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Rutting Performance Evaluation Using Waste Cooking Oil and Ground Tire Rubber in Asphalt Mixture

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Abstract

The quality of road pavement is a critical factor in establishing an efficient transportation system. To address issues like fatigue cracking and rutting, significant efforts have been devoted to enhancing pavement quality and adopting innovative design approaches. Recent years have seen a growing interest among traffic engineers in improving asphalt performance by incorporating various additives and substituting traditional asphalt binder materials with recyclable alternatives. This study involves blending bitumen grade 80/100 with varying percentages (0%, 1%, 2%, 3%, and 4%) of waste cooking oil (WCO) and 20% ground tyre rubber (GTR), relative to the weight of the bitumen. The physical and rheological properties of both the base bitumen and the modified binder were assessed through penetration, softening point, and dynamic shear rheometer (DSR) tests. As a result of this modification, the specifications of the modified binder are expected to align with those of bitumen grade 40/50, rendering bitumen 80/100 obsolete due to its subpar performance. The research findings indicate that the optimal content for the modified binder is 1% WCO and 20% GTR. Furthermore, the Resilient Modulus (RM) test demonstrates that asphalt mixtures featuring GTR/WCO-modified binders exhibit a reduced susceptibility to rutting compared to conventional bitumen-based asphalt mixtures. This suggests the potential for more durable and rut-resistant road surfaces, aligning with the broader goal of improving transportation infrastructure.

1. Introduction

Service temperatures, weather conditions, and traffic volume have a significant impact on asphalt, as it is a viscoelastic material. It is ductile and susceptible to plastic deformations and changes in service temperature [1]. To mitigate the impact of external factors on the strength of asphalt mixtures, mixture quality can be enhanced by incorporating recycled or commercially available additives derived from waste materials. The adjustment enables the improvement of inadequate qualities and the optimisation of asphalt mixture performance when compared to current requirements. It produces an asphaltic combination that is enhanced in terms of resistance to moisture damage, rutting, and permanent deformation. In recent decades, an increasing number of pavement engineers and academics have focused on modifying bitumen using waste [2]. Rapid urbanisation and civilisation have generated massive amounts of waste, resulting in significant disposal issues and a negative impact on the environment. Like the majority of developing countries, Malaysia is facing an increase in trash output, as well as challenges with waste disposal. According to Aja & Al-Kayiem [3], local communities generate approximately 30,000 tonnes of municipal solid waste per day, with an average of 1.17kg of waste per capita. Therefore, the utilisation of waste materials for asphalt bitumen is considered a smart strategy for sustainable development [4].

With remarkable success, numerous studies have examined the use of waste cooking oil-modified asphalt. For instance, Sun et al. [5] created an environmentally friendly bio-asphalt with a high WCO content by adding polymers. Road performance tests, DSR, and BBR testing verified that the high WCO content asphalt mixture outperformed the SBS-MA combination in low-temperature and fatigue tests [6]. WCO does not, however, have a completely positive effect on asphalt. According to pertinent research, adding WCO lowers bitumens' complex modulus and creep stiffness, which lowers their ability to withstand deformation and perform elastic recovery [7], [8]. As a result, to use WCO extensively, asphalt bitumen must be modified with a WCO composite material that can compensate for its shortcomings. Due to its remarkable impact on high-temperature asphalt performance, cost-effectiveness, and environmental protection, tyre rubber (GTR) has recently been proposed as a high-performance asphalt modifier [9]-[11]. Some research, as conducted by Mashaan et al. [12], confirmed the effect of waste tyre rubber in asphalt mix and discovered that adding 10% rubber tyre by bitumen weight improves the qualities of the rubber-asphalt mixture over standard asphalt pavement. Given this context, it is believed that the composite modified asphalt bitumen, prepared by incorporating WCO and GTR into the base asphalt in this study, would offer better-performing asphalt mixes. Conventional tests, such as penetration tests and softening points, are used to determine the properties of modified asphalt bitumen. Nevertheless, traditional tests, which are typically used for base asphalt, are insufficient to characterise the performance of the modified asphalt. A relevant rheological test is performed, and the impact of WCO and GTR content on the performance of modified asphalt bitumen is thoroughly examined. Furthermore, the Resilient Modulus (RM) test is used to assess the stiffness and deformation properties of asphalt mixtures under repeated loading, providing useful information to evaluate the potential for rutting in the asphalt mixture.

Moreover, in response to government action, the implementation of Sustainable Development Goals (SDGs) has been encouraged. The use of waste materials, such as waste cooking oil, combined with ground tyre rubber, is one aspect of Sustainable Development Goal 12 (Responsible Consumption and Production). This research also focuses on sustainable methods, where the utilisation of waste materials as a new innovative solution has been emphasised in SGD number 9, "Industry, Innovation and Infrastructure". Finally, one of the aims of SDG 13, "Climate Action" is to reduce climate change by utilising waste cooking oil and ground tyre rubber, which are both substantial contributors to pollution.

2. Materials and Methodology

2.1 Materials

Bitumen of penetration 80/100 provided by PETRONAS was tested, and its basic properties are illustrated in Table 1. GTR was obtained from discarded tyre rubber via mechanical crushing, and WCO was provided from the frying process in the kitchen. All dirt elements were removed through filtering using filter paper.

Table 1 *Properties of bitumen 80/100*

Bitumen 80/100	Specification
Penetration @ 25°C (mm/10)	80-100
Softening Point (°C)	42-50
Ductility @ 25°C (cm)	100 min

2.2 Preparation of Modified Asphalt Bitumen

The preparation of the modified bitumen in this experiment was done using a wet technique. Firstly, the original bitumen was pre-heated in an oven at 140°C for 30-60 minutes. Then, WCO was heated for 10-20 minutes at 140°C to entirely remove the moisture. Next, four different amounts of WCO, which are 1%,2%,3% and 4% by weight of the bitumen and 20% by weight of the bitumen of GTR, were added into the bitumen that was heated. After that, the bitumen was heated to 160-170°C and thoroughly mixed under a high-shear mechanical mixer, stirring for 60 minutes at a rate of 1500 rpm to uniformly disperse the modifiers.

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2.3 Properties Tests of The Bitumen

The physical properties of bitumen were assessed through the tests of ASTM International, 2006 [13] and ASTM International, 2009 [14]. ASTM International, 2008 [15] determined the penetration depth of a standard needle into the bitumen at 25°C in 5 seconds, indicating consistency. ASTM International, 2009 [14] measured the softening point by recording the temperature at which bituminous discs sagged 25 mm under a steel weight. The bitumen was cooled, placed in a ring, and immersed in water at 5 ± 1°C for 40 minutes. A gradual temperature increase was applied, noting when the specimen made contact with the bottom plate. Rheological properties were evaluated using the Dynamic Shear Rheometer (DSR) and the method described in ASTM International, 2008 [15]. It calculated complex shear modulus (G^*) and phase angle (δ), assessing deformation resistance and lag during shear loading, with a target rutting resistance factor ($G^*/\sin\delta$) exceeding 1.0 kPa.

2.4 Aggregate Tests

In the study, various aggregate tests were performed to assess the quality and suitability of construction aggregates, such as crushed stone, gravel, sand, or recycled concrete. These tests included the Aggregate Impact Value (AIV) test, Los Angeles (LA) Abrasion test, Specific Gravity of Coarse Aggregate, and Specific Gravity and Absorption of Fine Aggregate. The AIV test, according to British Standards Institution, 1990 [16], involved using aggregates passing a 12.5 mm sieve and retained on a 10 mm sieve. The sample was dried, and a metal measure's weight was recorded before filling it with the aggregate. After compaction and impact testing, aggregates passing a 2.36 mm sieve were weighed and recorded. The LA Abrasion test, following ASTM International, 2003 [17], assessed aggregate toughness and abrasion resistance. Aggregates were dried, weighed, and subjected to 500 revolutions in a drum containing steel balls. After sieving, retained aggregates were weighed. Specific Gravity of Coarse Aggregate, as per ASTM International, 2001 [18], determined aggregate density. Samples were soaked, weighed in SSD condition, immersed in water to measure container mass, dried, and their dry weight was calculated. Specific Gravity and Absorption of Fine Aggregate, according to ASTM International, 2007 [19], assessed fine aggregate properties. Samples were dried, and specific gravity was determined using a pycnometer filled with distilled water. Wet and dry aggregate masses were measured for absorption calculations.

2.5 Marshall Mix Design

The study utilised the Marshall Mix Design method to fabricate asphalt mixture specimens. Aggregates, encompassing coarse aggregate, fine aggregate, and mineral filler sourced from Kajang Rock Quarry, Semenyih, were categorised based on the JKR [20] - specified AC10 gradation. Around 1200g of aggregates and filler were heated to 150°C, mirroring the temperature at which modified bitumen was also heated. The initial bitumen trial, constituting 5% of the aggregate weight, was mixed into the heated aggregate at 160°C for approximately three minutes to ensure comprehensive coating of the aggregates. For compaction, a paper disk was positioned at the base of the mould, and the mix, along with a collar, was added to the mould. A heated spatula/trowel was employed to level the mixed surface, with another paper disk placed on top. Compaction was achieved through a Marshall Compactor machine, subjecting specimens (10.16 cm in diameter and 6.35 cm thick) to 75 blows on both top and bottom surfaces from a standard hammer drop height of 457 mm. After removing the base plate and paper disks, the specimen was cooled at room temperature for 30-40 minutes before being extruded from the mould using an extrusion jack. The cores were left to cool overnight before subsequent testing. Multiple specimens were prepared, varying the bitumen content from 5% to 7% in 0.5% increments. Each specimen underwent testing in accordance with ASTM International, 1996 [21] and ASTM International, 1976 [22] to assess its volumetric properties, stability, and flow. This process was conducted in triplicate for each trial bitumen content.

2.6 Resilient Modulus Test

The resilient modulus test, as described by ASTM International, 1995 [23], evaluates the elastic recovery and stiffness of bituminous mixtures following cyclic loading. Testing was conducted using the IPC UTM-5P Universal Testing Machine, which is housed in an environmental chamber. With 4% air spaces, cylindrical specimens with a diameter of 101.6 mm and a height of 63.5 mm were formed using a gyratory compactor. Two hours were dedicated to conditioning, and tests were conducted at 25°C and 40°C. Five conditioning pulses and five loading pulses were applied in a sinusoidal wave pattern to the specimens during cyclic loading. There was a 0.9-second rest interval between each 0.1-second loading pulse. Horizontal deformation was measured using linear variable differential transformers (LVDT), and the modulus was calculated based on the average of the five loading pulses. Different pulse repetition times were chosen to simulate high and low-volume traffic conditions.

3. Results and Discussion

3.1 Physical Properties

The key tests for assessing the physical properties of bituminous materials are the penetration and softening point tests. In Fig. 1, penetration test results for modified bitumen with varying percentages of waste cooking oil (WCO) and 20% ground tyre rubber (GTR) are presented. Notably, the modified bitumen with 4% WCO and 20% GTR exhibits the highest penetration value, followed by bitumens with 3%, 2%, and 1% WCO content, and unmodified bitumen. WCO inclusion leads to softer bitumen, while GTR addition increases stiffness, causing a reduced penetration value.

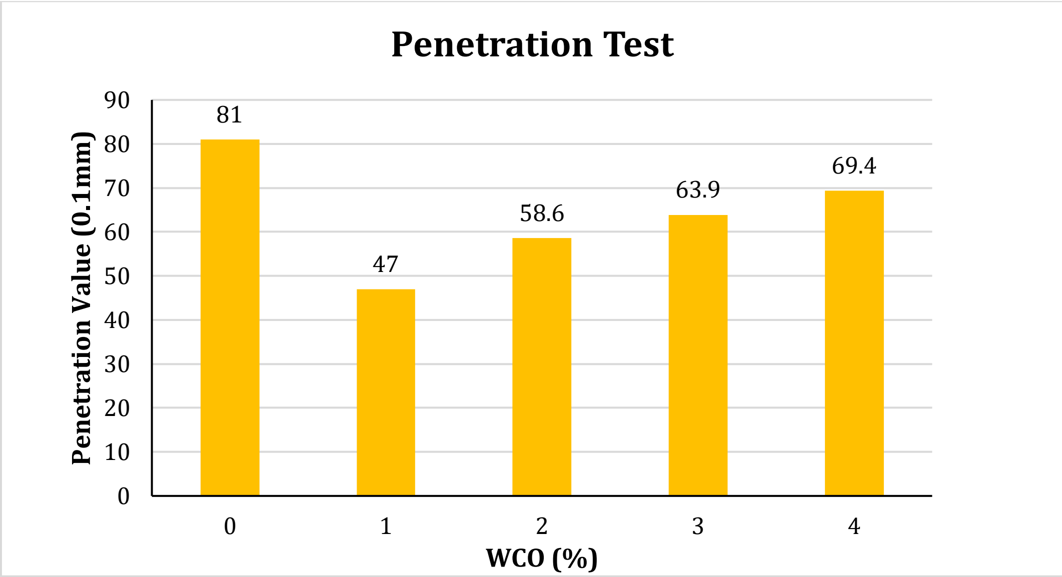

Fig. 1 *Penetration test result*

Fig. 2 illustrates the correlation between the softening point of modified bitumen and modifier concentrations in the bitumen. The results show a significant decrease in softening point as WCO content increases. Among the modified bitumen samples, the one with 1% WCO and 20% GTR content has the highest softening point at 58°C. These findings demonstrate that the addition of WCO makes the bitumen softer to a greater extent. However, all modified asphalt samples exhibit higher softening points compared to the original asphalt, indicating that the inclusion of ground tyre rubber (GTR) enhances the stiffness of the asphalt bitumen, making it more resilient to temperature fluctuations [24].

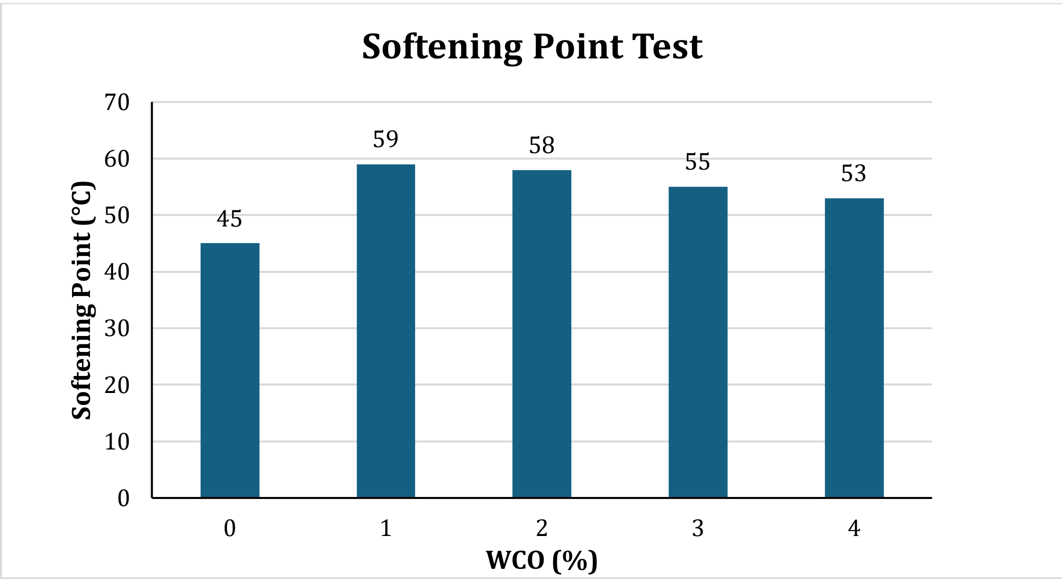

Fig. 2 *Softening point test result*

3.2 Rheological Properties

In the analysis of rutting characteristics, the temperature where $G^*/\sin\delta$ = 1 kPa signifies the maximum temperature for favourable viscoelastic pavement performance in rutting studies. Fig. 3 displays the failure temperature of the modified bitumen in relation to the rutting parameter ($G^*/\sin\delta$). The findings reveal that the modified bitumen with 4% WCO and 20% GTR content exhibits a lower failure temperature compared to the counterparts with 3%, 2%, and 1% WCO content, with temperatures of 82°C, 94°C, and 100°C, respectively.

It's worth noting that increasing WCO content while keeping the GTR percentage constant significantly reduces the rutting resistance of modified asphalt. This occurs because, at high temperatures, asphalt behaves like a purely viscous liquid with poor deformation resistance, leading to a decrease in G^*. Additionally, WCO addition makes asphalt more fluid, further diminishing its rutting resistance. However, at a GTR content of 20%, the impact of WCO on anti-rutting performance becomes more pronounced [24]. Importantly, all the modified asphalt bitumens in this study still exhibit higher rutting resistance than conventional bitumen, indicating their enhanced resistance to rutting deformation even under elevated temperatures.

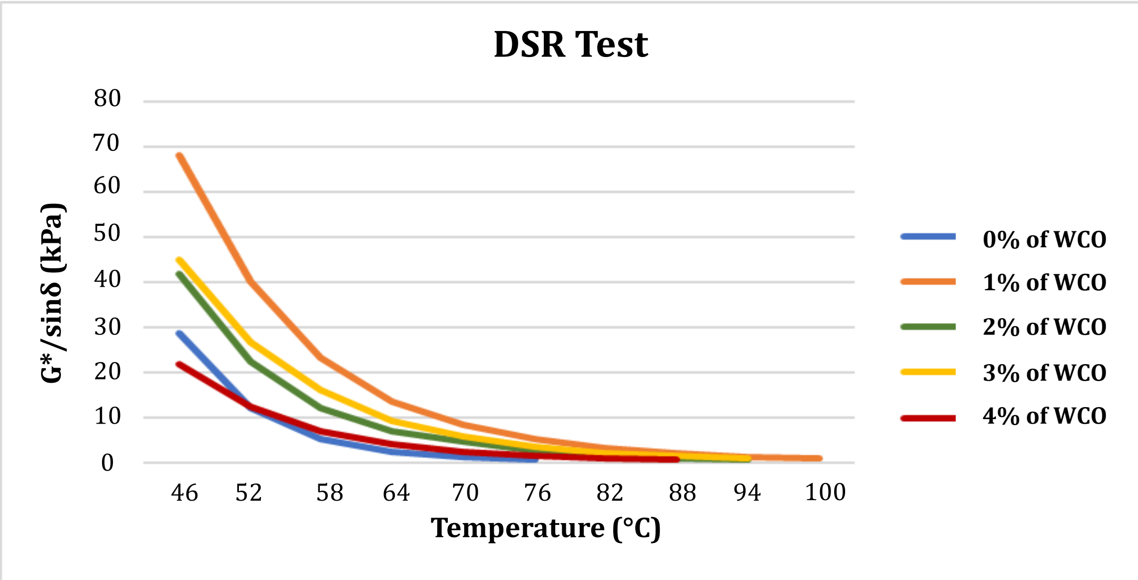

Fig. 3 *DSR test result*

3.3 Optimum Content of WCO and GTR

To minimise road damage, the Public Works Department (JKR) has prohibited the use of bitumen with a penetration grade of 80/100, allowing only concentrated bitumen mixtures for road resurfacing [24]. Consequently, the utilisation of bitumen grade 40/50 in asphalt mixtures proves advantageous. It offers sufficient stiffness and resistance to deformation, making it suitable for withstanding traffic loads and preventing rutting or permanent deformation in asphalt pavements. Moreover, this grade is well-suited for Malaysian weather conditions, ensuring the bitumen remains resilient to heat without becoming overly soft or susceptible to rutting. Consequently, the ideal WCO and GTR content in the asphalt bitumen aims to attain bitumen grade 40/50 characteristics. Table 2 demonstrates that the penetration and softening point values of the modified bitumen with 1% WCO and 20% GTR meet the goal of equivalence to bitumen grade 40/50. Therefore, 1% WCO is deemed the optimal content for enhancing the properties of asphalt bitumen.

Table 2 *Properties of bitumen 40/50*

Bitumen 40/50	Specification
Penetration @ 25°C (mm/10)	40-50
Softening Point (°C)	52-60
Ductility @ 25°C (cm)	100 min

3.4 Aggregate Properties

Aggregates play a crucial role in pavement load transfer capacity. To ensure the quality, performance, and durability of construction materials, it is imperative to subject them to aggregate testing. This process facilitates the selection of suitable aggregates, enables performance prediction, ensures compliance with industry standards, and, most importantly, enhances the safety, longevity, and sustainability of infrastructure projects. As indicated in Table 3, the results for Aggregate Impact Value (AIV) and Los Angeles (LA) Abrasion meet the specifications outlined by the Public Works Department (JKR). Meeting these specifications signifies that the aggregates possess the desired characteristics, properties, or performance criteria for their intended application. This assurance ensures that the aggregates will make a positive contribution to the overall quality, strength, durability, and functionality of the construction or engineering project.

Table 3 *Summary of aggregate properties*

Aggregate Test	Result (%)	Criteria (%)
Aggregate Impact Value	21.16	<30
Los Angeles Abrasion	36.12	<45

3.5 Mixture Design Properties of Marshall

In this study, fifteen different Marshall design mixtures were created by blending mineral aggregates with bitumen percentages ranging from 5% to 7% in increments of 0.5% by weight of the mixture. After conducting stability and flow tests, each specimen underwent specific gravity and void analysis to determine the percentage of total air voids (VTM) and the percentage of air voids filled with asphalt (VFA). The mean values for density, stability, flow, VFA, and VTM were plotted separately against the bitumen content, resulting in smooth curves. The optimum bitumen content was determined at the peak of the stability curve, which yielded a 3 mm flow from the flow curve, 4% VTM from the VTM curve, and 75% VFA from the VFA curve. These values were compared to JKR design specifications.

A prior study by Ahmad et al. [25] found an optimum bitumen content (OBC) of 6.1% for unmodified bitumen asphalt mixtures. In the current study, the tests yielded an OBC of 6.5%. The plotted graphs indicated stability, flow, stiffness, VTM, and VFA values of 10520 N, 3.25 mm, 3260 N/mm, 4.5%, and 76%, respectively, all meeting JKR specifications. Satisfying these volumetric property requirements indicates that the Marshall mix has been designed and produced in line with the specified criteria. Table 4 summarises the volumetric properties of design mixtures corresponding to the mix's OBC, along with the mix design criteria.

Table 4 *Volumetric properties of design mixture*

Parameter	Asphalt Mixture with Unmodified Bitumen	Asphalt Mixture with Modified Bitumen	Criteria
OBC (%)	6.1	6.5	-
Stability (N)	10200	10520	>8000
Flow (mm)	3.2	3.25	2-4
VTM (%)	4	4.5	3-5
VFA (%)	75	76	70-80

3.6 Resilient Modulus

The resilient modulus test is a crucial assessment for asphalt mixtures used in pavement construction, evaluating their ability to resist deformation and recover their original shape. This test compared asphalt mixtures: one with an unmodified bitumen (Sample 1) from a previous study by Ahmad et al. [25], and the other with a GTR/WCO modified bitumen (Sample 2) tested at temperatures of 25°C and 40°C. Resilient modulus values at 25°C indicate fatigue resistance, while those at 40°C signify rutting resistance. The test employed pulse repetitions of 1000ms and 3000ms to simulate high and low traffic volumes, respectively.

At 25°C (see Fig. 4), asphalt mixtures with the modified bitumen exhibited higher resilient modulus values for both low and high traffic volumes compared to mixtures with unmodified bitumen. Sample 2, particularly at a pulse repetition period of 1000ms, showed the least fatigue susceptibility with values of 2222 MPa, while Sample 1 had values of 1958 MPa. The difference in modulus becomes more pronounced at 40°C (see Fig. 5), with Sample 2 having superior values of 625 MPa at 1000ms, while Sample 1 had 424 MPa.

These results suggest that asphalt mixtures with GTR/WCO modified bitumen are less prone to rutting compared to those with unmodified bitumen. The presence of WCO affected high-temperature performance, but GTR countered this, enhancing stiffness and reducing deformation under load. Consequently, GTR/WCO modified bitumen offer superior high-temperature performance. In summary, evaluating resilient modulus enables engineers to assess rutting and fatigue resistance, thereby aiding in the selection of materials and the design of pavements that can withstand anticipated traffic and environmental conditions throughout the pavement's design life.

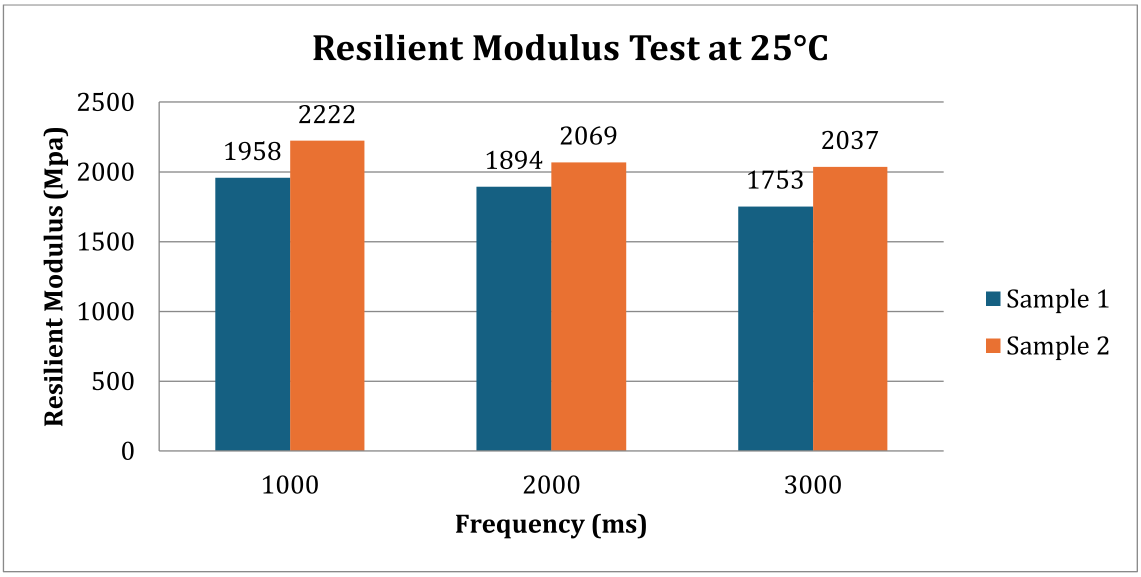

Fig. 4 *Resilient modulus test result at 25°C*

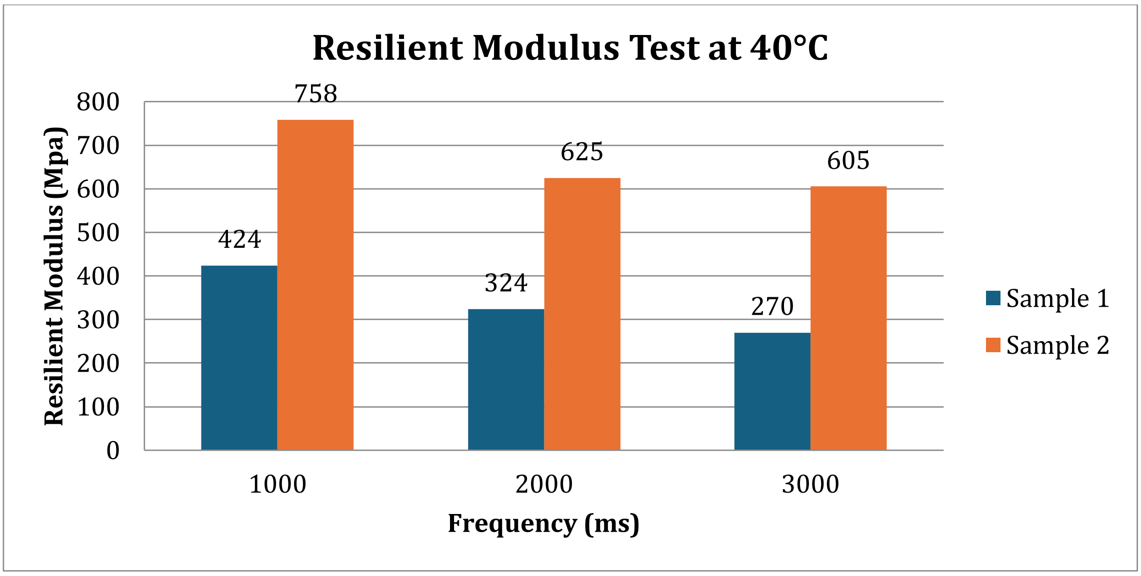

Fig. 5 *Resilient modulus test result at 40°C*

4. Conclusions

In summary, this study successfully modified asphalt bitumen using a combination of 1% waste cooking oil (WCO) and 20% ground tyre rubber (GTR), achieving equivalence to bitumen grade 40/50, as confirmed by penetration and softening point tests. All the lab tests have been prepared and conducted according to the standard and specifications as published by the relevant body and trusted references. The inclusion of 20% GTR significantly enhanced the asphalt's anti-rutting performance, leading to higher failure temperatures compared to conventional bitumen. The determined optimum bitumen content (OBC) for the asphalt mixture was 6.5%, meeting all volumetric properties' requirements per PWD specifications. Resilient Modulus Test results demonstrated that the use of modified bitumen in asphalt mixtures increased stiffness and elasticity, resulting in improved resistance to permanent deformation and rutting under heavy traffic loads. This combination of WCO and GTR in modified bitumen not only enhances the performance of asphalt mixtures but also offers environmental advantages by reducing the need for virgin materials and conserving natural resources.

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Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***Study conception and design:*** *Juraidah Ahmad, Ekarizan Shaffie, Norfarah Nadia Ismail;* ***Data collection:*** *Nur Athirah Lokman, Nur'aina Syamimi Nazri;* ***Analysis and interpretation of results:*** *Nur Athirah Lokman, Ekarizan Shaffie, Norfarah Nadia Ismail;* ***Draft manuscript preparation:*** *Wardati Hashim, M. A. Shafii, Ekarizan Shaffie, Norfarah Nadia Ismail, Nur'aina Syamimi Nazri, Nur Athirah Lokman. All authors reviewed the results and approved the final version of the manuscript.*

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