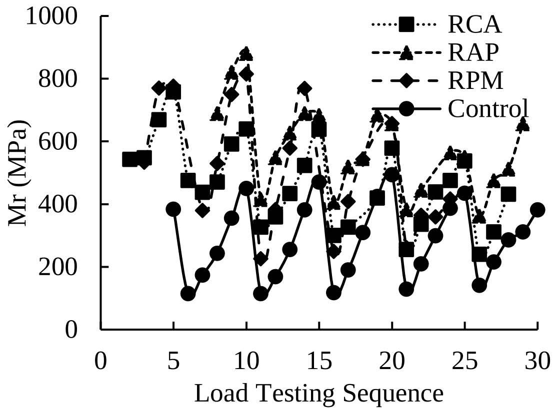

Fig. 1 The M_r at Load Testing Sequence for RCA, RAP, RPM, and Control Base Course

As seen in Table 2, the result showed that the three-recycled base course had a similar particle size distribution (Defined by A-1-a) but had different SRMs. RAP had highest SRM (480.3 MPa) while RPM provided lowest RRM (359.4 MPa). RAP was milled from the old asphalt layer might have better material quality than RPM which was milled asphalt surface mixed with lower quality of aggregate underlying base course. Compared to control base course, the studied recycled aggregates had higher SRM than lime stone, implying that recycled materials could be used for a base course with no need for stabilizing material properties.

Table 2 Witczack-Uzan's Fitting Parameters and Fredlund and Xing Fitting Parameters for Studied Base Course Aggregates

Aggregate	Witczak-Uzan Model				SRM (MPa)
	K_1 (MPa)	K_2	K_3	R^2	
RCA	23.5	0.69	-0.96	0.78	386.1
RAP	28.6	0.77	-1.06	0.89	480.3
RPM	19.5	1	-1.23	0.88	359.4
Limestone	8.2	1.07	-1.94	0,96	180.4

Fig. 2 presents the M_r predicted from Eq. (1) when compared to the M_r measured from the laboratory. Fig.3 is a plot of M_r versus (a) bulk stress, θ (t_{oct} = 48.6 kPa), (b) octahedron shear stress,t_{oct} (θ = 208 kPa) when fitted with Wiczak-Uzan Model for RCA, RAP, RPM, and Limestone (Control). The M_r increases with bulk stress. In contrast, M_r and decrease as octahedron shear stress decrease.

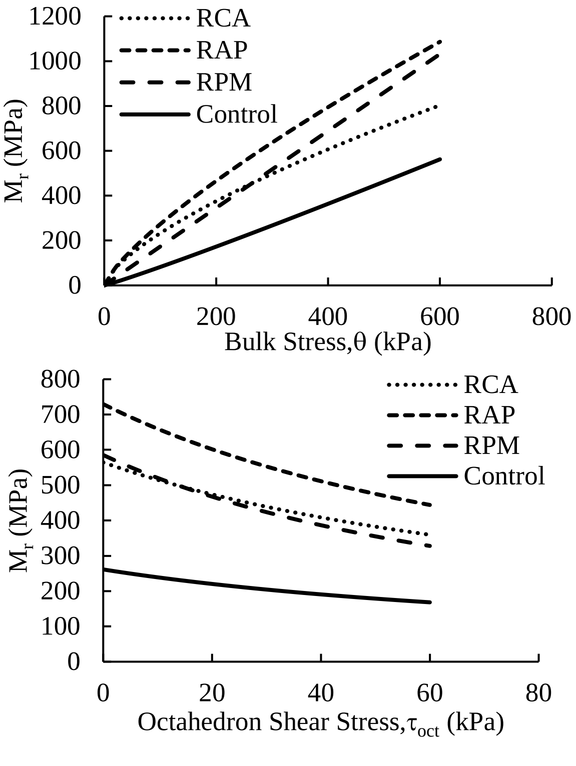

Fig.2 M_r versus (a) Bulk Stress, θ (τ_{oct} = 48.6 kPa) (b) Octahedron Shear Stress,τ_{oct} (θ = 208 kPa) when Fitted with Wiczak-Uzan Model for RCA, RAP, RPM, and Limestone (Control)

Fig.4 presents M_r fitted with the Witczak-Uzan Universal Equation for all tested recycled base course and limestone which was used as a control base course. The coefficient of determination (R^2), representing the goodness of model fitting, for RCA, RAP, RPM, and Control were 0.78, 0.89, 0.98, and 0.96, respectively.

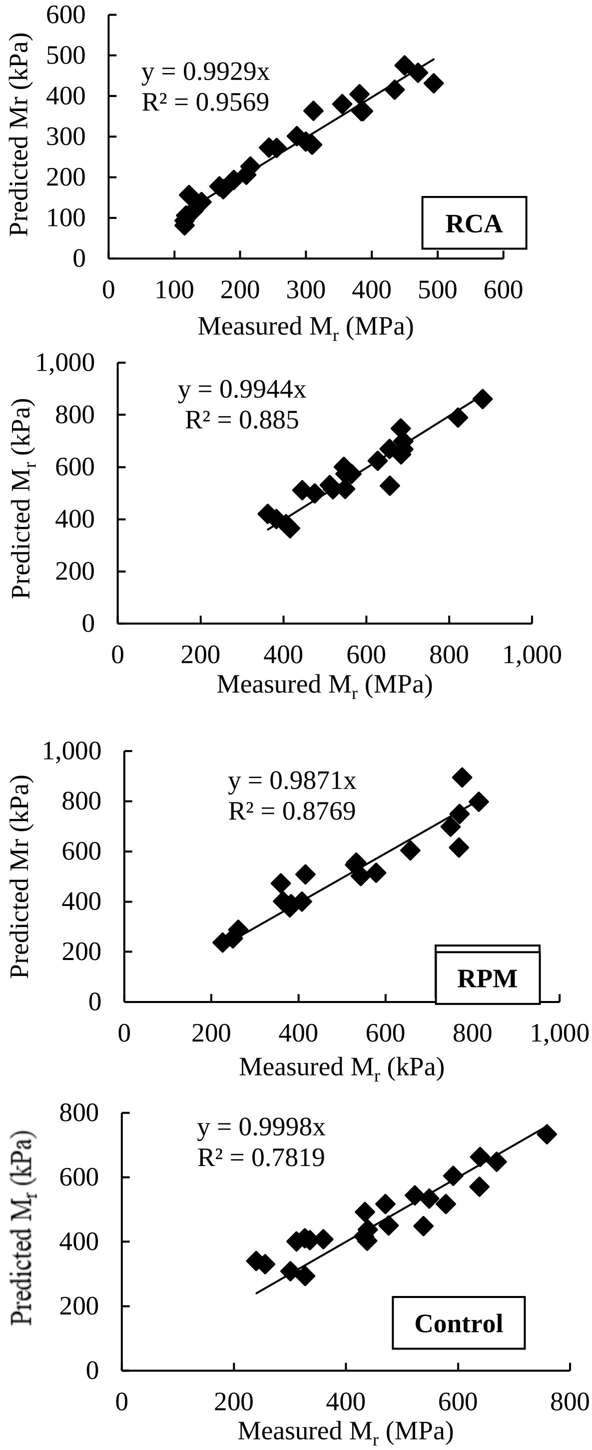

Fig. 3 M_r fitted with the Witczak-Uzan Universal Equation for RCA, RAP, RPM, and Control

4.2 Soil-Water Characteristic Curve

The M-EPDG requires soil water characteristic curve (SWCC), which is defined as the relationship between moisture and soil suction, for characterizing the impact of moisture to the M_r change. In theory, SWCC depends on pore size (d_{60}, d_{10}) and pore size distribution (Coefficient of Uniformity, C_u) of soil, thus soil with similar gradation curve should have identical SWCC shape. However, in this study, the result shown that type of aggregate could affect the SWCC shape.

Table 3 Fredlund and Xing Fitting Parameters, Coefficient of Determination (R^2), and air entry pressure, ψ_a for studied base course

Aggregate	Fredlund and Xing Parameters					ψ_a
	o_f	b_f	c_f	h_{rf}	R^2	kPa
RCA	1.4	1.2	0.2	104.8	0.99	0.9
RAP	1.4	0.4	0.7	97	0.99	0.16
RPM	2.4	1	0.3	97.1	0.99	0.75
Control	0.8	4.3	0.9	100	0.94	1.13

Figure 5 presents the SWCC of RCA, RAP, RPM and lime stone with Fredlund and Xing fitting curve. According to the SWCC characterization, RAP that comprised of a hydrophobic asphalt had a low percent of absorption (1.3%) and showed lowest air entry pressure value (a pressure which causes water start to drain, ψ_a). The SWCC of RAP also showed the steepest slope, indicating the ability to drain the water from the aggregate. Among studied material, the RCA had high, ψ_a and shallowest slope for the SWCC, implying the most ability to retain water in soil structure. The SWCC of control material presents a slight behavior of double porosity [14], which made the R^2 of the curve fitting provided Lowest (R^2 = 0.94). The Fredlund and Xing Model provided a smooth fit for the SWCC with R^2 ranging from 0.94-0.99. The fitting parameters for Fredlund were summarized in Table 3.

4.3 Distress Prediction by the M-EPDG

In flexible pavement, longitudinal cracking or surface down cracking is one of major distress which affects the pavement service live. The M-EPDG predicts the longitudinal cracking predicted by the function of a number of load repetition, tensile strain, and the stiffness of material [9]. Fig. 6 presents the cumulative longitudinal cracking with time for studied materials. The longitudinal cracking of pavement using studied material increases with time.

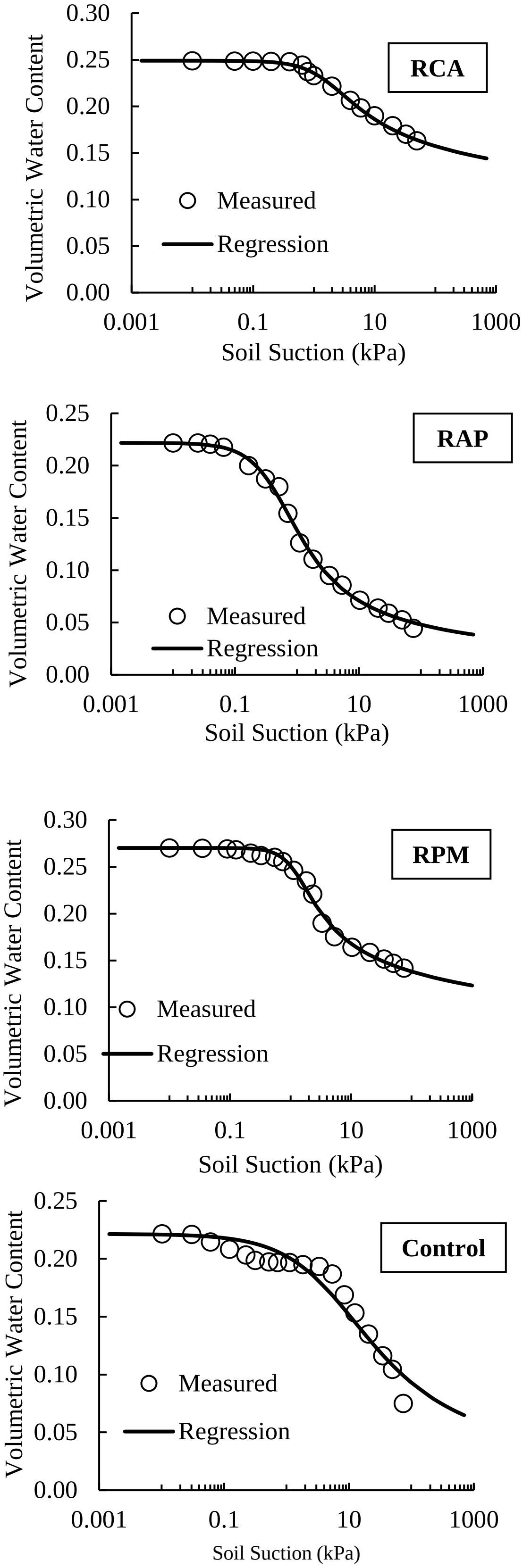

Fig.5 The SWCC fitted with the Fredlund and Xing[13] for RCA, RAP, RPM, Control

Asphalt pavement using three different typed of recycled base course generated lower longitudinal cracking when compared to lime stone. Pavement using RCA and RAP as a base course provided substantial low longitudinal cracking in comparison to control materials. However, as seen in Table 4 the longitudinal cracking at the 240th month is lower than the failure criteria (34,091 cm/km). This indicates that longitudinal cracking is not a major concern distresses in this analysis.

The alligator cracking is interconnected cracks resulting from fatigue cracking, which usually happen in the area of heavy traffic. The alligator cracking starts with the bottom of asphalt layer and the developed up to the surface of the asphalt pavement [9]. As the M-EPDG predict the alligator cracking by using the same equation with longitudinal cracking but the different constant value in cracking model, similar shape to cumulative longitudinal cracking with time was observed. As shown in Fig. 7 the alligator cracking of pavement using recycled base courses was lower than the control base course aggregates. As the failure criteria assigned from the M-EPDG for alligator cracking is 25%, the alligator cracking at the 240th month of all pavements was far less than the design criteria. This result indicates that the alligator cracking was not a critical distress for the pavement analysis.

The total rutting or permanent deformation is major load associated distresses in flexible pavement system. In the M-EPDG, total rutting was computed as a summation of plastic deformation of each pavement layer (surface, base course, subbase, and subgrade). Only plastic deformation due to volume change was calculated in the predicting model while the shear deformation under no volume change condition was not included in the model. Rutting is calculated based on mainly on the M_r of asphalt layer cumulative and repetition load. The temperature affects only for the asphalt layer. Fig. 8 present cumulative total rutting with time (month) for studied aggregates. The total rutting increased rapidly during at the beginning, and then after passing 20 months, the total rutting slowly increases. The total rutting of pavement using recycled base courses is lower than the control base course aggregates. As seen in Table 4, the failure criteria assigned from the M-EPDG for total rutting is 22.5 cm while the total rutting at the 240th month of pavement with control material as a base course is 22.3 cm, which almost reached the criteria.

The International roughness index (IRI) represents the smoothness of pavement. Generally, the IRI is usually used as a comprehensive indicator of pavement performance. In the US, a large number of state highways agencies measure IRI for considering pavement performance and pavement rehabilitation. In the M-EPDG, the IRI was predicted based on initial IRI, distresses, frost heave, and swell potential of the subgrade. Fig. 9 presents cumulative IRI with time (month) for studied aggregates. Like other distresses, the IRI increased with time. The IRI increased rapidly as road start to service, and then gradually increased. The IRI of pavement using recycled base courses was lower than the control base course aggregates. As the failure criteria assigned from the M-EPDG for IRI is 244 cm/km and the IRI of pavement with control material as a base course at the 240th month is 248.8, the design does not meet the criteria (See Table 4). This indicates that the IRI is a critical distress for this pavement distress analysis.

Table 4 A Summary of distresses at 20th year and failure criteria of pavement

Base Course	Longitudinal Cracking (cm/km)	Alligator Cracking (%)	Total Rutting (cm)	IRI
RCA	910	0.5	10.6	218.8
RAP	949	0.5	11.4	220.8
RPM	2182	0.8	13.5	226.4
Control	3000	1.8	22.3	248.8
Failure Criteria	34090	25	22.5	244.3

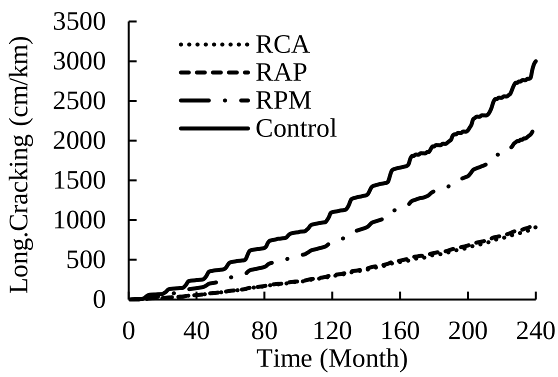

Fig. 6 Cumulative Longitudinal Cracking (km/s) with Time (month) for pavement using RCA, RAP, RPM, and Control Material as a base course layer

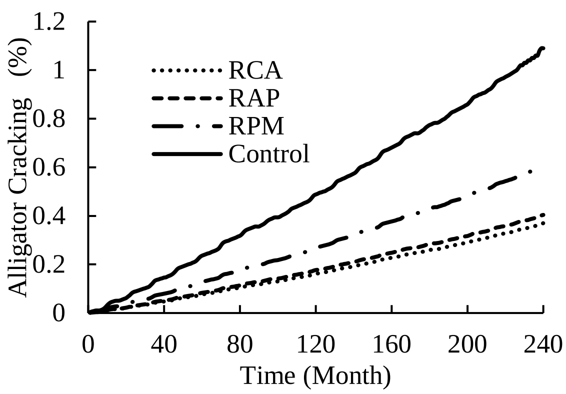

Fig. 7 Cumulative Alligator Cracking *(%)* with Time *(*month*)* for pavement using RCA, RAP, RPM, and Control Material as a base course layer

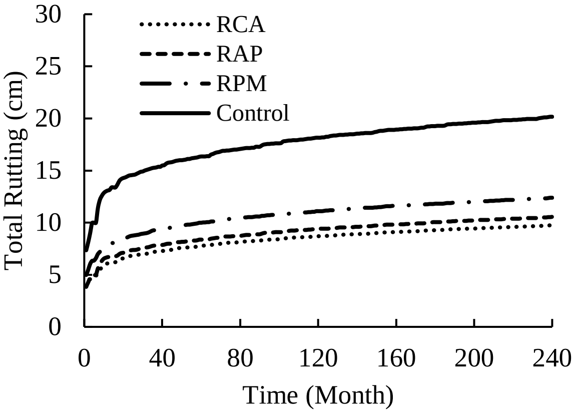

Fig.8 Cumulative Total Rutting with Time (month) for pavement using RCA, RAP, RPM, and Control Material as a Base Course Layer

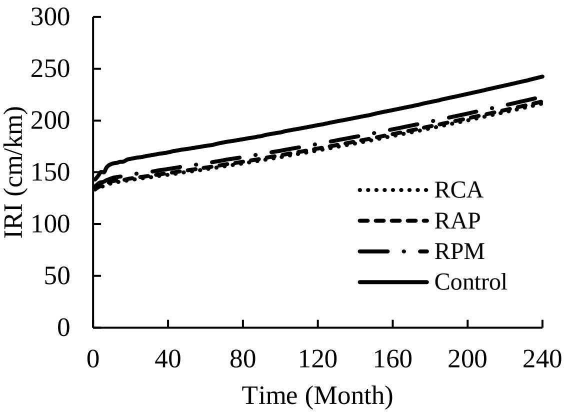

Fig. 9 Cumulative international roughness Index (IRI) with Time (month) for pavement using RCA, RAP, RPM, and Control Material as a Base Course Layer

4.4 Discussion

This study tried to characterize the pavement performance for recycled unbound aggregate. Although the samples had similar grain size distribution, RAP and RPM provide higher M_r characteristic than RCA and limestone. This result is similar to many researchers [4], [15], [16]. As RAP and RPM were obtained from asphalt layer, which is usually required high quality of aggregate than conventional base course and RCA. However, RAP and RPM tend to create high plastic deformation under repeating load, which is the major concern for using RAP and RPM [17]. as a base course. For RCA, the aggregated derived from crushed concrete surface course tends to create a mortar aggregate which is easy to brake under repeating load in Mr testing. As a result, RCA tend to provide low Mr. This observation is seen by many researchers [4], [18]. As distresses computed from the MEPDG are major affected by the M_r, aggregate with high M_r tend to have low distress ([9],[15]).

5. SUMMARY AND CONCLUSION

This study extensively evaluated the pavement performance when using RCA, RAP, and RPM as a base course in road structure. The M_r was determined for each material according to NCHRP 1-28A procedure, and fitted by using the Witczak-Uzan universal model. The SWCC was determined and fitted with the Fredlund and Xing[13]. The performances of studied pavements were evaluated by major distresses including longitudinal cracking, alligator cracking, total rutting, and IRI, which were predicted from the M-EPDG.

Although the recycled aggregates had similar grain size distribution, the M_r characteristic was different due to material type. RAP had highest SRM while RPM provided lowest SRM. All recycled aggregate had higher SRM when compared to limestone crush rock which was used as a control aggregate. The Witczak-Uzan model provides the good fitting with R^2 between 0.78 to 0.96.

The impact of material type was also observed in the SWCC. RAP comprised of a hydrophobic asphalt had lowest ψ_a and steepest slope for the SWCC while RCA had low ψ_a and shallowest slope for the SWCC. This implies that RAP has a tendency to have the ability to remove water, while RCA has most ability to retain water in their soil structures. The Fredlund and Xing [13] provide the excellent fitting with R^2 0.94 to 0.99.

All distress of pavement using recycled aggregate which was predicted the M-EPDG were major affected by the M_r characteristic. As RAP had highest Mr, all distresses of pavement using RAP as a base course calculated from the MEPDG provided lowest distress. In contrast, limestone which had lowest Mr provided the highest value for all distresses when computed by the MEPDG.

Among pavement distresses, the total rutting and IRI were a crucial distress which controls the life service of pavement. The longitudinal cracking and alligator cracking did not affect the service life of the pavement. The resulting form this study indicates that recycled materials can be used use as base course layer with excellent performance.

6. ACKNOWLEDGEMENTS

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