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Exploring the Potential of Waste Cooking Oil in Enhancing Warm Mix Asphalt Performance

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Abstract

The growing need for sustainable materials in road construction has led to the investigation of waste cooking oil (WCO) as a modifier for warm mix asphalt (WMA). This study evaluates the effects of chemically treated WCO on the mechanical properties of WMA, focusing on stability, resilient modulus, and dynamic creep performance. WCO was treated through transesterification and incorporated into 60/70 penetration grade asphalt at various dosages (0%, 3%, 4%, and 5% by weight of asphalt). The results showed that a 3% WCO-modified asphalt achieved the highest stability and acceptable resilient modulus, while maintaining satisfactory rutting resistance. Higher WCO content led to reduced stiffness and creep performance due to excessive softening. The study concludes that treated WCO can enhance WMA performance when used in optimal amounts, contributing to sustainable pavement practices.

Keywords: Waste, Cooking Oil, Warm Mix Asphalt, Acid, Transesterification

Introduction

Hot mix asphalt (HMA) and warm mix asphalt (WMA) are two commonly used technologies in road construction, with HMA traditionally being the standard method due to its proven durability and performance under heavy traffic and harsh environmental conditions [1]. HMA requires mixing aggregates and asphalt at high temperatures (140–160°C) [2, 3], ensuring adequate coating and compaction but leading to high energy consumption and emissions. In contrast, WMA is produced at lower temperatures (100–140°C) [4, 5] using chemical or organic additives, reducing energy requirements, greenhouse gas emissions, and worker exposure to hazardous fumes. Researchers increasingly prefer WMA due to its environmental and economic benefits, including improved workability, extended hauling distances, and the potential to incorporate recycled or alternative materials like waste cooking oil (WCO) [6, 7, 8].

The modification of asphalt with alternative materials has gained significant attention in recent years due to the rising demand for sustainable construction practices and the limitations of conventional binders. WCO has emerged as a potential bio-based modifier due to its abundance, low cost, and potential to improve the workability of asphalt mixtures [9, 10, 11]. WCO possesses chemical properties that reduce the viscosity of asphalt, facilitating easier mixing and compaction, especially in WMA applications. However, its high free fatty acid (FFA) content and instability in untreated form can lead to poor durability and undesirable aging behavior in asphalt binders [12]. These issues pose significant challenges to the long-term performance of WCO-modified asphalt, such as susceptibility to rutting, cracking, and reduced structural integrity under traffic loads and environmental conditions.

The incorporation of WCO into WMA presents a sustainable approach to enhance asphalt performance while addressing environmental concerns. Research indicates that WCO can serve as a rejuvenator and additive, improving the rheological properties and durability of asphalt mixtures. Luo et al. [13], Zhao et al. [14], and Li et al. [15] have collectively explored the potential of WCO as an additive in asphalt modification, offering valuable insights into its performance and sustainability. Luo et al. [13] conducted a comprehensive review on WCO-modified asphalt and asphalt mixtures, highlighting that moderate dosages of WCO enhance low-temperature flexibility and construction workability while reducing mixing and compaction temperatures by up to 15°C. However, the study also pointed out that WCO incorporation compromises rutting and fatigue resistance, necessitating careful dosage optimization to balance performance gains. In contrast, Zhao et al. [14] examined the full-component cascade utilization of WCO in asphalt materials, revealing that light and heavy oil components effectively rejuvenate aged asphalt by restoring rheological properties. Additionally, the waxy components, when hydrolyzed, act as warm mix additives, reducing energy consumption and emissions during construction while improving road durability. This approach aligns well with sustainable highway engineering practices. Li et al. [15] focused on chemically treated WCO as a rejuvenator in warm-mix recycled asphalt, finding that WCO dosages of 3.3%–5% significantly reduced viscosity, enhanced high-temperature performance, improved rutting resistance, and extended fatigue life. Their findings indicate that chemically treated WCO not only improves the mechanical properties of asphalt but also contributes to the environmental sustainability of pavement construction. Collectively, these studies emphasize the potential of WCO as a sustainable modifier, while also underscoring the need for further research into dosage optimization and the mitigation of high-temperature performance challenges.

Azahar et al. [16, 17] conducted an X-ray diffraction (XRD) analysis of asphalt modified with untreated and treated WCO, revealing that the amorphous structure remained consistent across all samples, indicating successful mixing

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and uniform dispersion between WCO and asphalt. This structural homogeneity is critical for ensuring compatibility and performance consistency in WCO-modified binders. Alkuime et al. [18] focused on the mechanical properties of WCO-modified asphalt mixtures, finding that WCO improved cracking resistance due to its softening effect, but excessive dosages reduced rutting resistance by making the asphalt softer and more flexible. This highlights the need for a careful balance between flexibility and stiffness to optimize the overall performance of asphalt mixtures. Jain and Chandrappa [19] examined the environmental and performance impacts of WCO as a rejuvenator in high recycled asphalt (RA) content mixtures. Their study demonstrated a reduction in embodied energy by up to 41.17%, with enhanced high- and intermediate-temperature performance, achieving cracking and rutting resistance comparable to traditional hot-mix asphalt. Additionally, the study emphasized the alignment of WCO use with circular economy principles, promoting sustainability through resource recycling. Collectively, these studies highlight the potential of WCO to improve asphalt performance and sustainability but underscore the critical need for dosage optimization to address performance trade-offs and ensure long-term durability.

Despite the potential benefits of using WCO in asphalt modification, existing studies often focus on its basic rheological and mechanical properties without fully addressing the challenges related to its chemical instability or quantifying its effects on critical performance indicators like stiffness, deformation resistance, and load-bearing capacity. There is also limited research on the optimal treatment of WCO, such as transesterification, to enhance its compatibility with asphalt while minimizing adverse effects. Furthermore, the relationship between WCO dosage and the mechanical performance of asphalt mixtures, particularly in terms of stability, resilient modulus, and rutting resistance, remains underexplored. This study aims to fill this research gap by systematically evaluating the influence of WCO, treated through transesterification, on the mechanical and rheological properties of warm mix asphalt.

Materials and Methodology

Asphalt Binder

In this study, 60/70 penetration grade asphalt binder was used as control asphalt binder.

Waste Cooking Oil

WCO was collected from university cafe in Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA). The longer the time WCO was used, the higher the resulting acid value. The raw sample was filtered first by placing filter paper in beaker to remove food and any impurities. The different qualities of WCO were determined from the acid value test, where high acidity correlates to a high FFA [6].

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Aggregate

The mix used in this study is AC14, which means the nominal maximum aggregates size is 14mm which passing 20mm sieve. Procedure use for the sieve analysis test follow the JKR/SPJ/2008-S4 [20].

Table 1. Gradation limit

Sieve size	Percentage passing (%)	Percentage retained (%)
14	95	5
10	81	14
5	56	25
3.35	47	9
1.18	26	21
0.425	18	8
0.15	10	8
0.075	6	4

Transesterification

The transesterification is type of chemical reaction in which WCO is reacted with methanol and catalysed using NaOH [6]. The alkali catalyst transesterification was conducted for further chemical treatment due to the high yield production in minimal time and low cost.

Preparation of Materials

Firstly, the PEN 60/70 asphalt binder was uniformly heated in an oven to get the liquid state for easily pourable. Then, modified asphalt binder was prepared by adding the WCO sample at different percentages, namely 0%, 3%, 4% and 5% and by the weight of asphalt and the mixed into the control asphalt binder.

Warm Mix Asphalt Mixture

The graded aggregates with desired size fractions (AC14) were mixed and coated with the modified asphalt binder at different percentages of WCO (0%, 3%, 4% and 5%) at mixing temperature of 100°C to 140°C. 75 blows of free fall of specified compaction hammer were applied to the WMA sample. Then sample was extruded and cooled at room temperature.

Experimental

This study investigates the potential of waste cooking oil (WCO) as a sustainable modifier for enhancing the performance of warm mix asphalt (WMA). The research begins with the preparation of key materials, including aggregates, 60/70 asphalt, and WCO. Aggregates undergo sieve analysis to ensure compliance with gradation requirements, while the asphalt binder is subjected to penetration and softening point tests to establish its baseline properties. The WCO is pretreated through filtration, acid value measurement, and transesterification to improve its compatibility with the asphalt binder. Modified asphalt mixtures are prepared by incorporating WCO at varying concentrations of 0%, 3%, 4%, and

5% by weight of asphalt. These mixtures are evaluated for their mechanical and rheological properties using Marshall stability, resilient modulus, and dynamic creep tests. The findings, presented in the results and discussions section, aim to elucidate the influence of WCO on WMA's performance, offering insights into its potential as an eco-friendly and cost-effective modifier for sustainable road construction.

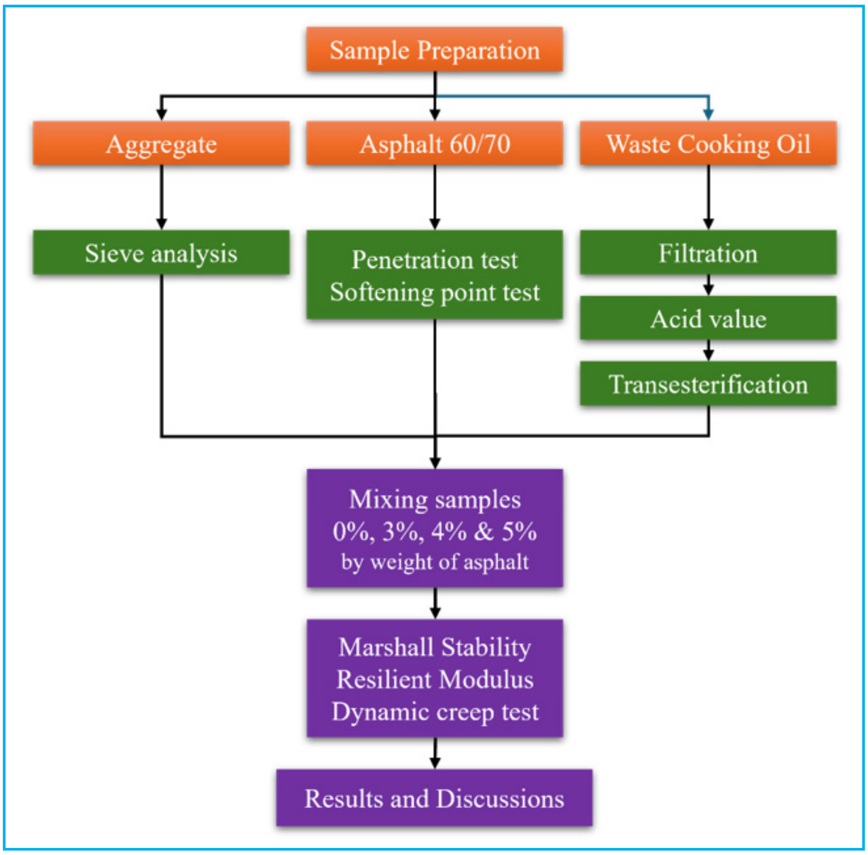

Figure 1. Methodology flowchart

Acid Value Test with Transesterification

The acid value test was conducted to determine the amount of free fatty acids (FFA) in the waste cooking oil (WCO) using the ASTM D664 [21] standard, which involves titration with potassium hydroxide (KOH) to neutralize the FFAs. This test is critical for evaluating the quality of WCO and its suitability for asphalt modification. Additionally, the WCO was treated through a transesterification process, which involved reacting the oil with methanol in the presence of sodium hydroxide as a catalyst. This chemical process reduces FFAs by converting them into esters, thereby improving the oil's chemical stability and compatibility with asphalt. These steps were performed to ensure that the modified WCO meets the required standards for use in warm mix asphalt applications.

Marshall Stability Test

The Marshall Stability test was conducted in accordance with ASTM D6927 [22] to assess the load-bearing capacity and stability of the asphalt mixtures.

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Twelfth samples were prepared by mixing aggregates with 60/70 penetration grade asphalt modified with varying contents of WCO (0%, 3%, 4%, and 5% by weight of asphalt) were placed in the water bath at 60°C for 30 – 40 minutes. The test involves subjecting cylindrical asphalt specimens to compressive loading at a constant deformation rate until failure. The maximum load sustained by each specimen was recorded as the stability value, which indicates the ability of the asphalt mixture to withstand traffic-induced stresses without deformation or failure.

Resilient Modulus Test

The resilient modulus of the asphalt mixtures was evaluated using ASTM D7369 [23], which measures the stiffness and elastic recovery of the mixtures under cyclic loading. The sample was tested 0°C and 90°C of rotation at 25°C in Universal testing machine (UTM) with pulse repetition of 1800ms. This test simulates traffic-induced stresses by applying repeated compressive loads to cylindrical asphalt specimens while monitoring their deformation and recovery. The resilient modulus was calculated based on the stress-strain relationship during the cyclic loading process. This test is essential for understanding the elasticity and deformation behavior of asphalt mixtures modified with WCO, particularly under varying traffic loads and environmental conditions.

Dynamic Creep Test

The dynamic creep test was performed in accordance with BS EN 12697 [24] to evaluate the resistance of asphalt mixtures to permanent deformation under repeated loading at elevated temperatures. Cylindrical specimens were subjected to a constant axial stress while the resulting strain was recorded over a specified time period. The test was conducted at a temperature of 40°C with 100 kPa stress and 3600 cycles to simulate high-temperature conditions typically experienced in service using universal testing machine (UTM). This test provides critical insights into the rutting resistance and deformation characteristics of asphalt mixtures modified with WCO, helping to determine their long-term performance under field conditions.

Results and Discussions

Acid Value Result

The acid value test results (Table 2), combined with the chemical process of transesterification, demonstrate the significant improvement in the quality of waste cooking oil (WCO) for use in asphalt modification. Initially, the untreated WCO exhibited an acid value of 4.40 KOH mL/g, indicating a high level of free fatty acids (FFAs), which can lead to oxidation and degradation of asphalt binders. After undergoing the transesterification process, which involves reacting the triglycerides and FFAs in the WCO with methanol) in the presence of a catalyst, the acid value reduced substantially to 0.78 KOH mL/g. This process effectively converted FFAs into esters, significantly lowering the oil's acidity and removing impurities.

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The transesterification process not only decreases the acid value but also enhances the overall stability and compatibility of WCO as a asphalt modifier. The reduced acid value ensures lower reactivity of the modified binder, minimizing the risks of oxidative aging and improving its durability in asphalt applications. Compared to standard requirements, the post-treatment acid value aligns with acceptable levels, confirming the efficacy of the transesterification process in producing a sustainable, chemically stable modifier for warm mix asphalt. This transformation underscores the necessity of pre-treatment processes in optimizing WCO for sustainable infrastructure solutions.

Table 2. Acid value result

Sample	Volume of KOH (mL)	Acid value (mL/g)
Untreated	7.62	4.40
Treated	1.36	0.78

Marshall Stability Results

The Marshall stability test results indicate a clear trend where the stability of the asphalt mixture increases with the addition of waste cooking oil (WCO) up to 4% by weight of asphalt, with a peak stability value observed at this percentage (Figure 2). The stability improves from 5789 N for the control sample (0% WCO) to 7428 N at 3% and 4% WCO, before slightly decreasing at 5% WCO. This suggests that moderate dosages of WCO enhance the cohesive and adhesive properties of the asphalt binder, contributing to improved stability. According to relevant standards [22], the stability values for all samples meet the minimum threshold for road construction applications, indicating the feasibility of using WCO as a modifier within this range.

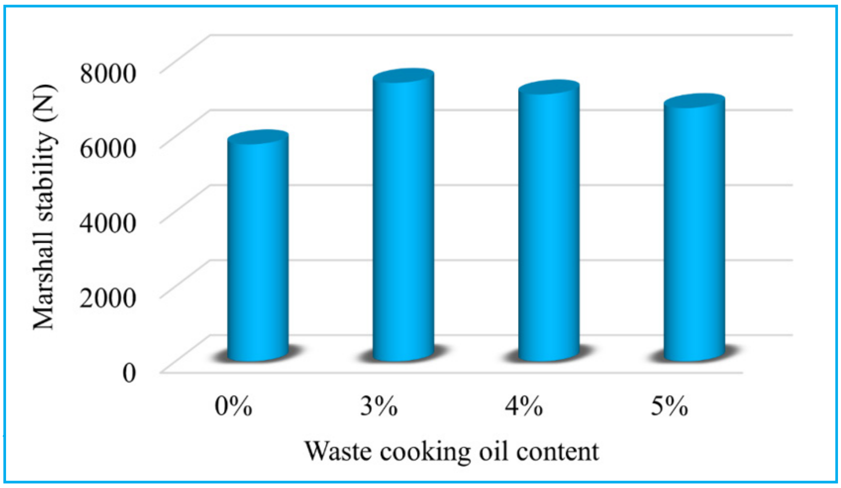

Figure 2. Marshall stability result

The decline in stability at 5% WCO may be attributed to excessive oil content, which could weaken the binder-aggregate adhesion by introducing a lubricating effect or reducing the stiffness of the binder. While WCO enhances workability and flow at lower percentages, higher concentrations may disrupt the balance

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between flexibility and strength, leading to reduced structural integrity. The peak performance at 4% WCO suggests an optimal modification level where the benefits of enhanced binder properties are maximized without compromising the mixture's mechanical stability. This finding underscores the importance of optimizing WCO content to achieve a sustainable yet durable warm mix asphalt mixture.

Resilient Modulus

The resilient modulus test results reveal a decreasing trend with increasing waste cooking oil (WCO) content in the asphalt mixtures. The control sample (0% WCO) exhibits the highest modulus value, 2500 MPa, indicating superior stiffness and resistance to deformation. As the WCO content increases to 3%, 4%, and 5%, the resilient modulus values drop significantly, reaching 1500 MPa, 1320 MPa, and 1020 MPa, respectively. According to relevant standards [23], a resilient modulus above 2,000 MPa is generally considered adequate for pavement structures subjected to heavy traffic loads. The results suggest that while the mixtures modified with lower WCO content maintain acceptable stiffness, higher WCO levels may fail to meet these structural requirements.

The reduction in resilient modulus with increasing WCO content can be attributed to the softening effect introduced by the oil. WCO reduces the stiffness of the asphalt binder, enhancing flexibility and workability but compromising the load-bearing capacity of the mixture. This behavior underscores a trade-off between flexibility and stiffness in WCO-modified mixtures. The sharp decrease in modulus at 5% WCO suggests that excessive oil content may dilute the binder matrix, weakening the inter-particle forces and compromising structural integrity. Optimizing the WCO dosage is therefore essential to balance improved workability with mechanical performance.

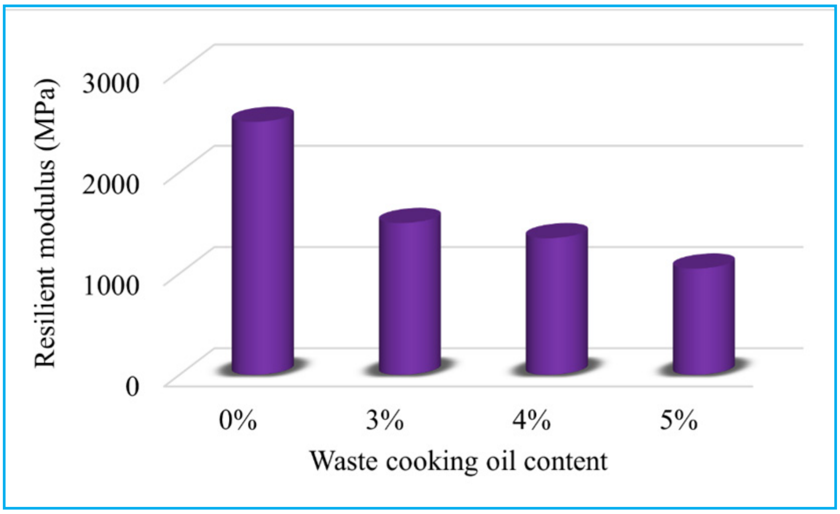

Figure 3. Resilient modulus result

Dynamic Creep Result

The dynamic creep test results at 40°C demonstrate a decreasing trend in creep modulus with increasing waste cooking oil (WCO) content. The control sample (0% WCO) exhibits the highest creep modulus, 14.5 MPa, indicating strong resistance to permanent deformation under repeated loading. As the WCO content increases to 3%, 4%, and 5%, the creep modulus values decrease to 7.9 MPa, 8.1 MPa, and 9.8 MPa, respectively. This trend signifies a reduction in stiffness and deformation resistance as more WCO is incorporated into the binder. When compared to relevant standards, such as those outlined in [24], the mixtures with lower WCO content (3% and 4%) still demonstrate acceptable performance under high temperatures, whereas the mixture with 5% WCO falls below the desired threshold for heavily trafficked pavements.

The reduction in dynamic creep resistance with increasing WCO content is likely due to the softening and viscosity-reducing effects of WCO on the asphalt binder. While the addition of WCO enhances workability and lowers mixing and compaction temperatures, excessive amounts compromise the binder's structural integrity, leading to increased susceptibility to permanent deformation. The results indicate that 3% and 4% WCO offer a balanced performance, maintaining adequate creep resistance while providing environmental and operational benefits. However, the significant drop in resistance at 5% WCO highlights the importance of optimizing the modifier dosage to ensure long-term durability.

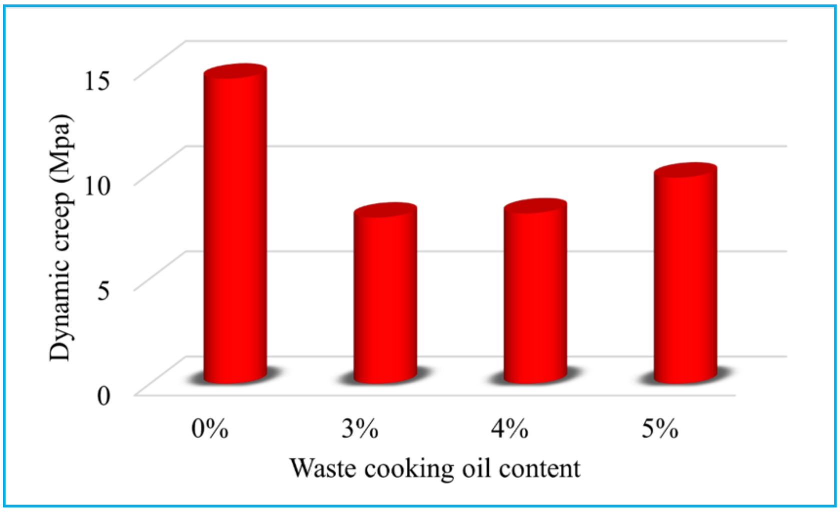

Figure 4. Dynamic creep result

Conclusion

In conclusion, this study highlights the significant impact of waste cooking oil (WCO) on the mechanical performance of warm mix asphalt (WMA), demonstrating both its potential benefits and limitations.

- The results indicate that the stability of warm mix asphalt (WMA) increases with WCO content, peaking at 3%–4%. This demonstrates an improvement in strength and load-bearing capacity at these levels.

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- Both the resilient modulus and dynamic creep resistance decline with higher WCO content, suggesting a softening effect that enhances flexibility but reduces stiffness and deformation resistance.
- The balance between strength and flexibility is achieved at 4% WCO, where the binder workability and stability are optimized without significant structural compromise.
- Beyond 4%, the excessive softening leads to reduced stiffness and deformation resistance, posing challenges for high-temperature or heavily loaded conditions.
- Moderated use of WCO (3%–4%) can effectively modify WMA, enhancing sustainability without sacrificing essential mechanical properties. Careful control of WCO content is crucial for practical applications.

Further studies, including field validations and additional testing like fatigue and rutting evaluations, are recommended to confirm the long-term performance of WCO-modified WMA under varying climatic and traffic conditions.

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Conflicts of Interest

The authors declare no competing interest.

Author Contributions

Ahmad Mujahid Hamzah: conceptualization, investigation, formal analysis, data curation, writing - review & editing. **Wan Noor Hin Mior Sani:** supervision, writing - original draft, writing - review & editing. **Indra Mawardi:** writing- original draft, investigation, data curation. **Haryati Yaacob:** formal analysis, conceptualization. **Kabiru Usman Rogo:** investigation, validation. **Mohd Hazree Hashim:** project administration, funding acquisition.

Data Availability Statement

The data used to support the findings of this study are included within the article.

References

[1] G. Ferrotti, E. Mancinelli, G. Passerini, and F. Canestrari, "Comparison of energy and environmental performance between warm and hot mix asphalt concrete production: A case study," Constr Build Mater, vol. 418, 2024, doi: http://dx.doi.org/10.1016/j.conbuildmat.2024.135453

[2] D. Khan, R. Khan, M. T. Khan, M. Alam, and T. Hassan, "Performance of hot-mix asphalt using polymer-modified bitumen and marble dust as a filler," Journal of Traffic and

Transportation Engineering (English Edition), vol. 10, no. 3, pp. 385–398, 2023, doi: http://dx.doi.org/10.1016/j.jtte.2022.12.002

[3] W. N. H. M. Sani, N. F. Allias, H. Yaacob, Z. H. Al-Saffar, and M. H. Hashim, "Utilisation of sawdust and charcoal ash as sustainable modified bitumen." Smart and Green Materials, 1(1), 13-32. 2024, doi: http://dx.doi.org/10.70028/sgm.v1i1.1

[4] W. N. H. M. Sani, R. P. Jaya, B. Bunyamin, Z. H. Al-Saffar, and Y. Arbi, "Waste motor engine oil – the influence in warm mix asphalt," Jurnal Pendidikan Teknologi Kejuruan, vol. 6, no. 4, pp. 248–255, 2023, doi: http://dx.doi.org/10.24036/jptk.v6i4.34623

[5] S. Zhang, Y. Cui, C. Du, L. Liu, and Q. Chen, "Low-temperature performance and micro-structure of warm mix recycled composite aged asphalt," Constr Build Mater, vol. 440, 2024, doi: http://dx.doi.org/10.1016/j.conbuildmat.2024.137443

[6] W. N. A. W. Azahar, R. P. Jaya, M. R. Hainin, M. Bujang, and N. Ngadi, "Chemical modification of waste cooking oil to improve the physical and rheological properties of asphalt binder," Constr Build Mater, vol. 126, pp. 218–226, 2016, doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.09.032

[7] C. Li, X. Han, J. Gong, W. Su, Z. Xi, J. Zhang, and H. Xie, "Impact of waste cooking oil on the viscosity, microstructure and mechanical performance of warm-mix epoxy asphalt binder," Constr Build Mater, vol. 251, 118994. 2020, doi: http://dx.doi.org/10.1016/j.conbuildmat.2020.118994

[8] J. Nithinchary, B. P. Dhandapani, and R. S. Mullapudi, "Application of warm mix technology - design and performance characteristics: Review and way forward," Construction and Building Materials, 414, 134915, 2024, doi: http://dx.doi.org/10.1016/j.conbuildmat.2024.134915

[9] K. Zhang, J. Xiong, C. Ruiz, and J. Zhang, "Design and performance assessment of sustainable road pothole patching materials using waste cooking oil, plastic, and reclaimed asphalt pavement," Constr Build Mater, vol. 429, 2024, doi: http://dx.doi.org/10.1016/j.conbuildmat.2024.136426

[10] U. Gaur, M. Musaib, and W. Akram, "Waste cooking oil and waste plastic used in bitumen modification," Journal of Emerging Technologies and Innovative Research (JETIR), 8(7) 2021.

[11] A. K. Banerji, D. Chakraborty, A. Mudi, and P. Chauhan, "Characterization of waste cooking oil and waste engine oil on physical properties of aged bitumen," in Materials Today: Proceedings, pp. 1694–1699. 2022, doi: http://dx.doi.org/10.1016/j.matpr.2022.03.401

[12] W. A. Wan Nur Aifa and A. B. W. Azahar, "Binder characterization and performance of asphaltic concrete modified with waste cooking oil," Doctorate Dissertation. Universiti Teknologi Malaysia. 2018.

[13] Y. Luo and K. Zhang, "Review on performance of asphalt and asphalt mixture with waste cooking oil," 16(4), 1341, 2023, MDPI, doi: http://dx.doi.org/10.3390/ma16041341

[14] Y. Zhao, M. Chen, S. Wu, Z. Cao, and X. Zhou, "Full-component cascade utilization of waste cooking oil in asphalt materials," Constr Build Mater, vol. 404, 2023, doi: http://dx.doi.org/10.1016/j.conbuildmat.2023.133355

[15] C. Li, Q. Liu, C. Fu, H. Wang, T. Wang, Y. Cheng, and D. Zhou, "Laboratory investigation on the properties of warm mixing-recycled asphalt containing waste oil and plastics," International Journal of Pavement Engineering, vol. 25, no. 1, 2301455. 2024, doi: http://dx.doi.org/10.1080/10298436.2023.2301455

[16] W. N. A. W. Azahar, R. P. Jaya, M. R. Hainin, M. Bujang, and N. Ngadi, “Mechanical performance of asphaltic concrete incorporating untreated and treated waste cooking oil,” Constr Build Mater, vol. 150, pp. 653–663, 2017, doi: http://dx.doi.org/10.1016/j.conbuildmat.2017.06.048

[17] W. N. A. Wan Azahar, R. Putra Jaya, M. R. Hainin, M. R. Mohd Hasan, and E. Shaffie, “X-Ray diffraction analysis of bitumen containing untreated and treated waste cooking oil,” International Journal of Recent Technology and Engineering, vol. 8, no. 3S3, pp. 435–438, 2019, doi: http://dx.doi.org/10.35940/ijrte.c1020.1183s319

[18] H. Alkuime, E. Kassem, K. A. Alshraiedeh, M. Bustanji, A. Aleih, and F. Abukhamseh, “Performance Assessment of Waste Cooking Oil-Modified Asphalt Mixtures,” Applied Sciences (Switzerland), vol. 14, no. 3, 2024, doi: http://dx.doi.org/10.3390/app14031228

[19] S. Jain and A.K. Chandrappa, “Performance and Life Cycle Assessment of Recycled Mixtures Incorporating Reclaimed Asphalt and Waste Cooking Oil as Rejuvenator: Emphasis on Circular Economy,” Journal of Materials in Civil Engineering, vol. 36, no. 7. 2024.

[20] JKR Malaysia, “Standard Specification for Road Works, Section 4: Flexible Pavement,” pp. 1–187, 2008.

[21] ASTM D664, “Test Method for Acid Number of Petroleum Products by Potentiometric Titration,” ASTM International, West Conshohocken, PA. 2018.

[22] ASTM D6927, “Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures,” ASTM International, vol. i, 2015.

[23] ASTM D7369, “Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test,” American Society for Testing and Materials, vol. 32, no. 2, 2012.

[24] BS EN 12697-25 “Bituminous Mixtures-Test methods BSI Standards Publication.” BSI Standard Limited 2016. 2016.