Performance of High Content Reclaimed Asphalt Pavilion (RAP) in Asphaltic Mix with Crumb Rubber Modifier and Waste Engine Oil as Rejuvenator

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Abstract: The utilisation of reclaimed asphalt pavement (RAP) as a suitable substitute for natural aggregate and binder offers an energy-saving and cost-effective approach to enhance the performance of asphalt mix. Realising the potential use of RAP as a promising recycling technique, many countries are seeking to recycle RAP as part of the global effort to address the rising challenge of climate change and contribute to a sustainable environment. This study aimed to develop an integrated approach to determine the amount of RAP to be used in an asphaltic concrete wearing course with 14 mm nominal maximum aggregate size (ACW14). The RAP was incorporated with two waste materials comprising waste engine oil (WEO) as a rejuvenator and Crumb Rubber (CRM) as a binder modifier. A total of five different mixes, which include R0 (control mix), R30, R50, R70, and R100 (replacement of 30%, 50%, 70%, and 100% of RAP aggregates in the mix, respectively) were evaluated. The Marshall parameters, resilient modulus (M\text{R}), indirect tensile fatigue, moisture susceptibility, and mass loss (ML) tests were conducted to investigate the performance of each mix. Finally, an arbitrary scale was developed to optimise the RAP content. The results showed that the Marshall parameters, moisture susceptibility, and ML values of the RAP mixes met the criteria outlined in the standard. According to the M\text{R} performance, the R50, R70, and R100 mixes were more resilient than the R0. In terms of fatigue resistance, the R30, R50, and R70 mixes showed better performance than the R0. Overall, the collective performance of all RAP mixes was above the R0 and it increased with the increment of RAP content. Therefore, it was possible to design ACW14 mixes with up to 100% RAP in combination with WEO and CRM.

Keywords: reclaimed asphalt pavement; ACW14 mix; hot mix asphalt; waste engine oil; crumb rubber modifier

1. Introduction

The use of reclaimed asphalt pavement (RAP) is referred to as the recycling of aged asphalt pavement since RAP is a suitable substitute for natural aggregate and binder. The utilisation of RAP could reduce energy consumption, mineral usages, relevant pollution, and costs [1–8]. In fact, the use of RAP could reduce gas emissions and production costs by as much as 35% and 70%, respectively [8–10]. However, the application of RAP remains limited in many countries due to the lack of awareness and non-standard recycling requirements [10–12]. Therefore, there is a need to establish a RAP assessment framework, especially when various RAP proportions are used in a hot mix asphalt (HMA) design. As such, the use of 30% RAP in HMA was reported to cause little or no complications at all [13–16].
Nevertheless, the incorporation of a high RAP content in HMA faces many challenges. For example, an asphalt mix with higher RAP content could result in higher rutting resistance due to changes in the viscoelastic property, which in turn could have a negative impact on thermal cracking at low temperatures [17]. Furthermore, high RAP content could influence the volumetric properties of the asphalt mix, which could affect its mechanical performance [16,18]. It was also observed that high RAP content could reduce the fatigue resistance [19–21] and the workability of the mix [22,23]. Despite the challenges, several studies indicated that the use of a specific amount of RAP enhances the performance characteristics of asphalt mixes. In terms of the performance against moisture damage, Colbert et al. [24] showed that a 35% RAP mix performed better than a 50% RAP mix, though both mixes outperformed the control mix. In another study, Celauro et al. [25] observed that a 50% RAP mix recorded a tensile strength ratio (TSR) value of nearly 95%, which indicated the low susceptibility against moisture damage. Tran et al. [26] also studied the performance of 50% RAP mix with and without rejuvenator. The study reported that a 50% RAP mix with a rejuvenator increased the cracking resistance without compromising moisture damage or permanent deformation resistance as compared to a 50% RAP mix without a rejuvenator. It was also observed that the use of a rejuvenator slightly improved the TSR with no detrimental impact. In addition, the compaction process is vital to achieving optimal rutting resistance through proper interlocking aggregates [27]. In particular, the laboratory study indicated that the aged binder in RAP affects the mechanical properties of the mixes due to its internal interaction [28]. For instance, the stiffness, viscosity, and softening point of the binder were reported to increase as the aged binder increased [28–30]. Based on these studies, the selection of the appropriate temperature, rejuvenator, binder and manufacturing process are all crucial factors to achieve the highest performance of the RAP mix [8,31,32].

Currently, rejuvenators have received increasing attention in asphalt technologies due to their ability to revive the properties of the aged binder [33–35], which potentially prevents thermal cracks and brittleness [36]. Moreover, rejuvenators could increase the durability of asphalt mixes [37]. Waste engine oil (WEO) is one of the common rejuvenators that restores and softens the aged binder [38–41] as well as enhances the workability of RAP mixes [23,39,42]. Although WEO can reduce the optimum binder content (OBC) [43], WEO has a lower percentage of volatile components since it is processed under high temperatures (above 220 °C) [9], which partly contributes to binder hardening. The selection of a proper dosage of rejuvenator is a critical issue [8,44–46] since the excessive incorporation of rejuvenator affects the stripping, adhesion, rutting, and heat cracking while inadequate dosages can stiff the mix [47–49]. In view of this, several studies have indicated that the effective dosage of WEO was estimated at 15% [50–52].

Despite the significant advantages of the rejuvenator, the most influential drawback of using rejuvenator is the potential reduction in the pavement’s rutting resistance ability and to resist moisture damage [23,43,53]. This is because rejuvenator could increase the flow value and softness of the mixes more than expected. Therefore, crumb rubber modifier (CRM) is a widely used eco-friendly additive to assist the shortcomings of the rejuvenator [23,54]. Wang et al. [55] showed that CRM was more resistant to ageing than the unmodified binder because of the ability of CRM to reduce carbonyl and sulfoxide. In addition, CRM was reported to improve the stability of asphalt mix, moisture resistance, cracking behaviour, fatigue resistance, and resilient modulus [7,23,56–60]. Overall, the asphalt mix would become more stable with stronger adhesion through the addition of CRM [61]. The suitable CRM content to achieve the highest stability and rigidity was found to be between 5% and 10% [61].

Currently, the lack of a uniform RAP recycling standard was considered a major obstacle for a wider application of RAP. Thus, it is crucial to develop and establish a reliable assessment of RAP in the asphalt mix. This study aimed to optimise the RAP content in ACW14 mix design by investigating the mechanical performances based on the above concepts. The mechanical performances were evaluated through the Marshall stability test,
resilient modulus test, indirect tensile fatigue test, moisture susceptibility test, and mass loss test. The high RAP content (from 30% to 50%, 70%, and 100%) was incorporated with two waste materials: WEO as a rejuvenator and CRM as a binder modifier.

2. Materials and Methods

2.1. Materials Properties

In this study, five primary materials were used to prepare ACW14 mix samples (Figure 1), comprising RAP, natural aggregates (NAs), binder, binder modifier, and rejuvenator. The RAP was collected from Kuala Lumpur, Malaysia. Meanwhile, crushed granite was used as NA, while 1.5% ordinary Portland cement (by % of total aggregate mass) was used as the active filler. Table 1 lists the basic properties of NA according to the ASTM and AASHTO standards. The properties of the NA were mandatory in order to follow the Malaysian Public Works Department (PWD) requirements. In addition, the 60/70 penetration grade bitumen was used as the virgin binder, which was modified with 6% CRM of 80 mesh size using a propeller mixer at a speed of 200 rpm for two hours at 160 °C. Table 2 summarises the basic properties of the asphalt binders. Furthermore, the binder modifier, which comprised 6% CRM (by % of virgin binder mass), was used to increase the rheological properties of the virgin binder, and 15% WEO (by % of aged binder mass) served as the rejuvenator to soften the aged binder. The specific gravity of the used WEO was 0.87 with a water content of 0.34%.

![Figure 1. Primary materials used in this study to prepare ACW14 mix samples.](image)

| Test Standard | NA | PWD Requirement (2008) |
|---------------|----|------------------------|
| Los Angeles abrasion ASTM C 131-14 | 25% | ≤25% |
| Flakiness index ASTM D 4791-05 | 7.3% | ≤25% |
| Elongation index ASTM D 4791-05 | 19.0% | - |
| Soundness test (MgSO₄) AASHTO T 104 | 0.8% | ≤18% |

Table 1. Basic properties of NA.

| Property | Temp. (°C) | Standard | Virgin Binder | Modified Binder | Extracted Aged Binder |
|----------|------------|----------|---------------|-----------------|----------------------|
| Penetration (100 g, 5 s, 0.1 mm) | 25 | ASTM D5 | 65 | 58 | 11 |
| Softening point (°C) | - | ASTM D36 | 50 | 53 | 71 |
| Ductility (cm) | 27 | ASTM D113 | >100 | 34.2 | - |
| Rotational viscosity (20 rpm, cP) | 135 | ASTM D4402 | 366 | 644 | 3513 |
| | 165 | | 144 | 200 | 632 |
| G*/sin δ (10 rad/s, kPa) | 58 | AASHTO T315 | 2.2 | 3.8 | 95.9 |
| | 64 | | 1.0 | 1.8 | 42.0 |
| | 70 | | 0.5 | 0.9 | 22.1 |

Note: G* = complex modulus; δ = phase angle.
The RAP was first crushed and air-dried. Meanwhile, the aged binder was extracted using the Abson method (ASTM D 1856) [62]. The solvent used to extract the aged binder was methylene chloride solution. The extracted aged binder was then characterised (Table 2). The RAP aggregates containing 4.1% aged binder (by % of RAP aggregate mass) were then used to determine the combined aggregate gradation. Finally, the aged binder was rejuvenated with 15% WEO (by % of aged binder mass), which catalysed to soften the aged binder [50–52].

2.2. Experimental Process and Mix Design

Figure 2 shows the flowchart for the experimental process used in this study. Specifically, experiments were performed on five different modified binder contents (4.5%, 5.0%, 5.5%, 6.0%, and 6.5%), four different RAP content (30%, 50%, 70%, and 100%), and a control mix (R0 with 0% RAP). The tests were performed in triplicates for each sample. Based on PWD specifications (2008) [63], the five ACW14 mixes (R0, R30, R50, R70, and R100) were selected for this study with wearing courses over 40 mm thickness. NA was used for the R0 mix (Table 3).

Figure 2. The experimental process in this study.
Table 3. The composition of each mix.

| Mix Type         | RAP (%) | NA (%) | Modified Binder Content (g/kg) |
|------------------|---------|--------|--------------------------------|
|                  |         |        | 4.5% | 5.0% | 5.5% | 6.0% | 6.5% |
| R0 (control mix) | 0       | 100    | 45.0 | 50.0 | 55.0 | 60.0 | 65.0 |
| R30              | 30      | 70     | 32.3 | 37.2 | 42.3 | 47.3 | 52.3 |
| R50              | 50      | 50     | 23.8 | 28.8 | 33.8 | 38.8 | 43.8 |
| R70              | 70      | 30     | 15.3 | 20.3 | 25.3 | 30.3 | 35.3 |
| R100             | 100     | 0      | 2.6  | 7.6  | 12.5 | 17.6 | 22.6 |

Note: RAP consists of a 4.1% aged binder.

2.3. Aggregate Gradation and Sample Preparation

The sequential gradation of RAP mixes should be identical to the R0 to ensure that the effects of overall differences in aggregate gradation were eliminated, particularly the particle size distribution of aggregates. The combination of NA and RAP aggregates was calculated using the composite formula as shown in Equation (1):

\[
N_i = \frac{(M_i - P_i \times a)}{(1 - a)}
\]

where \( N_i \) = the percentage amount of NA required to be added to satisfy the gradation envelope; \( M_i \) = the percentage of aggregate as per the standard gradation envelope; \( P_i \) = the actual or field size of RAP aggregate; \( a \) = the desired proportion of RAP, and \( i \) = the sieve size.

The samples were prepared using the Marshall mix design method. The NA, RAP, and modified binder were separately heated in the oven to 170 °C for one hour. Binder quantities varied from 4.5% to 6.5% at an increment rate of 0.5% for each sample. For the preparation of R0, the modified binder was mixed with the heated aggregate. Meanwhile, the 15% WEO was directly mixed with the heated RAP to allow direct contact with the aged binder. Then, NAs were added and followed by the modified binder. This process would stimulate diffusion, consequently activating the aged binder [64,65]. The asphalt mix was then placed in a mould and compacted to 75-blow/face following the ASTM D 6926 standard [66]. Meanwhile, the rotational viscosity of the modified binder was measured and graphed to determine the mixing and compaction temperatures. They were calculated at the viscosity values of 0.17 ± 0.02 Pa.s and 0.28 ± 0.03 Pa.s, respectively [67–69]. The mixing and compaction temperatures were found to be 167 ± 1 °C and 160 ± 2 °C, respectively. Finally, the prepared samples were cured at room temperature for 24 h before further analysis.

2.4. Volumetric, Stability and Flow Properties, and OBC Determination

The volumetric properties such as air voids in mix (VIM), voids in mineral aggregate (VMA), and voids filled with the binder (VFB) were measured according to the ASTM D 3203 standard [70] while the mix density was measured following the ASTM D 2726 standard [71]. In addition, the Marshall stability and flow values were determined for the five mixes at 60 ± 1 °C and a loading rate of 50.8 mm/min following the ASTM D 6927 standard [72]. The mean OBC was calculated by averaging the five corresponding binders’ content values of the following parameters: (i) the peak stability; (ii) the flow equals 3 mm; (iii) the density peak; (iv) VFB equals 75%, and (v) VIM equals 4.0%.

2.5. Mixes Performance Tests

Based on the OBC, other sets of ACW14 mixes were prepared for each RAP content. Mechanical performance tests were performed, namely, resilient modulus (M_r), moisture susceptibility, indirect tensile fatigue, and mass loss test. The following sections describe these performance tests in more detail.
The $M_R$ value demonstrates the reaction of the pavement system to traffic loading [73,74]. Samples were tested for $M_R$ using the Universal Testing Apparatus (UMATT), according to AASHTO T 342 method [75] for the five mixes. The samples were kept at 25 °C for four hours before the test. The $M_R$ test conditions included the application of haversine loading shape, 1000 N peak loading, 0.1 s loading time, and 3.0 s pulse repetition period.

Furthermore, a pavement comes into contact with moisture in many ways, especially in the tropics. Hence, it is crucial to consider the effect of moisture on the design of the pavement. A wet-versus-dry moisture conditioning test is widely used in the laboratory to evaluate moisture susceptibility [76,77]. The TSR is the indicator of the resistance capacity of the sample to moisture damage and was measured according to the AASHTO T 283 standard [78], commonly known as the modified Lottman test. It is defined as the ratio of the indirect tensile strength (ITS) of the samples under wet and dry conditions ($\text{TSR} = \frac{\text{ITS}_{\text{wet}}}{\text{ITS}_{\text{dry}}}$). In general, a higher TSR value indicates a higher resistance to moisture damage. TSR had an 0.80 minimum requirement [63,79].

Two sets of samples with a height of $63 \pm 1$ mm and a diameter of $101.6 \pm 0.1$ mm were prepared with $7 \pm 0.5\%$ air voids. The first set of samples (3 out of 6 samples) was classified as a controlled (dry) subset, while the others were classified as a conditioned (wet) subset. The dry subset was immersed in water at $25 \pm 0.5$ °C for 2 h $\pm$ 10 min. Conversely, the wet subset was immersed in a hot water bath at $60 \pm 1$ °C for 24 h $\pm$ 1 h and then kept in another bath for 2 h $\pm$ 10 min to maintain the temperature at $25 \pm 0.5$ °C. All samples were tested using the Marshall apparatus to determine the ITS value at 25 °C. The TSR was calculated as the wet subset’s ITS value ratio to the dry (control) subset’s ITS value.

It was also imperative to determine the fatigue characteristics of pavement materials due to the fact that fatigue failure is one of the major asphalt distresses as a result of exhausted traffic loading and environmental impact [80]. Indirect tensile fatigue testing is an effective method that can be performed either under a controlled stress (more acceptable for thick pavement layers) or control strain (more acceptable for thin pavement layers). In this study, the controlled stress (while the strain values were changeable) was used according to the BS EN 12697-24:2018 standard [81]. The major test conditions included the temperature, loading force, loading shape, loading time, and rest time at $25$ °C, 2600 N, haversine, 0.1 s, and 0.4 s, respectively.

The mass loss (ML) test is a reliable approach in determining the durability of compact asphalt mixes [82,83]. The durability performance test procedure for ML was based on the ASTM C131 method [84]. The Los Angeles abrasion machine was used to conduct the test without any steel ball. It was necessary to fix 300 revolutions at $25 \pm 1$ °C and the speed from 30 to 33 rpm. The ML in % was calculated by Equation (2):

$$P = \left(\frac{P_1 - P_2}{P_1}\right) \times 100$$  (2)

where $P = \text{ML (%)}$; $P_1$ = mass before the test; and $P_2$ = mass after the test. A higher ML value indicates lower resistance to ravelling.

3. Results and Discussion
3.1. Optimum Binder Content (OBC)

Table 4 describes the OBC and binder amount for the five mixes. Overall, the OBC for RAP mixes were lower than that of R0 in which the OBC of RAP mixes gradually decreased as the RAP content increased. This was probably due to an increment in the percentage of fine particles and the amount of WEO. However, the differences in OBC for all the mixes were relatively small. For example, the OBC for the R100 mix was roughly 8% lower than that of R0 in which other studies also reported the same trend [51,85–88]. In addition, the amount of binder used in RAP mixes was drastically reduced. For instance, only 13.6 g of binder was used to prepare the ACW14 samples of the R100 mix, which was 79.7% lower than the amount of binder used to prepare R0 samples. This is due to
the combination of WEO and CRM in the mixes. The use of WEO effectively softens and rejuvenates the aged binder while enhancing the workability of RAP mixes [23,42,43,89]. In addition, CRM enhanced the stability, efficiency, and consistency of the asphalt [23,61]. Moreover, the inclusion of RAP could have influenced the stability and flow properties of the mixes. Therefore, it was demonstrated that the stability and flow values of RAP mixes were more load-bearing and more flexible compared to R0. The Marshall stability and volumetric properties of the five mixes with respect to the five binder contents are included in Appendix A.

Table 4. Percentage of OBC and the amount of binder.

| Component                  | Mix Type |
|----------------------------|----------|
|                            | R0       | R30  | R50  | R70  | R100 |
| OBC (%)                    | 5.9      | 5.8  | 5.6  | 5.5  | 5.5  |
| 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 |

3.2. Marshall Parameters in OBC

Table 5 provides results on the changes in the Marshall parameters for R0 and RAP mixes in OBC. Based on the results, all mixes met the minimum 8 kN stability criteria for high traffic volume roads. Overall, the stability of all RAP mixes was higher than that of R0 as well as the standard limits.

Table 5. Marshall test results in OBC.

| Mix Types | Marshall Parameters |
|-----------|---------------------|
|           | Stability (kN)      | Flow (mm) | VIM (%) | VMA (%) | VFB (%) |
| R0        | 10.2                | 3.0       | 4.3     | 17.4    | 75.0    |
| R30       | 11.9                | 3.1       | 3.6     | 16.5    | 78.5    |
| R50       | 11.1                | 3.4       | 3.6     | 16.1    | 78.0    |
| R70       | 10.4                | 3.4       | 3.6     | 16.0    | 77.0    |
| R100      | 10.2                | 4.0       | 4.6     | 16.7    | 72.9    |
| PWD limit | ≥8.0                | 2–4       | 3–5     | ≥14.0 1 | 70–80   |

1 Asphalt Institute standard [90].

Specifically, the stability of RAP mixes improved from 32% to 48% compared to the standard PWD (2008) value of 8 kN, indicating that WEO was an efficient rejuvenator that could effectively enhance the properties of the aged binder [38,41,89]. Given that CRM could improve the mechanical performance of binders [23], the addition of CRM into the mix was assumed to improve the stability. Furthermore, all mixes followed a 2–4 mm flow standard. The flow of the mixes increased with the increment of RAP content due to the use of WEO in RAP mixes, which allowed aggregates to float in the mix. In addition, the amount of WEO increased with the increment of RAP content. The result also indicated that the rejuvenator softened the aged binder and increased the workability of the asphalt mix. Moreover, the inclusion of CRM in the mix enhanced its flow value [23,61,91].

Table 5 also includes the results of the volumetric properties for R0 and RAP mixes. Since the value of VIM of all mixes met the PWD standard of 3–5%, their permeability properties were considered substantial. Furthermore, it was relatively necessary to maintain the minimum 14% VMA standard set by the Asphalt Institute to adopt the binder film within the mix [90]. According to the result, the VMA values of all RAP mixes were above the minimum limit while the VFB values of all RAP mixes were within the threshold limit (70–80%). Therefore, the volumetric properties indicate that all RAP mixes were durable.

3.3. Resilient Modulus (\(\text{M}_R\))

Figure 3 shows the average values of \(\text{M}_R\) for R0 and RAP mixes. It can be seen that the \(\text{M}_R\) increased with the increment in RAP content. Mixes with higher \(\text{M}_R\) were assumed
to be more resistant against deformation. The main reason was the existence of an aged binder (the higher the RAP content, the more the aged binder), indicating that the aged binder was able to increase the elastic component of the viscoelastic HMA mix. Moreover, the incorporation of CRM, which has exceptional viscoelastic properties, increased the elastic recovery value. Nonetheless, the use of WEO reduced the $M_R$ as demonstrated by the slow growth rate of $M_R$ value by some 25% with R100 mix compared with the R0. This occurrence may be associated with the change in the binder’s rheological properties. Thus, it can be concluded that the combined use of WEO and CRM was effective to obtain a balanced $M_R$ value.

Figure 3. $M_R$ for the five mixes.

3.4. Moisture Susceptibility Test

Figure 4 illustrates the TSR values of the five mixes. Generally, the TSR values of all RAP mixes were above the R0 (0.89), and the standard value (0.80) with the highest TSR value was recorded for the R100 mix (0.97), which was approximately 10% higher than R0. Interestingly, the TSR value increased as the RAP content increased, except for the R50 mix (0.93) where the TSR value was only 1.8% less than that of the R30 mix. Thus, the addition of RAP was very significant towards the sample’s resistance capacity to moisture damage as represented by the TSR value. Furthermore, the TSR value is commonly associated with higher stiffness in RAP mixes. The moisture susceptibility is mainly characterised by the adhesive resistance between the aggregate and binder and the cohesive resistance of the binder particles. Since RAP aggregates were already covered with the aged binder, RAP mixes were generally less susceptible to damage compared to the virgin mix. The utilisation of rejuvenator in this study was successful in restoring the properties of the aged binder [30], although it could reduce the moisture resistance of the asphalt mix [23] while the use of 6% CRM effectively increased the rheological properties of the binder to reduce the impact of WEO [7,23,59]. Moreover, the rheological properties of the aged binder were also significantly higher (Table 2). Therefore, the combined use of WEO and CRM was effective in applying a high RAP content in the HMA mix design. It can be concluded that the use of RAP mixes for pavement construction prevents the likelihood of pavement suffering from unfavourable moisture damage.
3.5. Indirect Tensile Fatigue Test

According to the EN 12697-24 standard, fracture life corresponds to the total cycle, which results in the complete rupture of the sample [81]. The fracture life measures the ability of the asphalt to withstand repeated tensile forces during its service life for an extended period. Based on the number of failure cycles of the five mixes (R0 and RAP mixes) in Figure 5, R30, R50, and R70 RAP mixes produced higher fatigue resistances than the R0 with R50 mix recorded the highest fatigue resistance. In contrast, the R100 mix was approximately 5% less resistant to fatigue cracking than that of R0. The decrease in fatigue cracking may be due to inadequate blending and diffusion between WEO and aged binders, which could shorten the fatigue life. The fatigue life of a mix with a high RAP content was largely influenced by the quality of blending and diffusion between the rejuvenator, virgin, and aged binders. In addition, the use of CRM prolonged the fatigue life, as shown in many studies [57,58,92]. Therefore, the results showed that the fatigue performance improved with the addition of a modified binder, while WEO may cause limited improvements in fatigue prevention [43,93]. Since the fatigue value of all RAP mixes was close to or higher than that of the R0 value, this study suggested that the integration of WEO and CRM was effective.

![Figure 4. TSR values for the five mixes.](image)

![Figure 5. Fatigue results for the five mixes.](image)
3.6. Mass Loss (ML) Test

Figure 6 shows the comparison of ML of the five mixes obtained through Equation (2). According to the results, all ML values of the five mixes were well below the 15% standard limit set by PWD [63]. Although there were certain differences between the mixes, statistical analysis showed that there were no significant differences between them. The R50 mix obtained the highest ML value (3.5%), which was well below the acceptable limit. Therefore, it can be confirmed that all mixes produced promising results, which indicated that they were highly resistant against raveling. The ML test provided an indirect indication of the possible impact of such improvements on mix disintegration resistance, which was linked to mix durability and abrasion resistance [94]. Hence, the presence of CRM and WEO reduced the ML considerably, and all mixes were highly durable [82,83].

![Figure 6](image-url)

Figure 6. ML testing result for the five mixes.

3.7. Performance Comparison Based on the Arbitrary Scale

It is very important to evaluate the performance test results from a different perspective, such as the arbitrary scale, so that the optimum RAP content to be applied in HMA design can be determined. The arbitrary scale was developed to assimilate the five major performance test results by assigning a weightage for the obtained test values compared to the standards and other justifications. The arbitrary scale was based on the following aspect:

— If a test has a certain pass/fail value, it was given 1.0 point. However, if there is no standard requirement, the value of the R0 was assumed to be 1.0 point. Then, the points for other mixes were determined accordingly. For example: (1) according to PWD, the standard stability value is 8.0 kN. As the stability value of the R100 mix was 10.2 kN, thus the R100 mix gained 1.28 points; (2) PWD specifications do not have a standard M_R value. According to the test result, the M_R value of R0 was 13,544 mPa and was given 1.0 point. Since the M_R value of the R100 mix was 16,966 mPa, therefore R100 mix gained 1.25 points.

Figure 7 shows the comparison of the overall performance of the five mixes based on the arbitrary scale. The overall performance of all RAP mixes was higher than the R0 and more than the minimum of five points in total. The performance increased approximately to 7.4% with the increment in RAP content. Understandably, the collective performance of the five mixes was above the lower limit set by an arbitrary scale. Based on these findings, all RAP mixes can be recommended for the road construction industries where up to 100% RAP can be used in HMA design without significantly reducing the performance of the asphalt mix.
4. Conclusions

This study examined an integrated approach to optimise the RAP content of ACW14 mixes using high RAP content and waste materials (WEO and CRM) with the following conclusions:

1. The OBC of all RAP mixes was below the R0 value. It was demonstrated that the OBC values decreased gradually as the RAP content increased. Furthermore, it was anticipated that the use of higher RAP percentages in the asphalt mixes would lead to a significant revenue in the related pavement construction field.

2. The stability of all RAP mixes was higher than the R0 (10.2 kN) as well as the standard limits (8.0 kN). The increment of RAP content was found to increase the flow. The findings also showed that all RAP mixes satisfied the Marshall stability, flow, and volumetric properties criteria.

3. The value of $M_R$ increased with the increment in RAP content. All RAP mixes were more resilient than the R0 except the R30 mix, in which the $M_R$ value obtained was 1.6% lower than the R0. Thus, it was concluded that the combined use of WEO and CRM was effective to obtain a balanced $M_R$ value.

4. The TSR values of all RAP mixes were above the R0 (88.7%) and standard requirement (80%). Thus, it can be summarised that the RAP mixes were sufficiently resistant to moisture susceptibility.

5. In terms of fatigue performance, the R30, R50, and R70 mixes produced a higher fatigue resistance compared to the R0. The R100 mix was approximately 5% less resistant to fatigue cracking than the R0.

6. The lower threshold value (15%) of all mixes from the ML test showed promising results and indicated that the mixes were highly resistant to ravelling and sufficiently durable.

7. The arbitrary scale was successfully developed as an effective performance evaluation method to determine the five major performance test results. The collective performance of all RAP mixes was higher than the R0 with increased performance as the RAP content increased. Therefore, 100% RAP mix can be used in ACW14 mix design without significantly reducing the asphalt mix’s performance.
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Appendix A

All data of the Marshall and volumetric properties of the five mixes with respect to the five binder contents are included below:

Table A1. Marshall stability and flow results in various binder contents.

| Binder Content | Marshall Stability (kN) | Marshall Flow (mm) |
|----------------|-------------------------|---------------------|
|                | R0 R30 R50 R70 R100     | R0 R30 R50 R70 R100 |
| 4.5%           | 7.6 9.8 7.8 8.0 8.2      | 2.7 2.7 2.5 2.5 2.9 |
| 5.0%           | 8.7 11.8 9.7 9.2 9.3      | 2.7 3.0 2.8 3.5     |
| 5.5%           | 9.7 11.9 10.9 10.1 10.6   | 3.0 3.2 3.5 3.7     |
| 6.0%           | 10.7 11.5 11.3 11.6 9.8   | 3.0 3.0 3.7 3.9 4.9 |
| 6.5%           | 9.6 10.6 10.2 10.7 9.1   | 3.4 3.4 4.4 4.7 5.1 |

Table A2. Density and VIM result in various binder contents.

| Binder Content | Density (g cm⁻³) | VIM (%) |
|----------------|------------------|---------|
|                | R0 R30 R50 R70 R100 | R0 R30 R50 R70 R100 |
| 4.5%           | 2.23 2.27 2.27 2.28 2.22 | 8.2 6.5 6.8 6.1 8.8 |
| 5.0%           | 2.26 2.28 2.29 2.31 2.27 | 6.5 5.6 5.2 4.5 6.1 |
| 5.5%           | 2.29 2.30 2.31 2.31 2.28 | 4.8 4.3 3.9 3.6 4.9 |
| 6.0%           | 2.31 2.31 2.32 2.30 2.30 | 3.2 3.1 2.6 3.3 3.3 |
| 6.5%           | 2.29 2.32 2.31 2.30 2.27 | 3.0 1.9 2.3 2.8 4.0 |
Table A3. VMA and VFB result in various binder contents.

| Binder Content | VMA (%) | VFB (%) |
|----------------|---------|---------|
|                | R0      | R30     | R50     | R70     | R100    | R0      | R30     | R50     | R70     | R100    |
| 4.5%           | 17.9    | 16.5    | 16.7    | 16.1    | 18.4    | 54.5    | 60.3    | 59.1    | 62.0    | 52.5    |
| 5.0%           | 17.4    | 16.6    | 16.3    | 15.7    | 17.1    | 62.9    | 66.6    | 68.3    | 71.2    | 64.6    |
| 5.5%           | 16.9    | 16.5    | 16.2    | 15.9    | 17.0    | 72.0    | 74.2    | 76.1    | 77.6    | 71.7    |
| 6.0%           | 16.7    | 16.5    | 16.1    | 16.7    | 16.7    | 80.5    | 81.6    | 83.7    | 80.3    | 80.4    |
| 6.5%           | 17.5    | 16.6    | 16.8    | 17.3    | 18.4    | 82.7    | 88.3    | 86.6    | 83.8    | 78.0    |

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