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Evaluation of Bitumen Aging with the Addition of Waste Cooking Oil and Reclaimed Asphalt Pavement in Road Construction

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ABSTRACT

The increasing incorporation of reclaimed asphalt pavement (RAP) in asphalt mixtures provides substantial economic and environmental benefits, but poses challenges due to the stiff and brittle nature of aged RAP binders, which can lead to premature cracking. This study investigates the potential of waste cooking oil (WCO) as a sustainable and low-cost rejuvenator to restore the properties of aged RAP binders. Virgin binders of grade 60/80 and 80/100 were blended with RAP binder (25% and 50%) and varying percentages of WCO (1-5% by weight). The physical (penetration, softening point, viscosity) and rheological (complex shear modulus G*, phase angle δ, and Glover-Rowe G-R parameter) properties of these blends were evaluated under unaged, Rolling Thin Film Oven (RTFO), and Pressure Aging Vessel (PAV) conditions. Standard tests, including rotational viscosity and dynamic shear rheometer, were conducted to characterize the behavior of the blends. The addition of WCO effectively softened the RAP binder blends by increasing penetration and δ while decreasing softening point, viscosity, and G*. An optimal WCO dosage of 2%-3% restored the aged RAP binder properties to levels similar to the virgin binder, balancing improved flexibility with acceptable rutting resistance (G*/sinδ). Short-term aging increased stiffness across all binders, but WCO mitigated viscosity increases. However, long-term aging impacts require further investigation. This study demonstrates WCO's viability as a rejuvenator for high-RAP asphalt binders, offering potential reductions in mixing and compaction temperatures, improved workability, and enhanced sustainability.

Keywords: Bitumen aging, Reclaimed asphalt pavement (RAP), Waste cooking oil (WCO), Rejuvenator, Rheology, Penetration, Softening point, Viscosity, Glover-Rowe parameter.

INTRODUCTION

Reclaimed Asphalt Pavement (RAP) is a valuable resource generated from the removal of old asphalt pavements. Its reuse in new asphalt mixtures conserves natural resources (aggregates and virgin binders), reduces energy consumption, minimizes landfill waste, and lowers construction costs (Abdulfatai Adinoyi Murana, 2024; Al-Qadi, 2007; Copeland, 2011). Consequently, incorporating RAP has become a standard practice in the asphalt industry. However, the asphalt binder within RAP undergoes significant aging during its service life due to oxidation and volatilization, becoming stiffer and more brittle (Matolia et al., 2020; Rahmani et al., 2017; Wu et al., 2009).

Numerous studies have shown that the aging process of bitumen is complex. It primarily involves the evaporation of lighter components, the transformation of the maltene phase into the asphaltene fraction, and the formation of oxygen containing functional groups within bitumen molecules (Apostolidis et al., 2017; Ren et al., 2022; Tauste et al., 2018; Zhang et al., 2021). These factors collectively contribute to an increase in bitumen's stiffness, viscosity, and its susceptibility to cracking (Li et al., 2022). Concurrently, the drive for sustainable construction practices has promoted the use of Reclaimed Asphalt Pavement (RAP) as a valuable resource, conserving virgin materials and reducing costs (Al-Qadi, 2007; Board et al., 2013; Copeland, 2011). However, incorporating high percentages of RAP is often limited by the detrimental effects of the highly aged binder present in the RAP material, which can compromise the flexibility and cracking resistance of the final asphalt mixture (Chen et al., 2018; Mohammadafzali et al., 2017; Pradhan, 2023; Yuhong Wang et al., 2015).

To counteract the negative effects of aged RAP (Reclaimed Asphalt Pavement) binder and enable higher utilization, rejuvenators or recycling agents are employed (Ali et al., 2016; Kaseer et al., 2017; von Quintus et al., 2007). Rejuvenators are typically lower viscosity materials designed to restore the rheological and chemical balance of aged binders, primarily by replenishing the maltene fraction (particularly aromatics) lost during ageing, thereby reducing stiffness and improving ductility (Loise et al., 2019; West et al., 2013). Various materials have been investigated as rejuvenators, including petroleum-based products (aromatic extracts, paraffinic oils), bio-based oils (tall oils, vegetable oils), and waste products (Kaseer et al., 2017).

These agents aim to restore the physical and chemical properties of the aged binder, typically by rebalancing the asphaltene-maltene ratio, reducing binder viscosity and stiffness (Cavalli et al., 2018; Kaseer et al., 2019; Kumbargeri & Biligiri, 2016). While various petroleum-based rejuvenators exist, concerns regarding cost, potential volatility, and environmental impact persist (Airey, 1997; Radenberg et al., 2016). This has spurred interest in sustainable alternatives derived from waste streams.

In practical engineering, achieving complete dissolution of aged bitumen from RAP and uniformly blending it with rejuvenators to form a homogeneous rejuvenated binder is unattainable (Vassaux et al., 2018). Rather than dissolving separately, the rejuvenators are directly added to an asphalt mixture containing RAP, followed by mechanical mixing at elevated temperatures for a specified blending duration (Kaseer et al., 2019). It is anticipated that the RAP aggregates will be completely and uniformly coated with rejuvenators. These rejuvenators are expected to rapidly diffuse and distribute evenly within the aged bitumen, resulting in a consistent and homogeneous rejuvenated bitumen layer surrounding all RAP aggregates (Orešković et al., 2020). Achieving this goal within a short time frame can be challenging, as recycled mixtures often exhibit partial blending. This blending is significantly influenced by factors, such as the type of rejuvenator used, the RAP content, the aging level of the bitumen, the presence of warm-mix additives, and the mixing temperature and duration (Castorena et al., 2016; Lo Presti et al., 2020; Ren et al., 2022).

At present, various methods, including stage extraction (Mohajeri et al., 2014) microscopic observation (Margaritis et al., 2019), and Fourier transform infrared (FTIR) microscopy (Shirodkar et al., 2013) have been employed to assess the blending degree between fresh and aged bitumen. These evaluations aim to better understand the interaction and compatibility within the mixtures. Furthermore, it has been demonstrated that rejuvenators effectively enhance the blending level between fresh and RAP binders. However, the extent of this improvement is highly dependent on the specific type of rejuvenator used (Rad et al., 2014; Ren et al., 2022).

Waste Cooking Oil (WCO), a by-product generated in large quantities globally from food industries and households, presents a potential low cost and environmentally friendly option for bitumen rejuvenation (Ahmed & Hossain, 2020; Yildirim, 2007). WCO is rich in triglycerides and fatty acids, which can act as softening agents (Bajaj et al., 2020; Ma et al., 2020). Previous studies have indicated the potential of WCO and other bio-oils to reduce binder stiffness and improve low-temperature properties (Jäger et al., 2004; Kaseer et al., 2017; Osman & Taylor, 2017). However, comprehensive evaluations encompassing both physical and detailed rheological characterization, especially under simulated aging conditions relevant to pavement service life, are essential to understand its effectiveness and long-term implications. The interaction mechanism and optimal dosage require careful investigation to ensure balanced performance, avoiding excessive softening that could lead to rutting issues (Ahmed & Hossain, 2020).

Designing durable high-RAP (Reclaimed Asphalt Pavement) mixtures requires understanding the interaction between virgin binders, aged RAP binders, and rejuvenators, as well as the impact of aging on the blended binder (Abdelaziz et al., 2022). Laboratory aging protocols, such as the Rolling Thin Film Oven (RTFO) test for short-term aging and the Pressure Aging Vessel (PAV) test for long-term aging, are vital for performance evaluation (Garcia Cucalon et al., 2018; Zhang et al., 2012).

While various petroleum-based rejuvenators exist, concerns about cost, potential volatility, and environmental impact persist. This has driven interest in sustainable alternatives derived from waste streams. Waste Cooking Oil (WCO), a readily available by-product, has shown potential as a low-cost and environmentally friendly rejuvenator. However, its comprehensive effectiveness remains understudied, particularly in terms of physical and rheological performance under aging conditions. Moreover, the interaction mechanisms and optimal dosage of WCO require further detailed investigation to ensure balanced performance and avoid potential drawbacks, like excessive softening or rutting issues.

MATERIALS AND METHODS

Materials

Virgin Asphalt Binders: In Ethiopia, virgin asphalt binders commonly used include grades with a penetration range of 80/100 (ERA, 2013). These are selected due to their suitability for local conditions.

Reclaimed Asphalt Pavement (RAP): RAP material was obtained from milling operations on the Addis Ababa – Modjo – Meki highway project in Ethiopia. RAP was processed and characterized. Binder extraction (ASTM D2172) using trichloroethylene yielded an aged binder content of approximately 5.06% (Table 3).

Aged RAP Binder: RAP material was obtained from milling operations on the Addis-Modjo-Meki Heavy Maintenance Road project.

Rejuvenator: WCO was collected from a local restaurant (Sonan Cafe, Alemgana). Its chemical composition, primarily oleic (43.67%) and palmitic (38.35%) acids, is shown in Table 1.

Table 1. Chemical composition of waste cooking oil

Fatty acid	Waste cooking oil (%)
Oleic acid	43.67
Palmitic acid	38.35
Linoleic acid	11.39
Stearic acid	4.33
Myristic acid	1.03
G-Linoleic acid	0.37
Lauric acid	0.34
Linolenic acid	0.29
Cis-11 Eicosenoic acid	0.16
Heneicosanoic acid	0.08
Total	100

Crushed Stone Aggregate: Crushed stone aggregate (CSA) was obtained from the Sabata Quarry Site for comparative testing and potential mixture design considerations.

Methods

This study aims to provide precise and detailed insights into the effects of aging and recycling agents on both the macro-scale and micro-scale properties of high RAP (Reclaimed Asphalt Pavement) mixtures. A quantitative, descriptive, and comparative research methodology was employed to achieve the study's objectives. The primary focus of the investigation is to assess the impact of aging and recycling agents on the rheological and physical characteristics of high RAP content. The findings of this study are systematically analyzed based on the adopted research methodology, as illustrated in Figure (1).

Sample Preparation

The preparation process for binder blends involves several key steps. First, the RAP (Reclaimed Asphalt Pavement) binder was extracted and recovered using ASTM D2172 (ASTM, 2024a) and ASTM D5404 (ASTM, 2024b) test methods, employing trichloroethylene (TCE) solvent. The virgin binder was then pre-heated to approximately 170°C and blended with Waste Cooking Oil (WCO) as a recycling agent at specified dosages (0%, 1%, 2%, 3%, 4%, and 5% by weight of the total binder blend, as indicated in Table 2). Once mixed, the RAP binder was added to the blend and hand stirred three times to ensure uniformity and homogeneity in the final mixture.

The blends targeted three RAP binder content levels (25%, 40% and 50%) relative to the total binder. Blending was performed using an asphalt mixer operating for 1 hour at 163°C, consistent with standard blending temperatures of 160-170°C (ERA, 2013). The virgin binder 80/100 grade served as the unmodified control blend for comparison.

This systematic blending approach ensures effective dispersion of the components and allows for a comprehensive analysis of binder performance under different conditions.

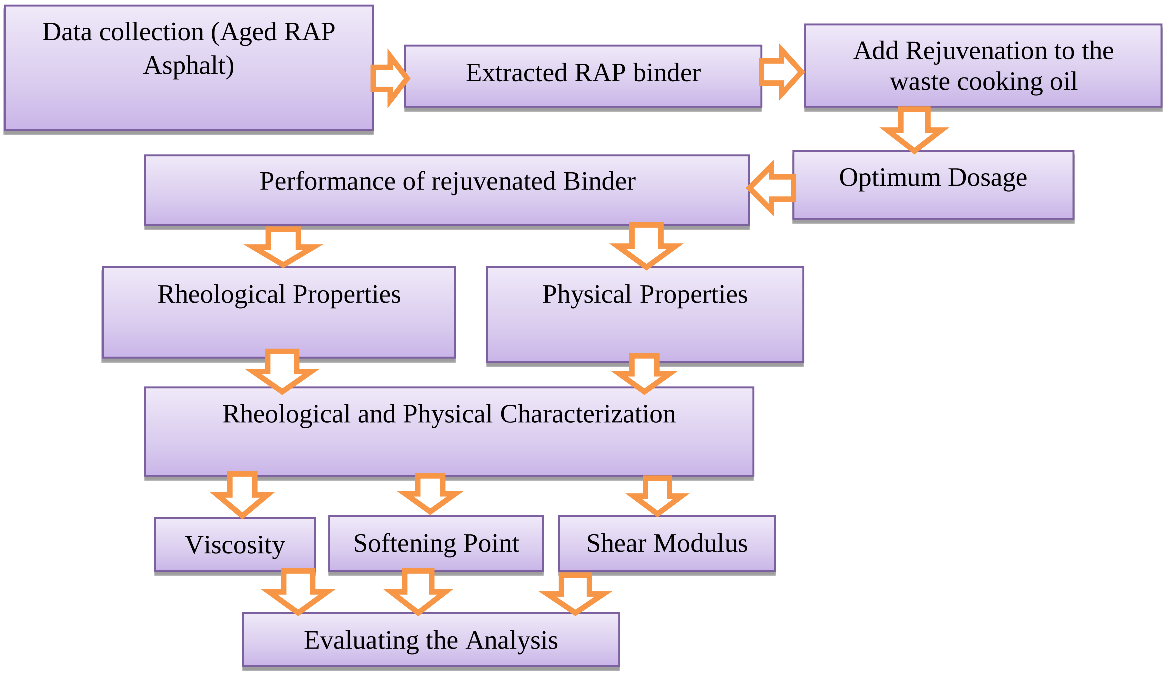

Figure (1): Research design methodology

Table 2. Total weight of modified bitumen material (WCO)

Sample No.	**Waste Cooking Oil (%)**	**Virgin bitumen (g)**	**Waste Cooking Oil (g)**	**Total Weight (g)**
1	0	300	0	300
2	1	300	3	303
3	2	300	6	306
4	3	300	9	309
5	4	300	12	312
6	5	300	15	315

Aging Simulation

Short-term Aging: Short-term aging was simulated using the Rolling Thin Film Oven Test (RTFOT) according to AASHTO T240 (AASHTO, 2013). Virgin binder, aged binder, and WCO rejuvenated blends were subjected to RTFOT conditions (163°C for 85 minutes) to simulate the aging that occurs during asphalt-mixture production and construction.

Long-term Aging (PAV): RTFO-aged samples were further aged in a Pressure Aging Vessel according to AASHTO R 28 (AASHTO, 2012) at 100°C for 20 hours (standard PAV) and 40 hours (extended PAV) to simulate in-service oxidative aging.

EXPERIMENTAL SETUP

RAP Extraction and Gradation Test

Bitumen extraction from asphalt pavement is conducted to measure the percentage of bitumen within the pavement. This test is essential, as the bitumen content significantly influences key pavement properties. These include durability, compatibility, and resistance to issues, such as raveling, bleeding, and rutting. As the binder for aggregates, bitumen plays a vital role in maintaining the pavement's performance and structural integrity.

The aged binder extracted from the RAP using trichloroethylene (TCE) yielded an aged binder content of approximately 5.06% according to ASTM D2172 (ASTM, 2024a) and recovered following ASTM D5404 (ASTM, 2024b). The average RAP aggregate gradation and properties are also characterized in Figure (2).

Table 3. Reclaimed asphalt pavement (RAP) extraction

Extraction Parameters	**Amount**
Mass of Sample (g), A	1169.05
Mass of aggregate after extraction (g), B	1106.4
Mass of filler and flter (g), C	18.6
Mass of filter (g), D	17.8
Mass of filler rdt. by filter (g), E=C-D	0.8
Mass of total aggregate (g), F=B+E	1107.2
Mass of dust in extract (g), G	2.65
Mass of total aggregate +filler (g), B+E+G	1109.9
Mass of bitumen (g), I=A-F	61.85
Uncorrected bitumen content (%) =I/A*100	5.29
Correction factor for mineral matter (g)= G/A*100	0.23
Corrected bitumen content (%), L=J-K	5.06

The percent of binder content is found using Eqn. (1).

$$\% BC=(W_1-(W_2+W_3)) *100/W_1 \quad (1)$$

where, W_1=Weight of mix taken before extraction, W_2= Weight of mix after extraction and W_3=Weight of filler collected in filter paper.

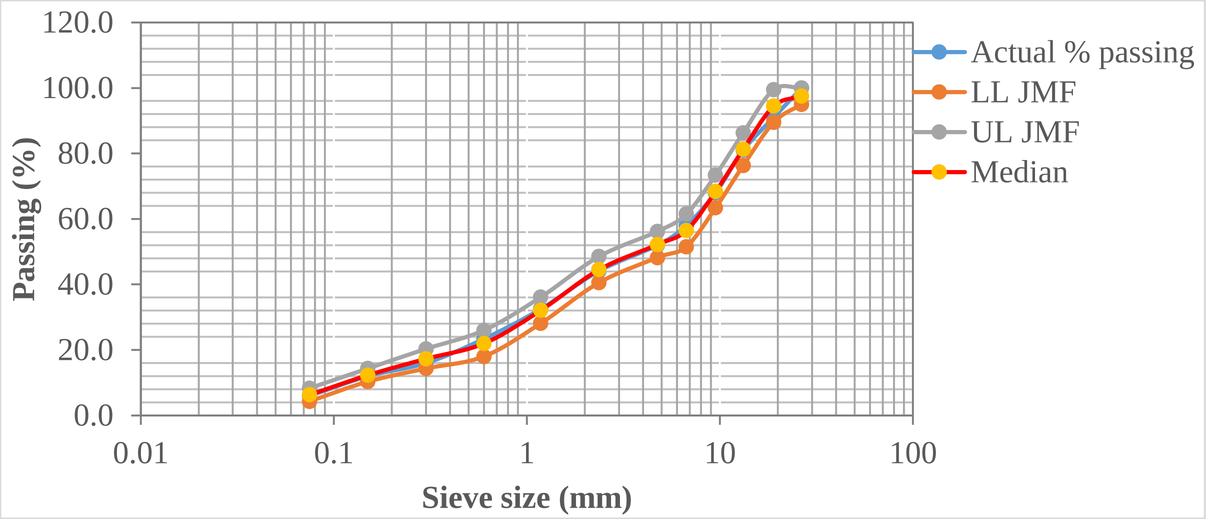

Figure (2): Reclaimed asphalt pavement (RAP) gradation curve

Crushed Stone Aggregate Gradation Test

Figure (3) shows that the average percentage passing curve lies comfortably between the upper and lower specification limits, suggesting that the sample meets the required grading criteria. The smooth, S-shaped curve that spans a broad range of sieve sizes indicates a well-graded material, meaning that it contains a good representation of both coarse and fine particles. This gradation is beneficial in many engineering applications, as it promotes high compaction, stability, and strength while minimizing voids. A well-graded aggregate also enhances workability and reduces the risk of segregation during handling and compaction.

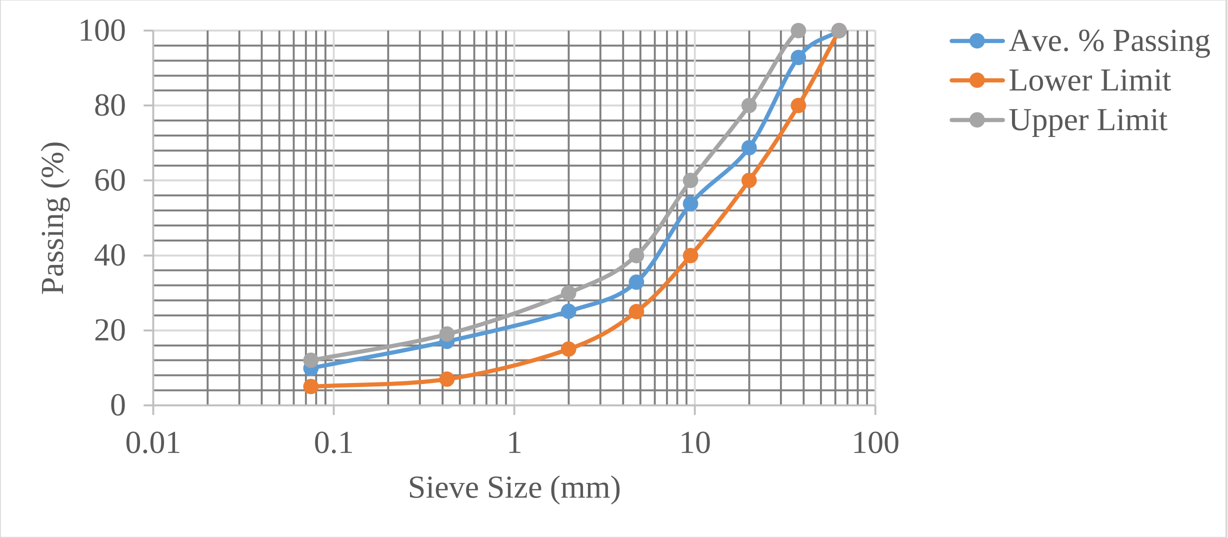

Figure (3): Crushed stone aggregate particle size distribution

The fineness modulus (FM) of an aggregate is a numerical index representing the average particle size of the aggregate material. It's calculated by summing the cumulative percentages of aggregate retained on a set of standard sieves and then dividing by 100 (Eqn. (2)). The FM is critical in determining the suitability of aggregates for various construction applications, such as concrete or mortar production.

F.M= cumulative % retained/100. (2)

The average aggregate fineness modulus (grade modulus) is 2.15. An average fineness modulus (FM) of 2.15 indicates a middle-ground aggregate between coarse and fine aggregates. This FM suggests that the aggregate has a fairly balanced distribution of particle sizes. It's neither too coarse nor too fine, making it versatile for various applications. Similarly, the effective specific gravity of aggregate is 2.974.

Penetration Test

Penetration test is conducted at 25°C according to ASTM D5 (ASTM, 2013) in order to measure binder consistency.

Softening Point Test (Ring and Ball)

This test is performed according to ASTM D36 (ASTM, 2020) to determine the temperature at which the binder achieves a specific viscosity.

Rotational Viscosity (RV)

RV is measured at various temperatures (from 90°C to 170°C, with specific focus on 135°C for workability) using a rotational viscometer (specific standard, e.g. ASTM D4402 (ASTM, 2023), to assess flow behavior at high temperatures.

Dynamic Shear Rheometer (DSR) Test

DSR test is conducted according to AASHTO T315 (AASHTO, 2020). Frequency sweep tests were performed at intermediate temperatures from 31°C to 83°C at an angular frequency of 10 rad/s (1.59Hz) to determine the complex shear modulus (G*) and phase angle (δ). These parameters were used to evaluate rutting potential (*via* G*/sinδ, though results focus on G* and δ) and fatigue characteristics. The rheological properties of asphalt binders are critical for assessing performance in various conditions. DSR testing is widely used to evaluate the visco-elastic characteristics of binder blends, focusing on parameters, such as stiffness (G*), phase angle (δ), and rutting resistance (G*/sinδ) (Farrar et al., 2015; Test, 2010; Zeng et al., 2022). These measures provide insights into the high-temperature rutting performance and fatigue cracking resistance of binders. The Glover-Rowe (G-R) parameter was calculated at 15°C and 0.005 rad/s from Eqn. (3) to assess fatigue and durability properties (King et al., 2012).

$$\text{G-R} = \frac{G*(\cos\delta)2}{\sin\delta} \quad (3)$$

where, G-R indicate rheological parameter, δ is phase angle, G is complex shear modulus.

RESULTS AND DISCUSSION

Effect of WCO on Physical Properties

Penetration Test Results

As shown in Figure (4), the addition of WCO progressively increased the penetration value of the aged (60/80) binder, indicating a significant softening effect. At approximately 1% WCO, the penetration of the aged binder approached that of the virgin bitumen of grade (80/100) binder. An aged bitumen penetration grade of 60/80 is similar as the original bitumen and 0.95% of waste cooking oil are mixed together.

Figure (5) confirms this trend for RTFOT aged binder, suggesting that WCO helps counteract short-term aging embrittlement. Approximately 2.4% WCO was needed for the RTFOT-aged blend to match the virgin bitumen of grade (80/100) penetration, highlighting the impact of aging. The statistical analysis (R^2=1) indicates that the test is reliable, repeatable and consistent.

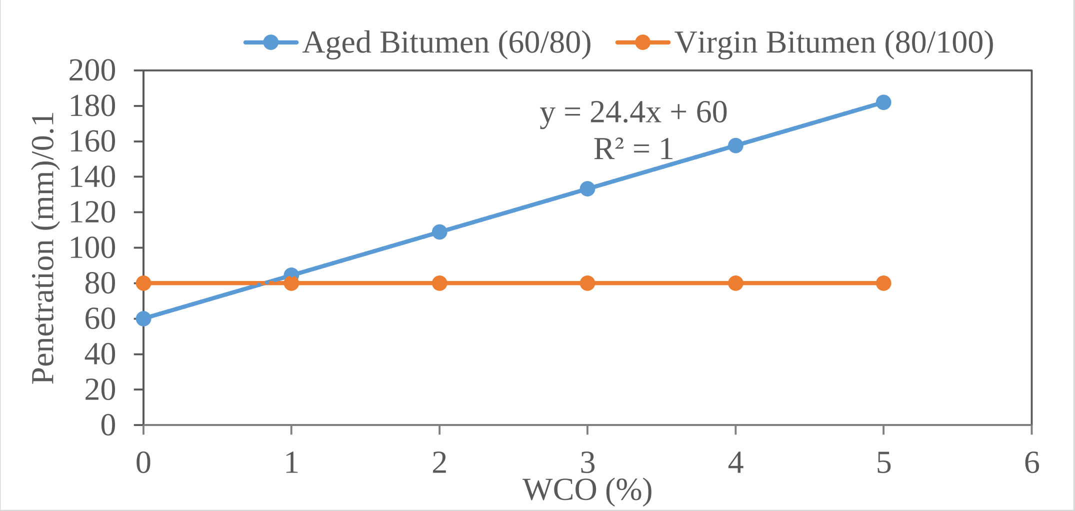

Figure (4): Effect of waste cooking oil on penetration value of bitumen

The addition of Waste Cooking Oil (WCO) to aged bitumen has a significant impact due to internal chemical and physical reactions. Aging leads to the oxidation of bitumen, which creates harder and brittle asphaltenes, reducing its malleability and flexibility (Zargar et al., 2012). When WCO is introduced, its unsaturated fatty acids and esters interact with these oxidized materials, breaking them down and softening the aged binder. Furthermore, WCO replenishes maltenes, the lighter fractions lost during aging, restoring a balance in the binder's composition and mimicking the properties of virgin bitumen (Asli et al., 2012; Zargar et al., 2012). This rejuvenation reduces the viscosity of aged bitumen, increasing its fluidity and resulting in higher penetration values, as observed in the tests.

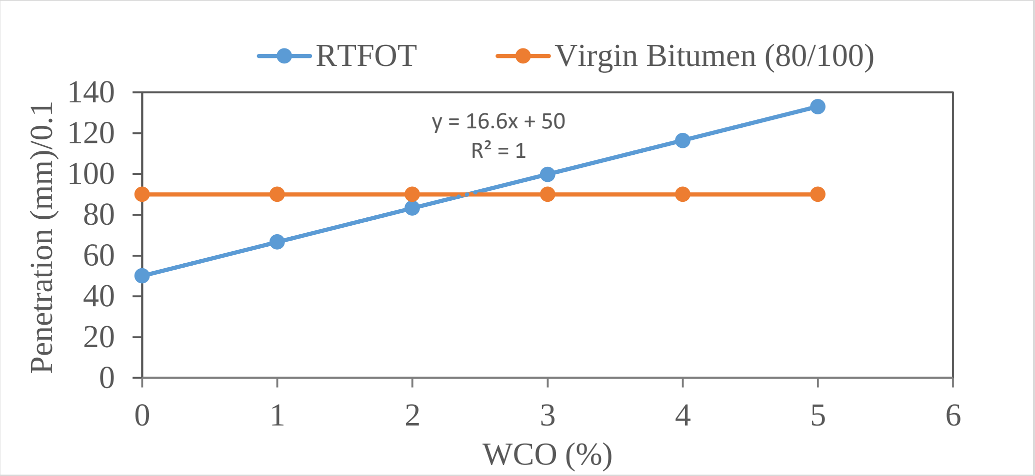

Figure (5): Effect of waste cooking oil on penetration value of bitumen RTFOT aged binder

WCO also improves the bitumen's flexibility, allowing it to better resist cracking and mechanical failures even after undergoing RTFOT aging. Additionally, the rejuvenated bitumen regains its compatibility with aggregates, enhancing the pavement's durability and resistance to defects, like rutting and raveling (Zhang et al., 2017). These changes underscore the effectiveness of WCO as a rejuvenator, which partially reverses the detrimental effects of aging in bitumen and extends the pavement’s lifespan.

Softening Point Test Results

Conversely, the softening point decreased with increasing WCO content (Figure (6)), consistent with the increased penetration and indicating a less viscous binder at elevated temperatures. The untreated aged (60/80) binder had a softening point of 49°C, while that of the virgin (80/100) binder was 46°C. Addition of 1% WCO brought the aged binder's softening point close to the virgin binder's value. This signifies a reduction in the binder's resistance to heat-induced flow.

Figure (7) illustrates that the softening point decreases almost linearly with WCO addition for both unaged and RTFOT-aged conditions. This adjustment helps restore the flexibility and usability of aged asphalt, which often becomes brittle due to oxidation and loss of volatiles. Similarly, the study conducted by Zhang et al. (2017) confirmed that waste cooking oil (WCO) has a notable impact on the softening point of bitumen. Studies showed that adding WCO to aged asphalt can lower its softening point, making it less temperature-sensitive.

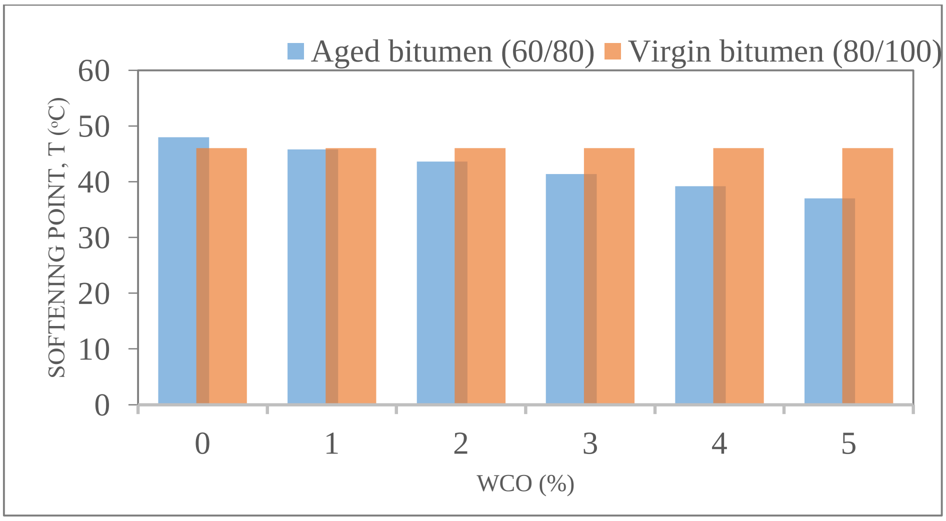

Figure (6): Effect of waste cooking oil on softening value of bitumen

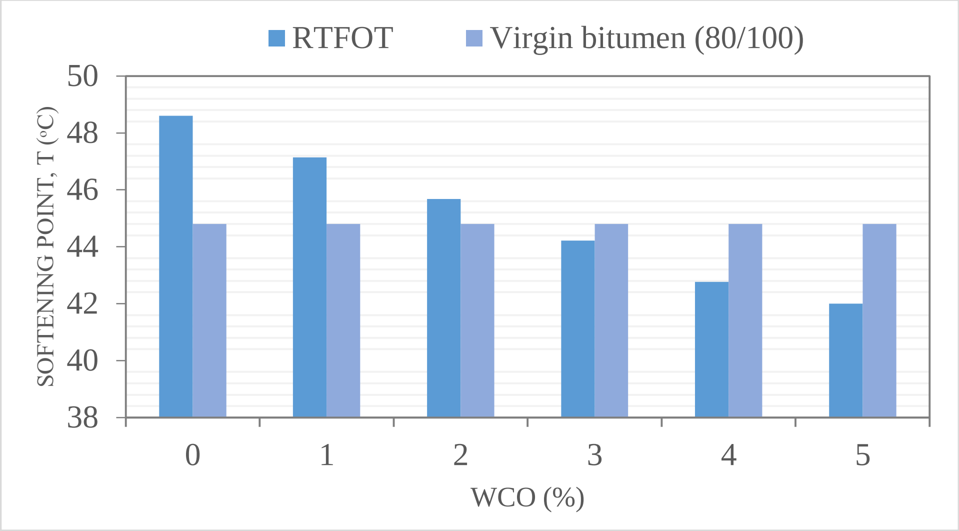

Figure (7): Effect of waste cooking oil on softening value of bitumen RTFOT-aged binder

Viscosity Test Results

Viscosity tests confirmed the softening effect of WCO. Figure (8) and Figure (9) show that increasing WCO dosage significantly reduced the viscosity of the binder blends across a range of temperatures (from 90°C to 170°C). This reduction was observed for both unaged and RTFOT-aged blends. This viscosity reduction implies potential for lowering asphalt mixture production (mixing) and construction (compaction) temperatures, leading to energy savings and reduced emissions (Sengoz & Isikyakar, 2008). The physical test results consistently demonstrate that WCO acts as an effective fluxing agent, reducing the consistency and stiffness of the aged RAP binder. Studies showed that adding WCO reduces the viscosity of aged asphalt, making it easier to work with during construction. This decrease in viscosity is particularly beneficial for improving the workability and mixing properties of asphalt mixtures, especially those containing reclaimed asphalt pavement (RAP) (Jain & Chandrappa, 2023).

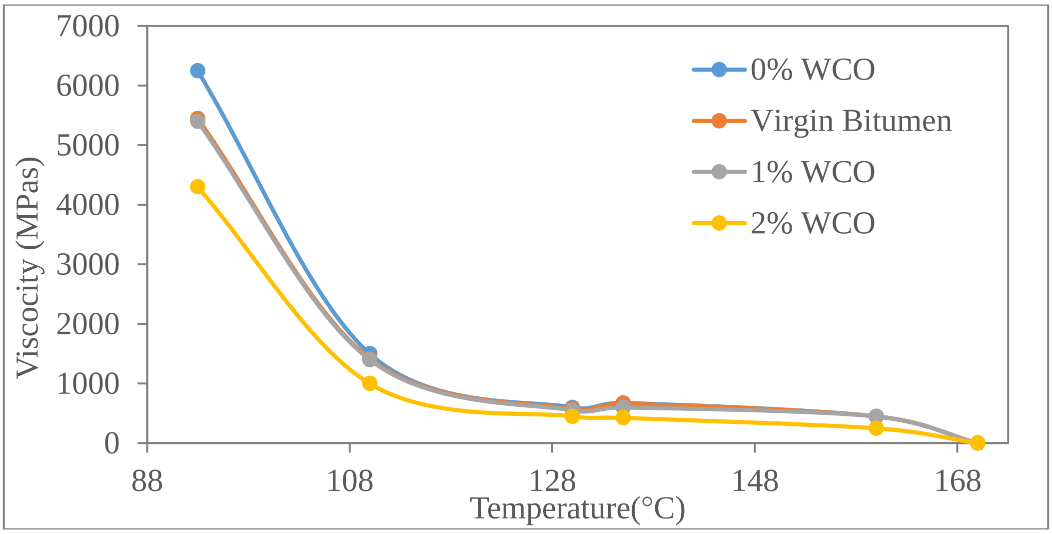

Figure (8): Effect of waste cooking oil on viscosity value of bitumen

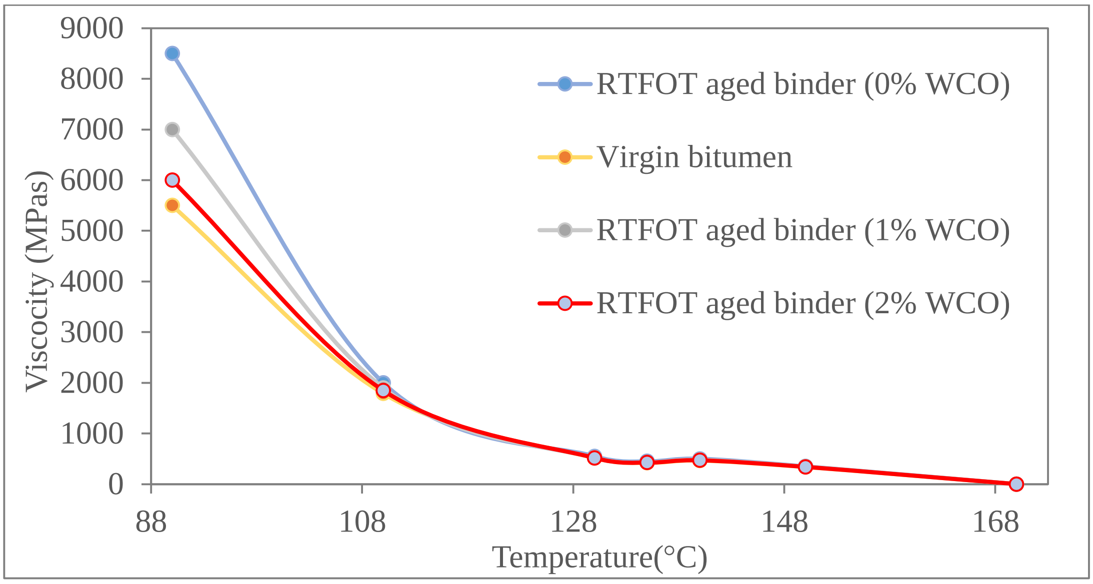

Figure (9): Effect of waste cooking oil on viscosity value of bitumen RTFO aged binder

At the control temperature of 135°C, the viscosity behavior of both unaged and RTFO-aged bitumen binders shows a clear influence from the addition of Waste Cooking Oil (WCO). In the unaged condition, the viscosity of the virgin bitumen is approximately 620 MPa, while the 0% WCO binder used as the control exhibits a slightly higher viscosity of around 650 MPa. The incorporation of WCO results in a noticeable reduction in viscosity, with the 1% WCO binder measuring about 590 MPa and the 2% WCO binder showing the lowest viscosity at approximately 500 MPa. This trend suggests that WCO enhances binder workability at the mixing temperature.

Similarly, in the RTFO-aged condition, viscosity values increase due to oxidative aging, but the softening effect of WCO remains evident. The RTFO-aged virgin bitumen has a viscosity of about 700 MPa, while the aged 0% WCO binder increases slightly to around 730 MPa, With the addition of WCO, the viscosity of the aged binders decreases to approximately 670 MPa for 1% WCO and 610 MPa for 2% WCO. These results indicate that the use of WCO, particularly at 2%, not only improves the binder’s initial workability, but also mitigates the stiffening effects of short-term aging. Overall, at 135°C, the inclusion of WCO leads to a consistent reduction in viscosity by up to 20%-25% compared to the control binder, demonstrating its potential to enhance construction efficiency and performance.

Effect of WCO on Rheological Properties

Complex Shear Modulus (G*)

Figure (10) shows that G* decreases significantly with increasing temperature and increasing WCO content for the unaged blends. The untreated aged binder exhibited the highest stiffness (G*), while WCO addition systematically reduced it. After RTFOT aging (Figure (11)), G* values increased for all binders, reflecting the stiffening effect of short-term aging. The graphs illustrate the variation of the complex shear modulus (G*) of virgin and modified bitumen with temperature, highlighting the effect of Waste Cooking Oil (WCO) content. As temperature increases from 30°C to 80°C, all binders show a rapid decrease in G*, indicating reduced stiffness and increased susceptibility to deformation.

At 30°C, the 0% WCO binder (control) exhibits the highest G* value, approximately 370 kPa, demonstrating its relatively high stiffness. In contrast, the virgin bitumen and binders modified with 1% and 2% WCO show significantly lower stiffness, with G* values around 150 kPa, 130 kPa, and 110 kPa, respectively. This trend continues across the temperature range, where WCO-modified binders consistently display lower modulus values than the unmodified control.

By 45°C, all binders converge to values below 50 kPa, and beyond 60°C, the differences become minimal, with G* dropping to nearly 10 kPa or less. The 2% WCO binder consistently shows the lowest G* value, indicating a softer binder with reduced resistance to deformation. Overall, the inclusion of WCO, particularly at 2%, leads to a notable reduction in complex shear modulus, suggesting enhanced flexibility, which may be beneficial in mitigating thermal cracking at lower temperatures, but may require further evaluation for high-temperature rutting resistance.

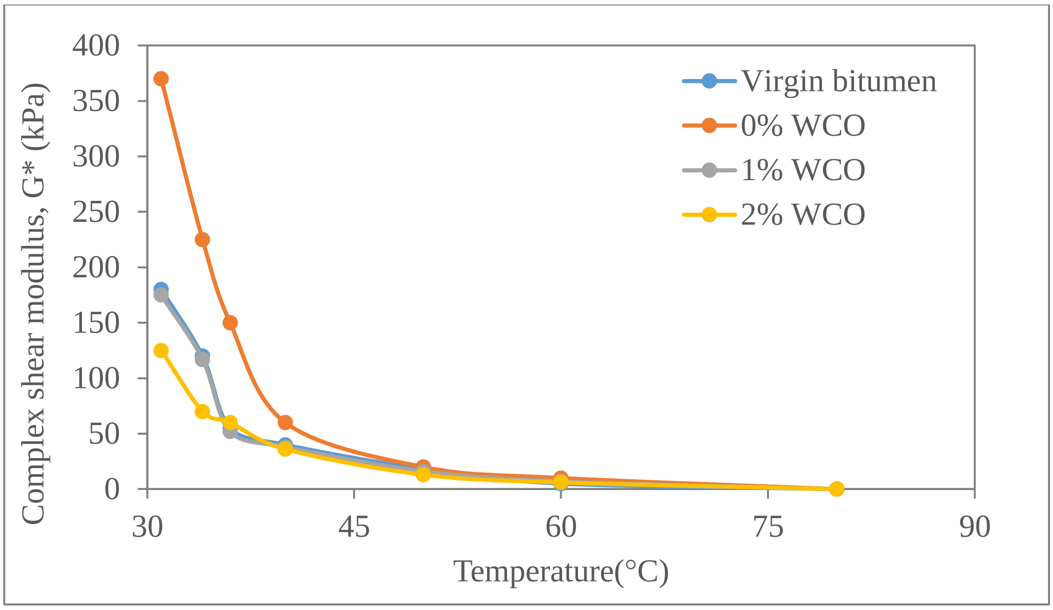

Figure (10): Effect of waste cooking oil on complex shear modulus value of bitumen

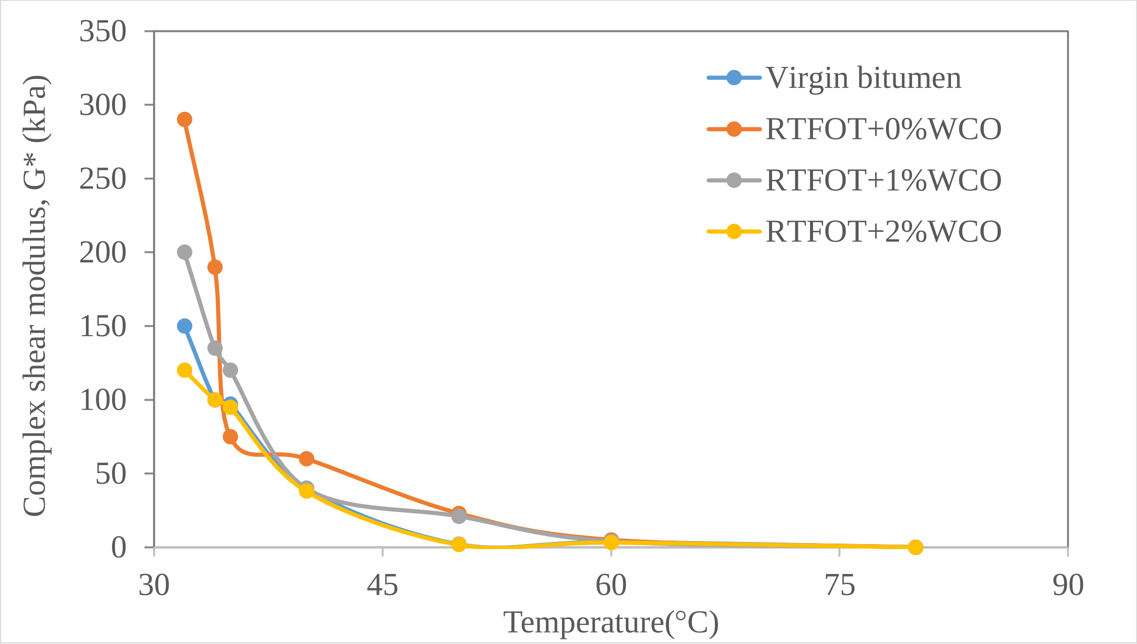

Figure (11): Effect of WCO on complex shear modulus value of bitumen after RTFOT aged binder

Phase Angle (δ)

The phase angle (δ, in degrees) represents the phase difference between stress and strain during oscillatory deformation, serving as a key measure of the visco-elastic properties of a material (Weigel & Stephan, 2016). A δ value of 90° indicates a purely viscous material, while a δ value of 0° corresponds to an ideal elastic solid. Elasticity refers to the binder's ability to store deformational energy at high temperatures, while flexibility describes its ability to dissipate deformational energy through flow at lower temperatures. Under certain conditions, the energy stored per deformation cycle becomes negligible compared to the energy dissipated as heat.

When an optimal amount of waste cooking oil (WCO) is added, the rejuvenated bitumen curve closely resembles that of virgin bitumen. This observation provides a promising basis for further exploration into the use of WCO as a rejuvenator for aged bitumen and reclaimed asphalt pavement (RAP) materials.

The phase angle indicates the visco-elastic balance of the binder. Figure (12) (unaged) and Figure (13) (RTFOT-aged) show that WCO addition generally increased the phase angle, particularly at lower test temperatures (e.g. 31°C-50°C). This suggests that WCO makes the aged binder behave more like a viscous liquid than an elastic solid, which is beneficial for relaxing stresses and improving low-temperature cracking resistance, but could negatively impact rutting resistance (elastic recovery) at high temperatures. The effect was more pronounced at lower temperatures, where cracking is a concern.

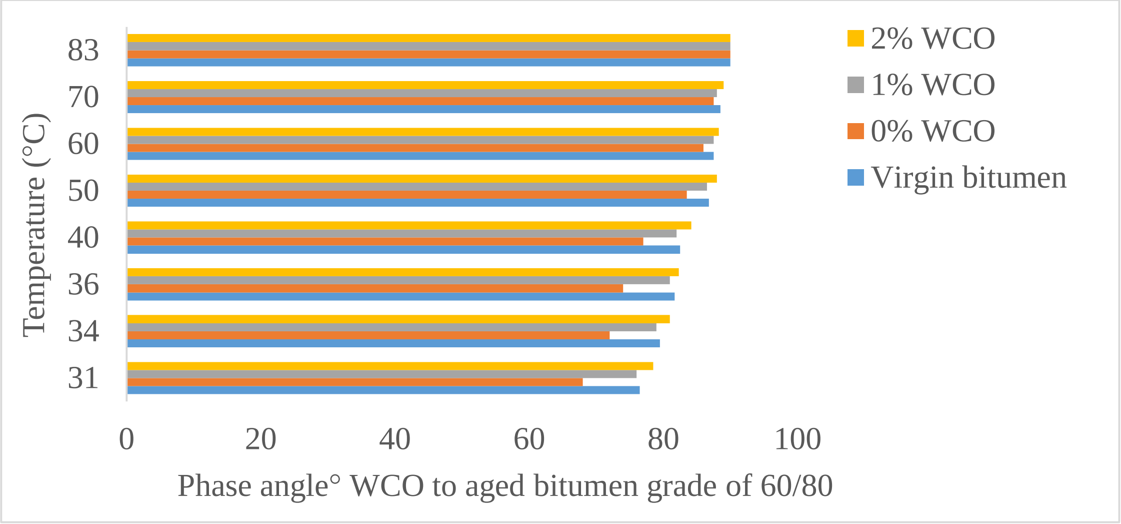

Figure (12): Phase angle curves for virgin bitumen and %WCO to aged bitumen grade of 60/80

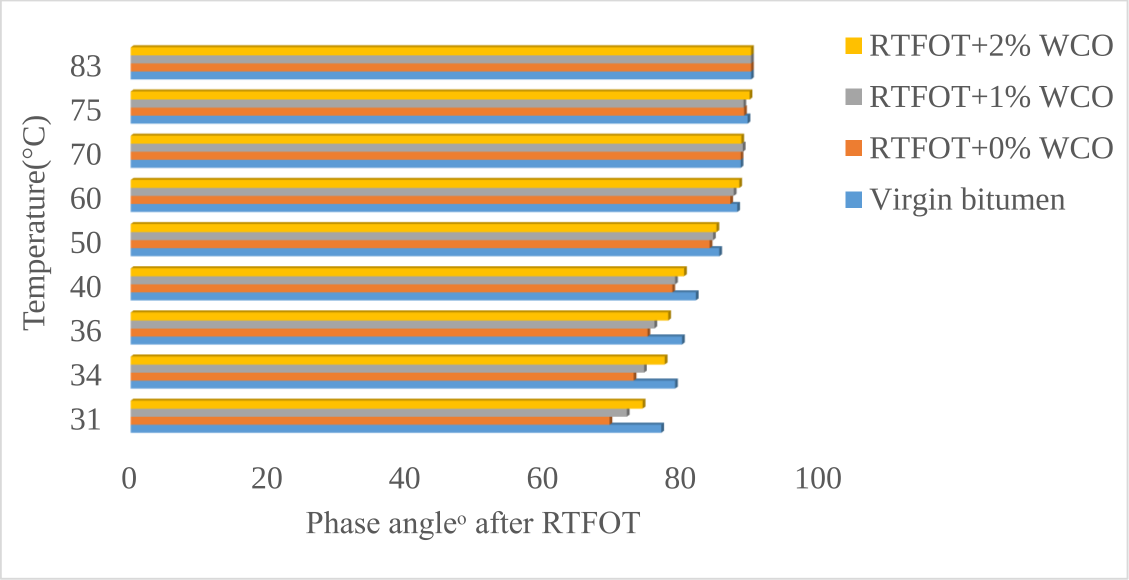

Figure (13): Phase angle curves for before fresh bitumen and after RTFOT aged binder

Rheology of Virgin Asphalt Binder Combined with High Percentages of RAP Binder Rejuvenated with Waste Cooking Oil

Dynamic Shear Rheometer (DSR) Results

The inclusion of reclaimed asphalt pavement (RAP) binder in virgin binder significantly increases the stiffness, as indicated by elevated G*/sinδ values. Figure (16) shows that at 64°C, the unaged 80/100 binder demonstrated a G*/sinδ value of 1.5 kPa, whereas blends containing 40% and 60% RAP exhibited higher values of 6.0 kPa and 10.3 kPa, respectively. This increase in stiffness translates to improved rutting resistance, but also higher susceptibility to cracking.

The addition of waste cooking oil (WCO), however, softens the binder and reduces the rutting resistance parameter. Incorporating 1-day and 11-day used WCO into the 40% RAP binder blend lowered the high-temperature performance grade of the binder to a level comparable to the virgin bitumen grade of 80/100 (Figure (17) and Table 4). This demonstrates the ability of WCO to modify the mechanical properties of aged binders effectively.

Another parameter (the G-R parameter) is used to evaluate the fatigue cracking potential of asphalt binders, with lower values indicating better durability and resistance to cracking. As shown in Figure (14) (unaged) and Figure (15) (RTFOT-aged), WCO addition significantly reduced the G-R parameter compared to the untreated aged binder, suggesting improved durability and fatigue performance. Even after RTFOT aging, the rejuvenated binders maintained lower G-R values than the aged control. This reduction is attributed to both the decrease in stiffness (G*) and the increase in the viscous component of response (higher δ).

Rheological results confirm the softening effect observed in physical tests and provide a further insight into the visco-elastic changes. WCO improves the binder's ability to dissipate energy (higher δ) and reduces overall stiffness (lower G*), which translates to potentially better fatigue and low-temperature performance, as indicated by the lower G-R parameter. However, the increased viscous behavior requires careful consideration for high-temperature performance.

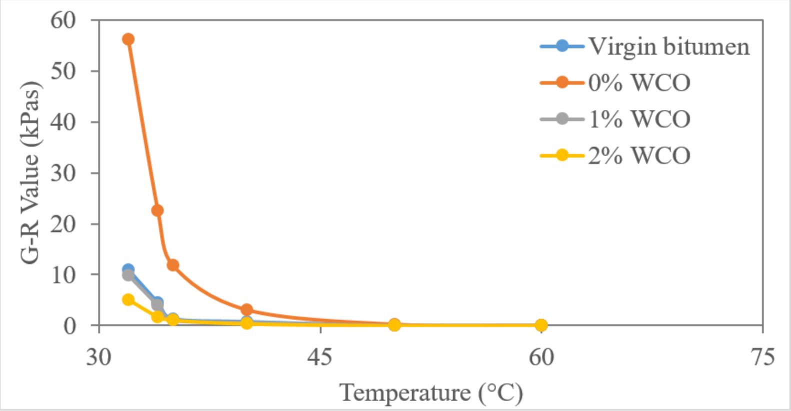

Figure (14): Rheological parameter of aged with virgin bitumen

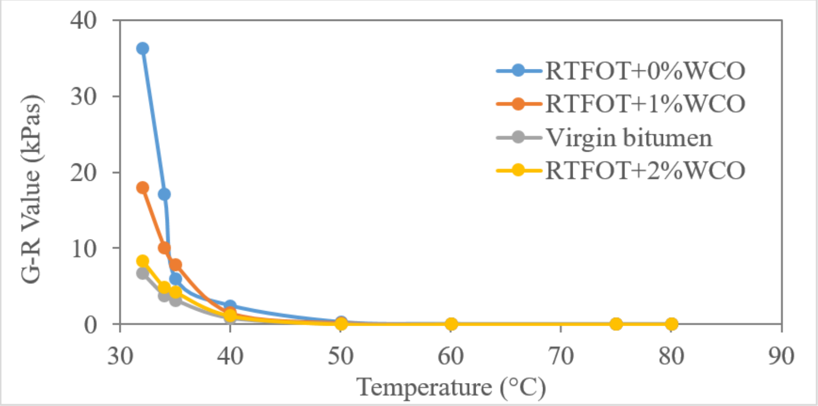

Figure (15): Rheology parameter after RTFOT

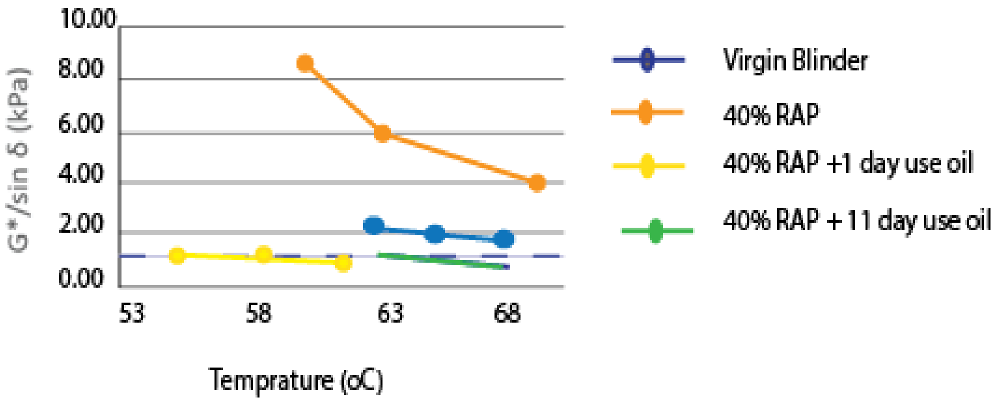

Figure (16): Rutting parameters of the unaged virgin binder and combined unaged RAP binders with and without WCO

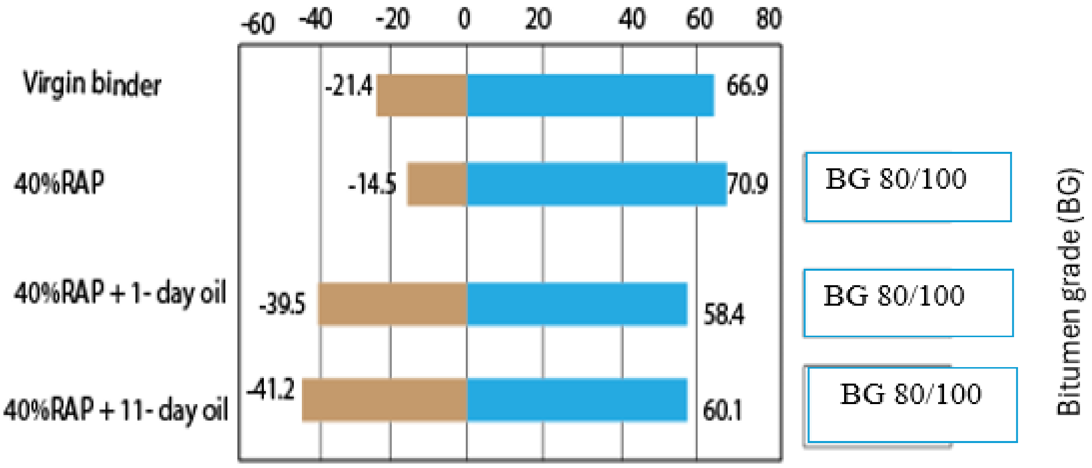

Figure (17): Performance grade of binder blends with and without RAP and WCO

Table 4. Composition of unaged and PAV-aged binders with WCO

Sample	C (mol %)	S (mol %)	O (mol %)
unaged virgin	98.1	0.7	1.2
PAV virgin	97.6	1.3	1.0
Unaged 40% + 1day WCO	96.5	3.0	0.6
PAV 40% + 1day WCO	96.8	2.0	1.2
Unaged 40% + 14day WCO	97.2	1.5	1.4
PAV 40% + 14day WCO	96.6	2.6	0.8

Statistical Analysis of Tests Results

The physical properties of bitumen under different conditions highlight key trends as shown in Table 5.

A) Penetration

Aged bitumen (60/80) has the highest penetration value (mean: 121.0, standard deviation: 41.7), suggesting significant softening over time. Virgin bitumen (80/100) remains consistent with lower penetration values (mean: 80.0 and 90.0, standard deviation: 0.0), reflecting manufacturing consistency. RTFOT-aged binders exhibit intermediate values (mean: 91.5, standard deviation: 28.3), indicating partial hardening due to oxidation. This illustrates a negative correlation between aging and hardness, where penetration increases as aging progresses.

Table 5. Statistical analysis of physical properties of bitumen

Bitumen physical properties	Variables' condition	Statistical analysis	
		Mean	Std. deviation
Penetration	Aged Bitumen (60/80)	121.0	41.7
	Virgin Bitumen (80/100)	80.0	0.0
	RTFOT	91.5	28.3
	Virgin Bitumen (80/100)	90.0	0.0
Softening Point	Aged Bitumen (60/80)	42.5	3.8
	Virgin Bitumen (80/100)	46.0	0.0
	RTFOT	45.1	2.3
	Virgin Bitumen (80/100)	44.8	0.0
Viscocity	0% WCO	1579.2	2135.7
	Virgin Bitumen	1426.2	1847.8
	1% WCO	1400.0	1836.0
	2% WCO	1070.8	1475.1
	RTFOT aged binder (0% WCO)	1764.3	2811.7
	RTFOT aged binder (1% WCO)	1525.0	2303.3
	RTFOT aged binder (2% WCO)	1372.0	1965.1
	Virgin bitumen	1289.9	1796.1

B) Softening Point

Aged bitumen has a mean softening point of 42.5°C, slightly lower than virgin bitumen (mean: 44.8°C), indicating degradation over time. RTFOT-aged binders display minor reduction in thermal stability, with a mean of 45.1°C. These changes reflect a weak inverse correlation between softening point and bitumen aging, likely driven by structural changes reducing thermal stability.

C) Viscosity

The addition of Waste Cooking Oil (WCO) reduces viscosity significantly, improving workability. For instance, 2% WCO has the lowest viscosity (mean: 1070.8, standard deviation: 1471.5). In contrast, RTFOT-aged binders show elevated viscosity due to oxidation (e.g. 0% WCO post-RTFOT: mean 1764.3, standard deviation 2811.7). WCO moderates this hardening effect, with viscosity levels decreasing as WCO content increases. A strong negative correlation exists between WCO content and viscosity ($r \approx -0.85$), while aging (RTFOT) correlates positively with viscosity ($r \approx 0.70$), particularly at lower WCO levels.

High standard deviations across all conditions (e.g. viscosity for 0% WCO: 2135.7) suggest significant variability, potentially influenced by external factors, such as temperature and mixing homogeneity. These findings offer valuable insights into the effects of aging, WCO addition, and oxidative hardening on bitumen properties, informing decisions for optimizing its performance in applications.

The rheological properties of bitumen change significantly with the addition of Waste Cooking Oil (WCO) and the effects of the Rolling Thin Film Oven Test (RTFOT), as shown in Table 6.

1) Complex Shear Modulus (G)*

Complex shear modulus (G*) values provide key insights. For instance, 0% WCO has a mean G* of 119.3 with a standard deviation of 127.9, indicating considerable variability. The inclusion of 1% and 2% WCO reduces G* to 57.9 and 44.3, respectively, with corresponding standard deviations of 60.2 and 41.2. This reduction demonstrates that WCO enhances the flexibility and workability of bitumen. After RTFOT aging, the modulus increases (e.g. RTFOT+0% WCO reaches a mean of 91.9), which reflects hardening due to oxidation. However, at higher WCO levels, this hardening effect is moderated, as seen in RTFOT+2% WCO (mean of 51.1).

2) Phase Angle (δ)

Phase angle (δ) values also reveal significant trends. Virgin bitumen has a δ mean of 84.1 (standard deviation: 4.5), suggesting elastic behavior. With WCO addition, δ increases slightly to 85.2 for 2% WCO, indicating improved viscous performance. RTFOT-aged samples show minor reductions in δ (e.g. RTFOT+0% WCO drops to 81.4), illustrating the impact of aging on elasticity.

Table 6. Stoical analysis of rheological properties of bitumen

Rheological properties	Variables' condition	Statistical analysis	
		Mean	Std. deviation
Complex shear modulus	0% WCO	119.3	127.9
	Virgin bitumen	59.7	61.9
	1% WCO	57.9	60.2
	2% WCO	44.3	41.2
	RTFOT+0%WCO	91.9	100.7
	RTFOT+1%WCO	74.3	71.8
	Virgin bitumen	56.1	55.4
	RTFOT+2%WCO	51.1	48.7
Phase angle	0% WCO	79.8	7.6
	1% WCO	83.8	4.6
	Virgin bitumen	84.1	4.5
	2% WCO	85.2	4.0
	RTFOT+0% WCO	80.6	7.1
	RTFOT+1% WCO	81.4	6.4
	Virgin bitumen	84.4	4.7
	RTFOT+2% WCO	83.5	5.7
G-R value	0% WCO	15.7	19.8
	Virgin bitumen	2.9	3.9
	1% WCO	2.6	3.5
	2% WCO	1.4	1.8
	RTFOT+0%WCO	7.7	12.1
	RTFOT+1%WCO	4.7	6.2
	Virgin bitumen	1.8	2.3
	RTFOT+2%WCO	2.3	2.9

3) The G-R Parameters

The G-R value, which combines G* and δ to indicate performance, further underscores these observations. Virgin bitumen has a mean of 3.9 (standard deviation: 3.9), whereas 2% WCO reduces it to 2.3 (standard deviation: 3.0), highlighting improved resistance to fatigue cracking. Post-RTFOT aging, G-R values increase (e.g. RTFOT+0% WCO reaches 7.7), reflecting aging-related hardening.

Statistical correlations provide deeper insights. A strong negative correlation exists between WCO content and viscosity (r ≈ -0.85), showing that increased WCO reduces stiffness. Conversely, a positive correlation is observed between aging (RTFOT) and viscosity (r ≈ 0.70), particularly at lower WCO levels, indicating oxidative hardening. High standard deviations across all conditions (e.g. G* for 0% WCO: 127.9) suggest that additional factors, such as temperature or mixing homogeneity, may influence outcomes.

These findings underscore the trade-offs between aging, WCO content, and rheological performance, offering valuable guidance for optimizing bitumen properties in paving applications.

Optimal Dosage and Aging Effects

The findings highlight the importance of determining an optimal dosage of waste cooking oil (WCO) to achieve the desired balance between softening and maintaining performance standards. For unaged binders, a WCO dosage of approximately 1%-1.5% appears suitable based on penetration and softening point comparisons with the virgin bitumen grade 80/100 binder. However, rheological data (G*) suggests that slightly higher amounts of WCO (~2%) might be required to achieve comparable properties after rolling thin-film oven test (RTFOT) aging. The reference to 1.25% likely reflects an average or specific target dosage.

RTFOT aging was observed to significantly increase the stiffness of all binders, including those treated with WCO. While rejuvenation using WCO effectively restores initial properties, it does not prevent subsequent aging. Aging consistently increased Glover-Rowe (G-R) values across all samples. Although WCO addition initially reduced G-R values, indicating rejuvenation, the effects of further aging on these rejuvenated blends need to be considered carefully for long-term durability.

Both short-term (RTFOT) and long-term (pressure aging vessel, PAV) aging resulted in increased stiffness (higher G*) and decreased phase angle (δ) across all binder blends. These changes reflect increased stiffness and brittleness, as expected. The G-R parameter, which integrates both stiffness and brittleness (calculated from G* and δ), consistently increased with aging. Lower G-R values are preferred, as they indicate better resistance to fatigue cracking.

Although WCO addition initially reduced G-R values and improved binder flexibility, aging diminished these benefits over time. This highlights the need for careful consideration of aging effects when evaluating the long-term performance of rejuvenated blends.

Table 7. Comparison of different rejuvenators

Rejuvenator Type	Effect on Penetration	Effect on Softening Point	Effect on Viscosity	Effect on Rheological Properties	Advantage	Disadvantage
HS1 Rejuvenator (Petroleum-based) (Wentong et al., 2021)	Increases penetration to meet bitumen 60/70 standards at about 9% content	Restores softening point to desired levels at about 9% content	Reduces viscosity	Provides good rheological recovery, especially under long-term aging	Effective in restoring aged bitumen properties	May accelerate subsequent aging
Soft Bitumen (Wentong et al., 2021)	Optimal for improving fatigue resistance and rheological performance	Softens aged bitumen effectively, improving workability	Reduces viscosity	Exhibits strong performance in fatigue resistance and rheological recovery	Optimal for fatigue resistance	May not be suitable for all climates
Modified Soybean Oil (RA3) (Nguyen et al., 2024)	Increases penetration	Lowers softening point	Reduces viscosity	Enhances viscous components and reduces stiffness	Renewable resource; improves cracking resistance	Less effective under long-term aging compared to RA1

Waste Engine Oil (WEO) (El-Shorbagy et al., 2019)	Increases penetration, indicating softer bitumen	Lowers softening point, making bitumen more pliable	Reduces viscosity, improving workability	Enhances fatigue life and rheological properties, with some trade-offs in rutting resistance	Utilizes waste materials, environmentally friendly	Potential environmental concerns if not properly managed
Waste Cooking Oil (This study)	Increases penetration, indicating softer bitumen	Decreases softening point, indicating improved flexibility	Reduces viscosity	Enhances rheological properties, reducing short-term aging	Cost-effective, sustainable	May require precise dosage to avoid over-softening

CONCLUSIONS

This study explored the potential of waste cooking oil (WCO) as a rejuvenator for asphalt binders containing high proportions of reclaimed asphalt pavement (RAP) binder under various aging conditions. The experimental results highlighted several key findings regarding the effectiveness and implications of WCO use; major findings can be stated as:

- WCO proved to be an effective softener for high-RAP binder blends, consistently increasing penetration and phase angle (δ), while decreasing the softening point, viscosity, and complex modulus (G*). These changes confirmed its capability as a rejuvenator. However, optimizing the dosage is essential to achieve a balance between improving flexibility and maintaining adequate rutting resistance (G*/sinδ) at high service temperatures. A dosage of approximately 2%-3% WCO appears suitable based on the restoration of conventional properties and its influence on rheology.
- Laboratory aging through RTFOT and PAV tests showed increased stiffness and reduced flexibility across all binder samples. While WCO mitigated initial stiffness and short-term aging effects, particularly in viscosity, its long-term effectiveness under extended oxidative aging requires further exploration.
- Another significant benefit of WCO was the reduction in viscosity, which facilitates lower mixing and compaction temperatures for high-RAP mixtures. This improvement offers potential energy savings and environmental benefits, making WCO a viable option for sustainable asphalt binder rejuvenation.
- WCO exhibits strong promise as a low-cost and sustainable solution for increasing RAP content in asphalt mixtures, particularly in regions, like Ethiopia, where resource efficiency is critical. However, further research is needed to fully understand its long-term performance under aging, variability across WCO sources, and chemical interactions with different binder types. Field trials will be necessary to validate these laboratory findings and assess the practical viability of WCO-rejuvenated high-RAP mixtures.

Data Availability

The data presented in this study is available upon reasonable request from the corresponding author.

Conflict of Interests

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

REFERENCES

AASHTO. (2012). "AASHTO R 28: Standard practice for accelerated aging of asphalt binder using a pressurized aging vessel (PAV)".

AASHTO. (2013). "AASHTO T 240: Standard method of test for effect of heat and air on a moving film of asphalt binder (rolling thin-film oven test)".

AASHTO. (2020). "AASHTO T 315: Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)".

Abdelaziz, A., Amy, E.M., Eyad, M., Edith, A.M., and Kaseer, F. (2022). "Effects of aging and recycling agents on the multi-scale properties of binders with high RAP contents. International Journal of Pavement Engineering, 23 (4), 1248-1270. https://doi.org/10.1080/10298436.2020.1797736

Abdulfatai Adinoyi Murana, J.O., Musa Ahmed Yerima, and Ibedu Kenneth Ejike (2024). "Properties of HMA containing high density polyethylene modified with reclaimed asphalt". Jordan Journal of Civil Engineering, 18 (3), 389-404. https://doi.org/10.14525/JJCE.v18i3.03

Ahmed, R.B., and Hossain, K. (2020). "Waste cooking oil as an asphalt rejuvenator: A state-of-the-art review". Construction and Building Materials, 230, 116985. https://doi.org/10.1016/j.conbuildmat.2019.116985

Airey, G. (1997). "Rheological characteristics of polymer modified and aged bitumens".

Ali, A.W., Mehta, Y.A., Nolan, A., Purdy, C., and Bennert, T. (2016). "Investigation of the impacts of aging and RAP percentages on effectiveness of asphalt binder rejuvenators". Construction and Building Materials, 110, 211-217. https://doi.org/10.1016/j.conbuildmat.2016.02.013

Apostolidis, P., Liu, X., Kasbergen, C., and Scarpas, A.T. (2017). "Synthesis of asphalt binder aging and the state-of-the-art of anti-aging technologies". Transportation Research Record, 2633 (1), 147-153. https://doi.org/10.3141/2633-17

Al-Qadi, I.L., Elseifi, M., and Carpenter, S.H. (2007). "Reclaimed asphalt pavement: A literature review". Illinois Center for Transportation, Rantoul, 7(FHWA-ICT-07-001), 1-23. http://hdl.handle.net/2142/46007

Asli, H., Ahmadinia, E., Zargar, M., and Karim, M.R. (2012). "Investigation on physical properties of waste cooking oil-rejuvenated bitumen binder". Construction and Building Materials, 37, 398-405. https://doi.org/10.1016/j.conbuildmat.2012.07.042

ASTM. (2013). "ASTM D5: Standard test method for penetration of bituminous materials". ASTM International.

ASTM. (2020). "ASTM D36/D36M-14: Standard test method for softening point of bitumen (ring-and-ball apparatus)". ASTM International.

ASTM. (2023). "ASTM D4402/D4402M: Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer". ASTM International.

ASTM. (2024a). "ASTM D2172/D2172M-17e1: Standard test methods for quantitative extraction of asphalt binder from asphalt mixtures". ASTM International.

ASTM. (2024b). "ASTM D5404/D5404M-21: Standard practice for recovery of asphalt binder from solution using the rotary evaporator". ASTM International.

Bajaj, A., Epps Martin, A., King, G., Glover, C., Kaseer, F., and Arámbula-Mercado, E. (2020). "Evaluation and classification of recycling agents for asphalt binders". Construction and Building Materials, 260, 119864. https://doi.org/10.1016/j.conbuildmat.2020.119864.

Board, T.R., National Academies of Sciences, E., and Medicine. (2013). "Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content". The National Academies Press. https://doi.org/doi:10.17226/22554

Castorena, C., Pape, S., and Mooney, C. (2016). "Blending measurements in mixtures with reclaimed asphalt: Use of scanning electron microscopy with X-ray analysis". Transportation Research Record, 2574 (1), 57-63. https://doi.org/10.3141/2574-06.

Cavalli, M.C., Zaumanis, M., Mazza, E., Partl, M.N., and Poulikakos, L.D. (2018). "Effect of aging on the mechanical and chemical properties of binder from RAP treated with bio-based rejuvenators". Composites-Part B: Engineering, 141, 174-181. https://doi.org/10.1016/j.compositesb.2017.12.060

Chen, J.-S., Lee, C.-T., and Lin, Y.-Y. (2018). "Characterization of a recycling agent for restoring aged bitumen". Journal of Materials in Civil Engineering, 30 (8), 05018003. https://doi.org/doi:10.1061/(ASCE)MT.1943-5533.0002388

Copeland, A. (2011). "Reclaimed asphalt pavement in asphalt mixtures: state of the practice [tech. report]". https://rosap.ntl.bts.gov/view/dot/40918

El-Shorbagy, A., El-Badawy, S., and Gabr, A. (2019). "Investigation of waste oils as rejuvenators of aged bitumen for sustainable pavement". Construction and Building Materials. https://doi.org/10.1016/J.CONBUILDMAT.2019.05.180

Ethiopian Road Authority. (2013). "Pavement design manual Volume I, Flexible pavements".

Farrar, M., Sui, C., Salmans, S., and Qin, Q. (2015). "Determining the low-temperature rheological properties of asphalt binder using a dynamic shear rheometer (DSR). "Report 4FP, 8, 20.

Garcia Cucalon, L., Kaseer, F., Arambula, E., Epps Martin, A., Morian, N., Pournoman, S., and Hajj, E. (2018). "The crossover temperature: significance and application towards engineering balanced recycled binder blends". Road Materials and Pavement Design, 20. https://doi.org/10.1080/14680629.2018.1447504

Jäger, A., R., L., Ch, E.-S., and Blab, R. (2004). "Identification of four material phases in bitumen by atomic force microscopy". Road Materials and Pavement Design, 5 (supl.), 9-24. https://doi.org/10.1080/14680629.2004.9689985

Jain, S., and Chandrappa, A.K. (2023). "Critical review on waste cooking oil rejuvenation in asphalt mixture with high recycled asphalt". Environmental Science and Pollution Research, 30 (32), 77981-78003. https://doi.org/10.1007/s11356-023-28098-4

Kaseer, F., Arámbula-Mercado, E., and Martin, A.E. (2019). "A method to quantify reclaimed asphalt pavement binder availability (effective RAP binder) in recycled asphalt mixes". Transportation Research Record, 2673 (1), 205-216. https://doi.org/10.1177/0361198118821366.

Kaseer, F., Martin, A.E., and Arámbula-Mercado, E. (2019). "Use of recycling agents in asphalt mixtures with high recycled material contents in the United States: A literature review". Construction and Building Materials, 211, 974-987. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.03.286

Kaseer, F., Yin, F., Arambula, E., and Epps Martin, A. (2017). "Stiffness characterization of asphalt mixtures with high recycled material content and recycling agents". Transportation Research Record: Journal of the Transportation Research Board, 2633, 58-68. https://doi.org/10.3141/2633-08

King, G., Anderson, M., Hanson, D., and Blankenship, P. (2012). "Using black space diagrams to predict age-induced cracking". 7th RILEM International Conference on Cracking in Pavements, Dordrecht.

Kumbargeri, Y.S., and Biligiri, K.P. (2016). "Rational performance indicators to evaluate asphalt materials' aging characteristics". Journal of Materials in Civil Engineering, 28 (12), 04016157. https://doi.org/doi:10.1061/(ASCE)MT.1943-5533.0001681

Li, F., Wang, Y., and Zhao, K. (2022). "The hierarchical structure of bitumen of different aging states at the molecular level and nano-scale". Fuel, 319, 123791. https://doi.org/https://doi.org/10.1016/j.fuel.2022.123791

Lo Presti, D., Vasconcelos, K., Orešković, M., Pires, G.M., and Bressi, S. (2020). "On the degree of binder activity of reclaimed asphalt and degree of blending with recycling agents". Road Materials and Pavement Design, 21 (8), 2071-2090.

Loise, V., Caputo, P., Porto, M., Calandra, P., Angelico, R., and Oliviero Rossi, C. (2019). "A review on bitumen rejuvenation: Mechanisms, materials, methods and perspectives". Applied Sciences, 9 (20), 4316. https://www.mdpi.com/2076-3417/9/20/4316

Ma, Y., Hu, W., Polaczyk, P.A., Han, B., Xiao, R., Zhang, M., and Huang, B. (2020). "Rheological and aging characteristics of the recycled asphalt binders with different rejuvenator incorporation methods". Journal of Cleaner Production, 262, 121249. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.121249

Margaritis, A., Tofani, G., Jacobs, G., Blom, J., Tavernier, S., Vuye, C., and van den bergh, W. (2019). "On the applicability of atr-ftir microscopy to evaluate the blending between neat bitumen and bituminous coating of reclaimed asphalt". Coatings, 9 (4), 240. https://www.mdpi.com/2079-6412/9/4/240

Matolia, S., Guduru, G., Gottumukkala, B., and Kuna, K.K. (2020). "An investigation into the influence of aging and rejuvenation on surface free energy components and chemical composition of bitumen". Construction and Building Materials, 245, 118378. https://doi.org/10.1016/j.conbuildmat.2020.118378

Mohajeri, M., and van de Ven, M.F.C. (2014). "Experimental study into the fundamental understanding of blending between reclaimed asphalt binder and virgin bitumen using nanoindentation and nano-computed tomography". Road Materials and Pavement Design, 15 (2), 372-384. https://doi.org/10.1080/14680629.2014.883322

Mohammadafzali, M., Ali, H.A., Musselman, J.A., Sholar, G., and Rilko, W.A. (2017). "Aging of rejuvenated asphalt binders". Advances in Materials Science and Engineering, 2017, 1-13.

Nguyen, L.N., Truong, V.Q., Dao, D., Nguyen, M.H., and Tran, T. (2024). "Effects of rejuvenators and aging conditions on the properties of blended bitumen and the cracking behavior of hot asphalt mixtures with a high RAP content". Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. https://doi.org/10.1177/14644207241236901

Orešković, M., Menegusso Pires, G., Bressi, S., Vasconcelos, K., and Lo Presti, D. (2020). "Quantitative assessment of the parameters linked to the blending between reclaimed asphalt binder and recycling agent: A literature review". Construction and Building Materials, 234, 117323. https://doi.org/10.1016/j.conbuildmat.2019.117323

Osman, K.S., and Taylor, S.E. (2017). "Insight into liquid interactions with fibrous absorbent filter media using low-field NMR relaxometry. prospective application to water/jet fuel filter–coalescence". Industrial & Engineering Chemistry Research, 56, 14651-14661.

Pradhan, S.K. (2023). "Short-term and long-term aging effect of the rejuvenation on RAP binder and mixes for sustainable pavement construction". International Journal of Transportation Science and Technology, 12 (4), 937-954. https://doi.org/10.1016/j.ijtst.2022.09. 005

Rad, F.Y., Sefidmazgi, N.R., and Bahia, H. (2014). "Application of diffusion mechanism: Degree of blending between fresh and recycled asphalt pavement binder in dynamic shear rheometer". Transportation Research Record, 2444 (1), 71-77. https://doi.org/10.3141/2444-08

Radenberg, M., Boetcher, S., and Sedaghat, N. (2016). "Effect and efficiency of rejuvenators on aged asphalt binder: German experiences".

Rahmani, E., Darabi, M.K., Little, D.N., and Masad, E.A. (2017). "Constitutive modeling of coupled aging: Visco-elastic response of asphalt concrete". Construction and Building Materials, 131, 1-15. https://doi.org/10.1016/j.conbuildmat.2016.11.014

Ren, S., Liu, X., Lin, P., Gao, Y., and Erkens, S. (2022). "Insight into the compatibility behaviors between various rejuvenators and aged bitumen: Molecular dynamics simulation and experimental validation". Materials & Design, 223, 111141. https://doi.org/10.1016/j.matdes.2022.11114

Sengoz, B., and Isikyakar, G. (2008). "Analysis of styrene-butadiene-styrene polymer modified bitumen using fluorescent microscopy and conventional test methods". Journal of Hazardous Materials, 150 (2), 424-432. https://doi.org/10.1016/j.jhazmat.2007.04.122.

Shirodkar, P., Mehta, Y., Nolan, A., Dubois, E., Reger, D., and McCarthy, L. (2013). "Development of blending chart for different degrees of blending of RAP binder and virgin binder". Resources, Conservation and Recycling, 73, 156-161. https://doi.org/10.1016/j.resconrec.2013.01.018

Tauste, R., Moreno-Navarro, F., Sol-Sánchez, M., and Rubio-Gámez, M.C. (2018). "Understanding the bitumen aging phenomenon: A review". Construction and Building Materials, 192, 593-609. https://doi.org/10.1016/j.conbuildmat.2018.10.169.

Test, O. (2010). "Determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)". Washington, DC.

Vassaux, S., Gaudefroy, V., Boulangé, L., Soro, L. J., Pévère, A., Michelet, A., Barragan-Montero, V., and Mouillet, V. (2018). "Study of remobilization phenomena at reclaimed asphalt binder/virgin binder interphases for recycled asphalt mixtures using novel microscopic methodologies". Construction and Building Materials, 165, 846-858. https://doi.org/10.1016/j.conbuildmat.2018.01.055

Von Quintus, H.L., Mallela, J., and Buncher, M. (2007). "Quantification of effect of polymer-modified asphalt on flexible pavement performance". Transportation Research Record, 2001 (1), 141-154. https://doi.org/10.3141/2001-16

Weigel, S., and Stephan, D. (2016). "Modelling of rheological and aging properties of bitumen based on its chemical structure". Materials and Structures, 50 (1), 83. https://doi.org/10.1617/s11527-016-0957-7

Wentong, H., Guo, Y., Zheng, Y., Ding, Q., Sun, C., Yu, J.-M., Zhu, M., and Yu, H. (2021). "Chemical and rheological characteristics of rejuvenated bitumen with typical rejuvenators". Construction and Building Materials, 273, 121525. https://doi.org/10.1016/J.CONBUILDMAT.2020.121525

West, R.C., Willis, J.R., Marasteanu, M.O., National Research Council. Transportation Research, B., National Cooperative Highway Research, P., American Association of State, H., Transportation, O., and United States Federal Highway, A. (2013). "Improved mix design, evaluation, and materials management practices for hot mix asphalt with high reclaimed asphalt pavement content". Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_752.pdf

Wu, S.-p., Pang, L., Mo, L.-t., Chen, Y.-c., and Zhu, G.-j. (2009). "Influence of aging on the evolution of structure, morphology and rheology of base and SBS modified bitumen". Construction and Building Materials, 23 (2), 1005-1010. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2008.05.004

Yildirim, Y. (2007). "Polymer modified asphalt binders". Construction and Building Materials, 21 (1), 66-72. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2005.07.007

Yuhong Wang, P.E., Zhao, K., Glover, C., Chen, L., Wen, Y., Chong, D., and Hu, C. (2015). "Effects of aging on the properties of asphalt at the nanoscal". Construction and Building Materials, 80, 244-254. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2015.01.059

Zargar, M., Ahmadinia, E., Asli, H., and Karim, M.R. (2012). "Investigation of the possibility of using waste cooking oil as a rejuvenating agent for aged bitumen". Journal of Hazardous Materials, 233-234, 254-258. https://doi.org/10.1016/j.jhazmat.2012.06.021

Zeng, Z.A., Underwood, B.S., and Castorena, C. (2022). "Low-temperature performance grade characterisation of asphalt binder using the dynamic shear rheometer". International Journal of Pavement Engineering, 23 (3), 811-823.

Zhang, D., Chen, M., Wu, S., Liu, J., and Amirkhanian, S. (2017). "Analysis of the Relationships between Waste Cooking Oil Qualities and Rejuvenated Asphalt Properties". Materials, 10 (5), 508. https://www.mdpi.com/1996-1944/10/5/508

Zhang, H.L., Yu, J.Y., Feng, Z.G., Xue, L.H., and Wu, S.P. (2012). "Effect of aging on the morphology of bitumen by atomic force microscopy". J. Microsc, 246 (1), 11-19. https://doi.org/10.1111/j.1365-2818.2011.03578.x

Zhang, S., Cui, Y., and Wei, W. (2021). "Low-temperature characteristics and micro-structure of asphalt under complex aging conditions". Construction and Building Materials, 303, 124408. https://doi.org/10.1016/j.conbuildmat.2021.124408.