# OPTIMIZATION OF HIGH RECLAIMED ASPHALT PAVEMENT IN ASPHALT WEARING COURSE USING CRUMB RUBBER AND WASTE ENGINE OIL

**Md Zahid Hossain Khan[1*], Suhana Koting[2], Mohd Rasdan Ibrahim[3], Herda Yati Binti Katman[4], Ali Mohammed Babalghaith[5] and Obada Asqool[6]**

[1] *Executive Engineer, Local Government Engineering Department (LGED), Bangladesh, e-mail: zahid_lged@yahoo.com*
[2] *Senior Lecturer, Department of Civil Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia, e-mail: suhana_koting@um.edu.my*
[3] *Senior Lecturer, Department of Civil Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia, e-mail: rasdan@um.edu.my*
[4] *Lecturer, Department of Civil Engineering, Universiti Tenaga Nasional (UNITEN), Malaysia, e-mail: Herda@uniten.edu.my*
[5] *Ph.D, Department of Civil Engineering, Faculty of Engineering, University of Malaya, Malaysia, e-mail: bablgeath@hotmail.com*
[6] *Department of Civil Engineering, Faculty of Engineering, University of Malaya, Malaysia, e-mail: oasqool@gmail.com*

***Corresponding Author**

## ABSTRACT

The present study aimed to investigate the properties of reclaimed asphalt pavement (RAP) mixes to determine their suitability for preparing conventional hot mix asphalt (HMA) for wearing courses. To effectively recover the properties of the aged binder, the RAP was combined with two waste materials such as waste engine oil (WEO) as a rejuvenator and crumb rubber (CR) as a binder modifier. The effect of WEO on the rheological and physical characteristics of the extracted aged binder was investigated by analysis. Five different HMA mixes were prepared with different percentages of RAP aggregate replacing virgin aggregates at 0%, 30%, 50%, 70%, and 100%. The flow, volumetric properties, and Marshall stability tests were examined in this study. Every RAP mix showed adherence to the 8.0 kN minimum stability requirement. The Marshall flow showed an increasing trend as the binder and RAP content increased. Notably, each mix met the minimum (2.0 kN/mm) Marshall quotient criteria. The results demonstrated that the optimum binder content (OBC) gradually decreased as the RAP content rose. With the increase in RAP content, there was a noticeable increase in the binder saving rate. Particularly, 79.7% less binder was used in the R100 mix compared to the R0 mix. Statistical analysis clearly showed that the amount of RAP and binder significantly influences the effectiveness of the mix's design. the effectiveness of the mix's design. Therefore, the combination of CR and WEO allows for the creation of HMA compositions with up to 100% RAP.

***Keywords:*** *Hot mix asphalt, crumb rubber, reclaimed asphalt pavement, waste engine oil, Marshall parameter, optimum binder content*

## 1. INTRODUCTION

Reclaimed asphalt pavement (RAP) use involves recycling aged asphalt pavement, which can replace natural aggregates and binders. This method not only achieves performance standards but also conserves energy, and minerals, reduces pollutants, and cuts costs (Izaks et al., 2015; Milad et al., 2020). Previous studies have shown that a 100% RAP mix reduces gas emissions by 18 kg or 35% CO2eq and production costs by 70% per ton compared to virgin mix (Zaumanis et al. (2014, 2016). Han et al. (2019) found that high-content RAP can save 63% of binder content. However, low awareness and non-standard recycling standards limit widespread RAP adoption in many countries (Baaj et al., 2013; Zaumanis et al., 2016). Therefore, a framework is needed to properly integrate high-content RAP into hot mix asphalt (HMA) design.

Moreover, RAP mixes' mechanical performance depends on aged pavement ingredients such as binder and aggregates, making high-content RAP challenging to incorporate into HMA design. Laboratory investigations have shown that the internal interaction between aged binder and final binder mix affects mechanical properties (Noferini et al., 2017). Aged binder enhances viscosity, stiffness, and softening point (Hussain et al., 2013; Noferini et al., 2017). While recycling may boost complex modulus (Safi et al., 2019), high RAP reuse can make asphalt pavement brittle by oxidizing and hardening the aged binder. Applying rejuvenators or additives to restore the aged binder's characteristics is strongly advised. Asphalt rejuvenators are becoming increasingly widespread since they can restore aged binder qualities (Elkashef et al., 2018). Waste engine oil (WEO) can soften and renew aging binders (Li et al., 2019; Tarsi et al., 2020). This rejuvenator makes RAP mixes practical (Li et al., 2019; Mangiafico et al., 2016) and lowers the optimum binder content (Jia et al., 2015). Low rejuvenator dosages may stiffen the mix, while high dosages might affect adhesion, stripping, rutting, and fatigue cracking (Cong et al., 2016; Im et al., 2016). Preheating RAP materials impacts rejuvenator diffusion in aged binders (Liu et al., 2019). According to previous studies, 15% of WEO is effective (Khan et al., 2021; Mamun et al., 2018). Thus, the revived aged binder's physical and rheological properties were assessed.

Although the rejuvenator has many benefits, one disadvantage is that it may reduce the binder's viscosity while improving the mix's flow value and softness to an acceptable level. Although rejuvenators can soften tough aging binders, they may not fully restore their rheological and mechanical properties. Instead, they can reduce their stiffness. Due to the drawbacks of rejuvenators, crumb rubber is one of the most often utilized as an eco-friendly modifier (Majidifard et al., 2019). Crumb rubber also resists low-temperature cracking better than other modifiers (Babalghaith et al., 2016). The modified crumb rubber binder would have more age resistance than an unmodified one (Wang et al., 2020). Due to the ability of the crumb rubber modification (CRM) to reduce carbonyl and sulfoxide. Additionally, adding CRM to an asphalt mix may improve its resistance to rutting and stability (Bilema et al., 2021; Fakhri et al., 2017). For optimum stability and rigidity, it was discovered that a CRM content of between 5% and 10% would be required (Khan et al., 2021; Mashaan et al., 2013). Mogawer et al. (2016) assert that rejuvenators reduce asphalt's resilience to rutting by including 50% RAP. However, Polymer Modified Binder (PMB) can be used to reduce this deterioration.

This study investigates the effects of WEO on extracted aged binder and optimized binder contents for five HMA designs for a conventional asphaltic concrete wearing course with a nominal maximum aggregate size of 14 mm, ACW14 with different RAP percentages (0%, 30%, 50%, 70%, and 100%). The WEO was a rejuvenator to integrate the RAP, and the CRM serves as a binder modifier. Statistical analysis is employed whether RAP-binder ratio changes affect mix design stability, flow, and volumetric properties.

## 2. MATERIALS AND METHODS

### 2.1. Binders, Aggregates, RAP, and Rejuvenator

This study used two raw materials, a virgin binder and natural aggregate (NA), along with three waste materials, a binder modifier, RAP, and a rejuvenator, to prepare ACW14 mix samples. The virgin binder modified with crumb rubber was used as a reference asphalt binder. A 60/70 penetration grade bitumen and 6% (by mass of virgin binder) crumb rubber modifier (CRM) 80-mesh size were used. Virgin binder and CRM were mixed for 2 hours at 160°C in a propeller mixer at 200 rpm (Mashaan et al., 2013) to increase the rheological properties of the virgin binder (Majidifard et al., 2019). The fundamental properties of various binders are summarized in **Table 1**. The ASTM and AASHTO standards were used to test the granite aggregate's physical properties, which are summarized in **Table 2**. The aggregate properties are shown in **Table 2**. RAP was air-dried after loosening. The aged binder was extracted from RAP using ASTM D2172 (ASTM, 2011) and recovered using the Abson method (ASTM D1856) (D. ASTM, 2009). The aged binder was extracted with methylene chloride. The extraction process revealed that 4.1% of RAP aggregate was aged binder.

WEO was used to soften the aged binder after retrieval. Before rejuvenation, the aged binder was heated at 160°C for an hour. The mix was blended for 30 minutes at 800 rpm with a propeller mixer. After rejuvenation, the aged binder's physical and rheological properties were assessed at 15% WEO (**Table 1**). The specific gravity and water content of the used WEO were 0.87 and 0.34%, respectively.

Table 1: Properties of the Binders

| Property | Temp. (°C) | Standard | Virgin pen 60/70 binder | Modified binder | Extracted aged binder | Rejuvenated aged binder |
|---|---|---|---|---|---|---|
| Penetration (100 g, 5 sec., 0.1mm) | 25 | ASTM D0005 | 65 | 58 | 11.0 | 45 |
| Softening point (˚C) | - | ASTM D0036 | 50 | 53 | 71 | 65 |
| Ductility (cm) | 27 | ASTM D0113 | >100 | 34.2 | - | - |
| Rotational viscosity (cP, 20 rpm) | 135 | ASTM D4402 | 365 | 645 | 3510 | 918 |
| | 165 | | 144 | 200 | 632 | 195 |
| G*/sinδ (10 rad/s, kPa) | 58 | AASHTO T315 | 2.2 | 3.8 | 95.9 | 21.7 |
| | 64 | | 1.0 | 1.8 | 42.0 | 10.7 |
| | 70 | | 0.5 | 0.9 | 22.1 | 5.0 |

Table 2: Properties of Granite Aggregates

| Test | Standard | Natural aggregates |
|---|---|---|
| LAA | ASTM C131-14 | 25% |
| Flakiness index | ASTM D4791-05 | 7.3% |
| Elongation index | ASTM D4791-05 | 19.0% |
| Soundness test ($MgSO_4$) | AASHTO T104 | 0.8% |

### 2.2. Experimental Process and Mix Design

The experimental process consisted of two main stages which are shown in Figure 1. The first stage focused on the asphalt binders and their properties. While the second stage concentrated on the asphalt mix. Five groups of asphalt mix with 75 samples were prepared using different RAP contents (0%, 30%, 50%, 70%, and 100%). Three samples with various amounts of asphalt binder (4.5%, 5.0%, 5.5%, 6.0%, and 6.5%) were prepared for each group. Finally, optimum binder content was determined for each mix based on the Marshall and volumetric properties.

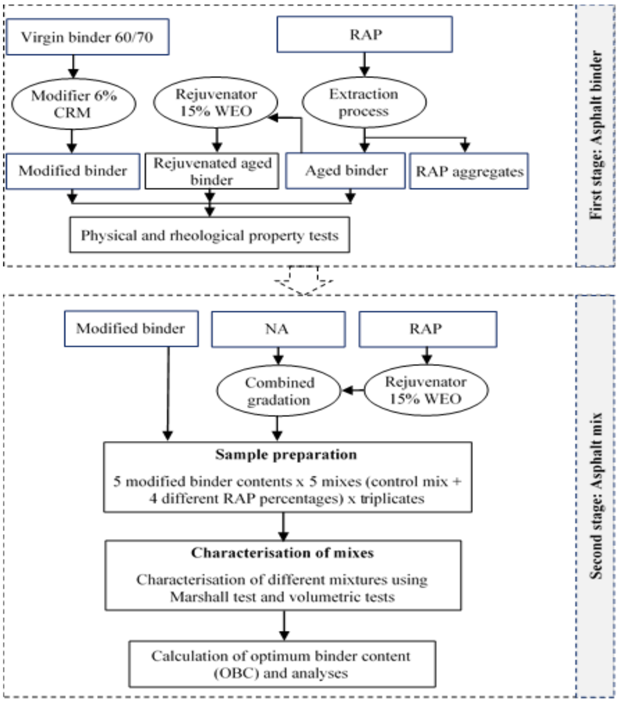



Figure 1: The experimental process in this research.

### 2.2.1 Combined Aggregate Gradation and Preparation of Sample

The gradation of aggregates plays a critical role in achieving pavement performance. Specifically, aggregate gradation issues become more significant for a mix with a high-content RAP (Al-Qadi et al., 2007; Park et al., 2020). The RAP aggregates and NA were distributed using **Equation 1** to eliminate the effects of combined gradation differences.

$$N_i = (M_i - P_i \times a) \div (1 - a) \quad (1)$$

$M_i$ = standard gradation aggregate percentage, $N_i$ = natural aggregate percentage required; $P_i$ = RAP aggregate field size, a = intended RAP percentage, and i = sieve size.

### 2.2.2. Preparation of Sample

The ACW14 mix samples for this study were formulated using the Marshall mix design process. Except for WEO, each component of the asphalt mix was first individually heated in the oven for an hour at the same temperature (170°C). Binder contents of 4.5%, 5.0%, 5.5%, 6.0%, and 6.5% were used. The modified binder was blended with heated NAs to prepare the control mix (R0). For the RAP mixes, however, WEO (15% of the aged binder mass) was combined directly with the heated RAP, allowing WEO to touch directly with the preheated RAP for optimum diffusion. Then, added the modified binder and NAs. The mixing and compaction temperatures were 166±2°C and 161±2°C, respectively. This mechanism stimulates diffusion and activates the aged binder (Zaumanis et al., 2019; Zaumanis et al., 2020). The asphalt mix was molded and compacted to 75 blows per face per ASTM D6926 (ASTM, 2016). Each sample measured 101.6±0.1 mm in diameter and 63±1 mm in depth. Following mold removal, the samples were stored in the lab at room temperature for 24 hours before analysis.

### 2.2.3. Volumetric Properties, Marshall test, and Optimum Binder Content (OBC)

To find the OBC, **Table 4** displays the volumetric characteristics and Marshall test standards for each combination. The OBC was calculated by averaging the corresponding binder amounts of the maximum stability, flow (3 mm), maximum density, VFB (75%), and VIM (4.0%). Results were analyzed using ANOVA with a 0.05 (α) significance level. Null hypothesis (Ho) was tested with two-factor ANOVA without replication. This is done to determine if RAP and binder changes do not alter the volumetric, flow, and Marshall stability of the ACW14 mix design.

Table 4: Marshall and Volumetric Property Test Standards

| Property | Temp. (°C) | Standard | Reference |
|---|---|---|---|
| Air voids in mix (VIM) | 25 | ASTM D3203 | (D3203, 2005) |
| Voids in mineral aggregates (VMA) | 25 | ASTM D3203 | (D3203, 2005) |
| Voids filled with the binder (VFB) | 25 | ASTM D3203 | (D3203, 2005) |
| Density | 25 | ASTM D2726 | (ASTM, 2017) |
| Marshall stability | 60 | ASTM D6927 | (ASTM, 2015) |
| Marshall flow | 60 | ASTM D6927 | (ASTM, 2015) |

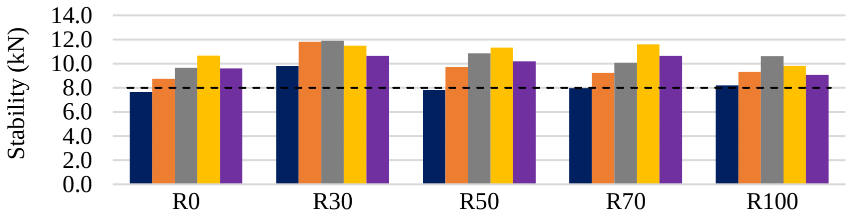
## 3. RESULTS AND DISCUSSION

### 3.1. Rejuvenation Effect on the Extracted-Aged Binder

Asphalt binder typically oxidizes with time, losing its properties and becoming stiffer. RAP becomes more brittle when added to the asphalt mix, especially in high content, which is one of the issues (Izaks et al., 2015; Tarsi et al., 2020). Thus, high-content RAP makes recovering aged binder characteristics challenging. The present study used WEO to rejuvenate aged binder properties. The physical and rheological properties of the aged binder that had been rejuvenated were evaluated after the rejuvenation process. **Table 1** displays the changes in properties with 15% WEO. WEO effectively enhanced the aged binder's penetration value while lowering its viscosity and softening point. Only 11 dmm of the removed aged binder's penetration value (before rejuvenation) was measured. When 15% of WEO was used, the penetration value increased to 45 dmm. It suggests that by making the aged binder less consistent, WEO can effectively soften it. At 135°C and 165°C, the aged binders' rotational viscosity test results were 3513 cP and 632 cP, respectively; following rejuvenation, they were 918 cP and 195 cP. As a result, using WEO reduced the viscosity of the revived aged binder. Because WEO has a softening impact on the aged binder, the viscosity values have decreased. **Table 1** further demonstrates that adding the WEO and rising temperature resulted in a drop in the $G^*/\sin\delta$ value. At 70°C and 15% WEO, the aged binder's rheological property regarding rutting resistance factor ($G^*/\sin\delta$) was restored to a level of 5.0 kPa. Therefore, it can be concluded that 15% WEO effectively softened the extracted aged binder.

### 3.2. The Marshall Stability, Flow, and Quotient (MQ)

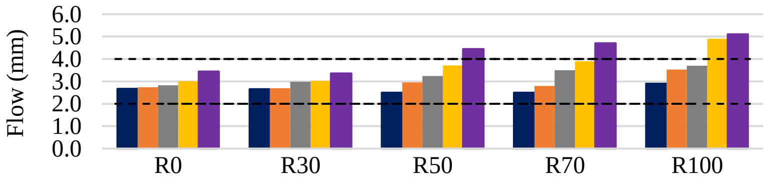
**Figure 2** shows the effect of RAP content on the Marshall stability for all mixes with five separate binder contents. The minimum stability requirements (8.0 kN) were fulfilled at a 4.5% binder for R30 and R100 mixes and a 5.0% binder for R0, R50, and R70 mixes. On the contrary, the maximum stability for R0, R50, and R70 mixes was achieved at 6% binders, while at 5.5% binder content for R30 and R100 mixes. Overall, all mixes with RAP showed more excellent stability compared to the standard requirements and R0. The stability of RAP mixes improved by 32% to 48% demonstrating that WEO could effectively restore the aged binder's properties (Hill et al., 2011; Joni et al., 2019). CRM was added to improve binder stability by improving mechanical performance (Majidifard et al., 2019; Mashaan et al., 2013).




| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 7.6 | 9.8 | 7.8 | 8.0 | 8.2 |
| 5.0% | 8.7 | 11.8 | 9.7 | 9.2 | 9.3 |
| 5.5% | 9.7 | 11.9 | 10.9 | 10.1 | 10.6 |
| 6.0% | 10.7 | 11.5 | 11.3 | 11.6 | 9.8 |
| 6.5% | 9.6 | 10.6 | 10.2 | 10.7 | 9.1 |
| Min value | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 |

Figure 2: Variation of the Marshall stability in various binder contents.

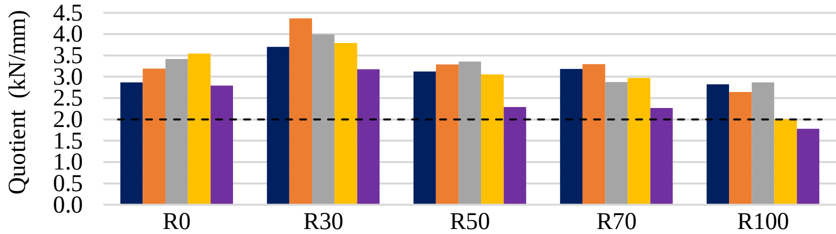
**Figure 3** shows the effect of RAP content on the Marshall flow for all mixes with five separate binder contents. It was found that almost all mixes met PWD's flow requirement of 2 - 4 mm (2008) except for four mixes (R50 and R70 mixes at 6.5% binder content and R100 mixes at 6.0% and 6.5% binder contents) with their Marshall flow values exceeding 4 mm. The flow generally increased as RAP and binder content increased, probably because of WEO in the RAP mixes, which helps float the aggregates. Given that WEO increased with RAP. The WEO softened the aged binder and improved the mixes' workability. Additionally, the flow value of the mix was raised by the addition of CRM (Mahrez, 1999; Mashaan et al., 2013). Usually, the plastic characteristic increases with the amount of binder and RAP present.




| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 2.7 | 2.7 | 2.5 | 2.5 | 2.9 |
| 5.0% | 2.7 | 2.7 | 3.0 | 2.8 | 3.5 |
| 5.5% | 2.8 | 3.0 | 3.2 | 3.5 | 3.7 |
| 6.0% | 3.0 | 3.0 | 3.7 | 3.9 | 4.9 |
| 6.5% | 3.4 | 3.4 | 4.4 | 4.7 | 5.1 |
| Max value | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| Min value | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |

Figure 3: Variation of the Marshall flow in various binder contents.

**Figure 4** shows the effect of RAP on Marshall quotient (MQ) for all mixes with five separate binder contents, in which most mixes met the minimum MQ value of 2.0 kN/mm (Public Works Department (PWD), 2008), except for the mix R100 at 6.5% binder content with 1.78 kN/mm. The highest MQ occurred in R30 at 5% binder content with 4.37 kN/mm. The efficacy of rutting or permanent deformations of the mixes is presumably to blame for the general fall in MQ value seen with increased RAP content (Geraldin et al., 2020). Since most MQ values were above the average, the mix design was probably more durable—less likely to degrade.

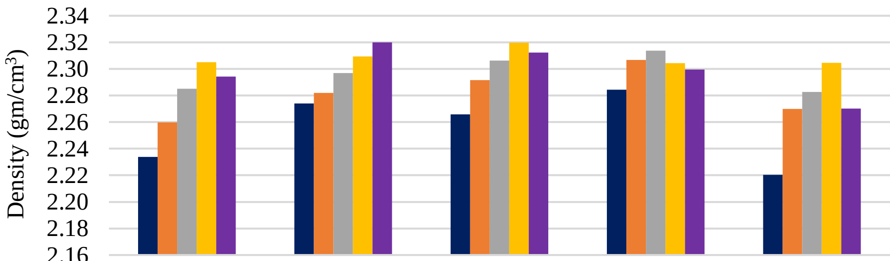



| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 2.9 | 3.7 | 3.1 | 3.2 | 2.8 |
| 5.0% | 3.2 | 4.4 | 3.3 | 3.3 | 2.6 |
| 5.5% | 3.4 | 4.0 | 3.4 | 2.9 | 2.9 |
| 6.0% | 3.5 | 3.8 | 3.1 | 3.0 | 2.0 |
| 6.5% | 2.8 | 3.2 | 2.3 | 2.3 | 1.8 |
| Min value | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |

Figure 4: Variation of the MQ in various binder contents.

### 3.3. The Volumetric Properties of Mixes

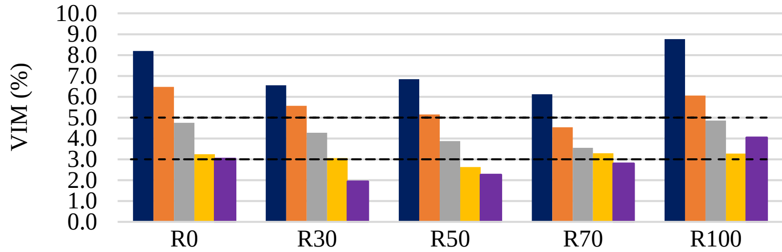
All mixes with five different binder contents are shown in **Figure 5** to illustrate the impact of RAP content on density. The density of ACW14 mixes increased by 6% with increasing binder content, except for the R70 mix. Density rose by 70% as a result of RAP substitution. It is hypothesized that the more excellent filling of gaps between aggregate particles by the binder led to increased mass with unchanged volume. Since higher asphalt mix density improves long-term performance (Asphalt.Institute, 2014), RAP mixes may be as durable as R0.




| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 2.23 | 2.27 | 2.27 | 2.28 | 2.22 |
| 5.0% | 2.26 | 2.28 | 2.29 | 2.31 | 2.27 |
| 5.5% | 2.29 | 2.30 | 2.31 | 2.31 | 2.28 |
| 6.0% | 2.31 | 2.31 | 2.32 | 2.30 | 2.30 |
| 6.5% | 2.29 | 2.32 | 2.31 | 2.30 | 2.27 |

Figure 5: Variation of density in various binder contents.

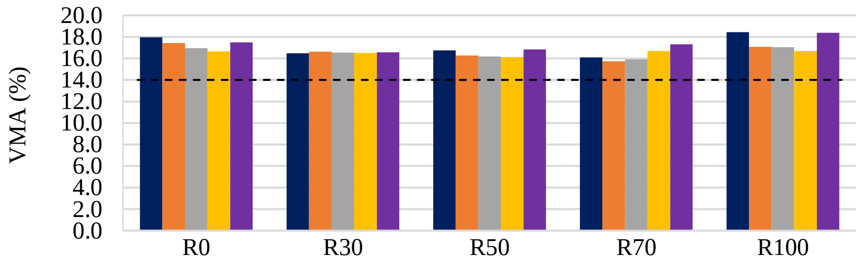
**Figure 6** shows the effect of RAP content on the VIM for all mixes with five separate binder contents, in which all mixes displayed the same pattern, i.e., the VIM decreased as the binder content increased. All mixes met 3–5% but had varied binder contents (R0 at 5.5%, 6.0%, 6.5%; R30 at 5.5%; R50 at 5.5%; R70 at 5.0%, 5.5%, 6.0%, and R100 at 5.5%, 6.0%, and 6.5%). Since all mixes met the PWD requirement, their permeability properties were considered substantial.




| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 8.2 | 6.5 | 6.8 | 6.1 | 8.8 |
| 5.0% | 6.5 | 5.6 | 5.2 | 4.5 | 6.1 |
| 5.5% | 4.8 | 4.3 | 3.9 | 3.6 | 4.9 |
| 6.0% | 3.2 | 3.1 | 2.6 | 3.3 | 3.3 |
| 6.5% | 3.0 | 1.9 | 2.3 | 2.8 | 4.0 |
| Max value | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Min value | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |

Figure 6: Variation of VIM in various binder contents.

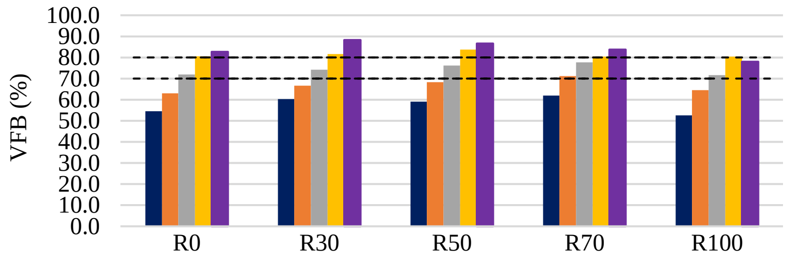
**Figure 7** shows the effect of RAP content on the VMA for all mixes with five separate binder contents, in which the lowest VMA value of all mixes exceeded the Asphalt Institute's threshold of 14% (Asphalt.Institute, 2014). All mixes showed a similar pattern for VMA value, i.e., the VMA decreased and then increased. To use the mix's binder film, the VMA standard (14%) has to be met. VMA values of RAP mixes were substantially above the lower limit (14%), indicating durability.




| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 17.9 | 16.5 | 16.7 | 16.1 | 18.4 |
| 5.0% | 17.4 | 16.6 | 16.3 | 15.7 | 17.1 |
| 5.5% | 16.9 | 16.5 | 16.2 | 15.9 | 17.0 |
| 6.0% | 16.7 | 16.5 | 16.1 | 16.7 | 16.7 |
| 6.5% | 17.5 | 16.6 | 16.8 | 17.3 | 18.4 |
| Min value | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 |

Figure 7: Variation of VMA in various binder contents.

**Figure 8** shows the effect of RAP content on the VFB for all mixes with five separate binder contents, in which R0 and R100 mixes met the VFB requirements (70 - 80%) at 5.5% binder content, while R50, R30, and R70 mixes at 5.0% binder content (Public Works Department (PWD), 2008). The pattern of change of VFB in all mixes showed a similar pattern for VFB, i.e., the VFB increased along with the binder content. Given that VFB values of RAP mixes were inside the upper and lower limits in different binder content, RAP mixes were likely to be durable.




| | R0 | R30 | R50 | R70 | R100 |
|---|---|---|---|---|---|
| 4.5% | 54.5 | 60.3 | 59.1 | 62.0 | 52.5 |
| 5.0% | 62.9 | 66.6 | 68.3 | 71.2 | 64.6 |
| 5.5% | 72.0 | 74.2 | 76.1 | 77.6 | 71.7 |
| 6.0% | 80.5 | 81.6 | 83.7 | 80.3 | 80.4 |
| 6.5% | 82.7 | 88.3 | 86.6 | 83.8 | 78.0 |
| Max value | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 |
| Min value | 70.0 | 70.0 | 70.0 | 70.0 | 70.0 |

Figure 8: Variation of VFB in various binder contents.

### 3.4. Optimum Binder Content (OBC)

Based on the volumetric and Marshall results, the OBC for the five mixes is summarized in **Table 5**. It was found that all RAP mixes had lower OBC than R0 and that the OBCs gradually decreased with increasing RAP content. This was most likely associated with an increase in the WEO concentration and the ratio of fine particles. But there weren't too many variances in the OBCs between the mixes. For instance, the OBC for mix with 100% RAP (R100) was only about 8% lower than the R0. The same behavior was reported by previous studies (Arshad et al., 2017; Mamun et al., 2020). RAP mixes employed minimal binder by mass. Example: The R0 mix utilized 66.7 g of binder, while the R100 mix used only 13.6 g, saving 79.7%. Therefore, more RAP could yield a more significant economic benefit. WEO and CRM in the mixes likely caused this. WEO softened and rejuvenated the aged binder and improved RAP mix workability (Joni et al., 2019; Majidifard et al., 2019). CRM can improve asphalt stability, efficiency, and consistency (Majidifard et al., 2019; Mashaan et al., 2013). RAP could have influenced the mixes' Marshall parameters.

Table 5: OBC and the Amount Binder Savings in Different Mixes

| Component | Mix type | | | | |
|---|---|---|---|---|---|
| | R0 | R30 | R50 | R70 | R100 |
| OBC (%) | 5.93 | 5.83 | 5.58 | 5.49 | 5.45 |
| Modified binder used (%) | 100.0 | 78.2 | 62.0 | 45.9 | 22.2 |
| Binder amount saving (%) | 0.0 | 23.2 | 41.7 | 57.4 | 79.7 |

### 3.5. Statistical Analysis (ANOVA)

**Table 6** summarizes ANOVA results, with all parameters scoring $p$-values < 0.05 ($\alpha$) and F-statistics exceeding F-critical values (F>Fcrit and $p$<0.05). Thus, the null hypothesis (Ho) was rejected, and RAP and binder concentrations affected ACW14 mixes significantly. An ANOVA on volumetric and Marshall parameters showed that binder and RAP content affected OBC optimization. The ANOVA showed that binder and RAP contents affected Marshall stability, flow, quotient, and volumetric parameters of the five ACW14 mixes.

Table 6: ANOVA test results (two-factor without replication)

| Test | Variation source | F | *p*-Value | $F_{crit}$ |
|---|---|---|---|---|
| Stability | Binder% | 17.53166 | 0.00001 | 3.00692 |
| | RAP% | 8.60967 | 0.00066 | 3.00692 |
| Flow | Binder% | 16.63945 | 0.00001 | 3.00692 |
| | RAP% | 8.72680 | 0.00062 | 3.00692 |
| Quotient | Binder% | 10.24726 | 0.00026 | 3.00692 |
| | RAP% | 19.87519 | 0.00000 | 3.00692 |
| Density | Binder% | 14.75419 | 0.00003 | 3.00692 |
| | RAP% | 7.67314 | 0.00119 | 3.00692 |
| VIM | Binder% | 69.41357 | 0.00000 | 3.00692 |
| | RAP% | 7.72022 | 0.00115 | 3.00692 |
| VFB | Binder% | 135.78380 | 0.00000 | 3.00692 |
| | RAP% | 7.93653 | 0.00101 | 3.00692 |
| VMA | Binder% | 3.64873 | 0.02695 | 3.00692 |
| | RAP% | 7.63496 | 0.00122 | 3.00692 |

## 4. CONCLUSION

The present study examined the optimization of the binder content of the ACW14 mix combined with various RAP content and waste materials (WEO and CRM), and the following conclusions were drawn:

- In all RAP mixes, OBC values were lower than R0. It is recommended that 15% WEO effectively softens the extracted aged binder. Adding WEO increased the penetration of the aged binder while decreasing the softening point, viscosity, and G*/sinδ values.
    - When binder amounts were unexpectedly reduced in RAP mixes, OBC values gradually decreased as RAP content increased. Since it used 79.7% fewer binders than R0, R100 performed better economically.
    - Based on the Marshall stability, all RAP mixes met the criteria of PWD requirements (2008) in different binder contents. The Marshall flow increased as the binder and RAP content increased. Besides, all mixes met the minimum MQ value of 2.0 kN/mm.
    - The compacted sample density value slightly increased by an increment of up to 70% RAP content. The VIM value decreased along with the increment of binder content. In contrast, the VMA value decreased at first and then increased. Moreover, the VFB requirement of all mixes was met between 5.5% and 6.0% of the binder content.
    - ANOVA results revealed that the size of RAP and binder in the ACW14 mix design significantly affected Marshall stability, flow, and volumetric parameters.
    - Overall, the RAP proved appropriate for use up to 100% in the ACW14 mix that could satisfy the mix design criteria of the PWD, Malaysia requirements. These findings have the potential to contribute to cost minimal and the conservation of natural resources.

## ACKNOWLEDGMENTS

The authors sincerely thank the University of Malaya, Malaysia, and the Local Government Engineering Department (LGED), Bangladesh.

## REFERENCES

Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). *Reclaimed asphalt pavement—a literature review* (FHWA-ICT-07-001). Retrieved from http://hdl.handle.net/2142/46007

Arshad, A. K., Mohammad, M., Shaffie, E., Hashim, W., & Halim, A. A. (2017, 05 April 2017). *Volumetric Analysis and Performance of Hot Mix Asphalt with Variable Rap Content.* Paper presented at the International Symposium on Civil and Environmental Engineering 2016 (ISCEE 2016), Wuhan, China.

Asphalt.Institute. (2014). MS-2 asphalt mix design methods. In. Lexington Kentucky, USA: Asphalt Institute.

ASTM. (2011). D-2172: Standard test methods for quantitative extraction of bitumen from bituminous paving mixtures. In: American Society for Testing Materials, West Conshohocken, PA, USA.

ASTM. (2015). D6927-15 : Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures. In: American Society for Testing Materials, West Conshohocken, PA, USA.

ASTM. (2016). D6926 Standard practice for preparation of asphalt mixture specimens using Marshall apparatus. In. West Conshohocken, PA, USA: American Society for Testing and Materials (ASTM).

ASTM. (2017). D2726: Standard test method for bulk specific gravity and density of non-absorptive compacted asphalt mixtures. In: American Society for Testing Materials, West Conshohocken, PA, USA.

ASTM, D. (2009). Standard test method for recovery of asphalt from solution by Abson method. In. West Conshohocken, PA, USA: ASTM.

Baaj, H., Ech, M., Tapsoba, N., Sauzeat, C., & Di Benedetto, H. (2013). Thermomechanical characterization of asphalt mixtures modified with high contents of asphalt shingle modifier (ASM®) and reclaimed asphalt pavement (RAP). *Materials and Structures, 46*(10), 1747-1763. doi:10.1617/s11527-013-0015-7

Babalghaith, A. M., Alsoliman, H. A., & Al-Suhaibani, A. S. (2016). Comparison of rheological properties for polymer modified asphalt produced in riyadh. *International Journal of Civil Environmental Engineering Science, 10*(2), 197-201.

Bilema, M., Aman, M. Y., Hassan, N. A., Memon, Z. A., Omar, H. A., Yusoff, N. I. M., & Milad, A. (2021). Mechanical Performance of Reclaimed Asphalt Pavement Modified with Waste Frying Oil and Crumb Rubber. *Materials, 14*(11), 2781.

Cong, P., Hao, H., Zhang, Y., Luo, W., & Yao, D. (2016). Investigation of diffusion of rejuvenator in aged asphalt. *International Journal of Pavement Research Technology, 9*(4), 280-288.

D3203, A. (2005). Standard test method for percent air voids in compacted dense and open bituminous paving mixtures. In. West Conshohocken, PA, USA: American Society for Testing Materials.

Elkashef, M., Williams, R. C., & Cochran, E. (2018). Investigation of fatigue and thermal cracking behavior of rejuvenated reclaimed asphalt pavement binders and mixtures. *International Journal of Fatigue, 108*, 90-95.

Fakhri, M., & Azami, A. J. J. o. C. P. (2017). Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement and crumb rubber. *Journal of Cleaner Production, 165*, 1125-1132.

Geraldin, J., & Makmur, A. (2020). *Experimental Study on the Effects of Reclaimed Asphalt Pavement towards Marshall Parameters on Asphalt Course-Wearing Course.* Paper presented at the IOP Conference Series: Earth and Environmental Science.

Han, S., Cheng, X., Liu, Y., & Zhang, Y. (2019). Laboratory Performance of Hot Mix Asphalt with High Reclaimed Asphalt Pavement (RAP) and Fine Reclaimed Asphalt Pavement (FRAP) Content. *Materials, 12*(16), 2536. doi:10.3390/ma12162536

Hill, D. R., & Jennings, A. A. (2011). *Bioasphalt from urban yard waste carbonization: A student study*. Retrieved from 1980 West Board Street, Columbus, Ohio 43223:

Hussain, A., & Yanjun, Q. (2013). Effect of reclaimed asphalt pavement on the properties of asphalt binders. *Procedia Engineering, 54*, 840-850. doi:10.1016/j.proeng.2013.03.077

Im, S., Karki, P., & Zhou, F. (2016). Development of new mix design method for asphalt mixtures containing RAP and rejuvenators. *Construction and Building materials, 115*, 727-734.

Izaks, R., Haritonovs, V., Klasa, I., & Zaumanis, M. (2015). Hot mix asphalt with high RAP content. *Procedia Engineering, 114*, 676-684. doi:10.1016/j.proeng.2015.08.009

Jia, X., Huang, B., Moore, J. A., & Zhao, S. (2015). Influence of waste engine oil on asphalt mixtures containing reclaimed asphalt pavement. *Journal of Materials in Civil Engineering, 27*(12), 04015042. doi:10.1061/(ASCE)MT.1943-5533.0001292

Joni, H. H., Al-Rubaee, R. H., & Al-zerkani, M. A. (2019). Rejuvenation of aged asphalt binder extracted from reclaimed asphalt pavement using waste vegetable and engine oils. *Case Studies in Construction Materials, 11*, e00279. doi:10.1016/j.cscm.2019.e00279

Khan, M. Z. H., Koting, S., Katman, H. Y. B., Ibrahim, M. R., Babalghaith, A. M., & Asqool, O. (2021). Performance of High Content Reclaimed Asphalt Pavement (RAP) in Asphaltic Mix with Crumb Rubber Modifier and Waste Engine Oil as Rejuvenator. *Applied Sciences, 11*(11), 5226. doi:doi.org/10.3390/app11115226

Li, H., Dong, B., Wang, W., Zhao, G., Guo, P., & Ma, Q. (2019). Effect of waste engine oil and waste cooking oil on performance improvement of aged asphalt. *Applied Sciences, 9*(9), 1767.

Liu, Y., Wang, H., Tighe, S., Zhao, G., & You, Z. (2019). Effects of preheating on the rheological properties of rejuvenated asphalt binder. *Transportation Research Record, 2673*(4), 546-557. doi:10.1177/0361198119834908

Mahrez, A. (1999). *Properties of rubberised bitumen binder and its effect on the bituminous mix [MS thesis]*. University of Malaya, Kuala Lumpur, Malaysia,

Majidifard, H., Tabatabaee, N., & Buttlar, W. (2019). Investigating short-term and long-term binder performance of high-RAP mixtures containing waste cooking oil. *Journal of Traffic Transportation Engineering, 6*(4), 396-406. doi:10.1016/j.jtte.2018.11.002

Mamun, A., & Al-Abdul Wahhab, H. (2018). Evaluation of waste engine oil-rejuvenated asphalt concrete mixtures with high RAP content. *Advances in Materials Science and Engineering (AMSCE), 2018*. doi:10.1155/2018/7386256

Mamun, A., & Al-Abdul Wahhab, H. (2020). Comparative laboratory evaluation of waste cooking oil rejuvenated asphalt concrete mixtures for high contents of reclaimed asphalt pavement. *International journal of pavement engineering, 21*(11), 1297-1308.

Mangiafico, S., Di Benedetto, H., Sauzéat, C., Olard, F., Pouget, S., & Planque, L. (2016). Relations between Linear ViscoElastic Behaviour of Bituminous Mixtures Containing Reclaimed Asphalt Pavement and Colloidal Structure of Corresponding Binder Blends. *Procedia Engineering, 143*, 138-145. doi:10.1016/j.proeng.2016.06.018

Mashaan, N. S., Ali, A. H., Koting, S., & Karim, M. R. (2013). Performance evaluation of crumb rubber modified stone mastic asphalt pavement in Malaysia. *Advances in Materials Science and Engineering (AMSCE)*. doi:10.1155/2013/304676

Milad, A., Taib, A. M., Ahmeda, A. G., Solla, M., & Yusoff, N. I. M. (2020). A Review of the Use of Reclaimed Asphalt Pavement for Road Paving Applications. *Jurnal Teknologi, 82*(3).

Mogawer, W. S., Austerman, A. J., Kluttz, R., & Puchalski, S. (2016). Using polymer modification and rejuvenators to improve the performance of high reclaimed asphalt pavement mixtures. *Transportation Research Record, 2575*(1), 10-18.

Noferini, L., Simone, A., Sangiorgi, C., & Mazzotta, F. (2017). Investigation on performances of asphalt mixtures made with Reclaimed Asphalt Pavement: Effects of interaction between virgin and RAP bitumen. *International Journal of Pavement Research Technology, 10*(4), 322-332. doi:10.1016/j.ijprt.2017.03.011

Park, B., Zou, J., Roque, R., Lopp, G., & Wu, Z. (2020). Approach for Determination of Maximum Reclaimed Asphalt Pavement Content in Polymer-Modified Asphalt Mixture. *Transportation Research Record, 2674*(6), 420-430. doi:10.1177/0361198120919403

Public Works Department (PWD), M. (2008). Standard specification for road works. In *Section* (Vol. 4, pp. S4-58). Malaysia: Jabatan Kerja Raya (JKR).

Safi, F. R., Al-Qadi, I. L., Hossain, K., & Ozer, H. (2019). Total Recycled Asphalt Mixes: Characteristics and Field Performance. *Transportation Research Record, 2673*(12), 149-162. doi:10.1177/0361198119849915

Tarsi, G., Tataranni, P., & Sangiorgi, C. (2020). The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. *Materials, 13*(18), 4052.

Wang, H., Liu, X., Apostolidis, P., van de Ven, M., Erkens, S., & Skarpas, A. (2020). Effect of laboratory aging on chemistry and rheology of crumb rubber modified bitumen. *Materials and Structures, 53*(2), 1-15.

Zaumanis, M., Boesiger, L., Kunz, B., Cavalli, M. C., & Poulikakos, L. (2019). Determining optimum rejuvenator addition location in asphalt production plant. *Construction and Building materials, 198*, 368-378.

Zaumanis, M., Cavalli, M. C., & Poulikakos, L. D. (2020). Effect of rejuvenator addition location in plant on mechanical and chemical properties of RAP binder. *International journal of pavement engineering, 21*(4), 507-515. doi:10.1080/10298436.2018.1492133

Zaumanis, M., Mallick, R. B., & Frank, R. (2014). 100% recycled hot mix asphalt: A review and analysis. *Resources, Conservation and Recycling, 92*, 230-245. doi:10.1016/j.resconrec.2014.07.007

Zaumanis, M., Mallick, R. B., & Frank, R. (2016). 100% hot mix asphalt recycling: challenges and benefits. *Transportation research procedia, 14*, 3493-3502. doi:10.1016/j.trpro.2016.05.315