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Performance Evaluation of Bioresource-Based Asphalt Mixtures Modified with Waste Cooking Oil and Ground Tire Rubber

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ABSTRACT

The rapid increase in vehicle population has intensified rutting and fatigue cracking, two critical distresses affecting pavement service life under Malaysia's tropical climate. To address these challenges, this study investigates the potential of bioresource modifiers waste cooking oil (WCO) and ground tire rubber (GTR) to improve bitumen stiffness and elasticity without increasing production cost or environmental footprint. The research was conducted in three phases: (1) characterization of modified bitumen, (2) optimization of mix design using the Marshall method, and (3) performance evaluation through resilient modulus and moisture susceptibility tests. Bitumen with a penetration grade of 80/100 was modified with varying WCO contents (0%, 1%, 2%, 3%, and 4%) and a fixed 20% GTR by bitumen weight. The physical and rheological properties were evaluated through penetration, softening point, and dynamic shear rheometer (DSR) tests, while Marshall Stability, resilient modulus, and tensile strength ratio (TSR) tests assessed mixture performance. The findings demonstrated that the addition of 1% WCO and 20% GTR significantly enhanced bitumen performance, as evidenced by a 42% reduction in penetration, a 31% increase in softening point, and a 79% improvement in resilient modulus at 40 °C (1000 ms). These improvements reflect substantial gains in stiffness and elasticity, confirming the superior rutting and fatigue resistance of the optimized WCO–GTR-modified asphalt bitumen. Overall, the results suggest that WCO and GTR-modified asphalt mixtures offer a cost-effective and sustainable solution for improving pavement durability while promoting waste recycling and environmental sustainability.

Keywords: Asphalt mixture; waste cooking oil; ground tire rubber; permanent deformation; modified bitumen; sustainable pavement

INTRODUCTION

A country's road network is an important part of its economic infrastructure because it makes transportation more efficient, cuts down on travel time, and makes roads safer. The quality of road pavement directly affects the performance of the transportation system, and enhancing pavement durability has emerged as a primary objective in contemporary road building. In Malaysia, the registered car population has reached around 38.7 million, exceeding the human population of about 34.1 million, consequently exerting significant pressure on the nation's current pavement infrastructure. Increasing traffic congestion during peak and festival periods exacerbates pavement deterioration, particularly on roads subjected to substantial traffic volumes and severe environmental conditions. Zhang et al. (2021) states that traffic load, frequency, and environmental conditions are pivotal in influencing the permanent deformation properties of asphalt mixtures. As a result, fatigue cracking and rutting have become major problems that compromise pavement longevity. The fundamental issue lies in the inadequacies of conventional bitumen, which frequently fails to provide adequate stiffness and thermal resistance to endure contemporary loading circumstances (Provatorova & Vikhrev 2020).

To tackle these challenges, investigations have focused on the modification of bitumen using alternative and sustainable materials. Waste Cooking Oil (WCO) and Ground Tire Rubber (GTR) have surfaced as promising modifiers, offering both environmental and economic advantages. Malaysia generates around 40,000 tonnes of WCO and 57,391 tonnes of GTR each year (Rahman et al. 2017), establishing them as plentiful and sustainable materials for use in pavement applications. WCO, a byproduct of the food industry, has been utilized as a rejuvenator to restore aged asphalt bitumens, enhancing flexibility and decreasing brittleness (Li et al. 2021; Niu et al. 2021; Jaya K.P et al. 2019). Nonetheless, high levels of WCO content may result in unwanted softening and diminished resistance to permanent deformation (Zahoor et al. 2021).

Alkuime et al. (2024) conducted a study on the incorporation of waste cooking oil (WCO) into asphalt mixtures, employing the Balanced Mix Design methodology alongside thorough performance evaluations. The findings indicated that WCO enhanced the cracking resistance of the control mixture; however, it diminished its rutting resistance, especially at higher WCO dosages where a statistically significant effect was noted. Luo et al. (2023) performed a thorough review of asphalt bitumens and mixtures modified with waste cooking oil (WCO). Their findings indicate that moderate dosages of WCO enhance low-temperature crack resistance and workability; however, they may decrease high-temperature rutting and fatigue performance if not meticulously balanced.

Conversely, GTR obtained from recycled tires improves elasticity, viscosity, and high-temperature performance, while also promoting waste recycling and resource circularity (Babadopulos et al. 2016; McGovern et al. 2016). Recent investigations into rubberised and bio-resource-based asphalt have demonstrated that the inclusion of ground tire rubber (GTR) can markedly improve rutting and fatigue performance, while also promoting the valorisation of waste tires. Ban et al. (2025) found that crumb rubber-modified asphalt mixtures demonstrated increased stiffness and enhanced resistance to deformation caused by temperature changes compared to traditional mixes. In a similar vein, Aljarmouzi et al. (2022) illustrated that the integration of waste tire rubber with waste/bio-oils can effectively rejuvenate or alter asphalt, all while minimizing the environmental impact, suggesting a promising avenue for bioresource-GTR hybrid systems. Duan et al. (2022) conducted a synthesis of the performance mechanisms of crumb-rubber-modified asphalt, emphasizing the necessity for optimized blending and swelling conditions to ensure the stabilization of GTR in the binder. The work conducted by Zhang et al. (2025) demonstrated that optimizing swelling time enhances the processability of rubberised binders derived from plants, thereby facilitating the extensive application of waste tyres in pavement construction. The collective findings substantiate the current study's emphasis on assessing the performance of bioresource-based asphalt mixtures enhanced with GTR.

Although the individual benefits of WCO and GTR are clearly documented, there is a lack of research exploring their combined effects. The incorporation of GTR into WCO-modified asphalt is expected to counteract WCO's softening tendency while enhancing the reinforcing and elastic properties of rubber. Previous studies have shown that GTR-modified asphalt mixtures provide enhanced rutting resistance in comparison to conventional mixtures (Lee et al. 2018; Zhang et al. 2020). The use of WCO generally leads to a softening of the bitumen and a decrease in rutting resistance, while GTR contributes to increased stiffness and elasticity. Their combined modification establishes a compensatory mechanism, leading to enhanced deformation resistance (Lee et al. 2018; Zhang et al. 2023). The combination of these two modifiers presents a promising synergy that improves performance across both high and low temperatures. The independent study of both WCO and GTR has been conducted, yet their combined modification in the context of tropical pavement conditions has not been thoroughly investigated.

The global transition to sustainable construction has increased interest in bio-based asphalt technologies. The application of WCO and GTR contributes to multiple Sustainable Development Goals (SDGs), such as SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The recycling of industrial and domestic waste into road materials plays a significant role in lowering carbon emissions and enhancing resource efficiency. This investigation aims to improve the rutting resistance of asphalt pavements and promote sustainability through the inclusion of Waste Cooking Oil (WCO) and Ground Tire Rubber (GTR) as bioresource modifiers in bitumen. The findings aim to offer valuable insights into creating pavement materials that are both resilient and environmentally sustainable, specifically tailored for tropical climates.

MATERIALS AND METHODOLOGY

MATERIALS

Bitumen with a penetration grade of 80/100, supplied by PETRONAS, was used as the base bitumen. Table 1 presents the essential properties of the bitumen. The Ground Tire Rubber (GTR) depicted in Figure 1 was obtained from used tires and underwent a mechanical crushing process to reach the specified particle size. The Waste Cooking Oil (WCO) depicted in Figure 2 was sourced from kitchen frying activities and subsequently purified through a filtration process utilizing filter paper, ensuring it serves as a clean modifier for the asphalt mixture. Both GTR and WCO served as modifiers to improve the performance of the base bitumen.

TABLE 1. Properties of Bitumen 80/100

Testing	Specification
Specific Gravity @ 25°C	1.01-1.06
Penetration @ 25°C (mm/10)	80-100
Softening Point (°C)	42-50
Ductility @ 25°C (cm)	100 min

FIGURE 1. Ground Tire Rubber (GTR)

FIGURE 2. Waste Cooking Oil (WCO)

PREPARATION OF MODIFIED ASPHALT BITUMEN

The modified bitumen for this experiment was prepared using the wet blending technique. The mechanical mixer was used to blend the bitumen, WCO, and GTR mixture. WCO was collected from domestic frying sources, filtered with 20 µm paper, and tested (acid value = 1.45 mg KOH/g; viscosity = 74 cP at 60°C). GTR was obtained from a single recycling facility with consistent particle size (0.6 mm) to ensure homogeneity and reproducibility. First, the original bitumen was preheated in an oven at 140°C for 30 to 60 minutes. Simultaneously, the Waste Cooking Oil (WCO) was heated at 140°C for 10 to 20 minutes to eliminate any moisture. Four different percentages of WCO; 1%, 2%, 3%, and 4% by weight of the bitumen were added, along with 20% Ground Tire Rubber (GTR) by weight of the bitumen. The dosage range of 0–4% WCO with 20% GTR was selected based on preliminary optimization showing that beyond 5%, excessive oil content caused phase separation and reduced cohesion. After the WCO and GTR were added to the preheated bitumen, the mixture was further heated to a temperature of 160–170°C and stirred using a high-shear mechanical mixer at a speed of 1500 rpm for 60 minutes to ensure uniform dispersion of the modifiers throughout the bitumen.

BITUMEN TESTING

To evaluate the physical and rheological properties of the modified bitumen, three laboratory tests were conducted: the penetration test (ASTM D5), the softening point test (ASTM D36), and the dynamic shear rheometer (DSR) test (AASHTO T315). These tests are essential for ensuring that asphaltic concrete complies with the Standard Specification for Road Works (JKR/SPJ/2008-S4) requirements. Penetration test was carried to evaluate the consistency and hardness of the specimen. Furthermore, softening point was carried out to measure the softening point of the bituminous material and the dynamic shear rheometer is carried out to determine the rheological properties of asphalt bitumen.

AGGREGATE TESTING

In this research, all aggregate materials underwent rigorous screening processes to ensure the quality of the mixture. Selecting appropriate mineral aggregates was crucial to meeting the specified requirements and ensuring high material quality. Several aggregate tests were conducted to evaluate the quality and suitability of construction aggregates, including crushed stone, gravel, sand, and recycled concrete. The tests performed included the

Aggregate Impact Value (AIV) test, the Los Angeles (LA) Abrasion test, Specific Gravity of Coarse Aggregate, and Specific Gravity and Absorption of Fine Aggregate. The AIV test, as outlined in BS 812, utilized aggregates that passed through a 12.5 mm sieve and were retained on a 10 mm sieve. The aggregates were dried, and the weight of a metal measure was recorded prior to filling it with the aggregate. After compacting the specimen and conducting impact testing, the weight of the aggregates passing through a 2.36 mm sieve was measured and documented. The LA Abrasion test, following ASTM C131, evaluated the toughness and abrasion resistance of the aggregates. The aggregates were dried, weighed, and subjected to 500 revolutions in a drum with steel balls. After the test, the aggregates were sieved, and the weight of the retained aggregates was recorded.

MARSHALL MIX DESIGN

The research used the Marshall Mix Design method to create asphalt mixture specimens with aggregates (coarse, fine, and mineral filler) sourced from Kajang Rock Quarry Semenyih, following the JKR-specified AC10 gradation. Approximately 1200 g of aggregates and filler were heated to 150°C, and bitumen (5% of aggregate weight) was added at 160°C for thorough coating. For compaction, a paper disk was placed in the mold, followed by a mix and a collar. The surface was levelled with a heated spatula, and another paper disk was added on top. A Marshall Compactor applied 75 blows to the specimens, which measured 10.16 cm in diameter and 6.35 cm thick. After cooling for 30-40 minutes, the specimens were extruded from the mold and allowed to cool overnight. Specimens were prepared with bitumen content varying from 5% to 7% in 0.5% increments. Each was tested according to ASTM D2726 and ASTM D6927-15 to assess volumetric properties, stability, and flow, with the process conducted in triplicate for accuracy.

RESILIENT MODULUS TEST

The Resilient Modulus Test, performed in accordance with ASTM D7369, evaluates the stiffness and elastic recovery of bituminous mixtures subjected to cyclic loading. Testing was carried out using the IPC UTM-5P Universal Testing Machine located within an environmental chamber. Cylindrical specimens, created using a gyratory compactor, measured 101.6 mm in diameter and 63.5 mm in height, with an air void content of 4 percent. After a two-hour conditioning period, tests were conducted at temperatures of 25°C and 40°C. The specimens were subjected to cyclic loading with a sinusoidal waveform, comprising five conditioning pulses followed by five loading pulses. Each loading pulse lasted 0.1 seconds, followed by a 0.9-second rest period. Horizontal deformation was recorded using linear variable differential transformers (LVDT), and the modulus was calculated based on the average of the five loading pulses. Various pulse repetition times were selected to simulate conditions of both high and low traffic volume.

MOISTURE SUSCEPTIBILITY TEST

The AASHTO T283 test method, also known as the Indirect Tensile Strength Test, assesses the moisture susceptibility of asphalt mixtures, which is crucial for evaluating their durability in varying weather conditions. The methodology involves preparing 6 cylindrical specimens of the asphalt mixture using selected aggregates and a specified bitumen, followed by compaction with a Superpave Gyratory Compactor. After initial conditioning, specimens are immersed in a 60°C water bath for 24 hours to simulate moisture exposure. Indirect tensile strength testing is then performed on both conditioned and unconditioned specimens using a Universal Testing Machine, measuring the maximum load until failure. The results are used to calculate the Indirect Tensile Strength (ITS) and the Tensile Strength Ratio (TSR) $\geq$ 80 % indicates acceptable resistance to moisture-induced damage, as commonly adopted by most highway agencies, thereby providing valuable insights for optimizing asphalt mixtures for enhanced performance and longevity.

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES BITUMEN

The primary evaluations for determining the physical properties of bituminous materials are penetration and softening point tests. Figure 3 illustrates the effect of different percentages of Waste Cooking Oil (WCO) on the penetration and softening point of modified bitumen. The penetration test findings indicate that at 0% WCO, the bitumen exhibits the greatest penetration value of 81 (0.1 mm), signifying a soft bitumen. As the WCO content rises, the penetration value initially decreases rapidly to 47 (0.1 mm) at 1% WCO, indicating that the bitumen becomes stiffer. Nonetheless, as WCO content grows, the penetration value rises to 58.6 (0.1 mm) at 2% WCO, 63.9 (0.1 mm) at 3% WCO, and 69.4 (0.1 mm) at 4% WCO. This indicates that small increments of WCO enhance stiffness, whereas higher quantities result in a softer bitumen. These findings correspond with prior research, including Niu et al. (2021), which shown that increasing WCO content markedly softens the bitumen.

The softening point results reveal that the unmodified bitumen (0% WCO) has a softening point of 45°C. The addition of WCO results in an initial increase in the softening point, attaining 59°C at 1% WCO, signifying a more rigid bitumen. As the amount of WCO increases, the softening point reduces to 58°C, 55°C, and 53°C for 2%, 3%, and 4% WCO, respectively. The increase in penetration values at higher WCO contents is attributed to the softening effect of excess oil. Excess WCO acts as a softening agent, reducing viscosity and increasing penetration values at higher dosages. When the WCO content exceeded 2%, the softening effects became dominant, leading to reduced stiffness and high-temperature resistance. At higher WCO contents (3–4%), the bitumen became noticeably softer and lost structural cohesion, confirming diminished high-temperature performance. This behavior indicates that excess oil weakens the internal bonding of bitumen, consistent with previous findings by Zahoor et al. (2021). Research by Zhang et al. (2023) indicates that ground tire rubber (GTR) enhances bitumen stiffness; however, the addition of waste cooking oil (WCO) mitigates this effect, resulting in a more manageable substance. The findings of this research corroborate previous research, indicating that high WCO concentrations render bitumen softer and more prone to temperature-induced softening.

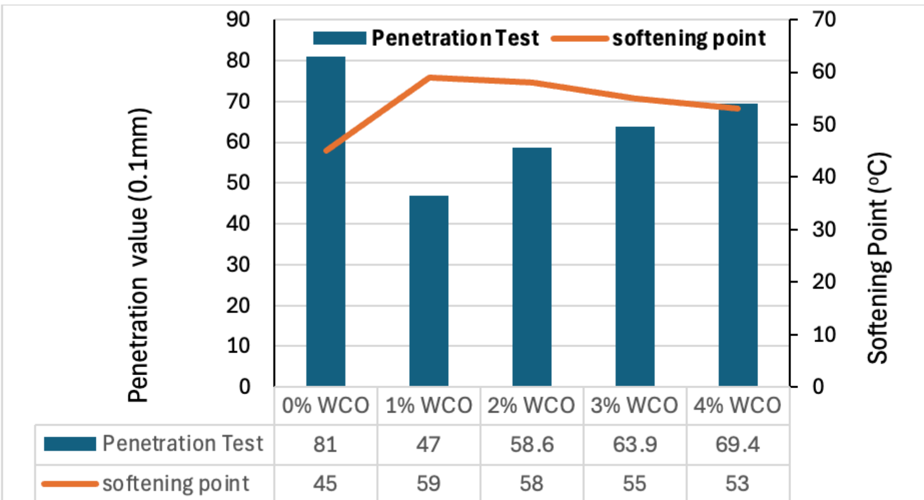

FIGURE 3. Penetration and Softening Point of Bitumen Modified with Varying %WCO

RHEOLOGICAL PROPERTIES BITUMEN

The dynamic shear rheometer (DSR) is used to assess the viscosity and elasticity of asphalt bitumen at medium to high temperatures. AASHTO T315 provides the standard procedure for measuring the rheological properties of polymer-modified asphalt bitumen using DSR. In this research, DSR tests were conducted on modified bitumen specimens containing 0%, 1%, 2%, 3%, and 4% Waste Cooking Oil (WCO) and 20% Ground Tire Rubber (GTR). The test began at an initial temperature of 46°C and increased in 6°C increments until the specimens failed. The results, as shown in Figure 4, indicate that the rutting parameter (G/sin δ*) was evaluated at performance temperatures following AASHTO T315, where unaged binders must exceed 1.0 kPa and RTFO-aged binders exceed 2.2 kPa. The modified binder with 1 % WCO + 20 % GTR satisfied these limits, indicating adequate rutting resistance.

Figure 4 shows that as WCO content increases in the modified bitumen, the Rutting parameter (G/sin δ*) decreases. Conventional bitumen exhibits the lowest rutting (G/sin δ*) compared to modified bitumen specimens. Among the modified specimens, the bitumen with the 1 % WCO + 20 % GTR binder-maintained elasticity up to 100 °C, with G/sin δ = 2.8 kPa, exceeding the rutting criterion, confirming superior high-temperature performance. However, the modified bitumen specimens with 2%, 3%, and 4% WCO exhibited failure at 94°C, 94°C, and 82°C, respectively. This trend aligns with the findings of Niu et al. (2021), who reported that increasing WCO content leads to lower failure temperatures in modified bitumen, which indicates reduced rutting resistance at high temperatures due to the softening effect of the oil. Therefore, further testing on the asphalt mixture's performance was carried out using the optimal ratio of 1% WCO and 20% GTR-modified bitumen, as it demonstrated superior bitumen strength and enhanced rutting resistance, establishing it as the preferable selection for this research. Zhang et al. (2023) support this, noting that reduced WCO concentrations, in conjunction with GTR, yielded superior resistance to deformation and higher durability in asphalt bitumen.

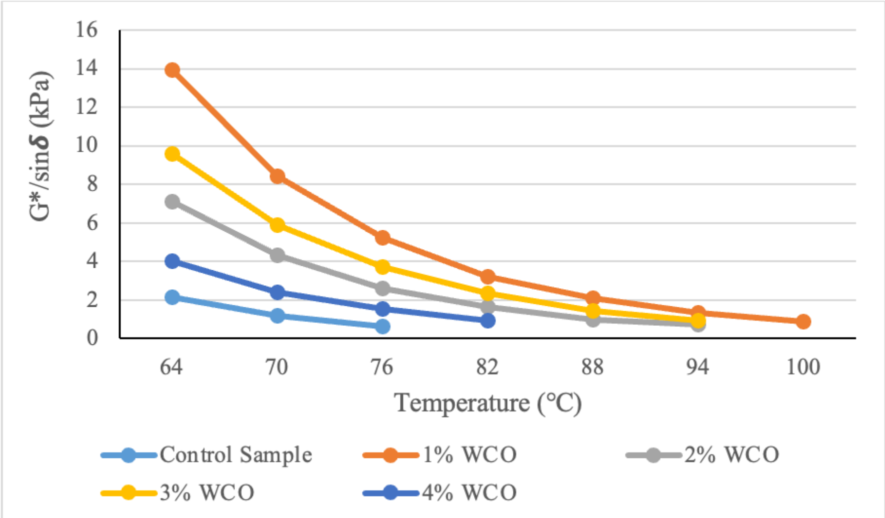

FIGURE 4. Rutting parameter (G/sin δ*) versus Temperature (°C) for Control and Modified Bitumen

AGGREGATE PROPERTIES

Aggregate plays a crucial role in the load transfer capability of pavement, making it essential for construction materials to undergo thorough aggregate testing to ensure quality, performance, and durability. These tests help in selecting suitable aggregates, predicting performance, meeting industry standards, and ultimately contributing to the safety, longevity, and sustainability of infrastructure projects. Based on the results in Table 2, the values obtained for the Aggregate Impact Value (AIV) and Los Angeles (LA) Abrasion tests indicate that both aggregates meet the specifications set by the Public Works Department (JKR). Meeting these specifications confirms that the aggregates possess the required characteristics and performance criteria for their intended application. This ensures that the aggregates will enhance the overall quality, strength, durability, and functionality of the construction or engineering project

TABLE 2. Summary of Aggregate Properties

Aggregate Properties	Specimen	Criteria	Standard
Aggregate Impact Value (AIV) (%)	21.15	< 30	BS 812
LA Abrasion (%)	36.12	< 45	ASTM C131

MARSHALL MIX DESIGN PROPERTIES

Aggregate is essential for the load transfer capability of pavement, making it a crucial element in construction. This analysis highlighted the volumetric properties of Hot Mix Asphalt (HMA) specimens to guide the selection procedure. In this research, Marshall specimens were created with bitumen concentrations between 5.0% and 7.0% by

weight of the AC10 asphalt mixture, in increments of 0.5%. Fifteen specimens were examined, and their bulk density, volumetric properties, stability, and flow values were assessed according to the JKR/SPJ/2008-S4 standards. Upon completing the test, the OBC was determined by averaging the values of maximum stability, bulk density at 3mm flow, air voids at 4%, and voids filled with bitumen (VFB) at 75%, as obtained from the plotted graphs.

The optimum bitumen content (OBC) for the asphalt mixture using modified bitumen was established at 6.5%, in contrast to 6.1% for the mixture with conventional bitumen. Using these OBC values, the Marshall properties including stability, flow, stiffness, voids in total mix (VTM), and voids filled with bitumen (VFB) were assessed to verify compliance to the requirements established by the Public Works Department (PWD). Table 3 shows the Marshall properties for the modified and conventional bitumen mixes. A direct correlation between stability, flow, voids in total mix (VTM), and voids filled with bitumen (VFB) was added to explain that higher stability and VFB indicate a stiffer and more durable mixture, while balanced VTM ensures workability and fatigue resistance. The findings demonstrate that all specimens complied with the JKR/SPJ/2008-S4 specification, validating the performance, durability, and suitability of the asphalt mixtures for their designated application.

TABLE 3. Volumetric Properties of Design Mixture

Parameter	Control Mix	GTR/WCO Modified Mix	Criteria	Remarks
Stability (N)	10200	10520	>8000	Passed
Flow (mm)	3.2	3.25	2.0 – 4.0	Passed
Stiffness (N/mm)	3188	3237	>2000	Passed
VTM (%)	4	4.5	3.0 – 5.0	Passed
VFB (%)	75	76	70 – 80	Passed

RESILIENT MODULUS

The resilient modulus test is a crucial assessment conducted on asphalt mixes for pavement design and construction. It assesses the material's capacity to withstand deformation while recovering to its original form. During the test, horizontal and vertical deformations are measured from opposing sides of the specimen, and the resilient modulus is computed appropriately. The research compared asphalt mixtures utilizing unmodified bitumen with those incorporating GTR/WCO modified bitumen at test temperatures of 25°C and 40°C. At 25°C, the resilient modulus denotes the mixture's fatigue resistance, but at 40°C, it indicates rutting resistance. Testing was performed utilizing load repeats of 1000 ms and 3000 ms to replicate high and low traffic volumes, respectively.

Table 4 illustrates the effect of temperature and repetition period (ms)on the resilient modulus (MR) of both control and GTR/WCO modified asphalt mixtures. At 25°C, the resilient modulus of the control mixture decreases with increasing repetition period, from 1958 MPa (1000 ms) to 1753 MPa (3000 ms). similarly, the modified asphalt mixture demonstrates a reduction in MR, from 2222 MPa (1000 ms) to 2037 MPa (3000 ms). The GTR/WCO modified mixture regularly surpasses the control mixture, demonstrating superior stiffness at all frequencies. This trend is intensified at 40°C, where the control mixture exhibits a significant decrease in MR, from 424 MPa (1000 ms) to 270 MPa (3000 ms). The modified mixture maintains considerably elevated MR values, varying from 758 MPa (1000 ms) to 605 MPa (3000 ms).

The variance in resilient modulus values at elevated temperatures indicates that the asphalt mixture incorporating GTR/WCO modified bitumen exhibits greater stiffness and enhanced resistance to deformation under load compared to the asphalt mixture with unmodified bitumen. The addition of WCO impaired the high-temperature performance of the asphalt mixture, while the incorporation of GTR mitigated the adverse effects of WCO. Although WCO tends to soften the binder at higher dosages, the inclusion of GTR counteracted this by improving stiffness and elasticity. The 1 % WCO + 20 % GTR blend achieved the optimum balance of high stiffness and sufficient flexibility, avoiding excessive softening. The modification of asphalt's viscoelasticity by GTR, through physical and chemical interactions, leads to a mixture characterized by elevated stiffness and modulus, thereby minimizing deformation under load (Niu et al. 2021). Consequently, it is possible to conclude that asphalt mixtures incorporating GTR/WCO modified bitumen have superior high-temperature performance. The decrease in MR at high temperatures is anticipated as a result of the softening of asphalt bitumen and diminished aggregate interlock, aligning with prior research findings (Huang, 2020; Airey et al. 2011). Higher temperatures result in a substantial reduction of stiffness in asphalt mixtures, especially in the control mix, which is unmodified to withstand thermal softening. The reduction in MR with higher repetition period underscores the viscoelastic characteristics of asphalt mixtures, wherein extended loading induces greater deformation (Bahia & Anderson, 1995). The superior performance of the GTR/WCO modified asphalt mixture is attributable to the improved bitumen characteristics, possibly resulting from polymer or additive modifications. These modifiers enhance the mixture's capacity to withstand deformation and thermal softening, especially at higher temperatures. At 40°C, the MR values of the GTR/WCO modified mixture are 79% greater than those of the control mixture at 1000 ms. This further substantiates the efficacy of integrating GTR/WCO in modified bitumen, which improves the high-temperature resistance of the asphalt mixture while preserving elevated stiffness and modulus values (Niu et al. 2021). This finding aligns with previous research demonstrating that modified bitumen improves the stiffness, durability, and resistance to permanent deformation of asphalt mixtures (Ali et al. 2018; Airey et al. 2011). The results indicate that GTR/WCO modified asphalt mixtures demonstrate enhanced resilience modulus values relative to the control mixture at all temperatures and loading frequencies. The incorporation of GTR into WCO-modified bitumen alleviates adverse thermal impacts and enhances high-temperature performance, yielding a stiffer and more durable asphalt mixture. The enhancement in performance is especially pronounced at elevated temperatures, highlighting the efficacy of GTR/WCO modified bitumen in augmenting the durability and rigidity of asphalt pavements. These findings highlight the significance of using modified asphalt technology, specifically GTR/WCO combinations, to enhance pavement performance under varying environmental and loading conditions.

TABLE 4. Resilient Modulus of Design Mixture

Temperature °C	25°C			40°C		
Repetition Period (ms)	1000	2000	3000	1000	2000	3000
Control Asphalt Mixture	1958	1894	1753	424	324	270
GTR/WCO Modified Asphalt Mixture	2222	2069	2037	758	625	605

Figure 5 illustrates the interaction graph and the predicted versus actual graph, which jointly highlight the relationship among resilient modulus (MR), temperature, and frequency, highlighting their significant influence on asphalt mixture performance. The interaction graph demonstrates that MR decreases as the temperature increases from 25°C to 40°C and frequency decreases from 3000 ms to 1000 ms, signifying that higher temperatures soften the asphalt bitumen, thereby decreasing stiffness, while extended loading durations (lower frequencies) intensify deformation. The Response Surface Methodology (RSM) employed a Central Composite Design (CCD) with two factors (temperature and repetition period) at three levels each. ANOVA results confirmed the model significance ($p < 0.05$) with $R^2 = 0.982$ and adjusted $R^2 = 0.969$, indicating excellent model fit. The regression equation for MR (MPa) = 1450 – 22.3 T – 180 P + 0.36 TP + ε describes the relationship between temperature (T, °C) and period (P, ms). At 25°C, the combination exhibits higher MR across all frequencies; however, at 40°C, the modulus markedly decreases, especially at 1000 ms, indicating more prone to deformation under higher temperatures and extended loading. These findings highlight the necessity of modifying bitumen qualities using modifiers such as polymers or crumb rubber to improve stiffness and elasticity in severe environments.

The graph comparing predicted and actual results further confirms these trends, illustrating a strong relationship between model predictions and experimental findings, with most data points closely aligning to the diagonal line. Model accuracy was verified via cross-validation ($R^2 = 0.987$; RMSE = 42 MPa). Future validation will use additional datasets from external laboratories to enhance generalization reliability. The relationship is particularly strong in the lower modulus range (below 1000 MPa), although slight variability is noted at high modulus values (over 1500 MPa). The color gradient in the graph indicates that lower modulus values (blue points) correlate with high temperatures and reduced frequencies, whereas higher modulus values (red points) are linked to reduced temperatures and increased frequencies. The concordance of results from both graphs validates the prediction model's efficacy in representing the relationship between MR, temperature, and frequency, hence confirming its utility in the design of resilient, high-performance pavements under varying environmental and loading scenarios.

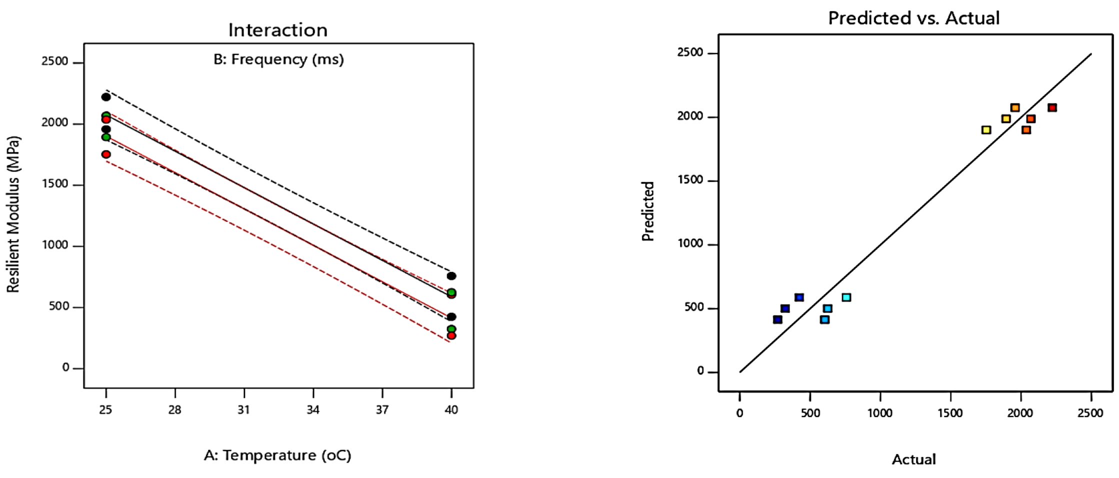

FIGURE 5. RSM analysis: a) Interaction; and b) Predicted vs. Actual While RSM provided good predictive fit, future validation with independent datasets and alternative models is necessary.

MOISTURE SUSCEPTIBILITY

Table 5 and Figure 6 show the moisture susceptibility of the design mixture, comparing the control mixture with the GTR/WCO modified asphalt mixture based on dry strength, wet strength, and Tensile Strength Ratio (TSR%). Moisture susceptibility is an important measure of pavement durability, as moisture exposure can compromise the adhesive contact between asphalt bitumen and aggregate, resulting in stripping. Moisture-induced damage generally manifests as a reduction in cohesiveness within the mixture or a decline in adhesion at the bitumen-aggregate contact (Airey, 2003). The moisture susceptibility test evaluates the reduction in strength caused by stripping damage under accelerated conditioning in a regulated laboratory environment. The standard procedure for assessing the moisture susceptibility characteristics, particularly the tensile strength ratio (TSR) of modified asphalt mixtures, is AASHTO T283.

At 25°C, the control combination attains an average dry strength of 702 kPa, whereas the GTR/WCO modified asphalt mixture exhibits a reduced average dry strength of 625 kPa. The wet strength of the control combination is 616 kPa, but the modified asphalt mixture exhibits a strength of 563.2 kPa. Although the changed asphalt combination exhibits a decrease in both dry and wet strengths, its TSR value is 90.1%, surpassing the control mixture's 87.7%. The AASHTO T283 stipulates that the Tensile Strength Ratio for both combinations must be a minimum of 80% to qualify as resistant to moisture-induced damage (Weldegiorgis & Tarefder, 2014). Table 5 indicates that the TSR values for both the control and modified asphalt mixtures surpass the 80% threshold, demonstrating compliance with the Modified Lottman Test standards and resistance to moisture damage (Gao et al. 2017). The amended asphalt mixture demonstrates a superior TSR value relative to the control mixture, indicating enhanced durability and reduced vulnerability to moisture-related damage (Habbouche et al. 2021). The findings demonstrate that the altered asphalt mixture exhibits enhanced adhesion between the bitumen and the aggregate surface, enabling it to endure significant tensile stresses prior to collapse (Weldegiorgis & Tarefder, 2014). The elevated TSR value of the modified asphalt mixture is due to the improved characteristics of the modified bitumen. Modification of polymers significantly enhances the mechanical properties of asphalt bitumen, especially under high temperatures and low loading rates, hence increasing their resistance to moisture-related damage (Lewandowski, 1994). This enhancement aligns with the function of GTR in augmenting bitumen elasticity and cohesion, mitigating the softening impacts of WCO, which would otherwise diminish the stiffness and durability of the combination (Niu et al. 2021).

TABLE 4. Moisture Susceptibility of Design Mixture

	Dry Specimens					
Specimen	Control Asphalt Mixture			GTR/WCO Modified Asphalt Mixture		
	1	2	3	1	2	3
Air Voids (%)	7.2	7.21	7.09	6.6	6.5	6.6
Dry Strength (kPa)	715.7	696.3	694.5	720.9	606.5	546.9
Average Dry Strength (kPa)	702			625		
	Wet Specimens					
Specimen	Control Asphalt Mixture			GTR/WCO Modified Asphalt Mixture		
	1	2	3	1	2	3
Air Voids (%)	7.0	6.9	6.9	6.6	7.0	6.9
Saturation (%)	75.7	73.5	70.6	70.9	72.6	79.2
Wet Strength (kPa)	599.4	640.4	608.4	621.0	556.5	512.1
Average Wet Strength (kPa)	616			563		
	Tensile Strength Ratio(%TSR)					
TSR%= Average Wet Strength (kPa)/ Average Dry Strength (kPa)	Control			Modified asphalt mixture		
	87.7			90.1		

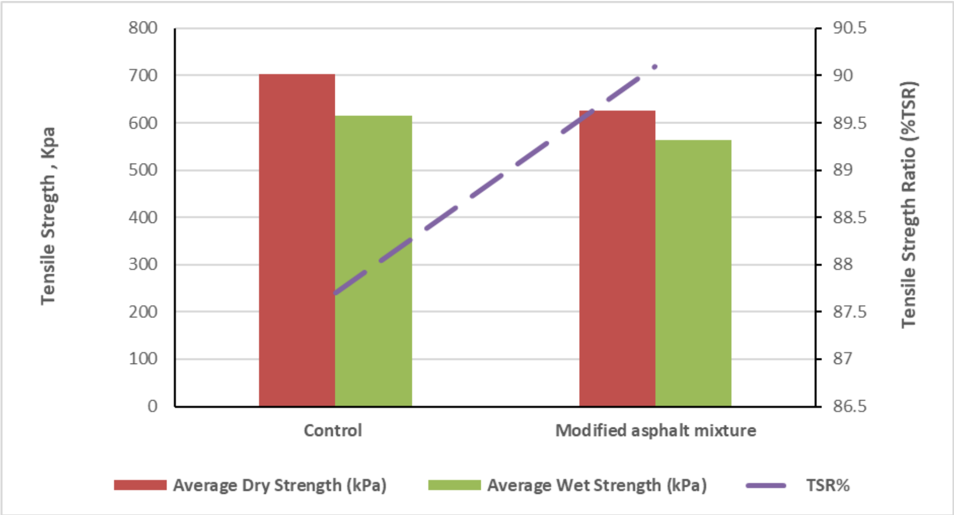

FIGURE 6. Tensile Strength and Tensile Strength Ratio (%TSR)

The response surface method (RSM) was utilized to optimize the correlation between ITSdry and ITSwet regarding TSR, a key indicator of moisture resistance in asphalt mixtures. The surface and contour plots (Figure 7) indicate that high values of ITSdry and ITSwet are associated with optimal TSR, highlighting the significance of both tensile strengths. ITSdry is crucial for preserving structural integrity, whereas ITSwet improves moisture resistance by enhancing bitumen-aggregate adhesion. The presence of water reduces the mixture, as indicated by areas with low ITSwet, leading to a reduction in TSR values (blue area). The trend indicates that attaining balance between ITSdry and ITSwet is crucial for optimizing TSR. The red area denotes the crucial TSR levels at which the mixture demonstrates enhanced moisture resistance performance. Nevertheless, if either ITSdry or ITSwet is excessively low, the TSR markedly decreases, as illustrated in the blue region, signifying diminished performance. This discovery corresponds with research (Weldegiorgis & Tarefder, 2014) that underscores the necessity of enhancing both dry and wet tensile strengths to get resilient asphalt mixtures. The analysis highlights the importance of formulating mixes with high TSR values to enhance resistance to moisture damage. Simultaneously optimizing ITSdry and ITSwet ensures that the mixture endures both dry and wet conditions without compromising its structural or functional integrity. These findings indicate the necessity for precise regulation of material parameters during the asphalt mixture design process for obtaining high-performance and moisture-resistant pavements. While RSM provided good predictive fit, future validation with independent datasets and alternative models is necessary.

In conclusion, the GTR/WCO modified asphalt mixture achieves superior resistance to moisture damage compared to the control mixture, as evidenced by its higher TSR value of 90.1%. This suggests that the use of GTR/WCO modified asphalt bitumen can enhance the durability and performance of asphalt pavements under moisture-related distress. Further research is needed to fully understand the mechanisms by which asphalt modification improves moisture resistance. The findings of this research have important implications for the design and construction of asphalt pavements. These results highlight the potential for GTR/WCO modified bitumen to improve the moisture durability of asphalt pavements, providing a sustainable and resilient solution for modern road infrastructure.

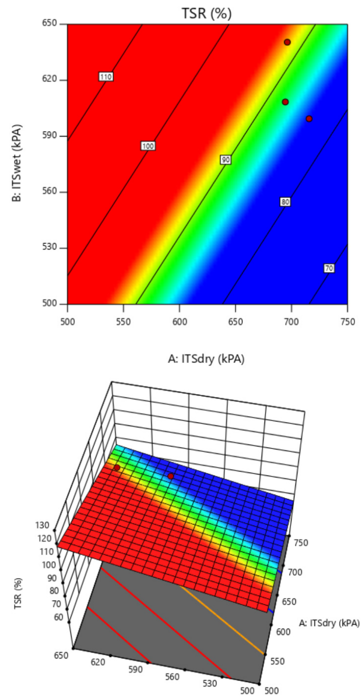

FIGURE 7. Surface and Contour Plot for Moisture susceptibility.

CONCLUSION

Based on the observations from this research, several conclusions can be drawn.;

1. The results of this research illustrate the effectiveness of utilizing waste cooking oil and ground tire rubber as modifiers to enhance the performance of asphalt mixtures. The incorporation of these bioresource-derived additives improved the physical, mechanical, and rheological properties of the asphalt mixtures, resulting in enhanced resistance to rutting, cracking, and fatigue.
2. The combination of 1% waste cooking oil (WCO) and 20% ground tire rubber (GTR) markedly enhances stiffness, elasticity, and resistance to permanent deformation, particularly at higher temperatures, in comparison with conventional asphalt mixtures. The addition of GTR alleviated the negative softening effect of WCO, enhancing the overall mechanical properties of the asphalt bitumen.

Laboratory tests, including Marshall Stability and moisture susceptibility (TSR), demonstrated that the modified asphalt displayed enhanced performance for durability and moisture damage mitigation. This research's findings have significant consequences for the development and maintenance of sustainable and economical road infrastructure, offering a feasible approach to mitigate the rising costs and environmental issues related to conventional asphalt materials.

The scope of this study was limited to a range of 0–4% waste cooking oil (WCO), maintaining a constant 20% ground tire rubber (GTR) content. Future research will extend the WCO dosage up to 8% and vary GTR proportions to determine the optimal blend that balances stiffness and flexibility. Further research are necessary to assess long-term field performance across various traffic and climatic conditions, accompanied by evaluations of cost–benefit and durability through accelerated aging tests. Challenges may arise in the industrial implementation regarding the uniform dispersion of GTR and the consistent blending of WCO. To ensure homogeneity during production, it is advisable to utilize continuous high shear mixing and maintain controlled storage temperatures between 160 and 170 °C. A pilot-scale field trial is set to confirm laboratory findings and assess the long-term rutting and fatigue performance of WCO–GTR-modified asphalt in tropical conditions.

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DECLARATION OF COMPETING INTEREST

None.

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