Research on Engineering Structures & Materials
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Research Article

Assessing recycled asphalt pavement: Impact of waste cooking oil and waste engine oil as rejuvenators on mechanical properties

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Article Info

Article history:

Received 25 Mar 2024
Accepted 02 Aug 2024

Keywords:

Recycled asphalt pavement (RAP); Aging of RAP; Performance characteristics; Physical properties of bitumen; Optimal rejuvenator content; Marshall stability; Asphalt mixtures

Abstract

Sustainable pavement construction is an extensively researched subject within the field of pavement engineering. Due to its environmental and commercial advantages, the construction of pavements utilizing recycled asphalt pavement (RAP) is progressively gaining popularity worldwide. Owing to the aging process, binder extracted from RAP is inherently harder than virgin binder and requires rejuvenation for application in high RAP blends. This paper investigates the performance characteristics of Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) as rejuvenators in RAP-incorporated asphalt mixtures to assess their suitability for pavement use. The optimal rejuvenator content is determined based on the performance of physical properties. The study indicates that asphalt mixes rejuvenated with Waste Cooking Oil (WCO) demonstrate higher Marshall Stability values compared to mixes rejuvenated with Waste Engine Oil (WEO) at both 30% and 60% Recycled Asphalt Pavement (RAP) levels. Additionally, mixes incorporating WCO exhibit increased flow values. Furthermore, WCO outperforms WEO in Tensile Strength Ratio (TSR) at 30% RAP, with a slight decrease at 60% RAP. Results from Marshall and Indirect Tensile Strength (ITS) tests suggest that both WEO and WCO are effective rejuvenators, playing a critical role in aligning the properties of RAP-inclusive asphalt mixes with those of virgin mixes.

1. Introduction

The rapid expansion of global infrastructure, particularly within the transportation sector, has significantly increased the demand for construction materials, leading to the depletion of natural resources, especially in developing countries. As a result, the adoption of environmentally sustainable construction practices has become imperative. One such practice is the reuse of existing pavement layers, known as recycled or reclaimed asphalt pavement (RAP), which allows for the effective reutilization of both binders and aggregates. However, the extent to which RAP materials can be reused remains an important area of research that requires further investigation.

It is essential to employ sustainable road construction practices and find alternatives to virgin materials [1]. People are becoming more aware of the need for sustainable pavements, and this puts pressure on the pavement construction industry to use recycled materials [2]. Recycled asphalt pavements (RAPs) are constructed using milled materials from existing pavement layers [3]. Using RAP is becoming more popular because of its environmental and economic feasibility [4]. People have been using RAP in asphalt mixes

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DOI: http://dx.doi.org/10.17515/resm2024.218me0325rs

as it is considered to be a cheaper alternative compared to virgin binder and aggregates [5]. But, the strength and performance criteria of RAP mixtures need to be investigated.

Scientific studies also show that RAP material, including aged asphalt and aggregates, improves the mechanical aspects, performance, and longevity of asphalt pavements. Depending on the construction mode and technical features, asphalt pavement recycling systems may be classified as central plant hot recycling (CPHR), hot in-place recycling (HIR), central plant cold recycling (CPCR), and cold in-place recycling (CIR) [6]. Hot in-place recycling (HIR) uses reclaimed asphalt pavement (RAP), a non-renewable resource, in its entirety. When combined with RAP, HIR requires just 10%–20% virgin materials and an insignificant quantity of rejuvenator [7]. Cold recycling of asphalt pavement is a more cost-effective maintenance method than hot recycling since it minimizes carbon emissions, eases the pressure on the construction material supply, and lowers the cost of paving rehabilitation. As loading frequency increased under dry conditions, permanent strain decreased, and among the four temperatures, the highest permanent strain was measured at the lowest loading frequency [8]. In the cold recycling process, fresh materials are mixed with reclaimed asphalt pavement (RAP), which is produced by cold milling the asphalt layer, to create a cold recycled mixture (CRM), which is subsequently inserted into the rebuilt pavement layer [9].

The incorporation of RAP into conventional asphalt pavements emulates a bigger leap toward the realization of sustainable pavement construction. It upholds the 3R concept of sustainability: Reduce, Reuse, and Recycle. As a petroleum-derived organic material, asphalt ages during the building (short-term aging) and service (long-term aging) processes [3]. The main advantage with RAP binder is its higher stiffness compared to virgin binder. To make RAP binder applicable for construction purposes, rejuvenators are added which rejuvenate the physical and chemical properties. Through oxidation, the maltenes component in asphalt changes to the more viscous asphaltenes component during aging. Asphaltenes with a greater molecular weight prefer to form a colloidal suspension with maltenes with a lower molecular weight. The viscosity of asphalt materials is mostly due to asphaltenes. Aging causes a rise in asphaltenes, resulting in high stiffness and a low creep rate [4]. Rejuvenators may be used to restore some of the mechanical properties of RAP binder. They restore the natural asphaltene-maltene ratio in aged binder and replace volatiles, and disperse oils while improving adhesion. The optimum quantity of rejuvenator to be added depends on the type and condition of the aged bitumen [10].

In terms of physical properties such as penetration, softening point, ductility, striping, and viscosity, researchers identified major differences between virgin and rejuvenated RAP binders [11]. When used appropriately and optimally, rejuvenators can assist in reversing the indications of aging and regulating its short-term and long-term aging. Understanding the role of aged binder as well as the influence of rejuvenators is critical for selecting the most ecologically and economically beneficial solution [12]. Rejuvenators are divided into two types: rejuvenating and softening agents [10]. Based on chemical composition, rejuvenators can also be broadly classified as bio-based and petroleum-based rejuvenators [13]. Commercial rejuvenators and bio-based oils contain volatile compounds in their chemical composition and are highly vulnerable to aging even though they possess a number of advantages. The presence of volatile components in waste oils like waste cooking oil (WCO) and waste engine oil (WEO) is significantly lower than that of fresh bio-oils since WCO and WEO survive high temperatures throughout the manufacturing process [14]. The addition of a suitable waste oil dosage can improve the conventional physical properties of RAP, and it will reduce the chances of other chemical reactions. Excessive waste oil addition will lead to an undesirable reduction in the viscosity of the asphalt [15].

Waste engine oil (WEO) is extracted from vehicles during normal oil changes at vehicle repairs. It has a comparable molecular structure, physical, and chemical qualities as petroleum asphalt [16]. Also, WEO becomes a common modifier in the asphalt industry due to ease of availability and efficiency [17]. WCO is used in a variety of products, including biodiesel, yellow grease, animal feed, and soaps. The issue with WEO and WCO is that the majority of them are illegally thrown into rivers and landfills, producing pollution and environmental issues, while only minor amounts are legitimately collected and processed. Thus, the use of WEO and WCO also adds to the concept of sustainability.

Understanding the role of Recycled Asphalt Pavement (RAP) binder, along with the influence of rejuvenators, is crucial for selecting the most ecologically and economically beneficial solution [12]. Numerous studies have evaluated the effects of rejuvenators on asphalt mixtures. Moisture can exacerbate existing pavement issues, underscoring the need to consider affordable and long-lasting asphalt mixtures [18]. It is important to comprehend the drainage and strength characteristics of the aggregate base course [19]. RAP concentration shows no discernible effect on Marshall stability, while the Tensile Strength Ratio (TSR) exhibited a trend that initially increased before eventually falling [15].

Capitão et al. [20] aimed to study cost-effective asphalt mixtures with high RAP content. El-Shorbagy et al. [10] examined the impact of rejuvenators on the mechanical qualities of the mix in direct comparison to a mix without a rejuvenator. It has been demonstrated that a low RAP concentration improves the moisture damage potential of the mixtures while enhancing the tensile strength ratio [21]. The gradation of blends with 80% and 60% RAP is closer to the limits of standard gradation because they contain virgin aggregate. Zhang et al. [22] investigated how the macroscopic mechanical characteristics of asphalt mixes are affected when European rock bitumen (ERB) and used cooking oil (WCO) are combined with asphalt. WCO can significantly enhance the anti-cracking effectiveness of asphalt-related mixtures at relatively lower temperatures [10]. The ERB/WCO composite alteration could improve the Marshall stability performance of the asphalt mixture. Similarly, petroleum-based rejuvenators such as fuel oil, aromatic extracts, naphthenic oil, coke oven gas, and waste engine oil have been subjected to scientific studies to understand their effects on RAP [13].

The overall influence of rejuvenators on Marshall properties varies according to RAP content and rejuvenator type, showing greater values for blends incorporating Waste Engine Oil (WEO). It is expected that the use of WEO for higher percentages of RAP (>30%) can meet the growing need for road construction materials in a more sustainable way [23]. The Indirect Tensile Strength (ITS) of the combination increases and the rejuvenator proportion to be added varies with the RAP content [24]. The addition of WEO to hot mix asphalt (HMA) is shown to have good fatigue resistance, although it has some drawbacks like reduced elastic recovery and rutting resistance [25].

The literature reveals broad gaps in the current understanding of using waste cooking oil (WCO) and waste engine oil (WEO) as rejuvenators in recycled asphalt pavement (RAP) construction. These gaps include a lack of comprehensive comparative analysis between WCO and WEO properties, insufficient details on the methodology for determining optimal rejuvenator content, and a dearth of information on the long-term performance, environmental impact, and comparative effectiveness with other rejuvenators in RAP mixtures. The present study compares the properties of WCO and WEO and investigates its suitability to be used as rejuvenator in RAP construction. The objectives of the study include: (i) Evaluate the performance of waste engine oil (WEO) and waste cooking oil (WCO) as rejuvenators in recycled asphalt pavement (RAP); (ii) Identify the optimal content of WEO and WCO as rejuvenators in RAP to achieve properties similar to VG 30 bitumen; (iii) Assess the stability and flow values of RAP-incorporated asphalt mixtures with the optimum content of WEO and WCO, comparing them to the virgin mix and mixtures without a rejuvenator; (iv) to measure and compare the moisture sensitivity of RAP mixtures with WEO and WCO.

2. Experimental Program Methodology: The Procedures and Protocols

The schematic diagram representing the methodology of the study is shown in Fig. 1. The mechanical parameters of RAP incorporated asphalt mixtures with and without rejuvenators (WEO & WCO) are compared with that of conventional mix.

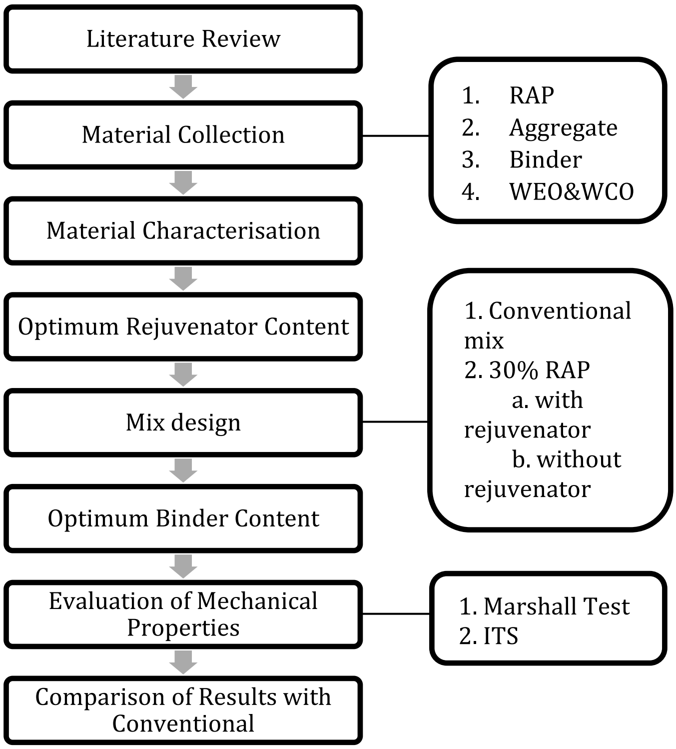


Fig. 1. Study methodology

India experiences an average hot climate. Given the fluctuations in climatic conditions, it is crucial to design pavements that can withstand varying temperatures. The investigation utilized VG 30 (Viscosity Grade) bitumen supplied by Hindustan Colas Ltd. (HINCOL). Recycled Asphalt Pavement (RAP) materials were milled from a 3.5-year-old National Highway pavement in Mangad, part of the Kollam bypass, processed, and shredded.

Aged binder was extracted using a centrifugal extractor with trichloroethylene as a solvent, following ASTM D 2172 -11 [26], and recovered using Abson's apparatus in accordance with ASTM D 1856 – 98A [27]. Given the rising demand for rejuvenators, the study explored the use of waste oils, including Waste Engine Oil (WEO) and Waste Cooking Oil (WCO). WEO, a dark oily liquid, was collected from a local repair garage and used without further treatment as a solvent. The WCO, specifically Palmolein oil, was obtained from various fritter shops (shown in Fig. 2).

(a) (b)

Fig. 2. Rejuvenators used in the study (a) discarded waste cooking oil (WCO) and (b) waste engine oil (weo) collected from automobile workshop

2.1. Experimental Methodology and Design

A laboratory investigation was carried out to assess the basic physical characteristics of materials. The study analysed the physical properties of the virgin binder (VG30), the extracted aged Recycled Asphalt Pavement (RAP) binder, and the aged binder treated with varying percentages (1.5%, 2.5%, 3.5%, 4.5%) of Waste Engine Oil (WEO) and Waste Cooking Oil (WCO). This analysis helped to determine the optimal rejuvenator content as a percentage of the total bitumen weight.

Five asphalt mixtures were prepared for testing, including a virgin mix, a 30% RAP mix, and a 60% RAP mix, both with and without the optimal rejuvenator content by weight of bitumen. The mix design involved determining the ideal binder content based on the volumetric properties of the virgin mix and Marshall stability data. The mechanical properties of these asphalt mixtures were evaluated using the Marshall test and indirect tensile strength (ITS) tests. Additionally, physical properties tests such as softening point, penetration, ductility, viscosity, and specific gravity were conducted.

2.1.1 Penetration Test

The penetration test measures the consistency of bitumen by evaluating its resistance to deformation. Penetration in bituminous materials is defined as the vertical distance, in tenths of millimeters, that a standard needle penetrates under specified conditions—standard temperature (25°C), standard load (100g), and standard time. The examination is conducted in compliance with IS: 1203–1978 [28].

2.1.2 Softening Point Test

The softening point is determined by the temperature at which two bitumen-coated rings soften enough to allow a 9.5mm diameter ball, weighing 3.5g, to drop. This test indicates the material's tendency to flow at elevated temperatures.

2.1.3 Ductility Test

In flexible pavement design, the binder must form a thin, ductile film around the aggregates to enhance overall performance and improve structural interlocking. The ductility test, conducted in accordance with IS: 1208–1978 [29], measures the adhesive properties of asphalt and its capacity to stretch under specific conditions. The ductility of bitumen is defined as the length, in centimeters, to which a standard briquette of bitumen can be stretched before the bitumen thread breaks.

2.1.4 Viscosity Test

The coefficient of viscosity is determined by the relationship between the applied shear stress and the fluid's shear rate. Viscosity, a key property of bitumen, allows it to resist flow, reflecting both its elastic and viscous behaviors. It's important to note that bitumen's viscosity decreases as temperature increases. This test procedure involves measuring apparent viscosity using a rotating viscometer. The test was conducted with a Brookfield Rotational Viscometer in accordance with ASTM D 4402–06 [30].

2.1.5 Marshall Stability Test

To determine the mechanical properties, Marshall stability test and ITS test was deployed.

When a compacted cylindrical specimen of a bituminous mixture is loaded diametrically at a deformation rate of 50 millimeters per minute, its resistance to plastic deformation is assessed. The Marshall mix design method comprises two primary components: (i) density-voids analysis and (ii) stability-flow tests. Marshall stability refers to the maximum load the specimen can withstand at the standard test temperature of 60°C. The flow value represents the specimen's deformation under loading until it reaches the maximum load, measured in units of 0.25 mm. The purpose of this test is to determine the optimal binder content based on the specific aggregate mix and the expected traffic load.

2.1.6 Indirect Tensile Strength Test

Six samples are used to evaluate the change in indirect tensile strength: three are tested dry, while the other three are subjected to water conditioning. For the Indirect Tensile Strength (ITS) test, the specimen is placed between two load strips and loaded radially at a rate of 50 mm per minute. The maximum load at fracture is recorded. This test helps assess the bitumen mix's ability to resist cracking and its overall durability under varying conditions.

3. Results and Discussion

Table 1 presents the results of the physical tests performed on the virgin binder, conducted in accordance with IS 73-13 [31] specifications. The test results indicate that the bitumen's physical properties comply with the standards set by the Bureau of Indian Standards (BIS).

Table 1. Physical properties of bitumen

Property	Value Obtained	Required Value	Standards
Ductility (cm)	100	Min 75	IS: 1208-1978
Penetration at 25^0C	48	Min 45	IS: 1203-1978
Softening point (°C)	49	Min 47	IS: 1205-1978
Viscosity (cst)	420	Min 350	IS: 1205-1978 Part II
Specific Gravity	1.01	0.97-1.02	IS: 1202-1978

The results obtained on virgin aggregate physical property testing are shown in Table 2. The tests were carried out under the standards of IS: 2386 Part 1 [32], Part 3 [33], and Part 4 [34]. The test findings show that aggregates' physical characteristics meet BIS requirements. After pre-processing and binder extraction and recovery, the Recycled Asphalt Pavement (RAP) material was tested in the laboratory. The test results, shown in Table 3, reveal that the properties of the RAP materials have deteriorated, particularly highlighting that the characteristics of the aged binder do not meet the standard limits.

Table 2. Physical properties of aggregate

Property	Value Obtained	Required Value	Standards
Aggregate crushing value (%)	35	Less than 30	IS :2386 Part IV
Aggregate impact strength (%)	19	Max 24	IS :2386 Part IV
Combined flakiness and elongation index	28	Max 35	IS :2386 Part I
Specific gravity test (%)	2.65	2.5-3	IS :2386 Part III
Water absorption test (%)	0.87	Max 2%	IS :2386 Part III

Table 3. Physical properties of extracted RAP

Property	Value Obtained
Binder Content (%)	4.8
Impact Strength (%)	16.5
Crushing Strength (%)	28
Softening Point (^{0}C)	72
Penetration(0.1mm) at 25^{0}C	18.5
Ductility (cm)	34
Viscosity at 135^{0}c (cSt)	840

3.1. Optimum Rejuvenator Content

In this paper, the optimal rejuvenator content is determined based on the physical property analysis of recovered Recycled Asphalt Pavement binder (RAPB) supplemented with 1.5%, 2.5%, 3.5%, and 4.5% of Waste Engine Oil (WEO) and Waste Cooking Oil (WCO). These analyses encompassed ductility tests, softening point tests, penetration tests, and Brookfield viscosity tests. Subsequently, the results obtained from all the RAP binder blends with the rejuvenator were compared to those of fresh binder. The findings are presented in Table 4. The two most crucial tests employed are the penetration and softening point tests. As bitumen is presumed to be stiff and capable of forming mixtures less susceptible to deflections and cracking from fatigue at elevated temperatures, bitumen with a higher softening point is preferred.

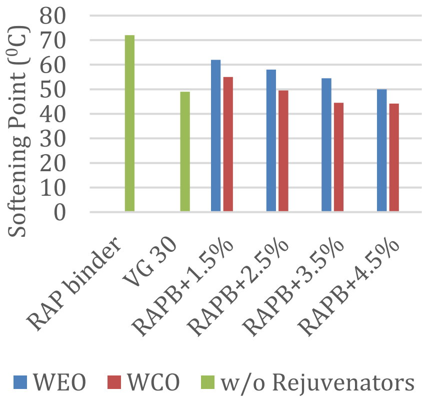
Fig. 3(a) shows the effect of combining Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) on the softening point of bitumen samples. The addition of WEO and WCO to the Recycled Asphalt Pavement (RAP) binder resulted in a decrease in the softening point temperature, which is below the minimum required threshold of 47°C. Specifically, the softening point of the RAP binder dropped to 50°C with 4.5% WEO and 49.5°C with 2.5% WCO, approaching the softening point of the VG30 grade binder. However, higher concentrations of WCO in the RAP blend led to a further decrease in the softening point, reaching levels deemed unacceptable.

Table 4. Physical properties of rejuvenated RAP binders

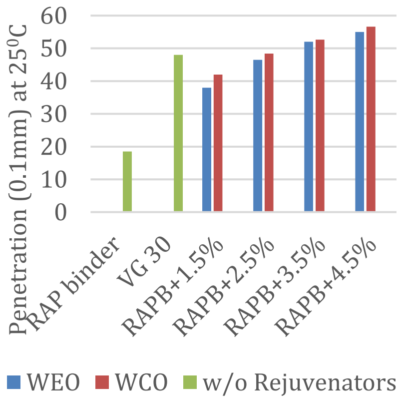
Property	RAPB+ 1.5%		RAPB+ 2.5%		RAPB+ 3.5%		RAPB+ 4.5%	
	WEO	WCO	WEO	WCO	WEO	WCO	WEO	WCO
Softening Point (°C)	62	55	58	49.5	54.5	44.5	50	44.2
Penetration at 25°C	38	42	46.5	48.4	52	52.65	55	56.6
Ductility (cm)	48	53	72	88	87	92	100	100
Brookfield Viscosity (cSt) at 135°C	840	525	684	440	460	400	418	395

Fig. 3(b) illustrates the penetration test results for bitumen treated with various ratios of WCO and WEO. The RAP binder had a penetration value of 18.5mm, which is below the standard value compared to the virgin VG30 binder. The penetration value increased with higher amounts of rejuvenator, reflecting a reduction in the asphaltene-to-maltene ratio. The optimal rejuvenator proportions were found to be approximately 4.5% for WEO and 2.5% for WCO, achieving a target penetration value of 48 (0.1mm) at 25°C. Similar trends were observed in ductility tests, as shown in Fig. 3(c), where the ductility values of the aged binder matched those of VG30 at WEO and WCO contents of 4.5% and 2.5%, respectively.

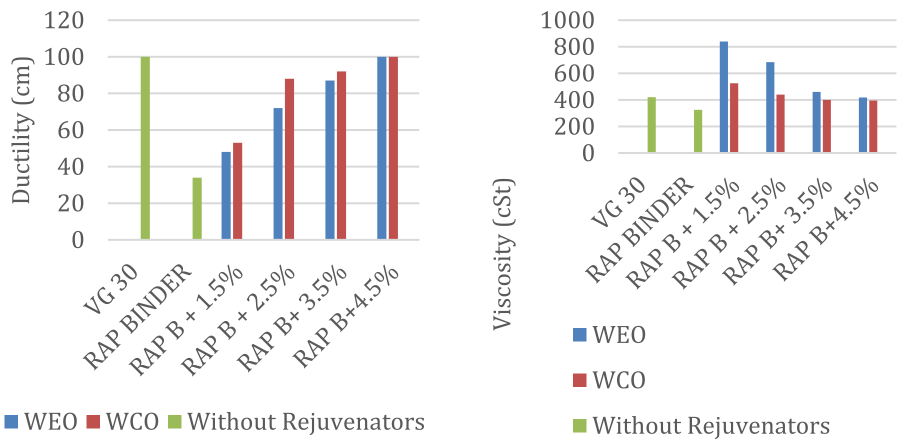
Fig. 3(d) presents the viscosity measurements of the RAP binder. The viscosity of rejuvenated aged binders containing WEO and WCO was significantly lower than that of VG30, measured at 840 cSt at 135°C. The reduction in viscosity indicates improved fluidity, allowing the RAP binder to coat aggregates effectively. Adding 4.5% WEO or 2.5% WCO as rejuvenators enabled the RAP binder to achieve physical properties comparable to the virgin VG30 binder, maintaining the desired level of workability for the rehabilitation procedure.



(a) Softening point



(b) Penetration (0.1mm) at 25° C



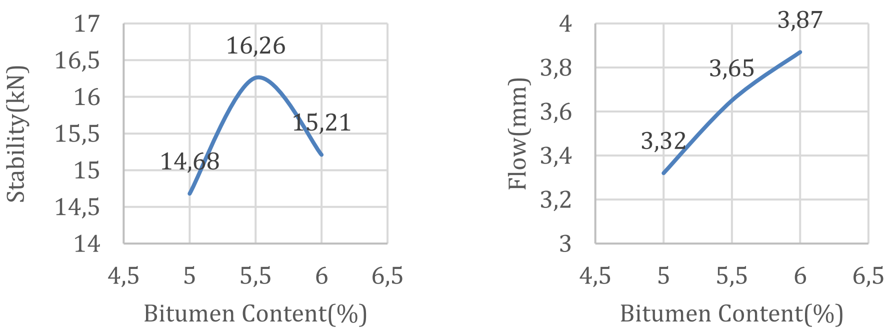
(c) Ductility (cm)

(d) Viscosity (cSt)

Fig. 3. Physical property values of VG30 and RAP binder with varying values of WEO and WCO %

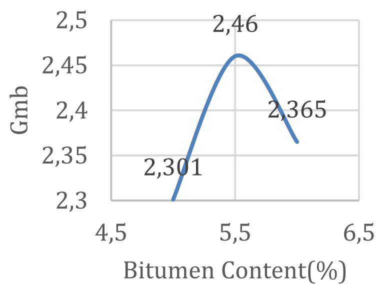
3.2. Marshall Stability and Flow Test

To evaluate the volumetric properties of standard bituminous mixes, Marshall samples were prepared with bitumen contents of 5%, 5.5%, and 6%. These samples followed the bituminous concrete Grade II gradation specified in MoRTH – 5th revision [35]. As shown in Fig.s 4(a) through 4(f), the optimal bitumen content for the asphalt mix was determined to be 5.5%, which achieved the lowest VMA, highest specific gravity, maximum stability, and 4% air voids. The primary aim of this research was to examine the impact of adding a rejuvenator on the mechanical properties of the mix compared to a mix without a rejuvenator.

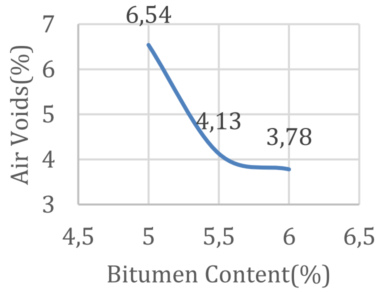


(a) Stability Vs Bitumen Content

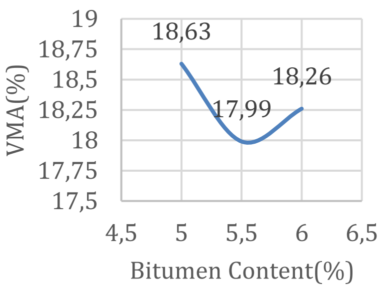
(b) Flow Vs Bitumen Content



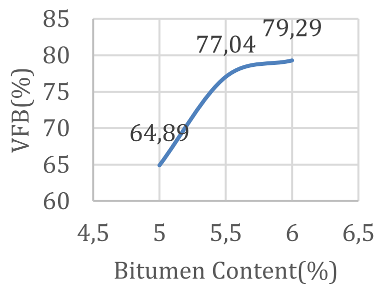
(c) Gmb Vs Bitumen Content



(d) Air Voids Vs Bitumen Content



(e) VMA Vs Bitumen Content



(f) VFB Vs Bitumen Content

Fig. 4. Volumetric properties of virgin mix

Marshall tests for stability and flow were conducted on seven mixtures: a virgin mix, 30% Recycled Asphalt Pavement (RAP), 30% RAP with 4.5% Waste Engine Oil (WEO), 30% RAP with 2.5% Waste Cooking Oil (WCO), 60% RAP, 60% RAP with 4.5% WEO, and 60% RAP with 2.5% WCO, all prepared according to the Asphalt Institute MS-2 specifications. The results of these Marshall tests are summarized in Table 5. Fig. 4 shows that the stability value and bulk specific gravity increase, peaking at a bitumen content of 5.5%, after which they decline. The flow values also increase with higher bitumen content, reaching up to 3.87 mm at 6% bitumen content. Air voids decrease as bitumen content rises, since more bitumen fills the voids within the mixture. Given that maintaining air voids at 4% is a critical criterion for laboratory asphalt mixes, the optimal binder content is identified based on this requirement.

For the Volumetric Mix Analysis (VMA), the binder content of 5.5% results in a low peak VMA value of 17.99%, which then increases. This occurs because bitumen, having a lower specific gravity than aggregates, displaces and separates them. The Voids in the Binder (VFB) is a measure used in mix design to ensure proper asphalt thickness. If VFB is too low or too high, the mix may become unstable. Based on these observations, the optimal bitumen content for the asphalt mix is determined to be 5.5%, which provides maximum stability, highest specific gravity, 4% air voids, and the lowest VMA.

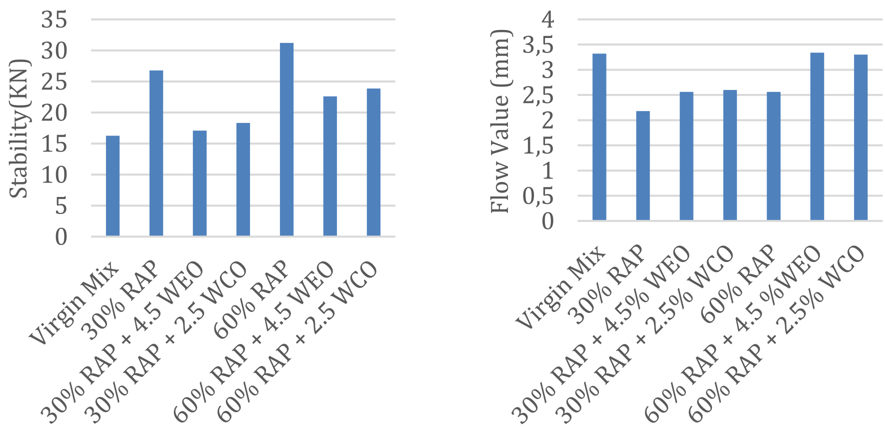
Table 5. Marshall test results of examined mixtures

Examined Mixtures	Virgin Mix	30% RAP	30% RAP + 4.5% WEO	30% RAP + 2.5% WCO	60% RAP	60% RAP + 4.5% WEO	60% RAP + 2.5% WCO
Marshall Stability (kN)	16.26	26.78	17.08	18.31	31.22	22.59	23.85
Flow Value (mm)	3.32	2.18	3.34	3.73	2.56	3.30	3.66

The main objective of this research was to assess how the addition of a rejuvenator influences the mechanical characteristics of the mix compared to a mix without a rejuvenator. According to MoRTH specifications, the minimum stability value for bituminous concrete should be 9 kN. Fig. 5(a) demonstrates that all tested mixtures meet this standard. The inclusion of Recycled Asphalt Pavement (RAP) positively affects stability values, with higher RAP content leading to significant improvements in stability, thereby enhancing rutting resistance and load-bearing capacity. This improvement in Marshall stability can be attributed to the stiffening effect of the RAP.

However, adding Waste Engine Oil (WEO) and Waste Cooking Oil (WCO) to RAP mixtures reduces the stiffness and softening point temperature of the RAP binder, which in turn lowers the stability values. Despite this, the stability of rejuvenated asphalt mixtures approaches that of the virgin mix, indicating that the rejuvenator effectively restores stability.

Fig. 5(b) shows that the flow values follow a similar trend to the stability results. An increase in RAP percentage leads to a decrease in flow characteristics, but this effect is countered by the addition of WEO and WCO rejuvenators, resulting in flow values comparable to those of the virgin mix. Notably, the use of WEO aligns more closely with the virgin mix results.



(a) Stability (b) Flow Value

Fig. 5. Results of Marshall test for examined asphalt mixtures

3.3. Indirect Tensile Strength Test

The Indirect Tensile Strength (ITS) test, conducted following AASHTO T 283 standards, was used to evaluate the moisture susceptibility of various mixtures. The test results are shown in Table 6. Fig. 6(a) presents the ITS values for both unconditioned and conditioned samples. Using the ITS values from the seven mixes described earlier, the Tensile Strength Ratio (TSR) was calculated and is illustrated in Fig. 6(b). These results aid in assessing the moisture susceptibility of the mixes.

Table 6. ITS test results of examined mixtures

Examined Mixtures	Virgin Mix	30% RAP	30% RAP + 4.5% WEO	30% RAP + 2.5% WCO	60% RAP	60% RAP + 4.5% WEO	60% RAP + 2.5% WCO
Unconditioned Strength (MPa)	0.643	0.715	0.654	0.642	0.748	0.674	0.541
Conditioned Strength (MPa)	0.532	0.612	0.543	0.537	0.650	0.558	0.650
TSR (%)	82.73	85.59	83.03	83.64	86.9	82.79	83.23

The test results show that increasing the concentration of Recycled Asphalt Pavement (RAP) in the mixtures improves the Indirect Tensile Strength (ITS). This enhancement is due to reduced strain and stress concentrations in bituminous mixtures with higher RAP content, attributed to the stiff binder of RAP and the additional binder in the mix. However, mixtures containing Waste Engine Oil (WEO) and Waste Cooking Oil (WCO) exhibit lower ITS values, as these additives negatively affect the indirect tensile strength. This is expected, as WEO significantly reduces the stiffness of the RAP binder, leading to decreased tensile strength.

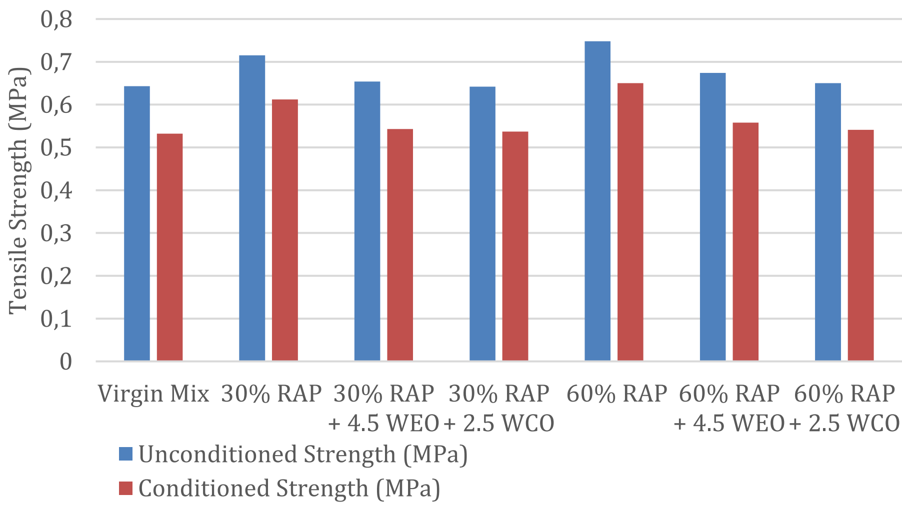


Fig. 6(a). ITS of dry and wet conditioned mixtures under examination

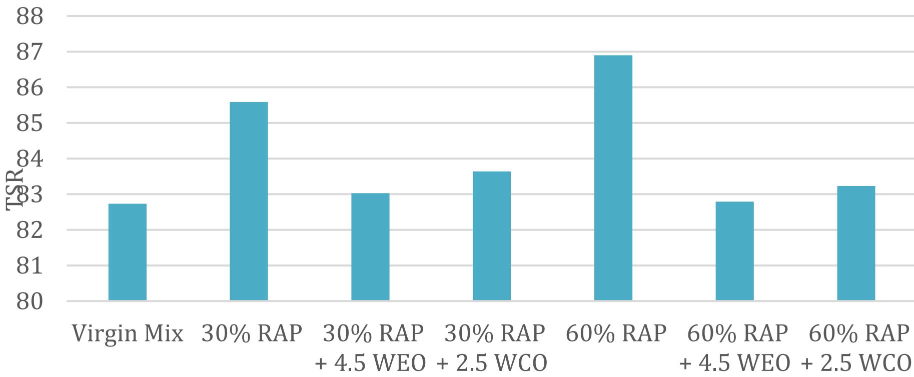


Fig. 6(b). TSR of mixtures under examination

All mixes achieved a minimum Tensile Strength Ratio (TSR) of 80%, as required by AASHTO T283. The highest TSR was observed in the mix containing 60% RAP, followed by mixes with 30% RAP, 30% RAP with 2.5% WCO, 60% RAP with 2.5% WCO, 30% RAP with 4.5% WEO, 60% RAP with 4.5% WEO, and the Virgin Mix. The TSRs of rejuvenated mixes and the virgin mix are nearly identical. This suggests that including RAP improves the tensile strength ratio, indicating better moisture susceptibility. This improvement may be linked to the strong binder coating on RAP aggregates, which reduces water penetration into the aggregate-bitumen interface and minimizes adverse effects on mechanical properties. Although the 60% RAP mix meets standard requirements, its lower TSR compared to the control mix is likely due to its increased surface roughness.

3.4. Comparison of Performance of WEO and WCO

The Marshall Stability values are higher for mixtures containing Waste Cooking Oil (WCO), with a peak of 18.31 kN, compared to 17.08 kN for Waste Engine Oil (WEO) in asphalt mixtures with 30% Recycled Asphalt Pavement (RAP). This trend continues with 60% RAP, where the stability value is 23.85 kN for WCO and 22.59 kN for WEO. In terms of Flow values, mixes with WCO exhibit higher values than those with WEO at the same RAP content. When compared to the virgin mix, the performance of WEO is more closely aligned.

The Tensile Strength Ratio (TSR) is higher for mixtures with WCO compared to those with WEO for 30% RAP content, though TSR values decline slightly for 60% RAP content. Based on the results from the Marshall stability and Indirect Tensile Strength (ITS) tests, both WEO and WCO are effective rejuvenators, successfully aligning the properties of RAP-containing asphalt mixtures with those of virgin mixtures.

4. Conclusion

This study evaluates the effectiveness of Waste Engine Oil (WEO) and Waste Cooking Oil (WCO) as rejuvenators for improving the quality of Recycled Asphalt Pavement (RAP). The findings indicate that under aged conditions, both WEO and WCO increase penetration values and decrease softening point temperatures as their concentrations rise, compared to VG30 bitumen. Adding 2.5% WCO or 4.5% WEO to RAP binder yields properties similar to VG30, with WCO demonstrating a more pronounced effect than WEO.

Asphalt mixtures with optimal rejuvenator content of WEO and WCO show stability and flow values comparable to those of virgin mixes, unlike RAP mixtures without rejuvenators. All tested mixtures meet the AASHTO T283 minimum Tensile Strength Ratio (TSR) of 80%, indicating excellent moisture resistance. For 60% RAP, the stability values were 23.85 kN for WCO and 22.59 kN for WEO, with WCO also showing higher Flow values than WEO. In comparison, WEO results were closer to those of the virgin mix.

In practical terms, the study demonstrates that the identified rejuvenator contents effectively improve the mechanical performance of RAP mixtures, making the use of WEO and WCO a viable and environmentally friendly approach for enhancing asphalt pavement quality. This research supports the use of waste oils in asphalt recycling, contributing to more sustainable and resilient road construction practices.

Some limitations of the study include the potential impairment of asphalt mixture properties due to excessive use of Waste Engine Oil (WEO) and Waste Cooking Oil (WCO), which could reduce durability and increase susceptibility to rutting and cracking. Additionally, maintaining the desired performance standards of the asphalt requires precise balancing of rejuvenator proportions.

Based on the study's findings, several recommendations are proposed. It is advisable to use dynamic shear rheometers and bending beam rheometers to assess the performance of the bitumen at both high and low temperatures, which will help determine the temperature sensitivity of the binder. Additionally, conducting chemical analyses, such as Fourier Transform Infrared Spectroscopy (FTIR), Atomic Force Microscopy (AFM), X-ray Diffraction (XRD), and Gas Chromatography-Mass Spectrometry (GC-MS), can provide detailed insights into the chemical properties of the bitumen. Furthermore, performing a life cycle cost analysis on aged asphalt modified with WCO and WEO should be considered before field application to evaluate its economic feasibility and long-term benefits.

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