TRANSACTIONS ON SCIENCE AND TECHNOLOGY

Maximization of waste recycling in pavement maintenance project

Lillian Gungat[1#], Meor Othman Hamzah[2], Nur Izzi Md. Yusoff[3]
1 Civil Engineering, Faculty of Engineering, University Malaysia Sabah, Jalan UMS, 88400 Sabah, MALAYSIA.
2 School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, 14300, Nibong Tebal, Seberang Perai Selatan, Penang, MALAYSIA.
3 Department of Civil Engineering, Faculty of Engineering and Built Environment, Universitti Kebangsaan Malaysia, 43600 Bangi, Selangor, MALAYSIA.
#Corresponding author. E-Mail: lillian@ums.edu.my; Tel: +6088-320000

ABSTRACT The most common method of recycling in road maintenance projects in Malaysia is in situ recycling. To maximize waste recycling, plant recycling can be an option since previous studies indicated good performance using reclaimed asphalt pavement (RAP). However, variability in RAP and mixing temperature are the main concerns in plant recycling. Hence, this study investigates the maximization of waste recycling from road maintenance projects in Malaysia for plant recycling in terms of quality control and the environment. The experimental design consists of materials characterization for three sources of RAP, determination of mixing temperature, analysis of environmental and energy consumption, and optimization of RAP production. The findings showed that based on RAP gradation the quality control in terms of RAP variability was less than 15% coefficient of variance and considered acceptable. The addition of RAP stiffened the RAP mixture which result in increased viscosity and mixing temperature. Higher mixing temperatures produced more greenhouse gas emissions and energy consumption. Optimization of RAP production indicated that in order to maximize the RAP usage, 50%RAP content added with RH-WMA at 140°C mixing temperature was the most ideal. The proposed design approach and evaluation of waste materials adopted in this study are beneficial for assessing the essential criteria for maximizing waste recycling in the pavement.

KEYWORDS: Recycling; Mixing Temperature; Environment; Energy Consumption; Pavement
Received 12 April 2023 **Revised** 7 August 2023 **Accepted** 11 August 2023 **Online** 6 September 2023

Original Article

INTRODUCTION

Roads, as an integral part of transport infrastructure, provide connectivity and accessibility to various locations worldwide. A good road network is an indicator of development in a country. Road development due to transport demand in both urban and rural enhance socio-economic growth. Thus, maintaining the road in good condition to increase its serviceability is challenging.

Roads need maintenance to prevent distress or restore performance to provide good service to the user (Amoatey *et al.*, 2020). Road maintenance can generally be divided into routine maintenance, periodic maintenance and emergency maintenance executed by road concessionaire. For any road maintenance project, systematic planning of pavement management is essential to ensure pavement sustainability. According to Khahro *et al.* (2022), a cost-effective decision model that suits local requirements is essential for maintaining good road conditions. The type of maintenance that will be carried out during road maintenance depends on the severity of road deterioration. Typically for highways, the road will be resurfaced after 3-5 years. During the resurfacing, the old pavement surface will be milled, removed, and replaced with a new surface layer. The milled pavement could be thrown away or recycled in situ or at the plant. The recycling methods for RAP are divided into four categories which are cold central plant recycling (CCPR), hot in-place recycling (HIR), cold in-place recycling (CIPR), and full-depth reclamation (FDR). The removed and processed used pavement is named reclaimed asphalt pavement (RAP). In-situ recycling method carried out at the construction site. In contrast, plant recycling method involves pavement recycling at a central plant which is away from the road construction site. Plant recycling is generally implemented for large recycling production. The advantages of recycling could be from an environmental and economic perspective.

Malaysia's most common road maintenance method is in situ recycling, whereby old pavement is reused as a sub-base. However, plant recycling is typical in other countries such as Europe, United State, United Kingdom and Japan. Using higher amounts of RAP in road construction saves cost and energy as well as ecologically sound. However, the production of RAP requires high temperatures, generally above 160°C to melt the aged binder due to the high stiffness of RAP materials. An attempt has been made to reduce the production temperature of RAP obtained from different sources using various types of WMA additives. However, it was found that the types of WMA additives and variations in RAP affected RAP's rheological and mechanical properties (Jamshidi *et al.,* 2014; Buss *et al.,* 2015). The percentage of RAP for new road or road maintenance varies. Many countries have been reluctant to utilize more than 30% RAP because the implementation needed more guidelines (FHWA, 2008). Other studies have suggested that RAP homogeneity influences the restriction of RAP content for incorporation into hot mix asphalt. Variability in RAP is the primary concern for plant recycling as the RAP comes from various sources. Gradation of RAP is used as a reference to control the variability in RAP. In addition, many studies have been conducted to identify the potential to incorporate higher RAP content for its environmental and economic benefits.

In Malaysia, waste recycling from pavement maintenance projects is mainly in situ. However, plant recycling can be proposed in future due to the massive amount of pavement waste. There are three criteria to be considered: cost-effectiveness, good performance and environmentally friendly to ensure the successful use of RAP (Dughaishi *et al.,* 2022). Therefore, a detailed study on the quality control of RAP at the plant is crucial to ensure RAP materials' performance is at par with conventional materials. This paper presents the maximization of waste recycling from road maintenance projects in Malaysia for plant recycling in terms of quality control and environment.

METHODOLOGY

Materials

A virgin asphalt binder grade PG64 was used in this study as the control binder. Table 1 presents the physical and rheological properties of the control binder. Used asphalt from road maintenance projects were milled and recycled. The recycled asphalt was processed and named RAP. A WMA additive named RH-WMA was used as an additive and mixed with reclaimed asphalt binder. RH-WMA additive was incorporated at 0 and 3% of the total weight of the asphalt binder to reduce the viscosity of RAP. The RAP was obtained from three sources and identified as R1, R2 and R3. These roads are located at KM 75.4 of NSE, section 685 Jalan Kamunting Perak and KM 138 of NSE, respectively. The NSE are the main highways connecting other states, while PWD roads are mainly used within the state. These roads were trafficked for about 5 to 7 years. This study focused on the utilization of RAP above 30% RAP content. Hence, 30%, 40% and 50% of RAP were incorporated in the asphalt binder and mixture study. A designation was adopted to simplify the identification of recovered asphalt blends. The first number denotes the percentage of reclaimed asphalt binder, followed by the source and additive. For example, 40R1-RH indicates that the binder blends consist of 40% reclaimed asphalt binder from PWD road or R1 and added with RH-WMA additive.

Table 1. Properties of control binder.

Condition	Properties	Value
Unaged	Penetration (dmm)	86
	Softening (°C)	47
	Ductility (mm)	>100
	Viscosity at 135 °C (Pa.s)	0.39
	G*/sin δ at 64°C (kPa)	1.529

Experimental Design

The experimental procedure for maximizing used asphalt recycling in pavement maintenance projects was divided into four phases: characterization of RAP, determination of mixing temperature, analysis of environmental and energy consumption and optimization of RAP production. RAP was characterized to ensure RAP can be used in asphalt mixture production. Other than physical properties, gradation of RAP is crucial during RAP fractionation to reduce the RAP variability for plant production since RAP is obtained from various sources. Since RAP binders are stiffer due to aging, it requires higher temperature for mixing and compaction. Hence, mixing temperature was obtained by conducting viscosity test and mixability observation at the lab. Viscosity testing was performed according to ASTM D4402-02 using Brookfield rotational viscometer at temperatures ranging from 120 to 170 °C at 10 °C increment. For maximization of recycling, environmental and energy consumption were determined by considering the parameters such as RAP content and mixing temperature. Then, optimization using response surface method (RSM) was carried out to determine the optimized RAP production. All required input parameters for RSM were based on Jabatan Kerja Raya (JKR) Malaysia or Public Works Department standard and established standard. Figure 1 illustrates the experimental design.

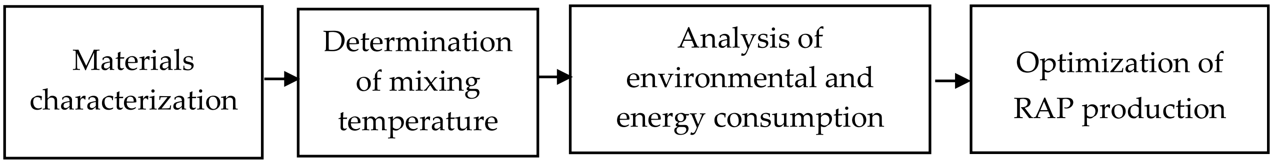

Figure 1. Flow chart of experimental design.

RESULT AND DISCUSSION

Materials Characterization

The experimental procedure for maximizing used asphalt recycling in pavement maintenance projects was divided into four phases: characterization of RAP, determination of mixing temperature, analysis of environmental and energy consumption and optimization of RAP production. When using RAP for road maintenance, two valuable materials that can be recycled in RAP which aggregate and binder. Hence, selected physical characterization was conducted, and results are presented in Tables 2 and 3, and Figures 2 and 3.

Table 2. Average percentage cumulative passing of recovered RAP aggregate.

Sieve size (mm)	R1		R2		R3	
	Cumulative Passing (%)	COV (%)	Cumulative Passing (%)	COV (%)	Cumulative Passing (%)	COV (%)
20	100.00	0.00	100.00	0.00	100.00	0.00
14	95.16	0.81	98.44	0.77	88.53	1.42
10	87.97	1.13	93.26	1.69	76.87	3.31
5	63.87	2.63	77.85	3.49	58.94	4.13
3.35	55.25	4.71	70.28	3.65	47.53	6.10
1.18	36.57	7.49	50.02	6.36	29.98	10.02
0.425	21.19	8.93	27.66	5.24	20.03	10.20
0.15	11.07	11.40	14.60	4.54	11.97	13.23
0.075	6.22	9.45	8.31	8.29	7.13	10.20

Table 3. Physical properties of recovered reclaimed asphalt binder.

Reference	Penetration (d mm)	Softening point (°C)	Viscosity at 135 °C (Pa.s)
R1	10	71	2.395
R2	19	70	2.275
R3	9	72	NA

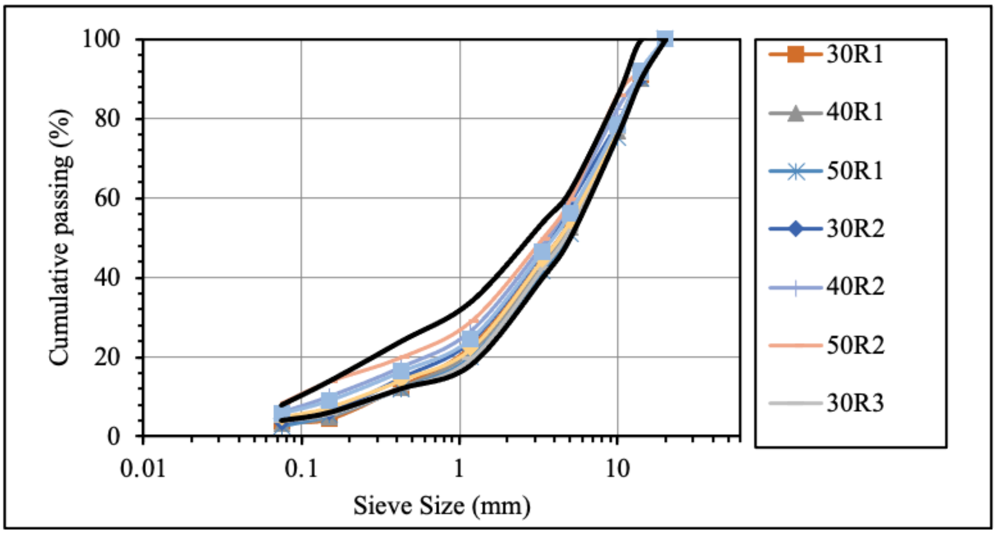

Figure 2. Aggregate gradation of recovered RAP and virgin aggregate based on target lower limit.

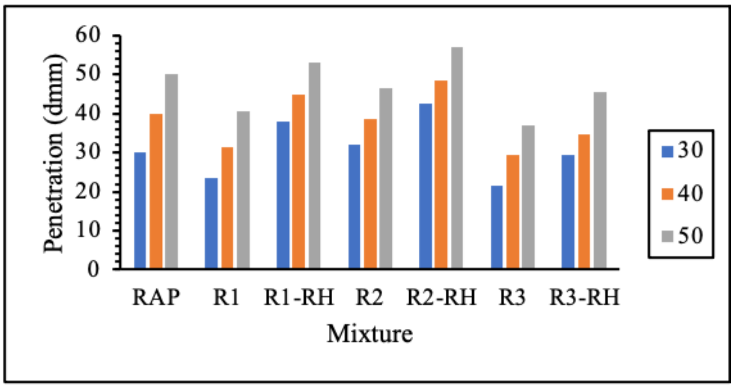

Figure 3. Penetration of RAP from various source with RH-WMA.

Table 2 presents the aggregate gradation of recovered RAP aggregate via the ignition method based on the average of 5 samples from each site are shown in Table 2. The coefficient of variance (COV) for all RAP sources is also presented in Table 2. The COV of all RAP aggregate is less than 15%. According to Newcomb *et al.* (2007). the COV of 15% on the key control sieve of recovered RAP is considered good. In this study, the key control sieve refers to the sieve size based on the AC14 gradation. Therefore, the aggregate distribution of the RAP used in this study is acceptable. For aggregate gradation at the lab, target gradation was used as a reference. After a few trials to ensure the blend of aggregate is within the gradation limit of AC14 of JKR specification, gradation was adjusted based on the target lower limit. The result is presented in Figure 2.

The physical properties of the recovered binder from three sources of roads are presented in Table 3. The penetration results show that the recovered RAP binders are stiffer. The RAP binder from R3 is the stiffest binder, followed by the RAP binder from R1 and R2. During service, asphalt ages gradually and harden through various mechanisms. Age hardening during construction and service was associated with oxidation, volatilization, polymerisation, syneresis and separation.

Other than that, the degree of ageing is also attributed to the condition of pavement prior to recycling (Al-Qadi *et al*., 2007). The pavement at the surface hardens faster. Hence, the changes in the physical properties of the RAP binders from the three different sources are related to the aforementioned factors.

The recovered RAP binder was blended with PG64 at 30%, 40% and 50%, and the results of a penetration are shown in Figure 4. The penetrations of RAP binders show similar trends with the penetration of the recovered RAP. When 3% RH-WMA additive is incorporated into recycled asphalt binder, the penetration slightly increases, indicating the RH-WMA additive's softening effect. In summary, the penetration of all recycled asphalt binders was reduced by incorporating RAP binder. Based on the physical properties test, the RAP can be used in a mixed design. Therefore, mixing and compaction temperature were determined based on viscosity test.

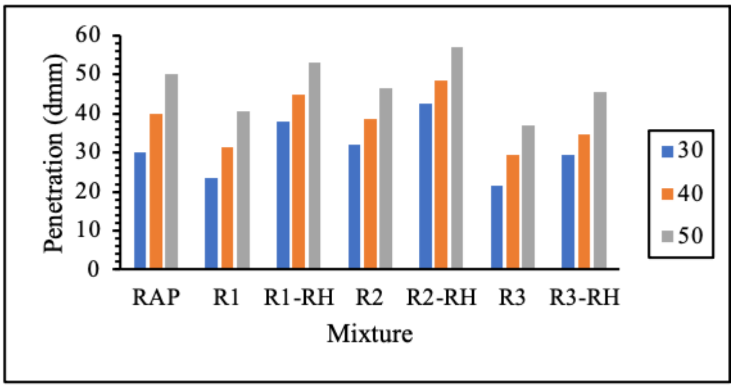

Figure 4. Penetration of RAP from various source with RH-WMA.

Mixing Temperature

Viscosity can be used to quantify the resistance of the fluid to flow. Figure 5 presents the viscosity of recycled asphalt binder from three sources of RAP containing 0% and 3% RH-WMA additive with various percentages of RAP binder. It can be seen that RAP source, RAP binder content, RH-WMA additive content and temperature affect the viscosity result. The viscosity increases with the RAP binder content. When more RAP binder content is incorporated with virgin asphalt binder, the flow resistance of the increases. On the other hand, the addition of RH-WMA additive reduces viscosity. The stiffest binder, which is the binder from R3, exhibits the highest viscosity. Increased stiffness of recycled asphalt binder implies higher mixing and compaction temperatures. Nevertheless, the addition of RH-WMA additive enables a reduction in mixing and compaction temperatures. The decrement of viscosity is able to lower the pavement construction temperature. The relationships between viscosity and temperature were also used to determine the mixing and compaction temperatures. According to the Asphalt Institute (2001) the recommended mixing and construction temperatures correspond to viscosity at 0.170±0.020 Pa.s and 0.280±0.030 Pa.s, respectively. Ideally, for a conventional mix, JKR specifies the viscosity at 135°C as a guide for compaction temperature. Table 4 presents the proposed mixing temperature based on viscosity test. It can be observed that higher RAP content requires a higher mixing temperature.

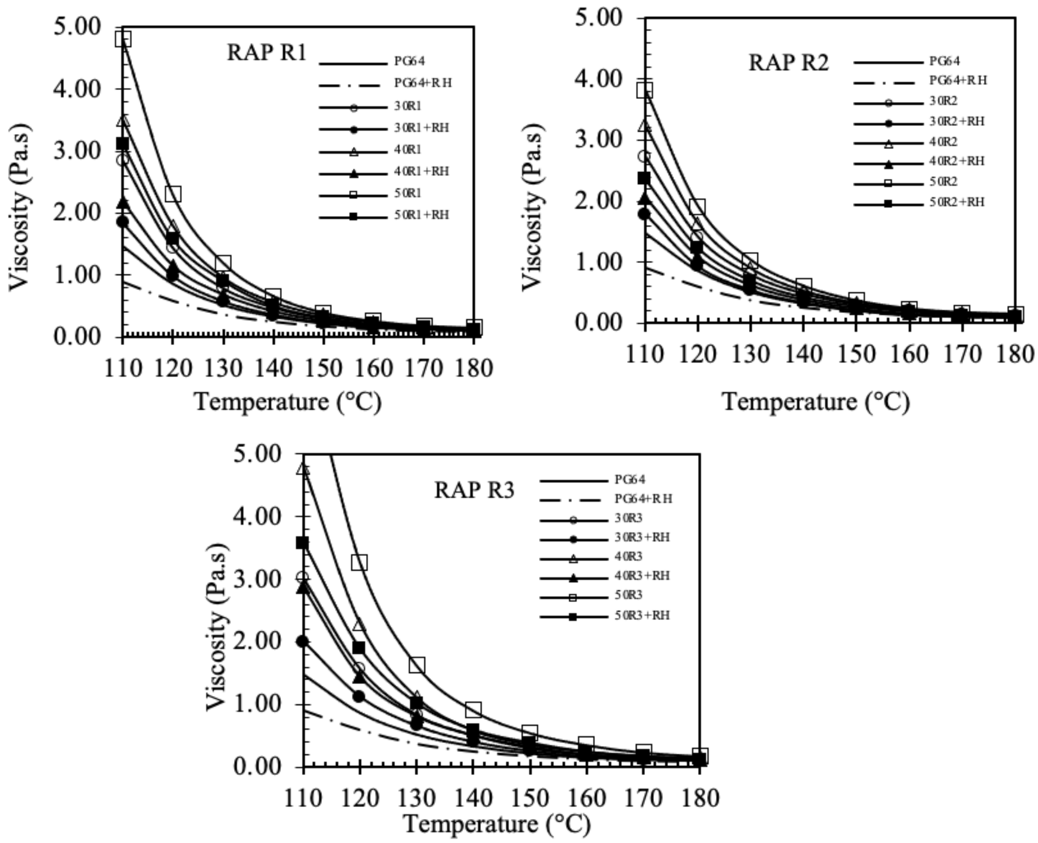

Figure 5. Effects of RAP content and RH-WMA on viscosity.

Table 4. Proposed mixing temperature based on viscosity test.

Sample R1	Mixing Temperature(°C)	Sample R2	Mixing Temperature(°C)	Sample R3	Mixing Temperature(°C)
30R1	165	30R2	166	30R3	170
40R1	170	40R2	170	40R3	170
50R1	175	50R2	173	50R3	176
30R1+RH	159	30R2+RH	157	30R3+RH	166
40R1+RH	161	40R2+RH	161	40R3+RH	169
50R1+RH	166	50R2+RH	163	50R3+RH	171

The selection of the mixing and compaction temperatures of the RAP mixture in the literature was based on the mixture performance of HMA-WMA, the manufacturer's recommendation, the binder viscosity and compatibility at different temperatures. In addition, engineering judgment may apply in some cases, as proper coating or compaction could not be achieved for some mixtures with higher RAP content. The limit is based on the compaction temperature of the mixture, which is governed by the temperature of the mix during storage and transport. The RAP should not be heated up to a very high temperature to prevent further ageing of the aged binder. Hence, mixability observation was conducted at the lab, and the mixing temperature obtained from the viscosity test was used as a basis for the determination of mixability of the mixture in the lab.

Analysis of Environmental and Energy Consumption

In addition to mixability observation, environmental and energy consumption analyses were conducted. For the environmental analysis, the fuel usage at desired mixture temperatures was estimated from a graph developed by Universal Pave Sdn. Bhd. for a premix plant in China. The type of fuel was diesel. The graph was developed for 1 ton of asphalt production. For further analysis, the fuel consumption was converted to CO_2 equivalent emissions based on conversion factors by fuel type given by the United Kingdom Department of Environment, Food and Rural Affairs (DEFRA, 2010) and shown in Table 5. The table shows that higher mixing temperature produces more GHG emission. Hence to reduce the GHG emissions, a lower temperature should be used during the asphalt production.

Table 5. Fuel usage and GHG emissions of RAP production.

Mixing Temperature (°C)	RAP Content (%)	Fuel Usage (liter)	Total GHG (kg CO_2e per unit)
170	30 40 50	12.0	32.0640
155	30 40 50	8.8	23.5136
140	30 40 50	7.7	20.5744

Energy consumptions was calculated using Equation (1).

$$Q = \sum_{i=0}^{n} m_i \times c_i \times \Delta\theta \quad (1)$$

Q is total energy (J), m_i *is* mass of material type *i* (kg), c_i *is* specific heat capacity of material type *i* (J/kg°C), *Δθ is* difference between the ambient temperature and mixing temperature (°C) and *i is* type of material. For calculation purpose, the energy requirement is calculated for a dual carriageway with 3.65 m width and three lanes for each direction. The road length is 10 km and 5 cm asphalt thickness. Parameters for energy consumption calculation is shown in Table 6. Other parameters such as the bulk specific gravity and OBC are depending on the asphalt mixture properties.

Table 6. Parameters for determination of energy consumption (Jamshidi *et al.*, 2012; Wen *et al.*, 2015).

Parameters	Unit	Value
Specific heat capacity of asphalt binder	J/kg°C	
PG64		920
PG70		1506
PG76		2093
Specific heat capacity of granite aggregate	J/kg°C	890
RAP content	%	30-50
Weight of WMA	Ton	1

Analysis was conducted using excel and further optimized using RSM. An example of RSM output is shown in Figure 6. Figure 6 demonstrates the effects of binder content and mixing temperature on the energy consumption for 1 ton of asphalt production at 40% RAP content. Similar trends. are observed for 30% and 50% of RAP content. Binder content and mixing temperature increase proportionally with the energy consumption of asphalt production. Mixing temperature has a notable effect on energy consumption as indicated by the slope of the graph despite the binder content. Stepper slope refers to the more significant changes in energy consumption with increasing mixing temperature. The rate of energy increment can be calculated by using the relationship between the energy and mixing temperature. For example, the energy consumption of R2-RH that contains 40% RAP with 6.0% binder content at 140°C and 160°C mixing temperature requires 2.878 TJ and 3.654 TJ. Similarly, R3-RH that contains 40% RAP with 6.0% binder content at 140°C and 160°C mixing temperature requires 3.001 TJ and 3.811 TJ. Hence, the rate of energy increment for R2-RH and R3-RH are 0.039 TJ/°C and 0.041 TJ/°C, respectively.

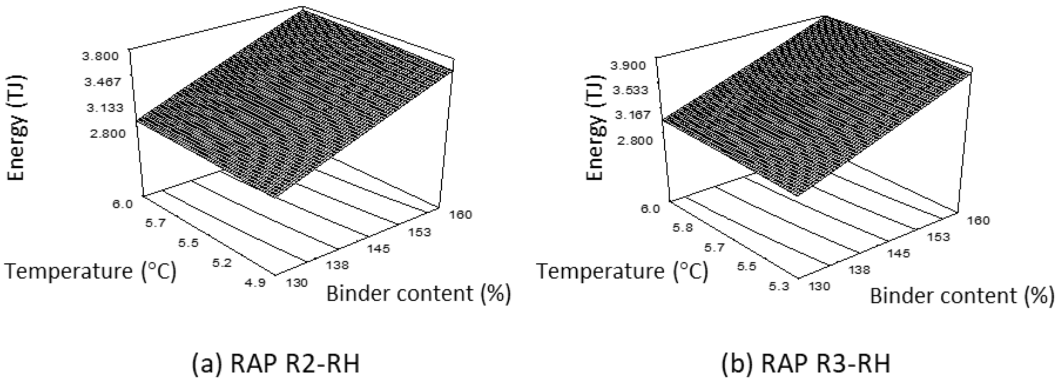

Figure 6. Effects of compaction temperature on energy consumption.

Optimization of RAP Production

Optimization of RAP with WMA additive in asphalt mixture production was conducted to identify and suggest the optimum binder content, RAP content and mixing temperature. The multi-objective optimization optimizes factors affecting the production of the material, namely the RAP content, temperature, binder content, energy consumption, fuel usage and GHG emission that produces mixtures with performance parameters that lie within the specification requirements. The Design Expert software optimized each parameter based on the desired goal of each factor and response that has been set. All factors for RSM input (RAP content, compaction temperature and binder content) were selected based on JKR specification, while the responses (cost and energy) were set as a minimum. Other factors such as volumetric and strength properties were set based on the JKR specification. Table 7 shows an example of optimized parameters that maximize the overall desirability function for the production of the mixture.

Table 7. Optimized parameters for production of RAP with RH-WMA.

RAP Source	Parameters	Solutions			
		1	2	3	4
R2-RH	RAP content (%)	50	50	50	50
	Mixing temperature (°C)	144	142	140	147
	Binder content (%)	5.4	5.5	5.5	5.4
	Energy (TJ)	2.967	2.909	2.875	3.067
	Cost of fuel consumption (RM)	14.10	13.70	13.30	14.30
	GHG emissions (kg CO_2e /unit)	19.77	19.24	18.70	20.04
	Desirability	0.630	0.629	0.627	0.623
R3-RH	RAP content (%)	50	50	-	-
	Mixing temperature (°C)	141	140	-	-
	Binder content (%)	5.6	5.6	-	-
	Energy (TJ)	2.950	2.946	-	-
	Cost of fuel consumption (RM)	13.50	13.30	-	-
	GHG emissions (kg CO_2e /unit)	18.70	18.70	-	-
	Desirability	0.763	0.763	-	-

As can be seen, four best solutions for R2-RH, and two solutions for the R3-RH are shown. The desirability of the recommended solution for R3-RH is higher than the R2-RH. Higher desirability indicates that the values of optimized parameters are close to the target value. The 3D plots of the overall desirability of the selected solution are shown in Figure 7.

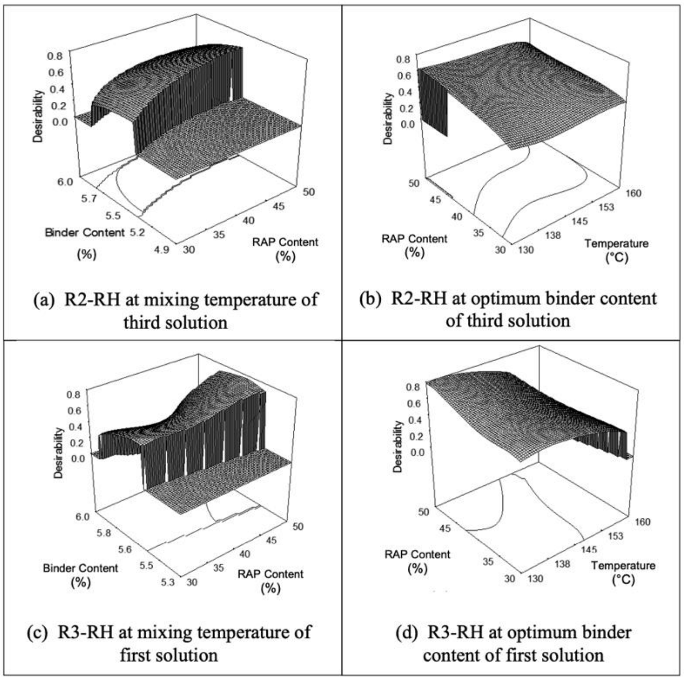

Figure 7. Response surface of overall desirability for different RAP content, mixing temperature and binder content.

By referring to Figure 6, the optimized parameters suggest that the benefits of RAP with WMA additive are optimum at 50% RAP content for both R2-RH and R3-RH. A solution that gives minimum mixing temperature was selected to verify the optimized parameters: the third solution of R2-RH and the first solution of R3-RH. Based on the optimized parameters, specimens were mixed in the laboratory at 140°C mixing temperature with optimized RAP content to verify the optimal conditions. This approach helps facilitate the evaluation of new materials for road construction. The design approach and evaluation of raw materials in mixtures fabrication are beneficial for assessing the essential criteria for a sustainable pavement which are optimization of resources, reduction in energy consumption and reduction in greenhouse gas (GHG) emissions.

CONCLUSION

Gradation of RAP is essential to ensure the variability of RAP is acceptable to be used for plant recycling. Based on the gradation study of the three sources of RAP, the COV is less than 15% and considered acceptable. RAP binder showed that all RAP had aged due to oxidation, volatilization, polymerization, syneresis and separation. The addition of 30%, 40% and 50% RAP content with WMA additive into virgin binder PG64 indicated softening effects which are shown in the penetration test result. This softening is able to reduce the stiffness of RAP. In terms of viscosity, the viscosity increases with the RAP content. Higher viscosity results in increased mixing and compaction temperature. The effects of viscosity and mixing temperature were further analyzed based on environmental and energy consumption. Based on the analysis, mixing temperature influenced the fuel usage, GHG emission and energy consumption for various amounts of RAP. Fuel usage, GHG emission and energy consumption increased with the increment of mixing temperature. Optimization of RAP production indicated that in order to maximize the RAP usage from road maintenance projects, 50%RAP content added with RH-WMA at 140°C mixing temperature is the most suitable. The proposed design approach and evaluation of raw materials in mixtures fabrication adopted in this study are beneficial for assessing the essential criteria in maximizing waste recycling in the pavement. For any waste recycling, optimization of resources, reduction in energy consumption and reduction in greenhouse gas (GHG) emissions can be selected as parameters for assessment.

ACKNOWLEDGEMENTS

Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff and financial support from university.

REFERENCES

[1] Al-Qadi, I. L., Elseifi, M. & Carpenter, S. H. 2007. *Reclaimed asphalt pavement-a literature review. FHWA-ICT-07-001.* Illinois Center for Transportation, Federal Highway Administration, Washington, D.C.

[2] Amoatey, P, Omidvarbona, H, Baawain, M. S., Al-Mayahi, A. & Al-mamun A. 2020. Exposure assessment to road traffic noise levels and health effects in an arid urban area. *Environmental Science and Pollution Research*, 27, 35051–35064

[3] Asphalt Institute. 2001. *Superpave mix design, superpave series*. Asphalt Institute, Lexington, KY, USA.

[4] Buss, A., Williams, R. C. & Schram, S. 2015. The influence of warm mix asphalt on binders in mixes that contain recycled asphalt materials. *Construction and Building Materials*, 77, 50-58.

[5] DEFRA. 2010. *Guidelines to GHGs calculations*. Department for Environment, Food and Rural Affairs. United Kingdom.

[6] Dughaishi, H. A., Lawati, J. A., Bilema, M., Babalghaith, A. M., Mashaan, N. S., Yusoff, N. I. M. & Milad, A. 2022. Encouraging sustainable use of RAP materials for pavement construction in Oman: A Review. *Recycling*, *7*(3), 35.

[7] FHWA. 2008. *User guidelines for by-product and secondary use materials in pavement construction.* FHWA Publication FHWA-RD-97-148, Federal Highway Administration, Washington, D.C.

[8] Jamshidi, A., Hamzah, M. O. & Shahadan, Z. 2012. Selection of reclaimed asphalt pavement sources and contents for asphalt mix production based on asphalt binder rheological properties, fuel requirements and greenhouse gas emissions. *Journal of Cleaner Production*, 23(1), 20-27.

[9] Jamshidi, A., Hamzah, M. O., Shahadan, Z. & Yahaya, A. S. 2014. Evaluation of the rheological properties and activation energy of virgin and recovered asphalt binder blends. *Journal of Materials in Civil Engineering*, 27(3), 1-11.

[10] Khahro, S. H., Memon, Z. A., Yusoff, N. I. M., Gungat, L. & Yazid, M. R. M. 2022. Pavement maintenance management framework for flexible roads: a case study of Pakistan. *Environmental Science and Pollution Research*, 29(7), 10771-10781.

[11] Newcomb, D., Brown, E. & Epps, J. 2007. *Designing HMA mixtures with high RAP content: A practical guide, quality improvement Series. 124.* National Asphalt Pavement Association. United State.

[12] Wen, H., Lu, J. H., Xiao, Y. & Deng, J. 2015. Temperature dependence of thermal conductivity, diffusion and specific heat capacity for coal and rocks from coalfield. *Thermochimica Acta*, 619, 41-47.