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Research Article

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Effects of waste engine oil and crumb rubber rejuvenator on the performance of 100% RAP binder

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Highlights

- Hybrid rejuvenator with CR and WEO was used to restore the aged binder
- Adding 100% RAP increased the stiffness and rutting resistance
- Proper use of WEO-CR rejuvenator enhanced the performance

Abstract

It is frequently essential to add rejuvenators to recycled mixtures comprising reclaimed asphalt pavement (RAP) to increase their performance. In this research, CR was desulfurized using WEO to produce a compound rejuvenator. The asphalt mixes containing 100% RAP binder were modified and rejuvenated with 0%, 3%, 6%, 9%, and 12% WEO-CR. The performance of the HMA samples were assessed using the Marshall stability-flow test, indirect tensile strength (ITS) test, and wheel-tracking device. The results showed that using a 9% WEO-CR rejuvenator restores the physical properties of the aged binder. In addition, the findings revealed that adding 100% RAP binder to the asphalt mixtures increased the tested properties of HMA samples; however, for the long-term performance of HMA, the aged binder may adversely affect the performance of the HMA mixture. Therefore, the addition of the WEO-CR rejuvenator was found to improve the overall performance of the mixture which improved the physical and chemical properties of the asphalt binder and enhanced the mechanical performance of HMA compared to the control mixture.

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1. Introduction

Using reclaimed asphalt pavement (RAP) in hot-mix asphalt (HMA) helps to reduce the overall cost of project, material transportation expenses, and also protects the environment [1]. As a result of the milling, RAP includes aggregate that is much finer than virgin aggregate. This issue may be solved by dividing the RAP into multiple sizes. Furthermore, the RAP binder is very stiff, resulting in mixes with undesirable cracking and workability properties at a lower temperature [2-3]. Therefore, Scientists have attempted following approaches such as soft asphalt binder, warm mix asphalt (WMA) additives, and recycling agents to address these issues [4-6]. In general, all these approaches may be recognized as recycling agents. The recycling agents act as softeners to decrease the impacts of the high stiffness of the aged binder and enhance its workability, or as rejuvenators to lessen the stiffness of the aged binder by halting the aging process, improving workability and mitigating cracking possibility [7].

The inclusion of some waste materials in any of the aforementioned procedures helps ensuring the long-term durability of the pavement. To increase the performance of the reclaimed binder, several rejuvenators have been applied. The disposal of waste engine oil (WEO) was extremely crucial as most states create substantial volumes of WEO annually [8]. The use of WEO as an asphalt rejuvenator was very beneficial, and other

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investigations have demonstrated that WEO has a great rejuvenation function [9-11]. Furthermore, WEO has a flash point of above 220 degrees Celsius, indicating that it is stable sufficient to be used in hot asphalt mixes [12]. However, the acidity and viscosity of WEO have a major concern of the rejuvenation process [13], therefore quality control in WEO is a critical issue [14]. Furthermore, the WEO-rejuvenated binders revealed a significant moisture sensitivity due to weak adhesion [15].

The adhesion of crumb rubber (CR) and asphalt binder are excellent [16-18]. The CR increases the elastic properties of asphalt mixes incorporating RAP and also keeping costs down [19]. On the other side, the inclusion of CR to asphalt mixes incorporating RAP has a negative influence on moisture susceptibility [20-21]. Furthermore, the rubber molecules do not mix well with the aged binders [22]. Incompatibility and deposition of rubber molecules are caused by variations in molecular size, polarity, and solubility between rubber and aged asphalt binder [23]. Lin et al. [24] reported that asphalt binders with a higher aromatic component liquefy more CR than an asphalt binder with a lower aromatic fraction. Compared with virgin asphalt binder, aged asphalt has fewer aromatic components [25]. Therefore, the compatibility of rubber with the aged binder has deteriorated. As a result, when CR is incorporated into an aged binder, the compatibility must be improved.

This paper intends to produce a CR and WEO rejuvenator to alleviate the difficulties described earlier and enhance the performance of mixtures comprising 100% RAP binder. The purpose of this study was to identify the optimum recycling agent dose in order to achieve the best performance of high-RAP mixes. The CR was implemented in this research to mitigate the reduction in rutting resistance caused by the addition of WEO. The objectives of this research were to evaluate the influence of compound rejuvenator (CR-WEO) on the physical and chemical properties of aged binder. In addition, the Marshall test, indirect tensile strength (ITS), and wheel-tracking test were performed to assess the mechanical properties of HMA samples. Finally, a cost analysis was carried out to assess the cost of HMA containing WEO-CR in comparison to the conventional HMA.

2. Materials and Sample Preparation

2.1. Materials

2.1.1. RAP binder

The RAP binder was recovered by melting it in methylene as stated by ASTM D2172 and afterward reclaiming it utilizing a rotary evaporator according to ASTM D5404. Before batching, all extracted binders were mixed to achieve consistent characteristics in the RAP binder. The RAP binder's performance grade (PG) was determined to be 94 and -4 °C. The RAP binder content was found to be 5.72 percent. Table 1 shows the characteristics of the RAP binder used in this study. The findings of physical testing of RAP demonstrate that it has a stiff character. The low penetration and ductility values demonstrate this.

Table 1. Physical properties of aged binder.

Property	Value	Specification	Standards
Penetration at 25°C, 5s, (0.1 mm)	14.8	60-70	ASTM D5-20 [26]
Softening point (°C)	75.9	48-52	ASTM D36-14 [27]
Ductility at 25°C, (cm)	9.7	>100	ASTM D113-17 [28]
Flash point (°C)	75.9	48-52	ASTM D36-14 [27]
Specific gravity	1.07	1.0-1.05	ASTM D70-21 [29]

2.1.2. Aggregates

Limestone aggregate was used as the virgin natural aggregate in this investigation. Table 2 shows the gradation of aggregate, and the prescribed gradation was following ASTM D3515.

2.1.3. Crumb rubber (CR)

CR with a maximum particle size of 0.157 mm (#80) was used for this experiment. It's important to mention that the CR was obtained from end-of-life tires using an ambient process.

2.1.4. Waste engine oil (WEO)

The WEO employed in this investigation was a 4,000-kilometer-use synthetic 5W20 gasoline oil. WEO had a kinematic viscosity of 0.041 Pas (ASTM D-4402) at 135 °C and a flash point of 265 °C (ASTM D-92).

2.2. Preparation of WEO-CR rejuvenator

WEO was initially heated at approximately 170 °C. The CR was gently combined with the WEO and sheared at 5000 rpm for 60 mins [30]. The percentage of WEO and CR of total weight of the compound rejuvenator was estimated to be 77% and 23%, respectively. Numerous samples having varying percentages of WEO and CR were examined by a trial-and-error procedure to determine the correct WEO-CR ratio. The production process of the WEO-CR rejuvenator is shown in Figure 1.

Table 2. Gradation of aggregates and specification

Sieve size	Passing%	Specification
25.40 mm	100	100
12.50 mm	92.4	80-100
9.50 mm	72.6	60-80
4.75 mm	50.3	48-65
2.38 mm	39.7	35-50
0.60 mm	25.5	19-30
0.30 mm	16.8	13-23
0.150 mm	8.2	7-15
0.075 mm	4.9	3-8

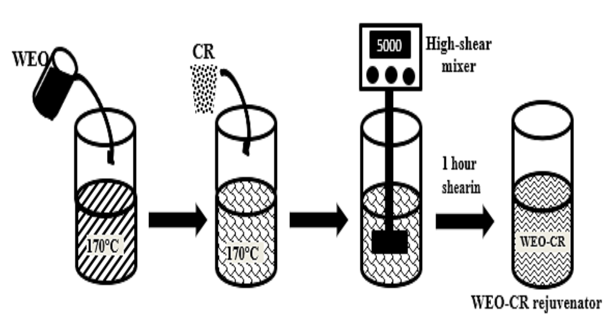

Figure 1. Process of production of WEO-CR rejuvenator.

2.3. Preparation of rejuvenated binder samples

To prepare the rejuvenated binders, the 100% RAP binder content was heated up to 140 °C before being combined with the rejuvenated WEO-CR for 15 minutes in a high-shear blender at 1000 rpm. The WEO-CR rejuvenator was mixed with the RAP binder at various doses (3%, 6%, 9%, and 12% by weight of the RAP binder). Figure 2 shows the production process of rejuvenated asphalt binder samples.

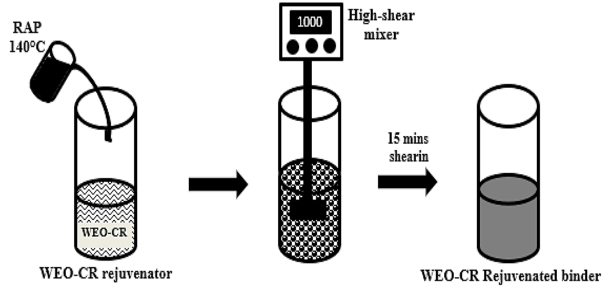

Figure 2. Process of production of the rejuvenated binder.

2.4. Preparation of asphalt mixtures

At 163 °C, rejuvenated binders comprising 100% RAP were mixed with natural limestone aggregate with a maximum nominal size of 12.5 mm (ASTM D2493). The mixture was left to cool down to a compaction temperature of 153 °C (ASTM D2493). The Marshall mix design showed that the optimum bitumen content was 6.02 % which achieved 4.0 % air voids in the overall volume of the mixtures. The optimum asphalt content and the volumetric properties for all HMA samples are shown in Table 3.

Table 3. Optimum asphalt content and volumetric properties of each mixture type.

Mixture type	Volumetric properties		
	Optimum asphalt content %	Total voids in mixture %	Density (gm/cm^3)
Control Mix	6.02	4.00	2.43
100%RAP	6.02	3.94	2.45
100%RAP+3%WEO-CR	6.02	4.02	2.46
100%RAP+6%WEO-CR	6.02	4.05	2.44
100%RAP+9%WEO-CR	6.02	4.06	2.43
100%RAP+12%WEO-CR	6.02	4.10	2.42

3. Methods

3.1. Temperature susceptibility assessment

Penetration index (PI) and penetration viscosity number (PVN) methods were used in this study to evaluate the effect of WEO-CR addition on the temperature susceptibility of rejuvenated asphalt binders. The Shell Bitumen Handbook [31] shows how to calculate PI using a traditional technique, as shown in Equation 1 beneath. Using the results of penetration and viscosity experiments, the PVN method is used to assess the temperature susceptibility of binders. Equation 2 [32] is used to calculate PVN.

$$\mathrm{PI} = \frac{1950-500\times\log(\mathrm{Pen})-20\times\mathrm{SP}}{50\times\log(\mathrm{Pen})-\mathrm{SP}-120} \tag{1}$$

$$\mathrm{PVN} = 1.5\times\left(\frac{4.258-0.7967\times\log(\mathrm{Pen})-\log(\mathrm{V})}{0.7951-0.1858\times\log(\mathrm{Pen})}\right) \tag{2}$$

Where;
Pen denotes the penetration at 25°C,
SP denotes the temperature of softening point,
V denotes the viscosity at 135°C in centistokes.

It should be stated that the low-temperature cracking is more likely in asphalt mixes consisting of binders with low PI values. Most acceptable paving binders have PI values from +1.0 to –1.0. In terms of the temperature sensitivity of binders, higher PI values indicate greater performance. On the other side, PVN values for asphalt binders typically range from +0.5 to -2.0 [32]. The temperature sensitivity of the binder increases as the PVN value decreases.

3.2. Marshall test

Marshall testing is used to determine the appropriate asphalt composition as well as the mixture's properties. This test is performed to measure the stability of the asphalt mixture and the deformation (flow). The capability of asphalt mixes to tolerate loads up to plastic discharge is indicted by stability. The load causes a change in form until it approaches the collapse limit, which is known as flow.

3.3. Indirect tensile strength test

The Indirect Tensile Strength test of asphalt mixes is performed by applying a load vertically to the cylindrical specimen's diameter at a specified rate of deformation and temperature. The highest load at the time of failure is utilized to calculate the indirect tensile strength of asphalt mixture. This experiment is also used to assess the quality of the asphalt mixture and to detect the possible water damage when the test results are acquired from separate specimens, especially when the test specimen is submerged and not soaked. This test was carried out at 25 °C according to the ASTM D6931-2017 [33].

3.4. Wheel-Track testing

The wheel tracking device is conducted to measure the resistance of asphalt mixtures to deformation of the wheel path, it also simulates traffic loads or vehicle wheel load on the asphalt surface until deformation occurs in the wheel path. Wheel path deformation is common on asphalt pavements, particularly in tropical regions. In this experiment, the HMA sample tests were tested at 50°C. The instrument has a wheel load of 0.705 kN and travels across the HMA sample's surface to make 10,000s passes. This test was run per the AASHTO T324-11 [34].

4. Results and Discussion

4.1. Physical properties of asphalt binder samples

Figures 3, 4, and 5 depict the penetration, softening point, and ductility of the virgin, RAP, and rejuvenated binder specimens. It can be observed, adding the RAP binder to a virgin binder enhances the stiffness, which makes the binder less susceptible to temperature owing to a the higher asphaltene content. Furthermore, the aromatics in the WEO-CR rejuvenator led to the development and incorporation of the asphaltene diffusion medium, which acts as a lubricant in the colloidal structure [15]. As a consequence, aromatics can reduce viscosity and soften asphalt binders. Furthermore, lowering the aromatic dosage reduces the penetration and ductility while increasing the softening point in virgin asphalt binder integrating RAP binder. Nevertheless, the characteristics of the RAP binders can be improved by utilizing the WEO-CR rejuvenator. WEO-CR rejuvenator can reduce the aging impact of RAP binders by decreasing the stiffness caused by oxidation and the interaction of the binder polar molecules. Further, the addition of the WEO-CR rejuvenator to the RAP binder increased penetration and ductility while decreasing softening point, shown in the figures, and the effects were more pronounced as the WEO-CR rejuvenator concentration increased. It can also be observed that the 9% content of WEO-CR yielded the optimum content that can restore the properties of the aged binder.

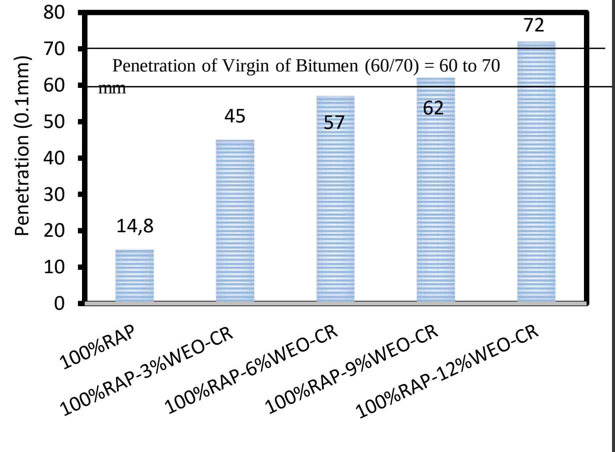

Figure 3. Penetration values of asphalt binder samples.

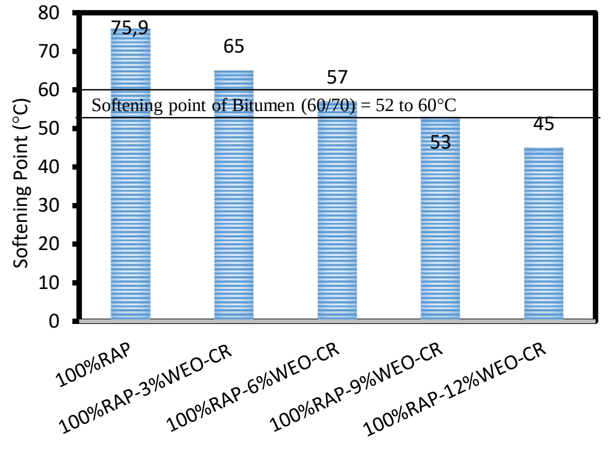

Figure 4. Softening point values of asphalt binder samples.

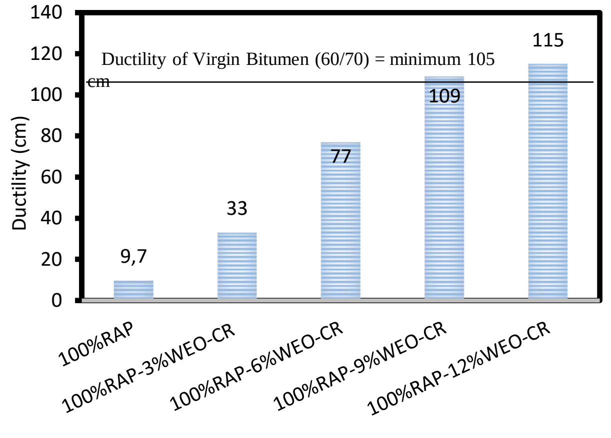

Figure 5. Ductility values of asphalt binder samples.

4.2. Temperature susceptibility assessment

Table 2 shows the PI and PVN values for the virgin, RAP, and rejuvenated binders. The results showed that the 100% RAP binder had the lowest values for PI and PVN, indicating that this binder is brittle, susceptible to cracking in cold climates, and rutting in hot climates. Furthermore, at 135°C, such binders have a low viscosity, which lead to tender mix issues (like instability, distortion, and rutting) during compaction under traffic loads [35]. On the other side, Table 4 exhibits that the RAP binders containing 3%WEO-CR and 6%WEO-CR had the highest values of PI and PVN, respectively. This indicates that these binders are the least susceptible to temperature.

Table 4. PI and PVN values of asphalt binder samples.

Asphalt type	PI	PVN
Virgin binder	+0.29	-0.18
100%RAP	-0.59	-0.21
100%RAP+3%WEO/CR	**+0.38**	+0.14
100%RAP+6%WEO/CR	+0.20	**+0.23**
100%RAP+9%WEO/CR	+0.34	-0.08
100%RAP+12%WEO/CR	+0.16	-0.18

4.3. Marshal stability and flow

The results of Marshall stability and flow of virgin, RAP, and rejuvenated HMA samples are shown in Figure 6 and Figure 7, respectively. Both graphs indicated that the RAP caused an increase in instability and a decrease in flow with the addition of a 100% RAP binder. This shows that RAP can boost the loading efficiency and the deformation resistance of the asphalt mixture. The enhancement was attributed to the brittle nature of the RAP, but it should be highlighted that it could be detrimental for asphalt mixtures at low and intermediate temperatures. Nevertheless, the finding is in agreement with the study of Moghadas et al. [36].

The addition of the WEO-CR rejuvenator also seems to have positively influenced the specimens' performance as shown in Figure 4 and Figure 5. This could be due to the higher elasticity of the compound rejuvenator when compared to the conventional mix, which also means that the rejuvenated HMA mixture can sustain higher loading and better resistance to deformation (flow). However, it is worth noting that, even with an increase in the content of the WEO-CR rejuvenator, the addition of RAP had increased the stability and decreased the flow of HMA samples, this is the main benefit of incorporating RAP into asphalt mixtures.

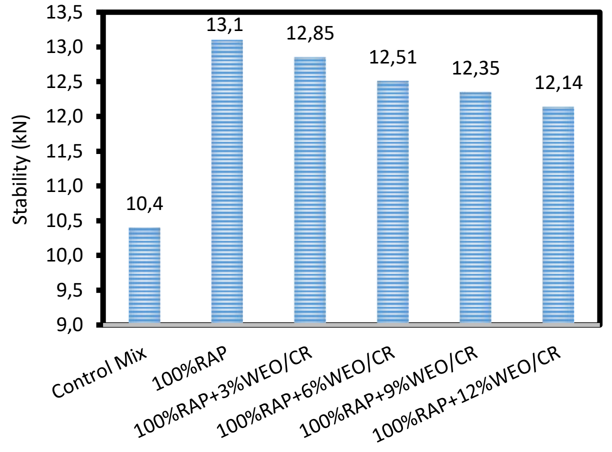

Figure 6. Stability of HMA samples.

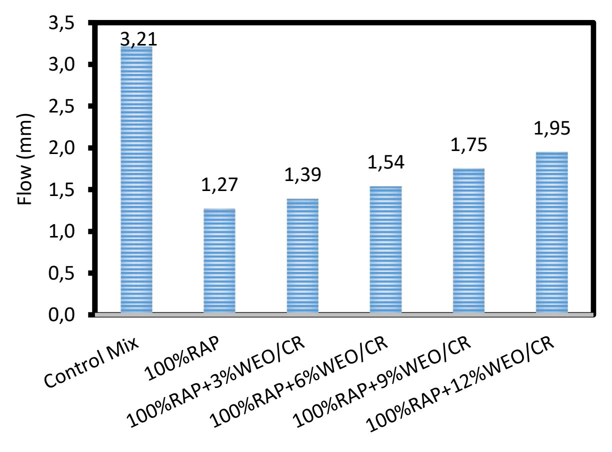

Figure 7. Flow values of HMA samples.

4.4. ITS of HMA samples

The HMA samples for the ITS test were produced with 4% voids, and the experiment was carried out following AASHTO T283. Figure 8 depicts the ITS results at 25 °C, where the ITS for the asphalt mixture incorporating 100% RAP was 2 times greater than the control mix (virgin mixture). The greater the ITS value, the stiffer and more viscous the RAP asphalt binders are. This finding is comparable to that of Eltwati et al. [37], who determined that RAP had a considerable influence on ITS, with larger RAP concentrations producing higher ITS values.

It can also be seen that the addition of a compound rejuvenator decreased the ITS values of HMA samples. The increases in the content of WEO-CR led to decrease ITS values of mixtures. This indicates that the rejuvenator decreased the ITS value by lowering the viscosity of the aged asphalt binder in the RAP. However, the ITS value of rejuvenated HMA samples was higher than the control mix (925 kPa). This conclusion was congruent with the findings of Eltwati et al. [38], who observed that the waste engine oil lowered the ITS value.

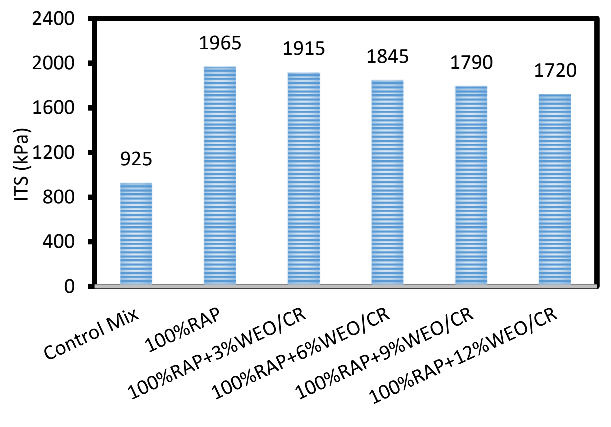

Figure 8. ITS of HMA samples.

4.5. Rutting resistance of HMA samples

Figure 9 illustrates that adding 100%RAP binder to the asphalt mixture increased the rut resistance of HMA samples. Rut depths was 0.91 mm for asphalt mixes containing 100% RAP. Because of the substantial amounts of carbonyl molecule in the RAP binder, the HMA samples containing 100% RAP had the lowest rut depth compared to all other HMA samples. This behavior is similar to the observations of Enieb et al. [39], who reported that high amounts of carbonyl in the aged binder lowered rutting depth.

It can be observed that the inclusion of the WEO-CR rejuvenator reduced the rut resistance of HMA samples. In addition, the increase in the amount of rejuvenator into asphalt mixtures led to increase in the rut depth of the sample. The content of the 12%WEO-CR rejuvenator had the highest rut depth compared to other samples. This finding is in line with the findings of Eltwati et al. [37], who determined that rutting resistance of WEO-rejuvenated mixtures was better than the conventional mixture. The reduction in rut resistance for asphalt mixes containing 100% RAP and rejuvenator was caused by the WEO, which softened the RAP mixture.

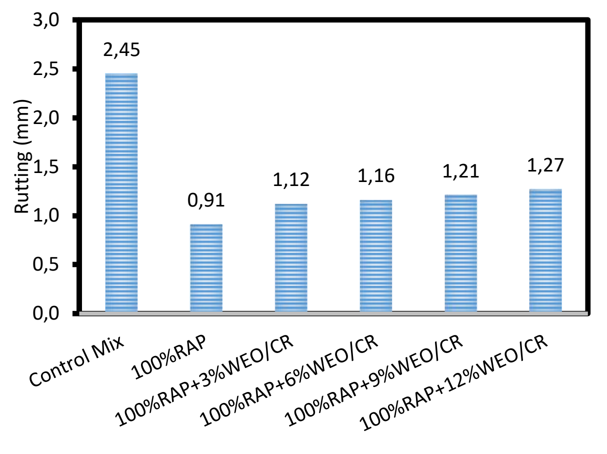

Figure 9. Rutting resistance of HMA samples.

4.6. Cost analysis

The cost of recycled HMA mixes containing WEO and CR was determined using cost analysis. Materials, plant production, transportation, and processing were the most important cost components identified by a previous study [40] for asphalt manufacture. Materials are the most expensive component, accounting for 70% of the total cost of HMA production [41]. Only materials like virgin aggregates, asphalt binder, RAP, WEO, and CR were priced in this analysis according to their usual pricing. Table 5 shows production costs per kg of HMA based on the virgin mixture and 100RAP+9%WEO/CR data. Because of the inclusion of RAP and WEO-CR in the mix, the price of asphalt mixes was reduced by 37.50 percent. The rejuvenated mixture (100RAP+9WEO-CR) is priced $26.76/ton, while the control Mix is priced at $42.85/ton, on the cost assessment. 100%RAP, on the other side, is significantly less expensive than a control Mix. However, due to their stiffness, which creates durability concerns, they cannot be included in the road surface, particularly as they aged.

Table 5. Cost analyses of asphalt mixture samples.

Materials	Price ($/kg)	Control Mix	100% RAP	100RAP+ 9WEO/CR
Virgin binder	0.48	23.85	-	-
Virgin aggregates	0.02	19.00	-	19.00
RAP binder	**0.006**	-	6.00	6.00
WEO	0.20	**-**	**-**	**1.39**
CR	0.18	-	-	0.37
Total cost ($/ton)	-	42.85	6.00	26.76

5. Conclusion

The current study used a research strategy that included a series of physical and chemical experiments to investigate the impacts of the WEO-CR on the characteristics of aged asphalt. In addition, the mechanical characteristics of HMA samples were tested. Based on the findings of the empirical investigation and subsequent discussions, a number of conclusions were established.

- The physical assessment of asphalt binder samples showed that the rejuvenator restored the properties of the aged binder, bringing them closer to the virgin binder. (60/70 penetration grade).
- The temperature susceptibility evaluation of binder samples showed that 100% RAP binder was susceptible to temperature variations. However, the incorporation of the content of 6.0 to 9.0% of WEO-CR to the aged binder improved the temperature susceptibility of the binder sample.
- WEO-CR was shown to improve RAP mixture performance in terms of Marshall tests, ITS, and rutting resistance. The performance of rejuvenated mixtures was even better than the virgin mixture.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement

A. Eltwati: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing **– M. Enieb:** Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing **– S. Ahmeed:** Conceptualization, Data Curation, Software **– Z. Al-Saffar:** Conceptualization, Data Curation, Formal analysis, Methodology, Resources, Software, Validation, Visualization **– A. Mohamed:** Conceptualization, Data Curation, Formal analysis, Methodology, Resources, Software, Validation, Visualization

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