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PAPER

Feasibility and mixture performance assessment of waste oil based rejuvenators in high-RAP asphalt mixtures

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Keywords: recycled asphalt mixtures, waste vegetable oil, waste engine oil, rejuvenator, indirect tensile strength, cost-benefit ratio, feasibility

Abstract

Asphalt pavements are amongst the most recycled materials in the contemporary world depending on the environmental and financial advantages. The introduction of Recycled Asphalt Pavement (RAP) on newly produced asphalt pavement is possible by the utilization of rejuvenating agents, which should contain oily fractions. For this purpose, within the scope of this study, three types of agents with optimum amounts (by weight of bitumen) were utilized 5.4% Waste Engine Oil (WEO), 5.1% Waste Vegetable Oil (WVO), and 6.8% Commercial Rejuvenating Agent (CRA). The highest applicable RAP content in mixtures depends on the rejuvenator type determined by Marshall Mix Design tests (air voids, flow, and stability). Rejuvenation facilitated the use of 50 to 60% of additional RAP material in the mixtures depending on the rejuvenator type. Indirect Tensile Strength (ITS) test results declared that RAP mixtures, when subjected to the rejuvenation process, resulted in relatively less brittleness and enhanced durability properties compared to the unmodified ones. Additionally, cost comparison analyses demonstrated encouraging results as the cost-benefit ratio exceeded up to 55% for mixtures involving high percentages of rejuvenated RAP. As a final analysis, Return on Investment (ROI) values were calculated for each rejuvenator type by the cost of upgrading the facility to handle RAP and the profit of RAP usage. Consequently, ROI was calculated as a return time in months, which unveils an extremely profitable opportunity in the industry.

1. Introduction

Every year, approximately 110 million tons of bitumen are used in the asphalt industry to construct pavements all over the world. Demand to build sustainable roads is inevitably increasing because of the fact that bitumen is a petroleum-based material, which is an exhaustible resource and its value of it has increased substantially over the last couple of decades [1]. Temperature variations and traffic loads significantly accelerate the aging process of asphalt during its service life [2–4]. In many countries, the utilization of Recycled Asphalt Pavement (RAP) has emerged as an ideal alternative to overcome the environmental and economic hazards of asphalt pavement reconstruction activities [5, 6]. RAP is processed aged asphalt, which is collected from milling and resurfacing operations, in order to reclaim in new applications.

Recycling of aged bitumen for new asphalt pavement applications yields a decrease in the required virgin bitumen content. This simple fact makes the utilization of RAP in Hot Mix Asphalt (HMA) economically attractive [7]. Many state agencies have also supported the fact that the introduction of RAP to asphalt pavement construction can result in substantial savings [8]. According to a study, reclaimed HMA pavement can save between 14 to 34% in material and construction costs of the pavement, with a RAP percentage ranging between 20 to 50% [9]. The highest amount of RAP application is in the surface and intermediate layers of flexible pavements wherein a relatively less expensive RAP binder substitutes the virgin binder which constitutes a significant portion of the HMA construction costs [10, 11]. However, it is challenging to accomplish as it would require a high level of attention since these layers are supposed to have high quality and to absorb harsh external and internal stresses as well as endure durability issues as compared to other underlying layers. In addition to the abovementioned benefits, higher RAP application in pavement construction also decreases the amount of RAP disposal, which is usually chargeable in many countries, and also avoids the transport and fuel costs incurred during their haulage to landfill sites by in-place recycling [12]. When it comes to environmental benefits, a detailed analysis revealed that using RAP materials in the paving industry can yield a 35% reduction in CO_2, which is critical for climate and global warming control [13].

Depending on the environmental and economic advantages, researchers and highway agencies have put their efforts to identify strategies for the utilization of high RAP contents in HMA constructions. One of the significant obstructions to using high RAP content within the HMA is increased stiffness of aged mixtures which causes durability-related problems such as fatigue cracking susceptibility [14]. Another concern about the utilization of high RAP content is the premature cracking distresses [15]. The recycling agent is an essential constituent of any effective asphalt recycling practice in the industry, as it helps to ensure smooth operation and application in the top-most asphaltic layers [16]. Rejuvenating agents are special types of additives intended to reverse the aged (oxidized) asphalt binder to a relatively less-aged condition by restoring chemical structures and rheological properties of aged binders by increasing the aromatic contents and decreasing the binder's overall viscosity [17, 18]. Rejuvenators are usually oil-based softening additives with a high content of light components, which can be added to the extracted aged bitumen or directly sprayed on the RAP itself. Utilizing the rejuvenated bitumen can fix the rheological, mechanical, thermal, and structural properties of the sample, which encourages the use of RAP in HMA production [19–26]. Some rejuvenators provide utilization of RAP content up to 100% however some are failed to meet the Marshall mix design criteria when used on high RAP content. Because the properties of the rejuvenator directly affect the RAP amount that can be used in road construction [13]. Different types of rejuvenators as organic oil, distilled tall oil, Sunflower oil, nut oil, etc can be utilised to enhance the RAP properties, which provides usage of high RAP within the asphalt mixtures. In the literature, oil based rejuevantors yielded satisfactory results, among them waste oils are more attractive to be used as rejuvenators, because it increases the usage of the wastes and provides more sustainable solutions [27–29]. Studies have shown that, the utilization of waste oils as a rejuvenator improved the aging, fatigue, and low temperature cracking resistance of asphalt mixtures [30].

The objective of this study is to investigate and characterize innovative recycling agents that mainly originated from waste oils. In this regard, Waste Engine Oil (WEO), Waste Vegetable Oil (WVO), and Commercial Rejuvenating Agent (CRA) were utilized and the performances of the rejuvenated samples were compared to the control (unrejuvenated) samples by Marshall and Indirect Tensile Strength (ITS) tests. In order to increase the sustainability of asphalt road construction, it is important for asphalt manufacturers to take action in the plants. However, a proper cost-benefit analysis on high-RAP involving asphalt mixtures and return on investment (ROI) value for the rejuvenation process in asphalt plant have not been investigated so far. Another important aim of the study is to evaluate the rejuvenation feasibility depending on the rejuvenator types and rates. The study also covered cost analyses and rejuvenation feasibility for various mixture types involving both rejuvenated and non-rejuvenated RAP to evaluate the benefits of the rejuvenation process.

2. Materials and method

2.1. Materials

2.1.1. Bitumen

A 50/70 penetration grade bitumen was used as the virgin asphalt binder. A 12-year-old existing surface course (Type-1) was milled and reduced for sampling purposes. A total of 16 batches RAP samples, each weighing 1000 gr., were randomly prepared with the help of separating equipment. Binder was extracted from the aged mixtures using a laboratory-type bitumen extractor and subsequently extracted bitumen was taken through the distillation process. The binder content of the RAP was determined as 4.30% by the aggregate weight. The conventional binder test results of virgin and extracted bitumen of RAP are given in table 1.

2.1.2. Aggregate

The asphalt mixtures were produced using limestone aggregates that gradation graph is given in figure 1. The results conform with Type-I wearing course as per specifications.

2.1.3. Rejuvenating agents

Three distinct rejuvenating agents were used: WEO, WVO, and CRA. WEO was procured from an authorized industrial collector. WVO consists of a mixture of two different waste frying oils (approximately 70% Olive oil + 30% Sunflower seed oil) used for only one frying cycle and it was provided by a local food restaurant. CRA was

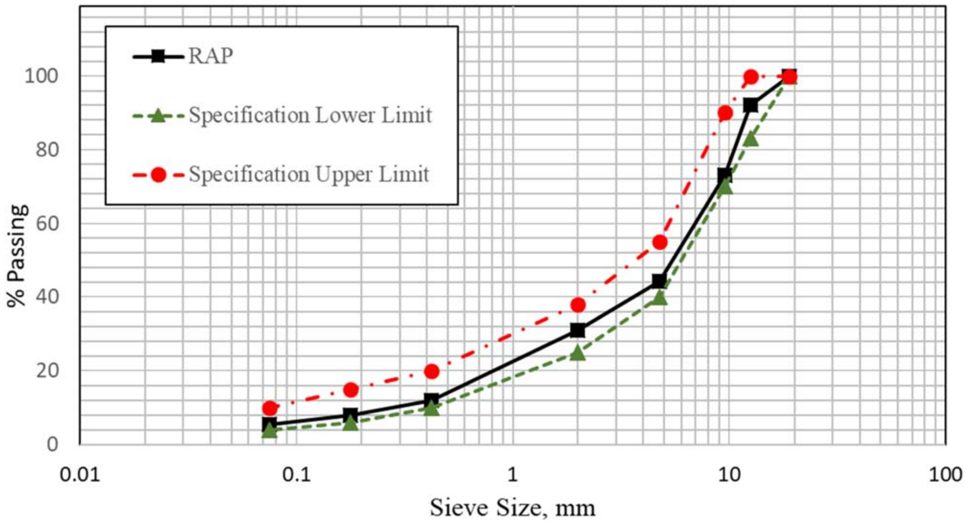


Figure 1. Extracted aggregate gradation chart.

Table 1. Laboratory test results for virgin bitumen and extracted RAP binder.

Test	Specification	Virgin bitumen	RAP binder	Spec. range
Penetration (@ 25 °C; 0.1 mm)	TS EN 1426	63	38	50–70
Softening point (°C)	TS EN 1427	49.7	61	46–54
Viscosity at (135 °C)-Pa.s	ASTM D4402	0.425	0.538	—
Viscosity at (165 °C)-Pa.s	ASTM D4402	0.1	0.188	—

Table 2. The physical properties of the rejuvenators.

Characteristics	WEO	WVO	CRA
Color	Dark Brown	Straw Yellow	Amber
Density (gr ml^{-1})	0.91	0.92	0.9
Viscosity @ 40 °C, mm2/s (centistokes)	90	50	50
Viscosity @ 100 °C, mm2/s (centistokes)	15	10	15
Flash Point (°C)	$\geqslant$200	$\geqslant$280	$\geqslant$140
Boiling Point (°C)	$\geqslant$280	$\geqslant$250	$\geqslant$350
Pour Point (°C)	$\leqslant -25$	$\leqslant$10	$\leqslant$0
Freeze Point (°C)	N/A	$\leqslant$5	$\leqslant -10$

acquired from a company known for supplying asphalt additives. The physical properties of the rejuvenators are given in table 2.

2.2. Methodology

Figure 2 summarizes the methods and the steps of the process. The optimum rejuvenator contents were taken from the previous study by the authors. Different RAP contents were then combined with virgin bitumen and fresh aggregates together with the pre-determined quantity of rejuvenators to determine the optimum RAP contents following the Marshall mix design procedure. Following, determined RAP contents were investigated in terms of stiffness indices by the Indirect Tensile Strength (ITS) test for each rejuvenated and non-rejuvenated mixtures. Finally, the cost-benefit was investigated considering the RAP contents of each mixture. The feasibility of the rejuvenation process was evaluated by the Return on Investment (ROI) values of each mixture.

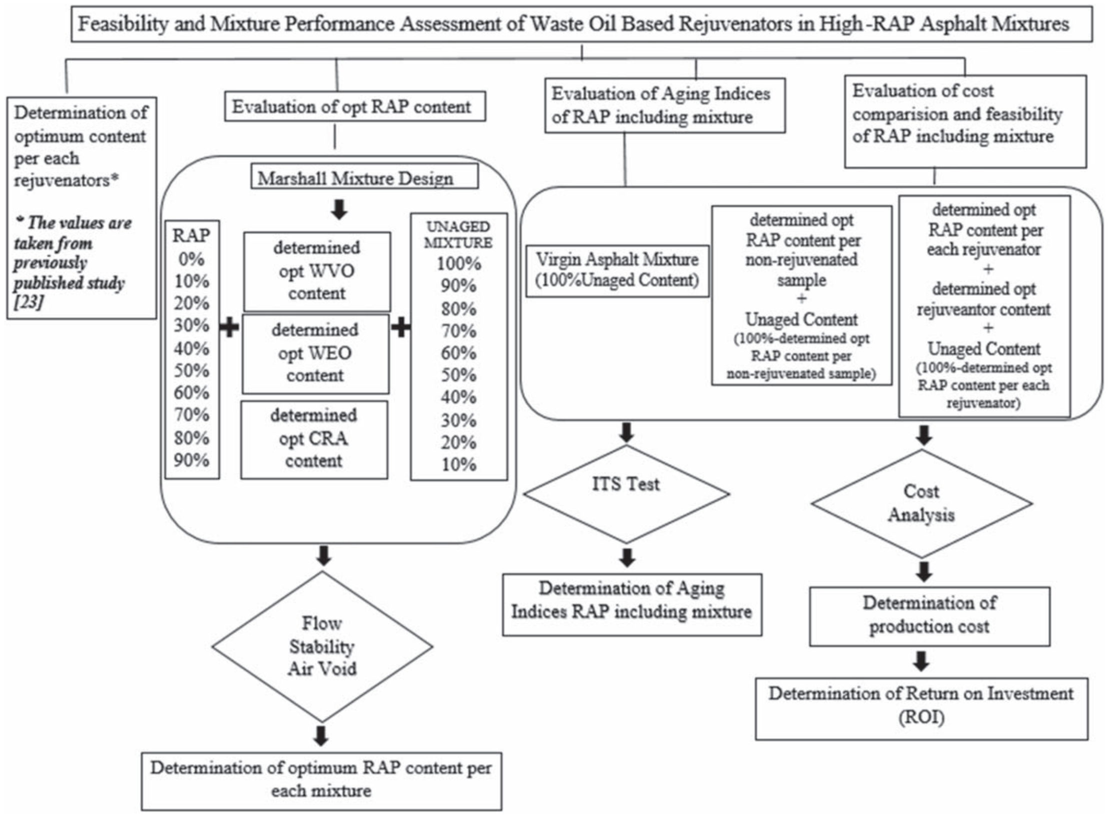


Figure 2. Flow chart of the study.

2.2.1. Evaluation of optimum rejuvenator content per each rejuvenator

This study is a continuation of a previous study, where the authors investigated the conventional, rheological, and microstructural properties of the same three rejuvenated aged bitumen (WEO, WVO, and CRA) [31]. The optimum content of each rejuvenator was determined in the previous study by the authors, where the penetration value was selected as the main criteria. Besides, softening point and viscosity tests at 135 °C and 165 °C were also carried out to ensure those values also meet the specification requirements. As a result, optimum values of each rejuvenator type are determined as 5.4%, 5.1%, and 6.8% by weight of RAP binder corresponding to the target penetration value of virgin bitumen for WEO, WVO, and CRA, respectively.

2.2.2. Evaluation of optimum RAP content per each rejuvenator

As first step, RAP mixtures were rejuvenated with the introduction of optimum rejuvenator content (for each rejuvenator type). Within the process, the rejuvenating agent was continuously sprinkled on RAP mixtures as mixing process was ongoing. Following, the Marshall mix design, based on the ASTM D6926 standard, was performed on rejuvenated mixtures with varying RAP contents. The produced specimens were subjected to volumetric analysis followed by the Marshall stability and flow test to determine the highest possible RAP content to be involved in the rejuvenated asphalt mixture. The virgin bitumen content to be added to the mixture containing RAP is determined by equation (1) based on the information given in the Bituminous Mixtures Laboratory Handbook published by the General Directorate of the State of Highway [32].

$$P_r = P_c - (P_a \times P_p) \tag{1}$$

Where; P_r is the % of virgin binder to be added in the mix containing RAP, P_a is the % of RAP binder in the mix, P_c is the % of total binder in the mix, and P_p is the percentage of RAP in the mix.

2.2.3. Evaluation of stiffness indices through the ITS Test

To evaluate the stiffness characteristics of both rejuvenated and non-rejuvenated specimens prepared with optimum RAP content, the Indirect Tensile Strength (ITS) test was conducted following the ASTM D6931 standard. The ITS results provide an evaluation criterion in terms of low temperature and fatigue cracking susceptibility of asphalt pavements. Some studies denote ITS as a good indicator in predicting the rutting potential of asphalt mixtures [33]. The test is widely used in the investigation of moisture-induced damage of bituminous mixtures. The raw data recorded from the test device are processed using the following equation (2)

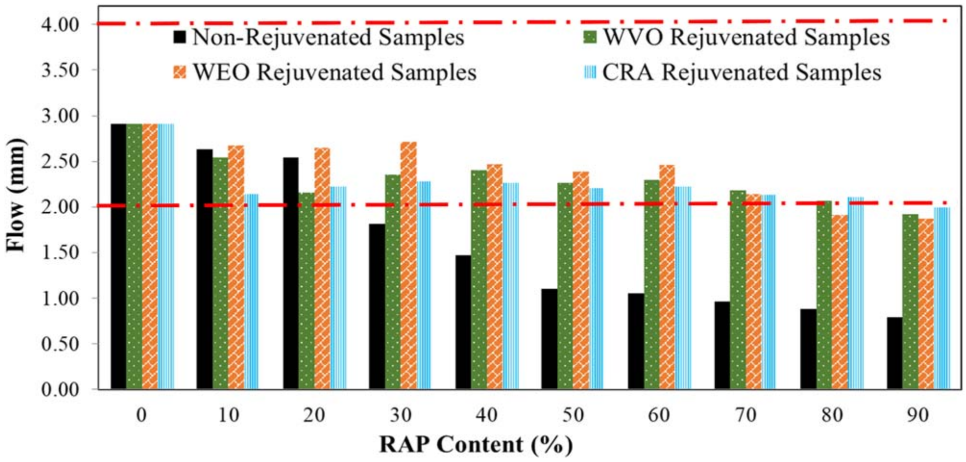


Figure 3. Flow rate results corresponding to different RAP contents per each rejuvenated and non-rejuvenated samples.

to obtain indirect tensile stresses:

$$ITS = \frac{(2000 \times P_{max})}{\pi \times t \times D} \qquad (2)$$

Where the ITS is the indirect tensile strength of the specimen in kPa, P_{max} is the measured maximum load at failure in Newton, t is the specimen thickness in mm, and D is the specimen's diameter in mm.

The stiffness indices were calculated as the ratio of ITS values of the non-rejuvenated and rejuvenated mixtures over ITS values of the control mixture (neat asphalt mixture).

2.2.4. Evaluation of feasibility of rejuvenated samples by cost analysis

Cost analysis within this study comprises of two parts: a) executing a cost comparison between the Asphalt Concrete (AC) (control mixture) and the mixtures produced at optimum rejuvenator dosages and their corresponding maximum RAP contents; and b) performing the feasibility study of producing such mixtures at a factory which highlights the economic gains from introducing non-rejuvenated and rejuvenated-RAP into mixtures. All prices are in US Dollars ($) and the calculations are made for the third quarter of 2022 costing.

A feasibility analysis was performed for a typical drum plant with 1,500 tons/day capacity. The total cost of upgrading the facility to handle RAP was calculated as $350,000 using conventional engineering economics. The plant is assumed to operate for 20 days in a month with 30,000-tons monthly production. The savings per ton for non-rejuvenated and rejuvenated mixtures were determined by calculating the difference in the cost between the virgin asphalt mixture and the non-rejuvenated or rejuvenated RAP involving mixtures. The feasibility of the rejuvenation process for the asphalt plant is evaluated by Return on Investment (ROI) values. ROI is calculated by dividing the profit earned on an investment by the cost of that investment.

3. Results and discussion

3.1. Mixture test results

3.1.1. Marshall mix design results

The highest RAP contents were determined for both mixtures containing non-rejuvenated and rejuvenated RAP to be employed within the Type-I wearing course. Volumetric analysis together with Marshall stability and flow values were set as the base criteria in the selection of maximum possible RAP contents. Results for flow rates, stabilities, and air void contents are presented in figure 3–5 for WEO, WVO, and CRA rejuvenated samples together with non-rejuvenated mixtures.

The flow rate was selected as the primary parameter in determining the maximum possible amount of both rejuvenated and non-rejuvenated RAP material. As presented in figure 3, the flow rate decreases with the increase of RAP content for the mixture involving both non-rejuvenated and rejuvenated samples, since the higher the RAP content, the lower the resistance to deformation depending on the increasing amount of aged bitumen. It can be seen that the flow values for the mixture containing over 30% of non-rejuvenated RAP exceed the range (2–4 mm). Therefore, 20% is proposed as the highest RAP content to be used for the non-rejuvenated samples. The flow rates of rejuvenated specimens were higher than the non-rejuvenated ones, indicating higher deformations under the same pressure. As the aged and virgin binder are better blended in the presence of

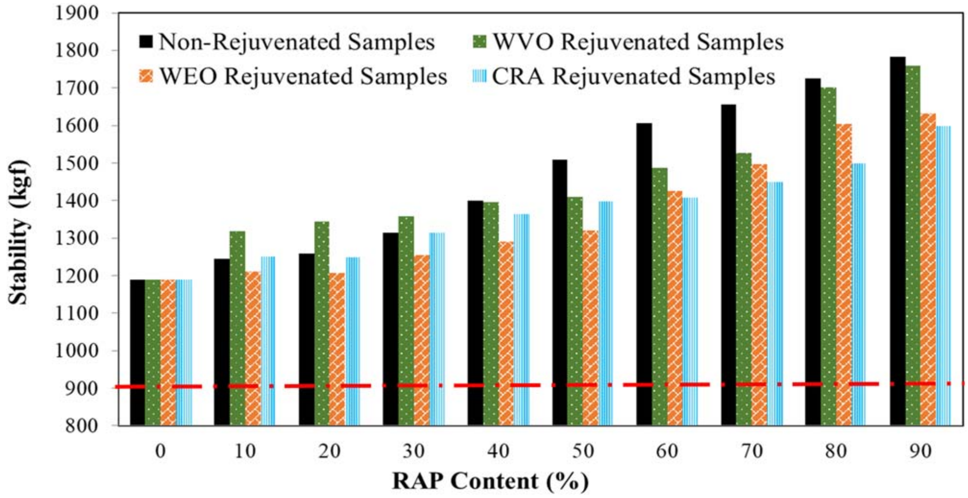


Figure 4. Stability results corresponding to different RAP contents per each rejuvenated and non-rejuvenated samples.

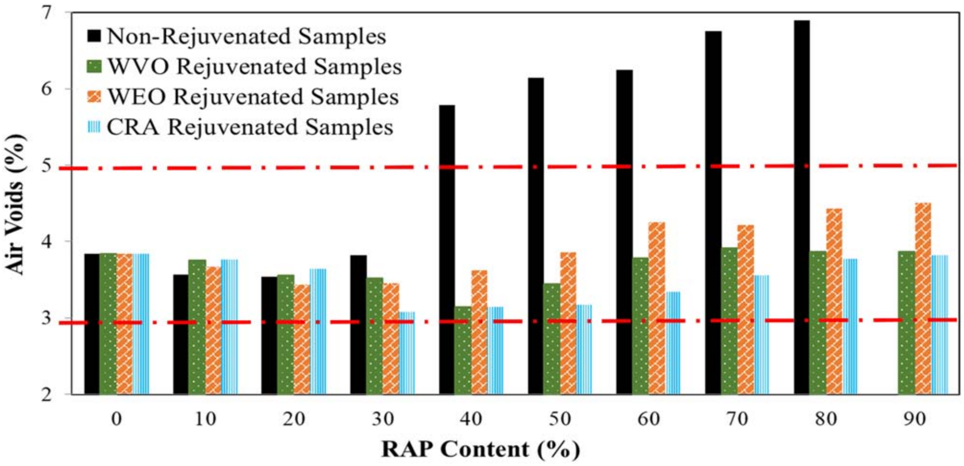


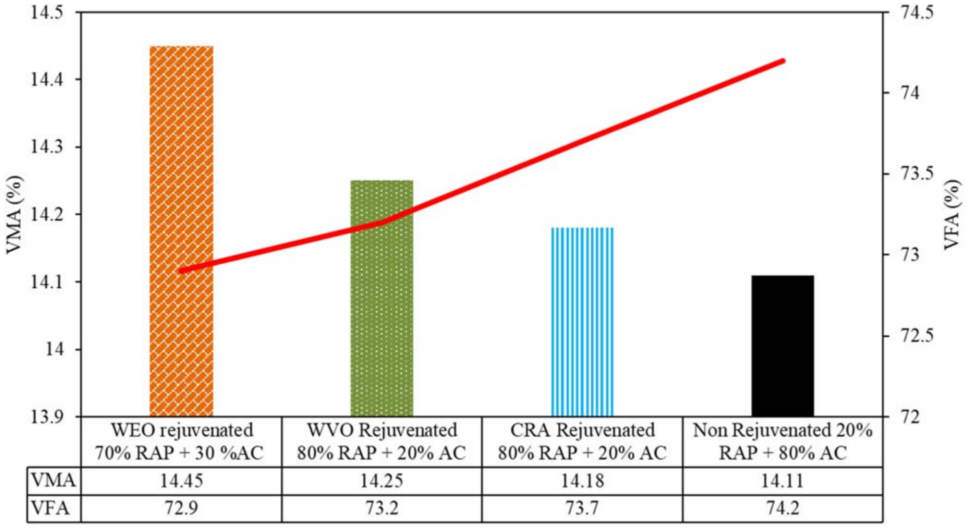
Figure 5. Air voids values corresponding to different RAP contents per each rejuvenated and non-rejuvenated samples.

rejuvenators and more restored aged binder from RAP is introduced, more effective binder content is yielded. That automatically results in decreasing the resistance of the mixture to deformation. Depending on the flow rate results, a maximum of 70% of WEO, 80% of WVO, and 80% of CRA rejuvenated RAP content can be employed within the Type-I wearing course.

According to figure 4, stability values for all specimens are well over the minimum specification limit (900 kgf). The result is as anticipated since mixtures with high RAP contents become stiffer, derived from the incorporation of aged binder, resulting in higher stability values. However, the primary concern regarding the utilization of mixtures involving RAP is the durability issue rather than stability. Therefore, volumetric characteristics and flow rates (somehow, as an indicator of flexibility) are deemed more crucial than the stability values when determining the maximum possible RAP content within the mixture.

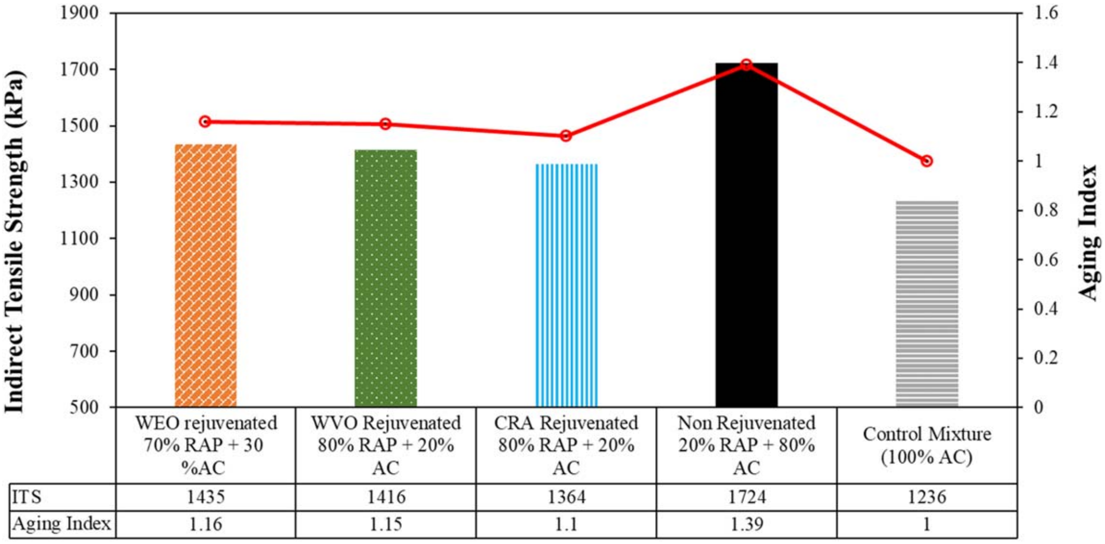
As presented in figure 5, no significant variation in the level of air void is obtained up to 40% RAP addition for both rejuvenated and non-rejuvenated samples. However, for over 40% of RAP utilisation, the air void level in the mixture tends to increase significantly, especially for non-rejuvenated samples. All mixtures containing rejuvenated RAP met volumetric criteria in terms of air voids (3%–5%). Whereas the mixtures failed to satisfy the desired air void content when containing more than 40% of non-rejuvenated RAP. The volumetric characteristic of rejuvenated RAP-containing mixtures remained within the range owing to lower viscosity values of the rejuvenated RAP binder and improved workability.

In this study, flow, Marshall stability, and air voids results of the mixtures were selected as the main criteria for determination of RAP content to be used in asphalt mixtures. However, Voids in Mineral Aggregate (VMA) and Voids Filled Asphalt (VFA) are among the other volumetric characteristics of asphalt mixture, which should



	WEO rejuvenated 70% RAP + 30 %AC	WVO Rejuvenated 80% RAP + 20% AC	CRA Rejuvenated 80% RAP + 20% AC	Non Rejuvenated 20% RAP + 80% AC
VMA	14.45	14.25	14.18	14.11
VFA	72.9	73.2	73.7	74.2

Figure 6. VMA and VFA values of the samples.



	WEO rejuvenated 70% RAP + 30 %AC	WVO Rejuvenated 80% RAP + 20% AC	CRA Rejuvenated 80% RAP + 20% AC	Non Rejuvenated 20% RAP + 80% AC	Control Mixture (100% AC)
ITS	1435	1416	1364	1724	1236
Aging Index	1.16	1.15	1.1	1.39	1

Figure 7. ITS test results and Aging Index values of the samples.

be controlled according to the design limits. As depicted in figure 6, VMA and VFA results of the mixtures involving determined RAP content were within the Marshall mix design criteria limits (min 14% for VMA, and %65–75 for VFA).

3.1.2. Indirect tensile strength and stiffness indices

The indirect tensile test was used to evaluate the characteristics of the samples in terms of mixture stiffness. The higher the ITS value, the more would be the capability of a mixture to withstand tensile strains prior to crack initiation and vice versa. As can be observed in figure 7, mixtures involving optimum rejuvenated RAP contents recorded lower ITS values compared to the non-rejuvenated ones. This could be sourced from the rejuvenation process causing mixtures to be more workable and softer thereby exhibiting improved flexibility.

Figure 7 also represents the aging (stiffness) indices of the samples. The aging index is simply the ratio of ITS values of rejuvenated/non-rejuvenated RAP samples over that of the control mixture. The closer the aging index value gets to '1', the less stiff the mixture behaves. It should be noted that the aging indices are the essential performance indicator for mixtures containing as high as 80% RAP contents. In general, rejuvenators are effective in terms of enabling the high-RAP accommodating mixtures to meet the minimum standards by lowering their aging index values in this manner softening the mixtures. As depicted in figure 7, the mixtures

Table 3. Unit prices for materials, transport, and operational expenses (3rd quarter of 2022).

Material cost	Unit	Unit cost (in USD)	Source
Virgin Aggregate (at Quarry)	Ton	4	KGM – 2019[a]
Virgin bitumen (50/70) in Refinery	Ton	580	TÜPRAŞ/Türkiye
RAP from the local stock	Ton	3	Local Market Analysis
WEO Rejuvenating Agent	kg	0.95	Local Market Analysis
WVO Rejuvenating Agent	kg	1.20	Local Market Analysis
CRA Rejuvenating Agent	kg	2.85	Local Market Analysis
Transportation Cost	Unit	Unit Cost (in USD)	
Solid Materials	Ton/km	0.025	Survey/Estimation
Liquid Materials	Ton/km	0.05	Survey/Estimation
Plant Operational Cost	Unit	Unit Cost (in USD)	
Energy Consumption	USD/day	500	Local Market Analysis
Extra Energy for Rejuvenation Process	USD/day	100	Local Market Analysis
Plant Maintenance (daily)	USD/day	50	Local Market Analysis
Miscellaneous (Staff wages and food)	USD/day	500	Local Market Analysis

[a] Turkish General Directorate of State Highways (KGM)—2019

containing rejuvenators yielded lower aging indices compared to the non-rejuvenated ones. Among the three rejuvenators, although not very significant, CRA demonstrated better results by having the aging index as 1.10.

3.2. Cost analysis

3.2.1. Material and production cost comparison

A plant with a 1,500-tons daily production capacity, that is upgraded to accommodate high-RAP contents is considered for cost comparison analysis. The approximate prices for essential asphalt mixture components and the transportation cost/ton/km to the plant are provided in table 3.

The prices given in table 3 were taken into account by considering the underneath combinations for cost analyses:

Asphalt mixture types:
Control sample = 100% AC
Non rejuvenated mixture = 80%AC + Non rejuvenated 20% RAP
WEO rejuvenated mixture = 30% AC + WEO rejuvenated 70% RAP
WVO rejuvenated mixture = 20%AC + WVO rejuvenated 80% RAP
CRA rejuvenated mixture = 20%AC + CRA rejuvenated 80% RAP
Bitumen contents:
OBC in AC: = 4.76% by wt. of aggregate
RAP bitumen content: = 4.30% by wt. of aggregate
Hauling distances:
Aggregate quarry to Plant: 10 km
Bitumen refinery to Plant: 100 km
Rejuvenator supplier to Plant: 100 km
RAP stock to Plant: 30 km

For producing 1,500 tons/day, the cost per ton of Asphalt Concrete =

[Aggregate cost (including transport) + bitumen cost (including transport) + daily energy consumption cost + daily plant maintenance cost + miscellaneous cost (staff wages and food)]/1,500 tons.

For producing 1,500 tons/day, the cost per ton of asphalt mixture containing 20% Non-rejuvenated RAP: =

[Aggregate cost (including transport) + bitumen cost (including transport) + RAP cost (Including Transport) + daily energy consumption cost + daily plant maintenance cost + miscellaneous cost (staff wages and food)]/1,500 tons.

For producing 1,500 tons/day, the cost per ton of asphalt mixtures containing rejuvenated-RAP: =

[Aggregate cost (including transport) + bitumen cost (including transport) + RAP cost (Including Transport) + rejuvenating agent cost (including transport) + daily energy consumption cost (including rejuvenation) + daily plant maintenance cost + miscellaneous cost (staff wages and food)]/1,500 tons.

A production cost comparison was performed for mixtures prepared at optimum rejuvenator dosages and the corresponding maximum RAP contents. The production costs of each rejuvenated and non-rejuvenated mixtures, together with the control mixture, were calculated and presented in figure 8.

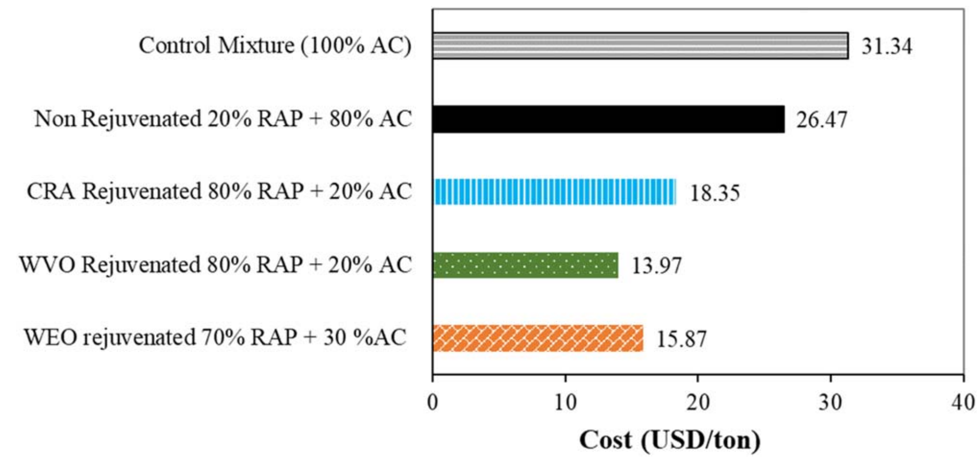


Figure 8. Production costs of mixture types, in USD/ton.

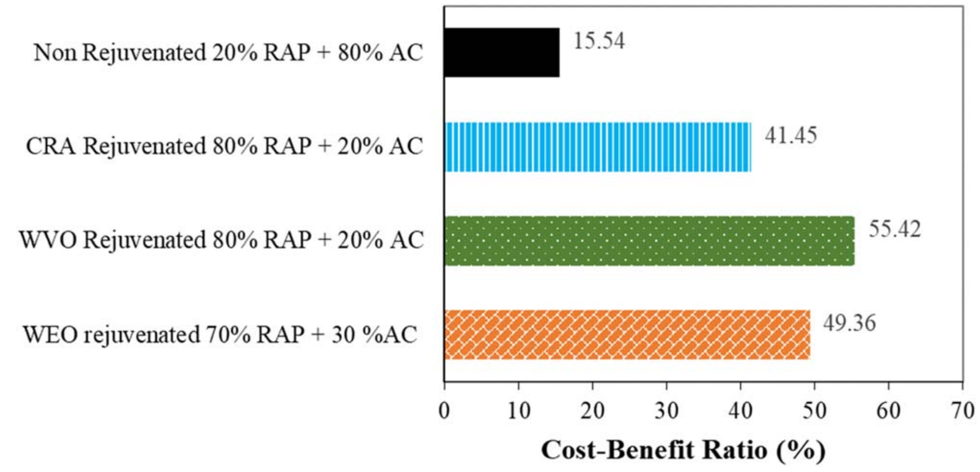


Figure 9. Production cost-benefit ratio.

In general, as expected, with the increase of RAP content in the mixture, the cost decreases remarkably, which is mainly attributed to the replacement of costly virgin bitumen and aggregate, with reclaimed asphalt. Although the introduction of rejuvenators slightly increases the production cost, they play an essential part in enabling the incorporation of high-RAP content. The production costs of the mixture containing WVO have the lowest value and the mixture containing WEO followed it with the second-lowest production cost. This is mainly due to the fact that WEO and WVO are waste oils, manufacturing costs are excluded only for collection, warehousing, and logistics. On the other hand, even though CRA is a commercial product and has a unit cost, the CRA rejuvenated mixture still has a lower production cost compared to virgin asphalt concrete and non-rejuvenated mixture. This attributes the benefit of rejuvenator utilization, which is not only the environment but also the production costs. Figure 9 illustrates the production cost-benefit ratio of the mixtures by calculating the decrease (%) in the production costs of the mixtures with and without rejuvenators.

One of the obvious trends observable in the chart is that the ratio increases with the RAP content, implying significant economic savings. Among the three rejuvenator types, WVO is the most effective one in terms of reducing the production cost, which is reduced from $31.34 to $13.97 (a 55.42% cost reduction). WEO and CRA rejuvenated mixtures followed the WVO rejuvenated samples in terms of reducing production costs by 49.36% and 41.45%, respectively. Among the rejuvenated samples, having the lowest cost-benefit ratio of CRA rejuvenated mixtures can be explained by its production cost. On the other hand, the mixture without any rejuvenator (80%AC+20%RAP) reduces the production cost by only 15.54%. In addition to bringing economic advantages onto the table, from a sustainability point of view, RAP re-usage also alleviates environmental issues and precludes further landfills. It is therefore a win-win situation to reintroduce as much RAP into road construction as feasible.

Table 4. Return on Investment (ROI) results of non-rejuvenated and rejuvenated samples.

Sample Name	Saving /ton	Monthly saving	ROI (month)
Non rejuvenated mixture	4.87$	146.100$	2.4
WEO rejuvenated mixture	15.47$	464.100$	0.75
WVO rejuvenated mixture	17.37$	521.100$	0.67
CRA rejuvenated mixture	12.99$	389.700$	0.9

3.2.2. Rejuvenation feasibility

A number of money-saving factors such as RAP utilization contribute to a relatively fast ROI. The smaller the ROI, the faster the benefit is achieved. In this study, ROI is the required month to save money by utilization of RAP to effort the cost of upgrading the facility (350.000$). The results are presented in table 4.

Based on the feasibility calculations, within a month, each rejuvenated mixture recovers the investment in the facility (upgrading the plant to handle RAP) by the savings achieved by the reutilization of RAP mixtures. This is an extremely profitable opportunity in the industry. On the other hand, without rejuvenators, the plant can recover the upgrading cost in three months, which is still a very good time.

4. Conclusions and recommendations

The impact of three different rejuvenators (WEO, WVO, and CRA) on the performance of RAP mixtures was investigated to obtain the maximum applicable RAP content within the asphalt mixture. The cost-benefit and rejuvenation feasibility analyses were then investigated considering the RAP contents of each mixture. The following conclusions were drawn from the study:

- Implementing WEO, WVO, and CRA as rejuvenators facilitates the addition of high RAP contents (up to 70%–80%) into the mix without severe adverse effects on pavement performance. This result is promising for asphalt road construction from a sustainability point of view.
- Depending on the ITS results of the samples, it is possible to declare that, the rejuvenation of RAP mixture reduces the brittleness and enhances durability. This result was supported by aging indices, which were calculated as the ratio of ITS values of rejuvenated/non-rejuvenated samples compared to control mixture. Based on the results of the aging indices, rejuvenation decreased the stiffness characteristics of the RAP samples. Among the rejuvenators, CRA yielded the minimum ITS value, which may be attributed to the enhanced fatigue properties of the CRA rejuvenated mixtures.
- Cost Analysis of RAP utilization depending on the rejuvenator types revealed that the rejuvenated mixtures ensure up to 55 percent of cost reduction. It is an important advantage of RAP utilization in addition to the environmental advantages. Rejuvenation is declared feasible in the plant with a higher cost-benefit ratio and the plant can recover the upgrading cost within three months.

The following areas are recommended to get explored in future studies:

- Determination of rejuvenated RAP mixtures' mechanical properties in accordance with the Superpave criteria is deemed necessary.
- For RAP mixtures, rutting, and fatigue performance evaluation are highly recommended, as these failures are prevalent in old pavements.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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