Research Article

Nadia S. Abd Ali*, Hasan H. Joni# and Rasha H. A. Al-Rubaee#

Effect of asphalt modified with waste engine oil on the durability properties of hot asphalt mixtures with reclaimed asphalt pavement

https://doi.org/10.1515/eng-2022-0529
received July 13, 2023; accepted September 05, 2023

Abstract: The increased demand for asphalt and other materials involved in the construction of pavement led to an increase in the cost of these materials, which calls for searching for alternatives to virgin materials that can be used to produce asphalt mixtures. Reclaimed asphalt pavement (RAP) was employed in this study and regenerated using oxidized asphalt modified with waste engine oil (WEO). This method can achieve economic and environmental benefits. After improving the properties of oxidized asphalt using WEO, it was used with reclaimed asphalt mixtures (RAP). When the RAP was added at ratios of 20, 30, 40, and 50%, an improvement can be noticed in the mechanical performance of the asphalt mixtures renewed with oxidized asphalt and WEO and an increase in its resistance to stripping. When reclaimed asphalt pavement (RAP) is added to hot mix asphalt (HMA) at concentrations of 20, 30, 40, and 50%, respectively, the Marshall stability of HMA is improved by 10, 20, 28, and 9.5%, the flow is declined by 1% for all ratios of RAP except for 50% RAP where the flow decline by 3%, the unit weight is enhanced, the quantity of air voids in the mix is preserved within allowable ranges, and the resistance to stripping is increased by 62, 77, 85, and 76%, respectively. Research also shows that incorporating 40% RAP enhances the resistance to moisture by about 5.9%. The addition of 40% RAP reduced the Cantabro loss values by about 2 and 16% for both aging and non-aging samples, respectively. The rutting resistance increased by 50 and 47% for mixes with 40% RAP at 50 and 60°C, respectively. As a result, it became evident that mixtures containing RAP material could be effectively adapted to satisfy the relevant volumetric and performance requirements.

Keywords: hot mix asphalt, rutting resistance, moisture damage, reclaimed asphalt pavement, waste engine oil

1 Introduction

Asphalt, a key component of road construction, plays a pivotal role in ensuring the durability and longevity of road networks. Its mechanical properties, particularly those of the hot mix asphalt (HMA) layer, are essential for withstanding the diverse and demanding loading scenarios experienced by highways and roads. These properties are not merely the result of a simple mix but rather emerge from a complex interplay of intricate internal processes [1]. The challenges posed by heavy loads, such as those from trucks and vehicles, can lead to significant deterioration of road surfaces over time [2]. One innovative solution to address the challenges of road maintenance and sustainability is the use of reclaimed asphalt pavement (RAP). RAP is essentially pulverized asphalt obtained from the removal of the previous road surface layer. Typically, it exists in the form of loose granules generated as a waste product during pavement repair or reconstruction. This byproduct has found its place as a valuable resource in road construction, often utilized as frequently as new pavement courses, including base and subbase layers [3,4].

In recent years, the concept of recycling and reusing materials has gained widespread acceptance in the field of transportation. RAP has emerged as a valuable resource due to its ability to serve as a partial substitute for raw aggregate and asphalt cement in asphalt paving mixtures [5]. This not only reduces the demand for fresh asphalt and aggregate but also aligns with the broader goals of sustainability in the transportation sector [6]. However, the binder

# These authors contributed equally to this work.

*** Corresponding author: Nadia S. Abd Ali,** Civil Engineering Department, University of Technology, Baghdad, Iraq; Directorate of Roads and Bridges, Dhi Qar, Iraq, e-mail: bce.21.48@grad.uotechnology.edu.iq
Hasan H. Joni: Civil Engineering Department, University of Technology, Baghdad, Iraq, e-mail: hasan.h.Joni@uotechnology.edu.iq
Rasha H. A. Al-Rubaee: Civil Engineering Department, University of Technology, Baghdad, Iraq, e-mail: 40323@uotechnology.edu.iq

within RAP undergoes significant changes over time. The loss of volatile substances and oxidation processes render the binder brittle and rigid, posing a considerable challenge. This aging of the asphalt binder raises concerns regarding the performance of bituminous mixtures that incorporate RAP, particularly their vulnerability to thermal fractures, fatigue, and disintegration [7]. While the environmental benefits of reusing RAP are evident, addressing the stiffness caused by asphalt binder aging is a critical issue that demands attention [8]. One approach to overcoming this challenge is the use of regenerating substances. These substances fall into two major categories: rejuvenating agents and softening substances. Rejuvenating agents can remarkably restore the lost chemical and physical qualities of aged bitumen. They play a vital role in rejuvenating the aged binder, making it more suitable for reuse [6]. Intriguingly, waste engine oil (WEO) has emerged as a promising rejuvenator for old asphalt materials. Research studies utilizing WEO have demonstrated its competitiveness with new materials in performance and effectiveness [9]. This finding suggests a sustainable and efficient way to repurpose WEO as a paving rejuvenator.

Exploring various waste types as asphalt enhancers or rejuvenating agents in HMA manufacturing is a continually encouraged avenue of research. Several factors drive the motivation for such investigations. Conventional bitumen can be expensive, making alternative solutions economically attractive. Additionally, stringent environmental regulations necessitate innovative approaches to deal with waste oils, which, when improperly disposed of, can contaminate rivers and other natural resources [10].

Numerous research studies have delved into the effects of waste oils on the durability and rutting resistance of hot asphalt mixtures containing RAP.

Hasan [11] conducted a comprehensive study focusing on the influence of four types of regenerators on Marshall stability and indirect tensile strength (ITS) in reclaimed asphalt mixtures. Their research involved varying proportions of virgin and old materials and different regeneration components, including used oil, used oil with crumb rubber, soft asphalt cement, and asphalt cement with sulfur. Aghazadeh Dokandari et al. [12] explored the impact of WEO and waste vegetable oil (WVO) on the performance of recycled bitumen concrete mixes. Their research encompassed a wide range of RAP ratios, from 10 to 80%, regenerated with WEO and WVO. The results revealed significant improvements in Marshall stability for the recovered blends, demonstrating the effectiveness of rejuvenation. Mamun and Al-Abdul Wahhab [6] extended the study of asphalt mixtures containing RAP, focusing on proportions of 30, 40, and 50% rejuvenated with WEO. Their findings underscored the superior moisture damage resistance of these mixes compared to the highest permitted values, marking a significant advancement in sustainability. Taherkhani and Noorian [13] delved into incorporating regenerating agents into asphalt concrete, specifically WEO and waste cooking oil. Their evaluation included varying percentages of RAP, ranging from 25 to 75%. Their research unveiled valuable insights into the influence of waste oils on the ITS of asphalt mixes.

Khaled [14] contributed to this growing body of research by investigating the impact of RAP proportions, ranging from 5 to 55%, in conjunction with asphalt grade (85–100) and waste motor oil. The results indicated an improvement in Marshall stability and ITS, along with increased moisture damage resistance, reaffirming waste oils' potential in enhancing asphalt mixtures. Joni et al. [15] conducted a comprehensive assessment, considering Marshall stability, ITS, and moisture damage, using two distinct regenerators: WEOs and penetration-grade (60–70) asphalt cement. Their research showcased the effectiveness of WEOs and penetration-grade asphalt cement in enhancing the resistance to moisture damage.

Further expanding the scope, Zaumanis et al. compared various recycling agents for 100% RAP–HMA mixtures. This comprehensive evaluation included traditional petroleum-based agents as well as innovative bio-recycling substances such as organic oil, aromatic extract, WEO, distilled tall oil, WVO, and waste vegetable grease. The findings consistently indicated the potential for high-temperature rutting mitigation [16]. Studies have also explored the mechanical properties of HMA mixtures containing different proportions of RAP. One study revealed that HMA mixtures containing 40% RAP exhibited high resistance to rutting, suggesting the viability of such combinations [17]. Another research study conducted wheel-tracking examinations on mixtures containing 25% RAP components. The results emphasized the importance of RAP, as the control blends without RAP demonstrated low durability, characterized by increased rut depth, particularly at elevated temperatures of 50 and 64°C [18]. While these studies collectively demonstrate the potential of waste oils and RAP in improving the performance of asphalt mixtures, it is essential to consider the broader implications and applications. For instance, Iraqi refineries produce oxidized asphalt cement with a penetration grade of 30–40, a product currently underutilized in road construction. However, by enhancing its properties by adding waste oils, a superior asphalt mix can be obtained, ideal for the renewal of reclaimed asphalt [19]. WEO is typically discarded from cars and vehicles during routine oil changes. Improper disposal of these oils can have detrimental effects on the natural environment and water sources, especially when environmental and health controls are lacking. Storing and reusing motor oil as a regenerator for RAP presents an economical and environmentally friendly method to rejuvenate materials and mitigate the potential damage caused by oil residues.

Globally and locally, several studies have been conducted on a limited scale that has explored the incorporation of waste oil as a regenerator for RAP. The body of research in this field continues to expand, driven by the imperative to address the aging transportation infrastructure in Iraq, which demands costly repairs and renovations. Embracing the concept of recycling and reusing existing pavement materials offer a promising avenue for mitigating the financial constraints associated with highway construction while conserving precious resources like aggregate and asphalt binder.

The present work encompasses a comprehensive study with a two-part focus. In the first part, we delve into the effect of adding WEOs to reclaimed asphalt pavement. This exploration involves optimizing asphalt properties by incorporating WEO in various proportions. Subsequently, we conduct a battery of physical and rheological tests to identify the optimal ratios for utilizing the improved asphalt in conjunction with reclaimed asphalt.

The second part of this study extends to the practical application of reclaimed asphalt pavement. We prepare hot asphalt mixtures incorporating reclaimed asphalt at varying proportions. The mechanical performance of these mixtures is rigorously evaluated through a series of laboratory tests, including assessments of moisture damage, Cantabro abrasion loss, and wheel track tests. The results of these tests are then systematically compared to the performance of conventional asphalt mixtures.

In summary, this article embarks on an investigative journey, aiming to unlock the potential of WEOs as a transformative element in different types of asphalt. By exploring the integration of waste oils into the renewal of reclaimed asphalt, we endeavor to shed light on the intricate dynamics of asphalt mixtures and their evolving characteristics. In doing so, we contribute to the ever-expanding body of knowledge to enhance the sustainability, durability, and performance of asphalt pavements in the face of evolving transportation needs and environmental imperatives.

2 Materials

Materials utilized in the present investigation were sourced regionally, readily obtainable, and economically advantageous, designated as virgin materials and recycled materials. The characteristics of the aforementioned materials were examined using conventional experiments, and the outcomes were contrasted to the State Corporation of Roads and Bridges (SCRB R/9, 2003) requirements of the specifications [20].

2.1 Virgin materials

2.1.1 Oxidized asphalt

Oxidized asphalt was gained from Nasiriyah Refinery in southern Iraq. Table 1 displays the physical characteristics of oxidized asphalt following the ASTM method (D-5, D-36, D-113, D-92, D-4402, D-1754, and D-70) [21–27].

2.1.2 Coarse and fine aggregate

In this investigation, crushed aggregates were brought from Al-Nibaie Quarry. The physical characteristics are shown in Table 2 for coarse and fine aggregates. The aggregates that were employed met all of the fine and coarse aggregate specifications required by the guidelines (R9/2003) issued by the State Corporation of Roads and Bridges (SCRB) for Type IIIA surface layer grading. Coarse aggregates in this investigation have a gradation from a nominal maximum sieve size of 3/4 in. (12.5 mm) to a sieve size of No. 4. (4.75 mm). Gradation of fine gravel varies from being sieved through a 4.75 mm (No. 4) sieve to being retained at a 0.075 mm (No. 200) sieve.

Table 1: Physical properties of oxidized asphalt

Tests*	Results
Penetration (1/10 mm)	35
Softening point (°C)	57
Ductility (cm)	100
Flashpoint (°C)	300
Rotational viscosity (cP)	
@ 135°C	615
@ 165°C	235
Residue after thin film oven test	
Retained penetration (%)	94.2
Retained ductility (cm)	91
Specific gravity	1.069

*Tests were performed in the Laboratories of the Department of the Civil Engineering/University of Technology and the National Center for Laboratories and Structural Research in Baghdad.

Table 2: Physical characteristics of aggregate

Property*	ASTM Designation	Coarse aggregate	Fine aggregate	Specification
Bulk specific gravity	C127,C128	2.615	2.625	—
Apparent specific gravity	C127,C128	2.642	2.661	—
Percent water absorption	C127,C128	0.362	0.48	—
Angularity	D5821	97%	—	Min. 95%
Toughness	C535	20.8%	—	Max. 30%
Soundness	C88	4.1	—	Max. 12%

*Tests were performed in the Laboratories of the Department of the Civil Engineering/University of Technology and the National Center for Laboratories and Structural Research in Baghdad.

2.1.3 Filler

The filler utilized in the current study was ordinary Portland cement with a bulk specific gravity of 3.2 acquired from Karasta Company. Table 3 presents the physical characteristics of ordinary Portland cement.

2.2 Recycled materials

In the present study, the following types of recycled materials were utilized.

2.2.1 RAP

The RAP in the current study was obtained from the Baghdad Mayoralty project in the Al-Qadisiyah region in Baghdad by scraping the surface layer from the road. The RAP was acquired through a milling machine by the removal of approximately 5 cm from the pavement surface of the road. An extraction test was carried out according to ASTM D2172 [28] to find the percentage of asphalt in the RAP and the gradation of aggregates in the RAP. The gradation of RAP before and after extraction is shown in Table 4. The asphalt content in the RAP was 4.5%.

Table 3: Characteristics of the ordinary Portland cement

Characteristics*	Test result
Bulk specific gravity	3.2
Passing sieve No. 200 (0.075 mm)	97%

*Tests were performed at the National Center for Laboratories and Structural Research in Baghdad.

2.2.2 WEO

WEO utilized in this investigation was derived from motor vehicle oils. WEO was tested for viscosity, specific gravity, and water content after being sieved through a #200 sieve to eliminate any particle debris, as shown in Table 5. The tests were performed at Baghdad's National Center for Laboratories and Structural Research.

Table 4: Gradation of RAP before and after extraction

Sieve size		Iraqi specification (SCRB R9,2003) surface layer type IIIA (% passing)		RAP specification*	
Standard sieves	English sieves	Min.	Max.	Passing %	
				Before	After
19 mm	3/4 in.	—	100	100	100
12.5 mm	1/2 in.	90	100	91.2	94.5
9.5 mm	3/8 in.	76	90	78.6	83.9
4.75 mm	#4	44	74	49.3	55.3
2.36 mm	#8	28	58	33.4	35.8
0.3 mm	#50	5	21	6.9	13.4
0.075 mm	#200	4	10	4.4	5.2
Pan	—				

*Tests were performed at the National Center for Laboratories and Structural Research in Baghdad.

Table 5: Physical properties of WEO

Tests*	Results
Viscosity (cP)	169
Specific gravity	0.97
Water content (%)	0.2

*Tests were performed at the National Center for Laboratories and Structural Research in Baghdad.

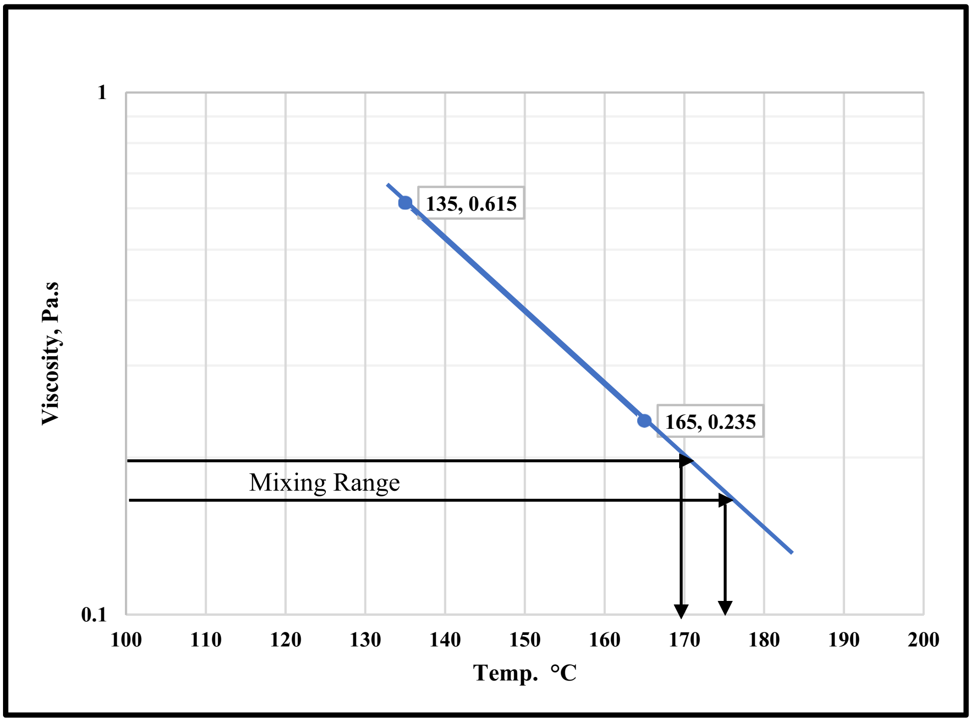

Figure 1: Temperature–viscosity diagram for oxidized asphalt.

3 Methods

3.1 Preparation of modified asphalt

The WEO-modified bitumen was generated by combining oxidized asphalt and WEO at 2, 3, and 4% concentrations. The waste oil and oxidized asphalt were combined for 30 min at 1,300 rpm in an experimental mixer to achieve a uniform mixture [29]. During the heating of the asphalt, waste oils have been added. According to the outcomes of the asphalt's rotational viscosity test, 170°C was the mixing temperature as displayed in Figure 1. The obtained specimens were then allowed to settle to room temperature in preparation for testing. Table 6 illustrates the physical characteristics of asphalt with and without WEO. The optimal WEO proportions were determined to be 3 and 4% by weight of asphalt, with corresponding penetration

Table 6: Physical properties of oxidized asphalt with and without WEO

Tests*	Results				ASTM standard
	0% WEO	2% WEO	3% WEO	4% WEO	
Penetration @ 25°C, 100 g., 5 s (0.1 mm)	35	38	46	66	D5
Softening point (ring and ball) (°C)	57	55	50	49	D36
Ductility @ 25°C, 5 cm/min (cm)	100	116	135	140	D113
Flash point (°C)	300	295	280	275	D92
Rotational viscosity (cP)					D-4402
@ 135°C	615	579	519	429	
@ 165°C	235	205	175	123	
Specific gravity	1.069	1.06	1.054	1.047	ASTM D70
After Thin Film Oven Test (ASTM D-1754, 2015)					
Retained penetration, % of original	94.2	92	80.5	89.4	D1754
Retained ductility @ 25 °C, 5 cm/min (cm)	91	102	110	125	

*Tests were performed in the Laboratories of the Department of the Civil Engineering/University of Technology and the National Center for Laboratories and Structural Research in Baghdad.

values of 46 and 66, respectively. According to Table 6, the performance of mixtures including (oxidized asphalt and 3% WEO) and (oxidized asphalt and 4% WEO) is equivalent to that of virgin binders with penetration grades of 40–50 and 60–70, respectively.

3.2 Gradation of aggregate

The gradation of aggregate, which was chosen for this project, follows the mid-point gradation in order to fulfill the prerequisites of the (SCRB R/9, 2003) [20] specification for the HMA-paving mixture. According to this specification, the maximum aggregate size in the surface layer type IIIA must be 19 mm, and the nominal maximum size must be 12.5 mm. Figure 2 depicts the particle distribution of sizes of each aggregate category, including the specification limitations and the surface layer's chosen midpoint.

3.3 Marshall mix design method

The Marshall method is implemented to identify the optimal amount of asphalt (OAC). The OAC is computed for the two modified asphalts (oxidized asphalt and 3% WEO) and (oxidized asphalt and 4% WEO) utilizing prepared samples with varying percentages of asphalt binder content (4, 4.5, 5, 5.5, and 6%). Each mixture was tested with a total of three specimens utilizing aggregate (12.5 mm) nominal maximum size gradation. Maximum stability, maximum bulk density, and four percent air voids were averaged to determine the acceptable OAC for the wearing course layer. The optimal asphalt content for surface layer type AIII is 4.9% for asphalt binder grade (40–50) and 5.0% for asphalt binder grade (60–70), as established through Marshall stability, flow, and bulk density analyses as well as the volumetric values. The volumetric mix characteristics (for two types of asphalt) and Marshall test parameters (for each percentage of asphalt content) for surface layer type AIII are detailed in Tables 7 and 8.

3.4 Preparation of recycled hot asphalt mixtures

According to AASHTO M-323 [30] and NCHRP Report-452 (2001) [31], varied RAP concentrations (20, 30, 40, and 50% by weight of the mixture) have been employed in the present investigation; additionally, the optimal binder quantity was employed to produce all recycled asphalt mixes. The effectiveness of the reclaimed asphalt mixes is contrasted to the mechanical characteristics of the control asphalt mixture, which comprises oxidized asphalt +

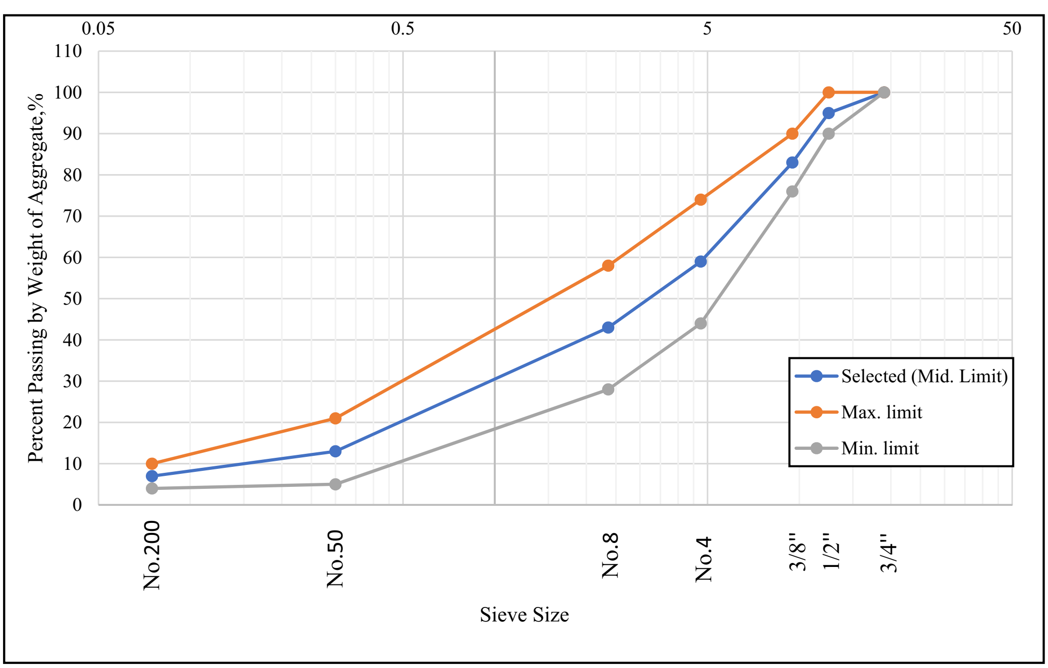

Figure 2: Gradation chart of aggregate with specification limits of surface layer.

Table 7: Marshall properties for asphalt grade (40–50)

% Asphalt	4	4.5	5	5.5	6
Marshall stability (kN)	9.7	10.4	11	9.5	8.6
Marshall flow (mm)	2.3	2.5	2.7	2.8	3
Bulk density (gm/cm^3)	2.253	2.271	2.323	2.290	2.280
Air voids (%)	6.66	5.5	4	3.7	3.63
Percent voids in mineral aggregate (VMA)%	18.5	18.82	16.84	18.46	19.24
Percent voids filled with asphalt (VFA)%	64	69	76	79	81

Table 8: Marshall properties for asphalt grade (60–70)

% Asphalt	4	4.5	5	5.5	6
Marshall stability (kN)	7.6	8.2	10	8.1	7.4
Marshall flow (mm)	3.4	3.5	3.55	3.6	3.7
Bulk density (gm/cm^3)	2.234	2.262	2.309	2.292	2.279
Air voids (%)	6.69	4.76	4.01	3.77	3.6
Percent voids in mineral aggregate (VMA)%	19.1	18.6	17.3	18.3	19.2
Percent voids filled with Asphalt (VFA)%	65	74	76	79	81.3

3% WEO with a penetration grade of 40–50 and contains 0% RAP content.

All HMA formulations were produced and compacted in the laboratory by the Marshall mix design technique. RAP must be preheated for 1 h prior to incorporating it with heated, dried aggregate, subsequently combined with asphalt at the mixture's temperature. In this method, 20% RAP is rejuvenated using oxidized asphalt and 3% WEO, which has a penetration grade of 40–50, while the other proportions of RAP are rejuvenated using oxidized asphalt and 4% WEO, which has a penetration grade of 60–70, taking into account the binder content of RAP. The asphalt grade was changed when using more than 20% RAP, according to the recommendations of the NCHRP Report-452 (2001). The type of asphalt binder grade altered in accordance with the NCHRP Report-452 (2001) method when the proportion of RAP increased by more than 20%, which necessitates the use of softer asphalt. The quantity of modified asphalt binder substituted with RAP binder is calculated by applying equation (1) [12]:

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

where P_r is the percent of virgin asphalt to be added to the mix containing RAP, P_a is the percent of RAP asphalt in the mix, P_c is the percent of total asphalt in the mix, and P_p is the percentage of RAP in the mix.

Table 9 lists the aggregate percentages for each kind (old and new) and the asphalt percentages for each RAP proportion in the asphalt blends.

4 Testing program

4.1 Marshall tests

The main goal of this test is to evaluate the stability and flow characteristics of mixes. The samples were submerged in a water stream for 30–40 min at a temperature of 60 ∓ 1°C. The samples were then put inside the Marshall stability testing apparatus using the ASTM D6729 standard procedure [32]. The load is deforming at a constant pace of 50.8 mm (2 in.) per minute until it fails. The Marshall stability is the maximum loading that results in sample failure, and the Marshall flow is the overall amount of deformation. For each mixing sample, the specific gravity and density, potential (maximum) specific gravity, and % air voids were identified according to ASTM (D2726-17) [33], D2041-11 [34], and D3203-17 [35], respectively.

4.2 ITS test

The purpose of this test is to figure out how moisture influences the asphalt mixture. ITS tests were performed in accordance with ASTM D6931-17 standard [36]. Specimens were made with a 7 ∓ 1 percent air void content. For each RAP percentage (0, 20, 30, 40, and 50%), there were six total specimens in a Marshall collection. Three of the specimens were evaluated without any conditioning, while the remaining three specimens underwent condition by soaking in a bath of water at 60°C for 24 h, followed by 1 h at 25°C (wet condition). The average tensile strength of

Table 9: Asphalt and RAP content in the mixtures

RAP (%) (by mix total weight)	OBC	Asphalt content (%) (by mix total weight)		Aggregate content (%)	
		New	RAP	New	RAP
0	4.9	4.9	0	100	0
20	4.9	4	0.9	80	20
30	5	3.65	1.35	70	30
40	5	3.2	1.8	60	40
50	5	2.75	2.25	50	50

conditional samples divided by the average tensile strength of unconditioned samples is known as the tensile strength ratio (TSR). The TSR is determined based on the ASTM D 4867 [37]. In accordance with the ASTM D 4867 standard, the TSR must be a minimum of 80%.

4.3 Double punch shear test

This assessment technique was employed to determine the removal of the binder from the aggregate. Three samples were conditioned for 30 min in water at 60 ∓ 1°C for 30 min by putting them in water immersion. The sample was placed in the middle of two precisely aligned cylinder steel punches with a diameter of 2.54 cm, and it was then loaded at a pace of 2.54 centimeters per minute until it broke. The highest possible resistance was then determined. Several studies have been published on this procedure [38–42]. The formula for calculating striking force is shown below:

$$\sigma_t = \frac{p}{\pi(1.2bh - a^2)}, \tag{2}$$

where σ_t is the punching shear stress, Pa; p is the maximum load, N; a is the radius of punch, mm; b is the radius of the specimen, mm; h is the height of the specimen, mm.

4.4 Cantabro abrasion loss test

The Cantabro abrasion loss test is conducted as stated in the specifications (ASTM D-7064-13) [43] in order to get an understanding of how resistant Marshall compacted samples are against abrasion. This test is performed under both the unaged and aged circumstances. To verify that the average void content of each category is comparable, the samples were partitioned into two categories. The unaged group underwent testing according to the Los Angeles (LA) equipment test technique (ASTM C131-14), while the aged group was heated to 140°F (60°C) for 7 days. After 7 days, the aging group was permitted to be cool for 24 h at the ambient temperature preceding undergoing inspection. Abrasion resistance was measured by determining the initial mass for every specimen, which was subsequently placed in a clean LA abrasion cylinder with no steel charge at a speed of 30–33 revolutions per minute (rpm) and a maximum of 300 rotations at 77°F (25°C) to measure its abrasion resistance. After 300 revolutions, the object was removed from the drum, brushed, and reweighed to validate the outcomes as displayed in Figure 3. The abrasion loss was computed by employing equation (3). A_i and A_f represent the initial and final masses, respectively, of the individual. Maximum permitted constraints are 20% for unaged samples and 30% for aged samples

$$\text{Abrasion loss\%} = \frac{(A_i - A_f)}{A_i} \times 100, \tag{3}$$

where A_i is the initial mass and A_f is the final mass.

4.5 Wheel tracking evaluation

The failure criterion or test completion signal is defined as the number of cycles necessary to attain a rutting depth equal to 20 mm or to complete 10,000 processes of device operating for all test samples. The rutting susceptibility of asphalt blends is typically evaluated using the Hamburg wheel-tracking test, a loaded wheel test designed to imitate road conditions. The procedure adheres to BS EN 12697-22 (2003) [44] and AASHTO: T324 (2013) [45] standards. In two different temperature states (i.e., 50 and 60°C), the

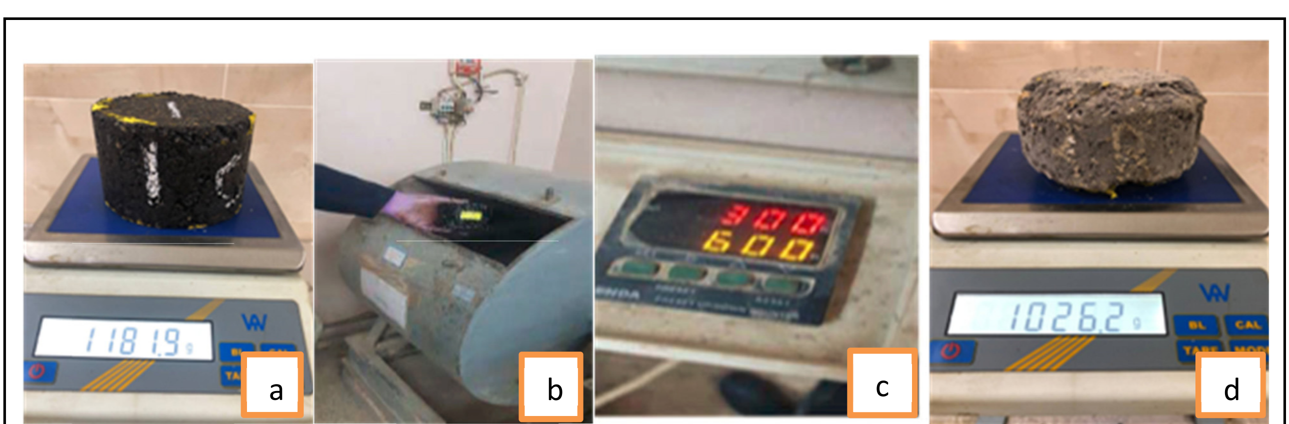

Figure 3: Cantabro abrasion loss test: (a) Weigh the sample before testing, (b) Place the sample in the LA cylinder, (c) Adjust equipment speed, and (d) Weigh sample after testing.

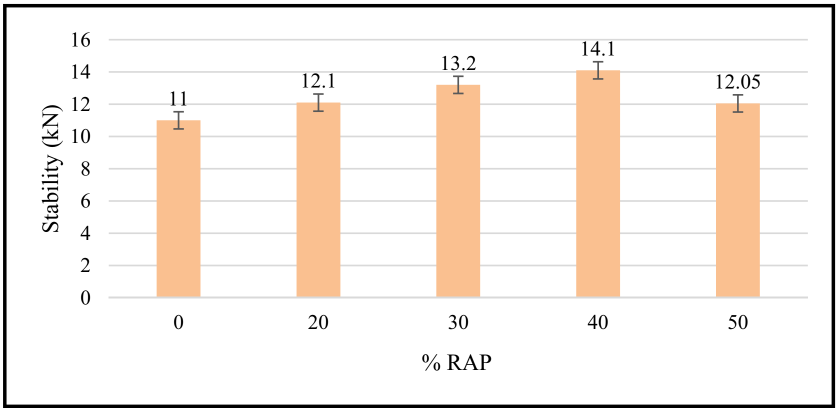

Figure 4: Effect of RAP on Marshall stability.

manufactured slab specimens are tested at a cycle rate of 27 per minute. Utilizing a roller compactor, asphaltic slabs are created with air spaces equivalent to 4%. The compacted slabs used in this study had dimensions of 400 mm in length, 300 mm in width, and 50 mm in height. At the interface area, the laden wheel exerts 700 N. A linear variable differential transformer with a precision of 0.01 mm was employed to determine the rut depth autonomously.

5 Analysis and discussion

5.1 Marshall test results

Figures 4–7 show the results for stability, flow, bulk density, and air voids, respectively, for all mixtures. All mixes fulfill the bulk density and air voids standards, and they all meet the minimal stability specifications of 8 kN for heavy traffic volume roadways for surface layer type AIII. At the same time, all combinations satisfy the Marshall flow requirement of 2-4 mm.

Compared to the standard combination, mixtures with higher percentages of RAP had higher Marshall stability and bulk density and lower flow and air void contents. It is noted that the value of Marshall stability is 11 kN at 0% RAP. It gradually increases with the increase in the RAP percentage until it reaches the highest value at 40% RAP, with a value of 14.1 kN, with an increase of 28%. This increase in the value of Marshall stability with the increase in the percentage of RAP in the mixture is due to the rise in the hardness and stiffness of the asphalt blend, in addition to the fact that the application of the regenerating agent (asphalt + waste oil) takes an effective function in recovering the attributes of the asphalt and thus improving the bonding cohesion with good workability and suitable compaction, which is commensurate with the low proportion of air voids in the asphalt blend. Although the differences in the proportion of air voids are small, it can be considered an indication of a decrease in the proportion of

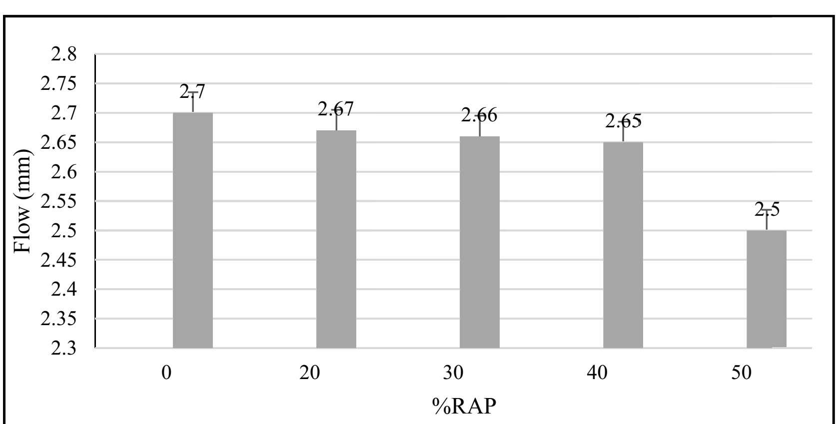

Figure 5: Effect of RAP on Marshall flow.

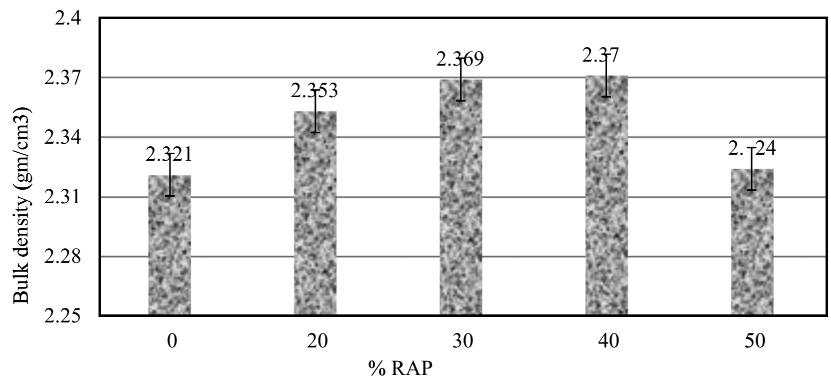

Figure 6: Effect of RAP on bulk density value.

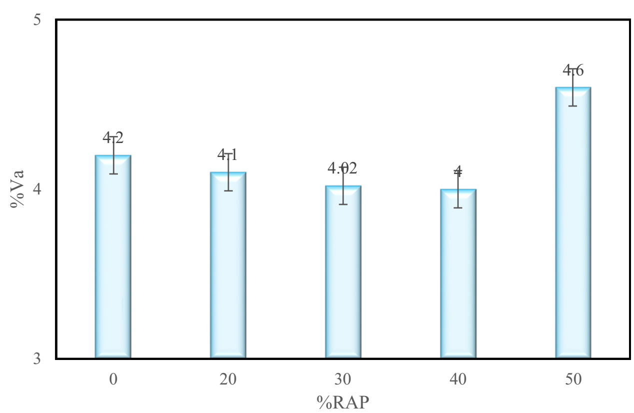

Figure 7: Effect of RAP on air void value.

air voids with an increase in the ratio of RAP, and this indicates the effect of the effectiveness of the rejuvenation process. As for the decline in the measurement of Marshall stability and bulk density when the ratio of the RAP is up to 50%, it may be attributed to an excessive increase in hardness as well as the increase in the percentage of aging asphalt, which in turn weakens the bonding and makes difficulty in workability and compaction leading to a rise in the proportion of air voids.These outcomes are in agreement with other studies [11,15,40,46].

5.2 Indirect tensile test results

The tensile characteristics of HMA mixes, which are linked to the cracking characteristics of the asphalt surface, are measured using the ITS test to evaluate the temperature range over which the combination performs adequately. Figures 8 and 9 show the impact of RAP content on the ITS for the conditioned and unconditioned samples. It is clear from the results that the value of ITS increases with the increase in the percentage of RAP, compared to the

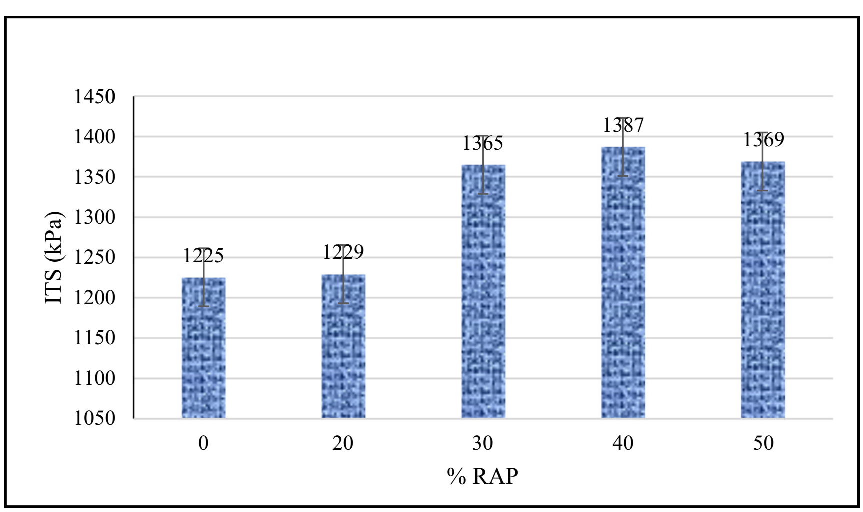

Figure 8: Effect of RAP on ITS for unconditioned samples.

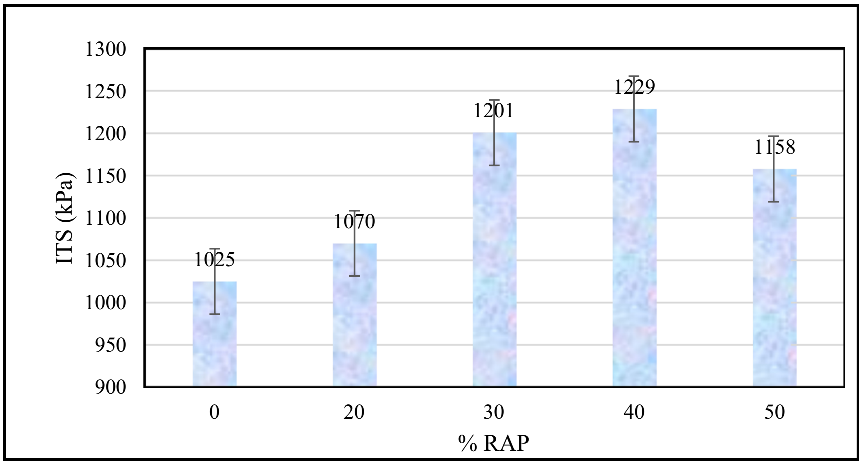

Figure 9: Effect of RAP on ITS for conditioned samples.

reference mixture, until it reaches 40% RAP, where it is the highest measure of the ITS (increase by about 13%) after which it declines at 50% RAP. The rise in ITS readings related to rising RAP content could possibly be due to the fact that RAP is a substance that has been aged. Consequently, the RAP binder gets harder over time. Thus, the aggregate and RAP binder connection grows stronger. The combination becomes stiffer with the addition of RAP (this can be identified by observing the remaining portion of the binder on the aggregate surface after washing with solvents, including trichloroethylene, throughout the extraction procedure) [12,14,39,41]. These findings agree with the findings from other studies [11,12,40].

The findings of the TSR are presented in Figure 10. According to the findings, mixtures had a greater resilience to moisture damage. This was proved by the realization that the TSR ratings for these mixes exceeded 80%, the limit that indicates the minimum criteria for the standards. The results demonstrate that the TSR values of the mixtures containing rejuvenated RAP are greater than the TSR values of the mixture that served as the reference. This rise in resilience to damage caused by moisture after renewal can be attributed to the reduction in the amount of air voids and restoring the properties of asphalt by WEO which produce better enhancement in the aggregate coating, as well as the increase in the bonding and adhesion between each of the mixture's components and the attainment of a dense, well-compacted combination and this is consistent with the outcomes attained by several experts [24,25,27,30].

Conversely, an ongoing rise in the proportion of reclaimed asphalt pavement (RAP) to over 40% causes a reduction in the tensile strength as well as the TSR of modified asphalt combinations. This is due to the brittleness that happened beyond the 40% threshold of the aged asphalt in RAP, which, in turn, decreases the workability of the mixes, thereby rendering it extremely hard to achieve an optimal covering of aggregate elements. As a result, the mixtures become fragile and are

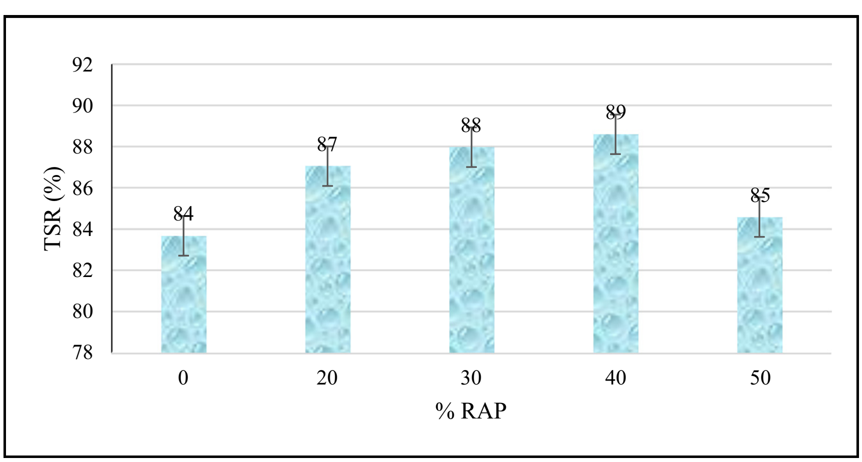

Figure 10: Effect of RAP on indirect TSR.

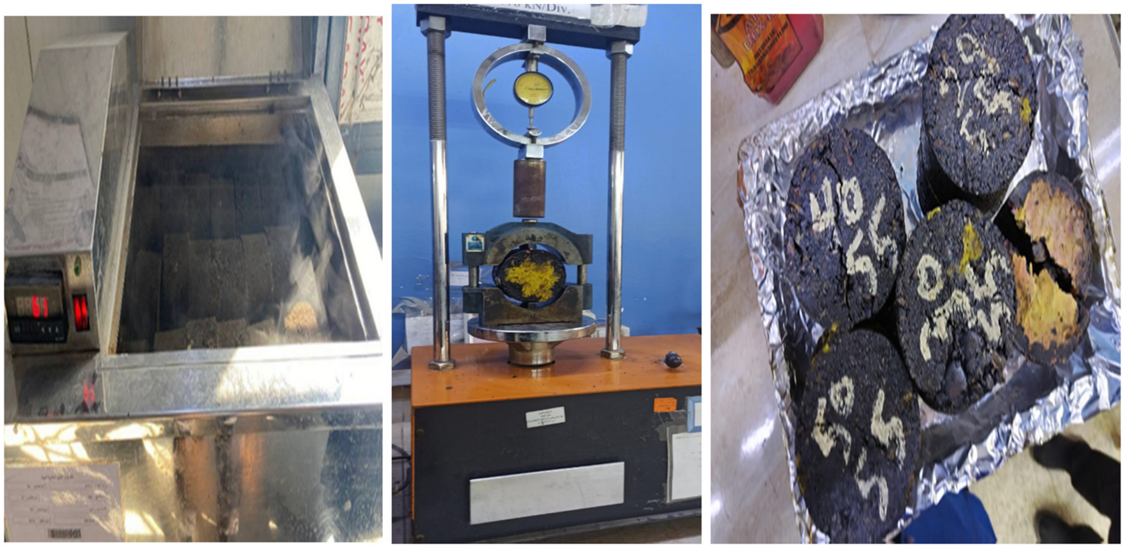

Figure 11: ITS test.

more susceptible to water damage. Figure 11 represents the samples under the ITS test.

5.3 Double punch shear test results

The findings of the double punch test showed that mixes with varying percentages of RAP materials outperformed pure mixtures in terms of performance. The punching power measured for mixes incorporating RAP improves with a greater amount of RAP, as illustrated in Figure 12, which displays the implications of double striking by higher RAP content in the hot asphalt mixture. This can be ascribed to the reality that asphalt treated with WEO enhances a blend's cohesive quality, producing the desired characteristics of elasticity, elongation, and binder viscosity, therefore, more resilience to the weight borne by the machine (punching load). This is consistent with the outcomes attained by several experts [15,40,47].

The punching resistance starts with 190 kPa at 0% RAP and continues to increase with the increase in the RAP ratio until it reaches its highest value of 353 kPa with an increase of 86% at 40% RAP, and after that, it decreases at 50% RAP. The reason for the decline in punching resistance is the high hardness that makes the asphalt more fragile and weaker in bonding with the aggregates and the ease of its separation from the aggregates under the applied load.

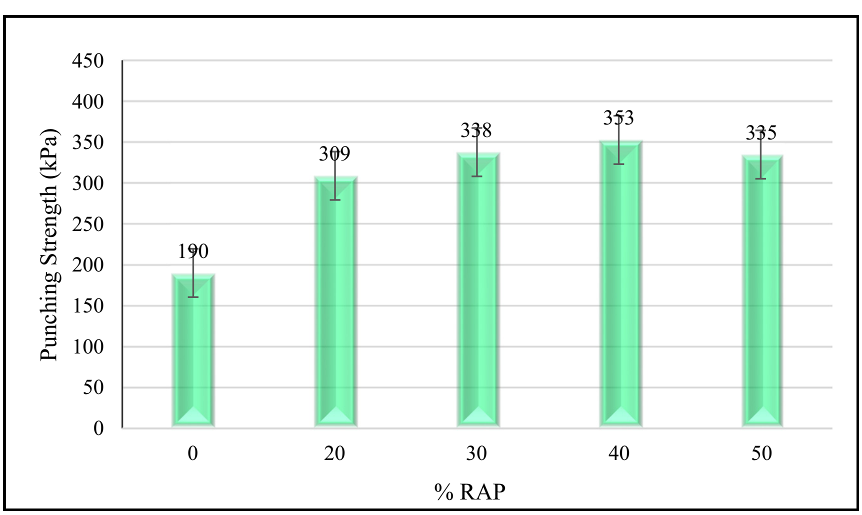

Figure 12: Effect of RAP on double punch shear results.

Figure 13: Samples under the double punch shear test.

Figure 13 represents the samples under the double punch shear test.

5.4 Cantabro abrasion loss results

The Cantabro abrasion loss test was carried out on two types of mixtures, i.e., the reference mixture without RAP, and the second mixture with 40% RAP. The mixture manufactured with 40% RAP was selected based on the results obtained from Marshall tests, indirect tensile test, TSR, and double punch test, as the best performance results for the four RAP ratios were for the asphalt mixture with 40% RAP. The results depicted in Figure 14 for both the aging and non-aging samples indicate that there was a reduction in the Cantabro loss values. The main explanation for this enhancement is the rise in stiffening that is brought by the increase in the viscosity of the hardened RAP binder, or it could be due to the high viscosity of the oxidized asphalt. A WEO-modified asphalt binder that has an elevated viscosity may contribute to the production of a thicker coating that covers the aggregates, which boosts the cohesion power. This, consequently, can increase the

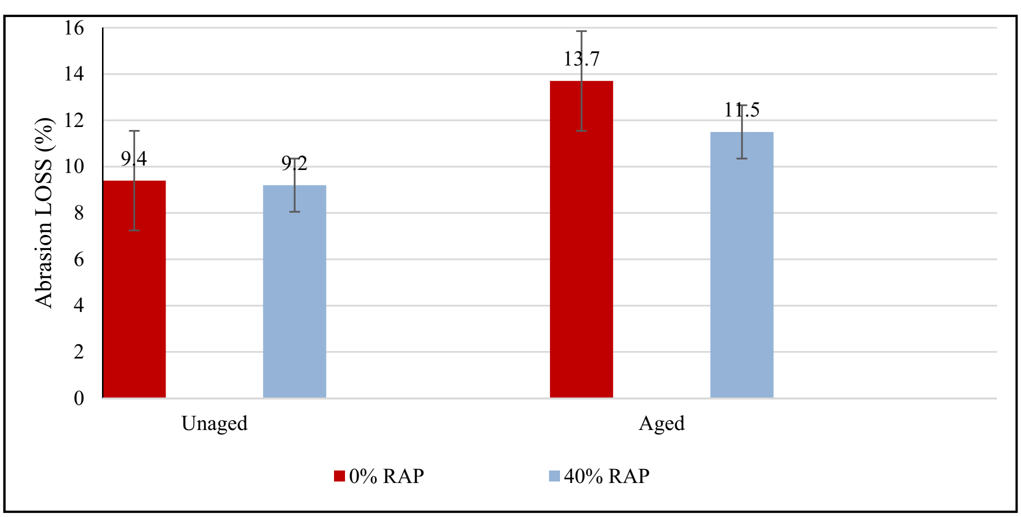

Figure 14: Abrasion for aging and UN-aging test result.

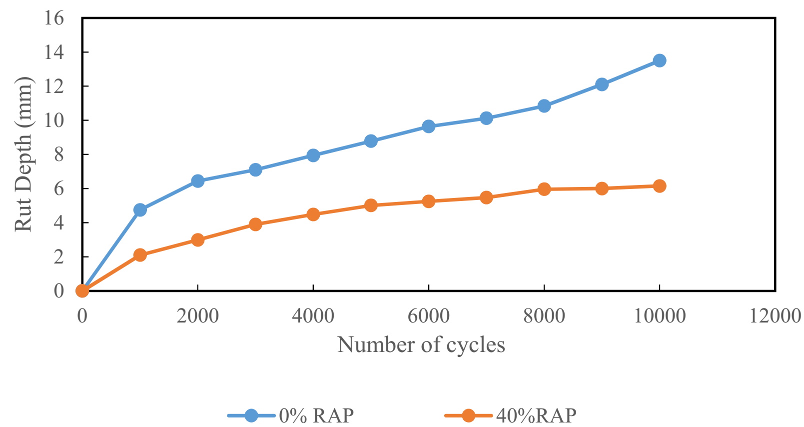

Figure 15: Effect of RAP addition on rutting depth value at 50°C.

lifespan of the pavement. The minor difference observed between the mixes (un-aged and aged) indicates that the addition of WEO-modified asphalt to asphalt mixes will not simply permit shifting the asphalt binder that is covered on the outside of the aggregate due to the enhancement of the adhesion and cohesion connections between asphalt and aggregates. This enhancement will provide enhanced resistance to temperature-induced damages, such as fatigue fractures, knowing that all results meet the requirements of the Cantabro examination.

5.5 Wheel tracking test results

The wheel track test was carried out on two mixtures, i.e., the reference mixture without RAP and the second mixture with 40% RAP. The mixture manufactured with 40% RAP was selected based on the results obtained from Marshall tests, indirect tensile test, and TSR, as the best performance results for the four RAP ratios were for the asphalt mixture with 40% RAP. Two mixtures of each type of these mixtures were made for testing at 50 and 60°C (to mimic the weather conditions and elevated temperature, notably in Iraq). Rut depth results are displayed in Figures 15 and 16 for two test temperatures of 50 and 60°C, respectively. It is clear that there is an improvement in the resistance to rutting, and a decrease in the rutting depth in the mixtures improved with RAP versus the original mixtures. The outcomes

Table 10: Effect of temperature change on permanent deformation

Type of mix	0% RAP (control mix)	40% RAP
Rut depth at 50°C (mm)	13.5	6.15
Rut depth at 60°C (mm)	18.12	8.4

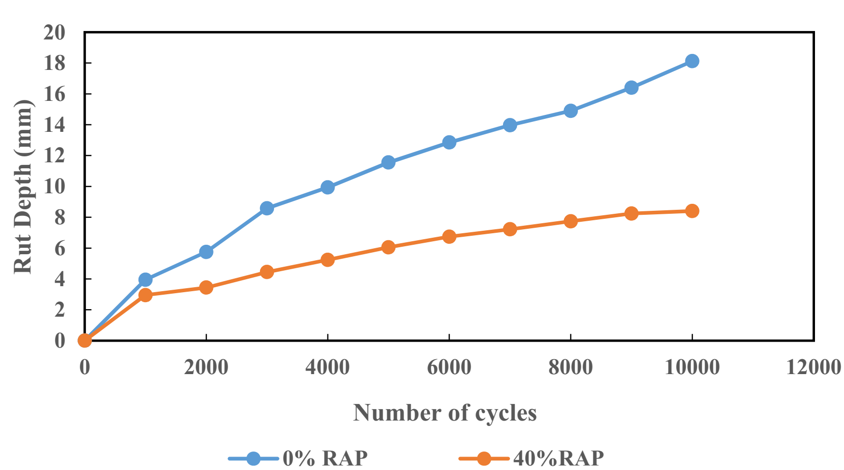

Figure 16: Effect of RAP addition on rutting depth value at 60°C.

demonstrate that incorporating RAP substances into virgin asphalt mixes produces stronger combinations, indicating improved rutting resistance, as the action of aged asphalt in RAP significantly impacts overall HMA behavior. Due to the increased rigidity of the old binder in RAP, the permanent deformation behavior has been enhanced when employing RAP. It is anticipated that the presence of a stiff binder in the RAP will have an advantageous effect on the rutting behavior of the HMA combination.

The temperature change also affects the rutting depth, as shown in Table 10. An increase has occurred in rut depth from 13.5 mm at 50°C to 18.12 mm at 60°C in the reference mixture, while this increase decreases when adding RAP, where the rut depth was 6.15 mm at 50°C and increased to 8.4 mm at 60°C for mix with 40% RAP, and thus the asphalt mixture was less affected by temperature when adding RAP. The permanent deformation (RD) rises when the temperature increases, as the asphalt binder is impacted by elevated temperature, which reduces the binder's viscosity; it is the primary material used to produce HMA. However, permanent deformation (RD) is not a type of problem linked to RAP combinations because a strong binder is anticipated to enhance the rutting performance, and the outcomes are consistent with those of other investigations [14,48,49].

6 Conclusions

The findings of the present study lead to the following conclusions:

1. The addition of WEO at concentrations of 2, 3, and 4% to oxidized asphalt has demonstrated a discernible enhancement in its physical and rheological properties.
2. Optimal WEO concentrations for reinstating the original penetration grades of oxidized asphalt, specifically from 30/40 to 40/50 and 60/70, have been determined as 3 and 4%, respectively.
3. When skillfully blended in appropriate proportions, combining oxidized asphalt, waste oil, and reclaimed asphalt significantly augments the mechanical performance of hot asphalt mixtures.
4. The introduction of reclaimed asphalt in varying proportions exerts notable effects on Marshall properties and volumetric characteristics. For instance, the inclusion of reclaimed asphalt pavement (RAP) at concentrations of 20, 30, 40, and 50% results in a substantial improvement in Marshall stability by 10, 20, 28, and 9.5%, respectively, while flow only experiences a marginal reduction, except at 50% RAP, where it decreases by 3%. Furthermore, unit weight increases, and air void content remains within acceptable limits, aligning with specified requirements.
5. The indirect tensile strength demonstrates an increasing trend with the escalation of RAP content when compared to control mixtures.
6. The findings underscore the robustness of RAP mixtures against moisture-induced damage. Specifically, 40% RAP enhances moisture resistance by approximately 5.9% compared to mixtures devoid of RAP.
7. The integration of RAP rejuvenated with a combination of oxidized asphalt and WEO substantially elevates resistance to stripping in hot asphalt mixtures, surpassing the performance of control mixtures. Stripping resistance increases by 62, 77, 85, and 76% upon incorporating 20, 30, 40, and 50% RAP, respectively.
8. The most favorable ratio for RAP is identified as 40% in relation to the weight of asphalt blends, accompanied by 4% WEO based on the asphalt binder's weight or 4% WEO combined with oxidized asphalt. These combinations consistently yield superior results in both the Marshall and ITS tests, along with remarkable resistance to moisture damage.
9. Irrespective of aging conditions, there is a noticeable reduction in Cantabro loss values, with decreases of approximately 2 and 16%, respectively.
10. Including RAP in asphalt mixtures significantly enhances their resistance to permanent deformation. Rutting resistance experiences a notable 50 and 47% increase for mixtures containing 40% RAP at temperatures of 50 and 60°C, respectively.
11. The presence of RAP materials mitigates the temperature-induced effects on rut depth, reducing their impact by approximately 51% for mixtures with 40% RAP.
12. In conclusion, it can be unequivocally asserted that the rejuvenation of RAP using a combination of oxidized asphalt and WEOs represents a pragmatic and environmentally beneficial approach. This approach holds promise for enhancing the performance of asphalt mixtures and contributes positively to economic and environmental considerations.

Funding information: We declare that the manuscript was done depending on the personal effort of the author, and there is no funding effort from any side or organization.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript.

The other datasets are available on reasonable request from the corresponding author with the attached information.

References

[1] Albayati AH. A review of rutting in asphalt concrete pavement. Open Eng. 2023;26:1–26.

[2] Hilal MM, Fattah MY. A model for variation with time of flexible-pavement temperature. Open Eng. 2022;8:176–83.

[3] Copeland A. Reclaimed asphalt pavement in asphalt mixtures: state of the practice. Rep No FHWA-HRT-11-021, Fed Highw Adm. 2011:1–56.

[4] Enieb M, Hasan Al-Jumaili MA, Eedan Al-Jameel HA, Eltwati AS. Sustainability of using reclaimed asphalt pavement: based-reviewed evidence. J Phys Conf Ser. 2021;16:1–16.

[5] DeDene CD. Investigation of using waste engine oil blended with reclaimed asphalt materials to improve pavement recyclability. M.s.c. Thesis. Department of Civil Engineering, Michigan Technological University; 2011. doi: 10.37099/mtu.dc.etds/229. https://digitalcommons.mtu.edu/etds.

[6] Mamun AA, Al-Abdul Wahhab HI. Evaluation of waste engine oil-rejuvenated asphalt concrete mixtures with high RAP content. Adv Mater Sci Eng. 2018;8:1–8.

[7] Carpenter SH, Al-Qadi IL, Aurangzeb Q. Impact of high RAP content on structural and performance properties of asphalt mixtures. Civ Eng Stud Illinois Cent Transp Ser No 12-002 UILU-ENG-2012-2006. 2012;107(12):1–107.

[8] Shams MK. Influence of using different rrjuvenators on recycled hot mix asphalt properties. M.s.c. Thesis, Department of Civil Engineering, University of Technology; 2020.

[9] Datt R, Kumar A, Kumar A. Waste cooking oil as a rejuvenating agent in aged bitumen. Int J Control Theory Appl. 2017;8(30):127–34.

[10] Asli H, Ahmadinia E, Zargar M, Karim MR. Investigation on physical properties of waste cooking oil - rejuvenated bitumen binder. Constr Build Mater. 2012;8:398–405. doi: 10.1016/j.conbuildmat.2012.07.042.

[11] Hasan EA. Assessing performance of recycled asphalt concrete sustainable pavement. M.s.c.Thesis. Department of civil engineering,University of Baghdad; 2012.

[12] Aghazadeh Dokandari P, Kaya D, Sengoz B, Topal A. Implementing waste oils with reclaimed asphalt pavement. World Congr Civil Struct Env Eng. 2017;12:1–12.

[13] Taherkhani H, Noorian F. Comparing the effects of waste engine and cooking oil on the properties of asphalt concrete containing reclaimed asphalt pavement (RAP). Road Mater Pavement Des. 2018;20:1–20.

[14] Khaled TT. Effect of adding RAP to enhance the performance of asphalt mixtures. M.s.c. Thesis. Department of Highways and Transportation Engineering Department, Collage of Engineering, Mustansiriayah University; 2018.

[15] Joni HH, Al-Rubaee RH, Shams MK. Assessment of durability properties of reclaimed asphalt pavement using two rejuvenators: Waste engine oil and asphalt cement (60–70) penetration grade. IOP Conf Ser Mater Sci Eng. 2021;13(1):1–13.

[16] Zaumanis M, Mallick RB, Frank R. Evaluation of different recycling agents for restoring aged asphalt binder and performance of 100 % recycled asphalt. Mater Struct Constr. 2014;14(8):1–14.

[17] Mogawer WS, Bennert T, Daniel JS, Bonaquist R, Austerman A, Booshehrian A. Performance characteristics of plant produced high RAP mixtures. Road Mater Pavement Des. 2012;36:1–36.

[18] Kim S, Shen J, Jeong M. Evaluation of resistance to rutting and moisture susceptibility on high RAP content asphalt concretes using hamburg wheel tracking device. Georg South Univ Res Symp. 2016;2:1–2.

[19] Abbas Z, Karim HI, Zaynab IQ. Durability and moisture susceptibility characteristics of reclaimed asphalt pavement mixture in Iraq. M.s.c Thesis. Department of Civil Engineering, University of Technology; 2017.

[20] SCRB/R9. General Specification for Roads and Bridges, Section R/9, Hot- Mix Asphalt Concrete Pavement, Revised Edition. State Corp Roads Bridg Minist Hous Constr Repub Iraq; 2003.

[21] ASTM-D5. Standard test method for penetration of bituminous materials. ASTM Int West Conshohocken, PA. 2018;4:1–4.

[22] ASTMD36-2018. Standard test method for softening point of bitumen (Ring-and-Ball Apparatus). ASTM Int West Conshohocken, PA. 2018;5:1–5.

[23] ASTM D 113-2018. Standard test method for ductility of bituminous materials. ASTM Int West Conshohocken, PA. 2018;5:1–5.

[24] ASTM-D92-2018. Standard test method for flash and fire points by cleveland open cup tester. ASTM Int West Conshohocken, PA. 2018;11:1–11.

[25] ASTM D4402-2015. Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer. ASTM Int West Conshohocken, PA. 2015;4:1–4.

[26] ASTM D1754. Standard test method for effects of heat and air on asphaltic materials (Thin-Film Oven Test). ASTM Int West Conshohocken, PA. 2009;6:1–6.

[27] ASTM- D70-2018. Standard test method for density of semi-solid bituminous materials (Pycnometer Method). ASTM Int West Conshohocken, PA. 2018;5:1–5, www.epa.gov/.

[28] ASTM-D2172. Standard test methods for quantitative extraction of bitumen from bituminous paving mixtures. ASTM Int West Conshohocken, PA. 2012;13:1–13.

[29] Joni HH, Al-Rubaee RH, Al-zerkani MA. Rejuvenation of aged asphalt binder extracted from reclaimed asphalt pavement using waste vegetable and engine oils. Case Stud Constr Mater. 2019;10:1–10. doi: 10.1016/j.cscm.2019.e00279.

[30] AASHTO_M323-15. Standard specification for superpave volumetric mix design. Am Assoc State Highw Transp Washington, USA. 2015;12:1–12.

[31] McDaniel R, Michael Anderson R. NCHRP REPORT 452 - Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual TRANSPORTATION [Internet]. National Cooperative Highway Research Program; 2001. p. 58. http://www.national-academies.org/trb/bookstore.

[32] ASTM-D-6729. Standard test method for marshall stability and flow of asphalt mixtures. 2015;7:1–7.

[33] ASTM-D2726-17. Standard test method for bulk specific gravity and density of compacted bituminous. ASTM Int West Conshohocken, PA. 2017;4:1–4.

[34] ASTM-D2041. Standard test method for theoretical maximum specific gravity and density of bituminous paving mixtures. ASTM Int West Conshohocken, PA. 2015;4:1–4.

[35] ASTM-D3203-17. Standard test method for percent air voids in compacted asphalt mixtures. ASTM Int West Conshohocken, PA. 2017;3:1–3.

[36] ASTM-D6931-17. Standard test method for indirect tensile (IDT) strength of bituminous mixtures. ASTM Int West Conshohocken, PA. 2017;5:1–5.
[37] ASTM-D4867-14. Standard test method for effect of moisture on asphalt concrete paving mixtures. ASTM Int West Conshohocken, PA. 2014;5:1–5.
[38] Jimenez RA. Testing for debonding of asphalt from aggregates. Transp Res Rec. 1974;17(515):1–17.
[39] Sarsam SI, AL-Zubaidi IL. Assessing tensile and shear properties of aged and recycled sustainable pavement. Int J Sci Res Knowl. 2014;9(9):444–52.
[40] Qadir Ismael M, Tariq Khaled T. Evaluation of hot mix asphalt containing reclaimed asphalt pavement to resist moisture damage. J Eng Sustain Dev. 2019;20(5):117–36.
[41] Joni HH, Al-Rubaee RH, Shames MK. Evaluating the mechanical performance properties of reclaimed asphalt pavement rejuvenated with different rejuvenators. Wasit J Eng Sci. 2020;11(1):46–56.
[42] Karim HH, Hasan HJoni, Haneen KY. Effect of modified asphalt with sbs polymer on mechanicalproperties of recycled pavement mixture. Glob J Eng Sci Res Manag. 2018;10:39–48. http://www.gjesrm.com.
[43] ASTM-D7064. Standard practice for open-graded friction course (OGFC) mix design. Annual book of ASTM standards. West Conshohocken, PA 19428-2959 U S. 2013;7:1–7.
[44] BS EN 12697 - 22. Bituminous mixtures-Test methods for hot mix asphalt, Part 33: Specimen prepared by roller compactor. Part 22: Wheel Track Test. 2003;29:1–29.
[45] AASHTO: T324. Standard method of test for hamburg wheel-track testing of compacted hot mix asphalt (HMA). Am Assoc State Highw Transp Off. 2014;10:1–10.
[46] Jaafar MA, Joni HH, Karim HH. Evaluation of reclaimed asphalt mixtures modified by nanoclay powder on moisture damage. IOP Conf Ser Earth Env Sci. 2022;11:1–11.
[47] Sarsam S, Hasan EA. Evaluating water damage resistance of recycled asphalt concrete mixtures. Univ Baghdad Eng Journa. 2018;13:163–75.
[48] Al-Qadi IL, Elseifi M, Carpenter SH. Reclaimed asphalt pavement – A literature review. Res Rep FHWA-ICT-07-001 A Rep Find ICT R27-11, Ill Cent Transp. 2007;25.
[49] Sabahfar N, Hossain M. Effect of asphalt rejuvenating agent on aged reclaimed asphalt pavement and binder properties. Kans State Univ Transp Cent Dep Civ Eng. 2016;99:1–99.