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Volumetric Properties of Waste-Modified Asphalt Mixtures through Marshall Stability

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Abstract

The rising needful for sustainable road construction materials yield to extensive research on asphalt modification using waste materials such as industrial and agricultural, therefore this study explores the use of palm oil fuel ash (POFA), garnet waste, and sawdust as individual modifiers to enhance the volumetric and mechanical properties of asphalt mixtures. The waste materials were individually mixed with 60/70 PEN asphalt binder at varying proportions of 0%, 3%, 6%, and 9%. The modified mixtures were evaluated through the Marshall stability test, focusing on volumetric properties, voids in total mix (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). The results validated that belnding individual waste materials significantly enhanced the stability of asphalt mixtures compared to the control sample, with the 6% POFA modification achieving the highest stability at 14.78 kN followed by 3% garnet waste (13.15 kN) and 3% sawdust (14.23 kN). The VTM and VMA values decreased with increasing waste content, indicating improved densification and binder adhesion, while VFA increased, reflecting better asphalt retention within the aggregate structure. This study highlights the feasibility of utilizing individual POFA, garnet waste, and sawdust as sustainable alternatives in asphalt mixtures, offering potential cost savings and reducing reliance on virgin materials. The modified mixtures exhibited satisfactory volumetric and mechanical properties, indicating their suitability for road applications, particularly in low to medium traffic pavements. However, further research is necessary to optimize the combination of these waste materials and assess their long-term durability, moisture susceptibility, and performance under diverse climatic and traffic conditions. The successful integration of these waste materials into asphalt pavements could contribute to more sustainable infrastructure development while ensuring compliance with engineering standards and road performance requirements.

Keywords: Volumetric, Modified Asphalt Mixture, Marshall Stability, POFA, Garnet Waste, Sawdust

Introduction

Asphalt modification plays a vital role in modern pavement engineering, aiming to enhance performance, durability, and sustainability in road construction. Conventional asphalt mixtures are prone to issues such as rutting, fatigue cracking, and moisture susceptibility, particularly under extreme climatic conditions and heavy traffic loads. To mitigate these challenges, researchers have explored various modification techniques, including polymer additives, nanomaterials, and waste-derived materials. Among these, the use of industrial by-products and agricultural residues as asphalt modifiers has gained considerable interest due to their ability to improve mechanical properties while contributing to environmental sustainability by reducing waste disposal issues. Building on this approach, this study explores the potential of palm oil fuel ash (POFA), garnet waste, and sawdust as sustainable asphalt modifiers to enhance pavement performance while addressing environmental concerns.

Palm Oil Fuel Ash (POFA) employ in modifying asphalt mixtures has been explored for its prospect to enhance the volumetric and mechanical characteristics of asphalt, contributing to more sustainable road construction practices. The blending of POFA in asphalt mixtures not only addresses environmental concerns by recycling waste materials but also enhances the engineering properties of the asphalt [1]. The complement of POFA to asphalt mixtures has been displayed to improve Marshall stability, a critical measure of the strength and durability of asphalt [2]. For instance, a study demonstrated that a 6% POFA content in the asphalt mixture resulted in optimal stability and performance, with a Marshall stability value of 22.33 kN [3]. POFA-modified asphalt mixtures also exhibit improved flow and bulk density characteristics, which are essential for the durability and longevity of road pavements [4].

Research indicates that garnet waste can effectively replace conventional aggregates, leading to improved performance metrics in asphalt applications. Garnet waste enhances the density of asphalt mixtures, which is crucial for durability [5]. Studies have determined that the optimum bitumen content can be adjusted when garnet waste is included, optimizing the overall mixture performance [6]. The use of garnet waste has been associated with favorable reductions in air voids, contributing to a denser and more stable asphalt mix [7]. The addition of garnet waste has been shown to improve the stability of asphalt mixtures, with optimal performance observed at specific percentages [3]. When compared to traditional granite aggregates, garnet waste mixtures exhibited superior stability under various aging conditions [8].

The optimal sawdust modification levels for enhancing the volumetric Marshall stability of asphaltic concrete have been identified through various studies. The consensus among the research indicates that a sawdust content of approximately 15% yields the best results in terms of stability and overall performance of asphalt mixtures. Multiple studies consistently report that 15% sawdust, whether burnt or in ash form, significantly improves the Marshall stability of asphalt mixtures [9-11]. At this level, the stability values reached approximately 18.2 kN, with favorable flow and density characteristics, indicating enhanced structural integrity [10]. Utilizing sawdust not only improves asphalt properties but also promotes environmental sustainability by repurposing waste materials, thus reducing reliance on non-renewable resources [11-12]. While

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15% sawdust is optimal, some studies suggest that varying combinations of sawdust and other materials, such as charcoal ash, can also yield beneficial results, indicating that further exploration of different mixtures may enhance performance even more [12].

Numerous studies have explored the impact of modified asphalt mixtures on volumetric properties, particularly voids in total mix (VTM), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA), highlighting their role in improving pavement performance. For instance, Usman et al. and Ahmad et al. [13-14] investigated the effects of POFA as a partial filler replacement in asphalt mixtures and found that increasing POFA content reduced VTM while improving VFA, leading to enhanced durability and moisture resistance. Similarly, Usman et al. [6] examined the incorporation of POFA as an fine dense-graded cold mix asphalt, reporting an increase in VMA and a corresponding improvement in binder adhesion, resulting in better fatigue resistance. A study by Liew et al. [15] analyzed the influence of sawdust ash as a filler in modified asphalt on volumetric properties, demonstrating that optimized sawdust ash content at 3% reduced VTM while maintaining a balanced VMA and VFA, which contributed to increased rutting resistance. In another study, Abbas et al. [16] assessed the performance of sawdust ash as mineral filler on modified asphalt mixtures, revealing that at 60 % optimal sawdust content (by weight of Portland cement), the values of stability, flow, bulk density, VFB, VTM, and VMA were 14.7 kN, 2.25 mm, 2.249 g/cm3, 74.7 %, 4.6 %, and 18.2 %, respectively. It shown higher sawdust ash content led to increased VTM, which required additional binder to maintain desirable VFA levels and ensure long-term performance. These studies collectively emphasize the significance of volumetric properties in asphalt modification and how different waste materials impact their values, ultimately affecting pavement durability and sustainability.

Despite the extensive research on asphalt modification using various waste materials, studies focusing on the individual effects of POFA, garnet waste, and sawdust on volumetric properties remain limited. Previous studies have primarily concentrated on the mechanical performance of modified asphalt mixtures, such as stability, flow, and rutting resistance, with less emphasis on the detailed volumetric analysis that governs long-term durability and workability. Additionally, most research has explored single waste-modified asphalt mixtures, while comparative assessments of different waste materials on volumetric properties remain scarce. Understanding how each material uniquely influences VTM, VMA, and VFA is crucial for optimizing mix design and ensuring structural integrity. Therefore, this study aims to fill this research gap by systematically evaluating the volumetric characteristics of asphalt mixtures modified with POFA, garnet waste, and sawdust using the Marshall stability test. By conducting a comprehensive analysis of these waste-modified mixtures, this study provides valuable insights into their feasibility for sustainable road construction. The findings will contribute to the advancement of eco-friendly asphalt technologies, supporting global efforts toward sustainable infrastructure development.

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Methodology

Asphalt Binder and Aggregate

A penetration-grade asphalt (PG 60/70) was used as the asphalt binder, ensuring suitable performance under moderate climatic conditions and traffic loads. The aggregates consisted of well-graded crushed granite with a nominal maximum aggregate size of 14 mm, complying with standard road construction specifications. The physical properties of the aggregates, including specific gravity, Los Angeles abrasion value, and water absorption, met the requirements of ASTM standards to ensure durability, stability, and proper interlocking in the asphalt mixture.

Waste Materials: POFA, Garnet waste and Sawdust

Palm oil fuel ash (POFA), garnet waste, and sawdust were used as waste-derived modifiers in this study. POFA is a by-product of palm oil mill combustion, primarily composed of silica, alumina, and calcium oxide, making it a potential filler of asphalt mixtures. Garnet waste, derived from abrasive blasting and waterjet cutting industries, consists of hard, angular particles rich in iron and aluminum oxides. Sawdust, a lignocellulosic material from wood processing, is lightweight and fibrous. These materials were selected for their availability, cost-effectiveness, and potential to enhance the volumetric properties of asphalt mixtures. All waste materials were sieve to obtain similar size at 25 µm (Figure 1).

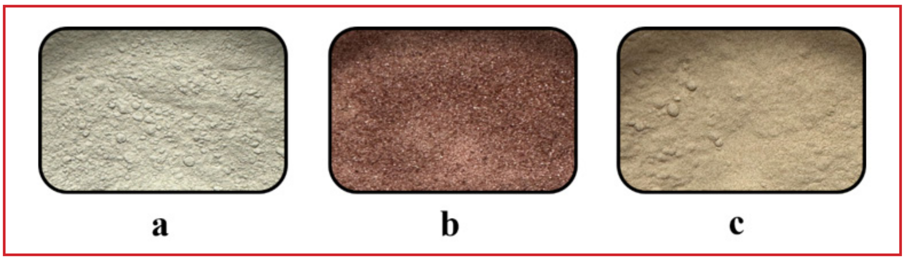

Figure 1. Waste materials (a) POFA, (b) garnet waste and (c) sawdust with 25 µm size

Sample Preparation of Modified Asphalt Mixture

The asphalt mixture design followed the Marshall mix design method ASTM D6927 [17] to determine the optimum binder content of 5% [18] and evaluate the volumetric properties of the modified mixtures. The asphalt binder modification was conducted using a high-shear mixer to ensure even dispersion of POFA, garnet waste, and sawdust within the asphalt. The binder modification process involved heating the binder to 150–160 °C and gradually adding the waste materials while continuously stirring at 1500 rpm for 60 minutes to achieve proper homogenization [19]. This method was adopted to enhance the interaction between the waste particles and asphalt, ensuring better compatibility and improved binder performance. The modified binders were then incorporated into the hot mix asphalt (HMA) to produce waste-modified asphalt mixtures.

The Marshall compaction method was employed to prepare the asphalt specimens, where the hot-mix asphalt was poured into standard cylindrical

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molds and compacted with 75 blows per side using a Marshall hammer [17]. This compaction procedure simulated field compaction conditions and ensured consistent density and stability across all samples. The prepared specimens were then subjected to volumetric analysis, focusing on VTM, VMA and VFA. The rationale behind selecting 0%, 3%, 6%, and 9% waste content was to evaluate the progressive impact of waste modification on volumetric properties, determining the optimum percentage that balances workability, durability, and performance. A 0% mix was used as a control sample, while 3%, 6%, and 9% represented incremental dosages to assess the influence of waste modification on air voids, binder absorption, and aggregate packing. These percentages were chosen based on previous studies, which suggest that excessive waste content beyond 9% may lead to excessive stiffness, increased air voids, and reduced workability [20 - 21]. The results from this study will contribute to optimizing waste-modified asphalt mixtures for sustainable road applications. Figure 2 shows the flowchart of the research.

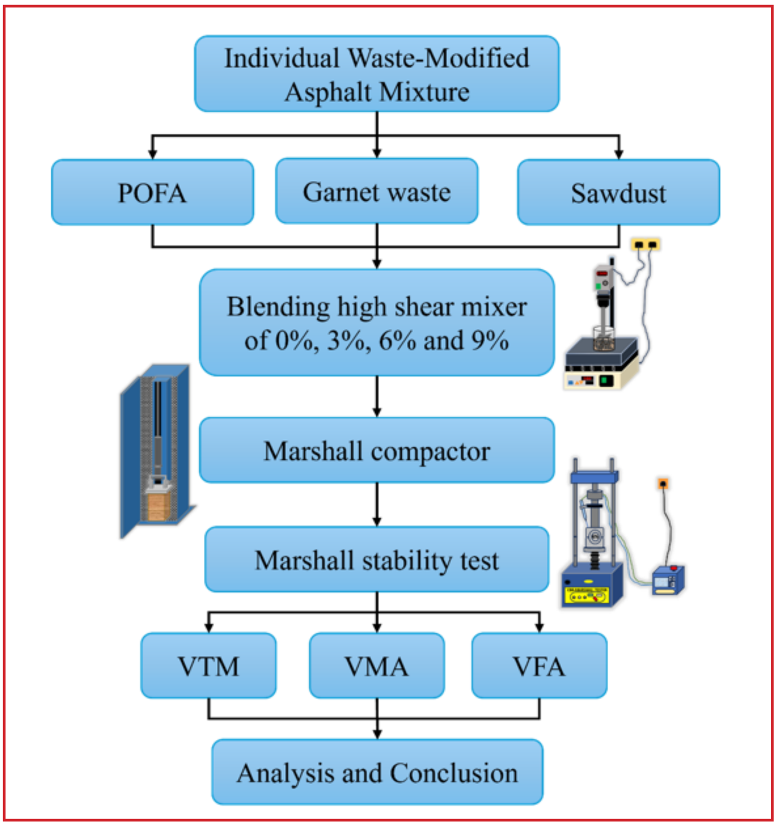

Figure 2. Flowchart of the research

Experimental

Marshall Stability Test

The Marshall stability test was conducted to evaluate the strength and deformation resistance of the waste-modified asphalt mixtures, following ASTM D6927 standards [17]. This test measures the maximum load (stability) that a compacted asphalt specimen can withstand before failure, along with the corresponding flow value, which indicates the mixture's flexibility. The primary

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objective of this test is to assess the load-bearing capacity and workability of asphalt mixtures, ensuring their suitability for pavement applications.

The testing procedure involved conditioning the compacted specimens by immersing them in a water bath at 60 °C for 30 - 40 minutes to simulate field temperature conditions. Each specimen was then placed in the Marshall testing head and subjected to a compressive load at a deformation rate of 50 mm/min until failure. The peak load (N) at failure was recorded as the Marshall stability value, while the vertical deformation (mm) at peak load was noted as the flow value. These results were used to compare the mechanical performance of different waste-modified asphalt mixtures, ensuring that the modifications did not compromise stability and flexibility. Figure 3 depict the overall testing process using Marshall equipment.

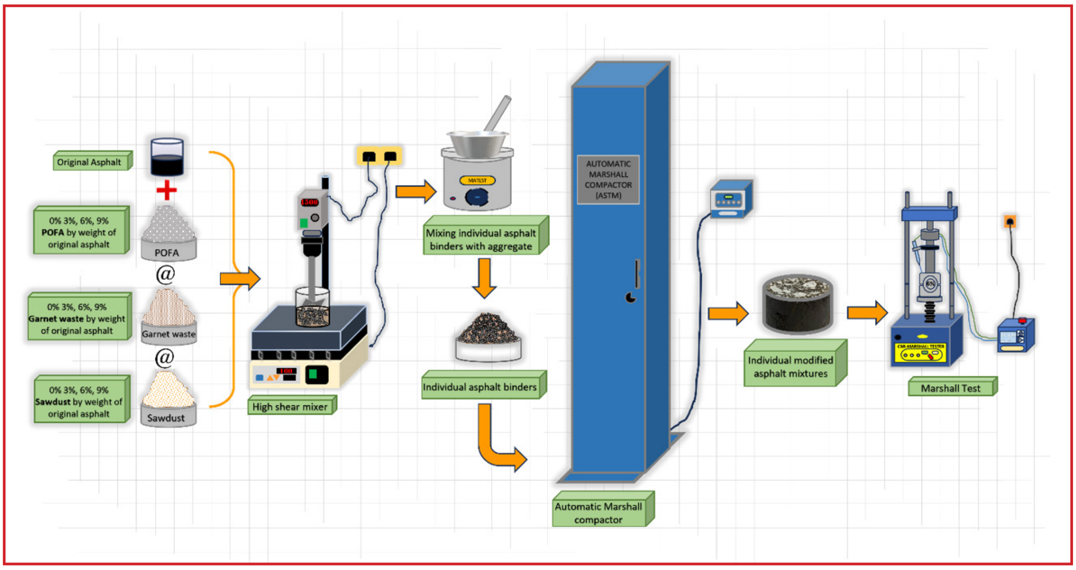

Figure 3. Testing process using Marshall equipment

Volumetric Test

Volumetric properties play a fundamental role in the performance and durability of asphalt mixtures, making them essential parameters in mix design and modification strategies. The key volumetric properties, voids in total mix (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) directly influence the strength, stability, and resistance of asphalt pavements to various distresses such as rutting, fatigue cracking, and moisture-induced damage.

The volumetric properties of the asphalt mixtures were calculated using the following Eqs. (1), (2) and (3) based on ASTM standards. Eq. (1) show a VTM to determines the percentage of air voids in the compacted mixture and its proper air void content (typically 3–5%) ensures durability and prevents excessive rutting or premature aging.

$$VTM = \frac{G_{mm} - G_{mb}}{G_{mm}} x\ 100 \qquad (1)$$

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Eq. (2) is a formula to measures the volume of voids in the aggregate structure, including those filled with asphalt binder. It is to ensures adequate binder content for long-term pavement performance.

$$VMA = \frac{G_{sb} - G_{mb}}{G_{sb}} x\ 100 \quad (2)$$

Eq. (3) shows a formula to determines the percentage of VMA occupied by the asphalt binder and higher VFA values indicate better binder coverage, preventing oxidation and fatigue cracking.

$$VFA = \frac{VMA - VTM}{VMA} x\ 100 \quad (3)$$

Where:

G_{mm} = Maximum theoretical specific gravity (ASTM D2041 [22])

G_{mb} = Bulk specific gravity of compacted mix (ASTM D2726 [22])

G_{sb} = Bulk specific gravity of aggregate (ASTM C127 [23], C128 [24])

Results and Discussions

Marshall stability and Flow Analysis

The Marshall stability test results indicate that individual waste materials: POFA, garnet waste, and sawdust into asphalt mixtures significantly affects the load-bearing capacity compared to the control (0% waste). The control sample consistently exhibited the lowest stability values across all percentages, reinforcing the role of waste modification in improving asphalt performance. Among the waste-modified mixtures (Figure 4), POFA demonstrated the highest stability at 6% of 14.78 kN, followed by garnet waste (3% at 13.15 kN) and sawdust (3% at 14.23 kN). The increasing trend from 3% to 6% of POFA-modified asphalt mixture suggests an optimal modification level where the waste materials enhance the binder-aggregate interaction, leading to better resistance against deformation. However, at 9% modification, a decline in stability is observed for all materials, indicating that excessive waste content may disrupt the internal structure of the mix, reducing load resistance.

When compared to established Malaysian Standard Specification for Road Works [18], which typically require a minimum stability of 8–12 kN for heavy traffic conditions, all modified mixtures exceeded the threshold, highlighting their suitability for practical applications. The stability of POFA-modified asphalt at 6% aligns with previous findings by [25], where POFA improved stiffness due to its high silica content. Garnet waste also showed strong performance, likely due to its dense, angular particles that enhance aggregate interlocking. However, sawdust displayed a unique trend, achieving the highest stability at 3% before slightly decreasing at 6% and 9%. This may be attributed to its porous nature, which, at higher contents, absorbs excessive binder, weakening the mixture's cohesion. These results partially align with [12], who observed that sawdust waste materials tend to reach peak performance at lower dosages before degradation occurs. The optimal performance of sawdust at lower doses compared to POFA and garnet waste can be attributed to its lower density and fibrous nature, which enhances asphalt binder absorption and particle distribution within the mixture. At higher dosages, excessive sawdust may lead to increased void content and reduced cohesion, negatively affecting the mechanical properties of the asphalt mixture, whereas POFA and garnet waste, being denser and more mineral-based, contribute to structural integrity even at higher replacement levels.

From a critical perspective, the study highlights the importance of optimal waste dosage in asphalt modification. While POFA and garnet waste exhibit a steady increase in stability up to 6%, the slight reduction at 9% suggests that excessive incorporation disrupts the asphalt matrix. The performance of sawdust, peaking at 3%, reinforces the need for controlled dosing, particularly for porous and fibrous waste materials. The results suggest that waste modification can be a viable approach to enhancing asphalt performance, but careful mix design optimization is necessary to prevent structural weaknesses.

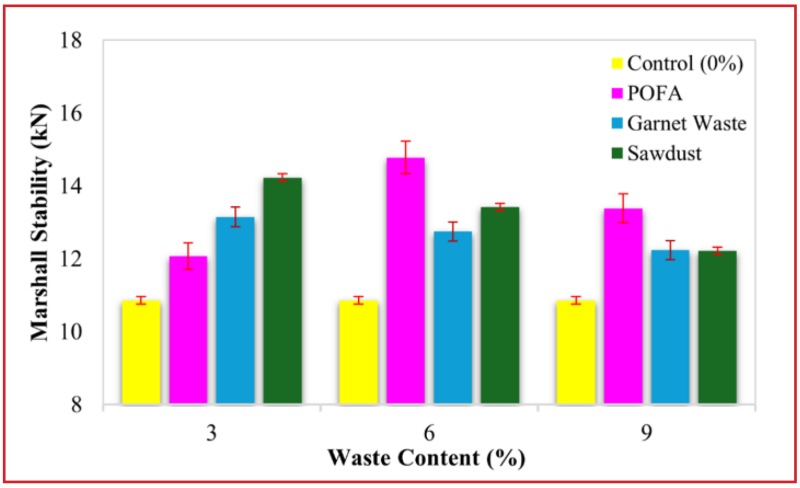

Figure 4. Marshall stability result for different waste materials and contents

The flow values of the individual waste-modified asphalt mixtures fall within the standard range of 2–4 mm, as specified by Malaysian Standard Specification for Road Works [18], ensuring acceptable deformation capacity. The control mixture (0% waste) for garnet waste-modified asphalt mixture exhibits the lowest flow values across all percentages, ranging between 3.4 and 3.5 mm, indicating a stiffer and less flexible mix (Figure 5). Among the modified mixtures, sawdust consistently records the highest flow values, increasing from 3.6 mm at 3% to 3.92 mm at 9%. This suggests that sawdust increases the mixture's ductility, likely due to its finer particle size and ability to slightly modify the binder's viscosity [21]. Garnet waste, in contrast, maintains relatively stable flow values, slightly higher than the control but lower than POFA, which indicates a balanced modification that does not excessively soften the mix. Sawdust follows a similar pattern to POFA but with a marginally lower increase, highlighting its role in slightly enhancing workability without significantly compromising stiffness.

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When comparing these results with previous studies, they align with findings by Yaro et al. [2], who reported that waste-derived silica-based fillers, such as POFA, tend to increase flow values due to their interaction with bitumen, reducing rigidity. However, the increasing trend beyond 4-6% suggests a potential trade-off, where excessive modification may lead to over-flexibility, increasing the risk of permanent deformation under heavy traffic loads. Nassef et al. [9] observed a similar effect in bio-waste-modified asphalt, where fibrous and porous materials like sawdust influenced binder absorption, slightly elevating flow values while maintaining structural integrity. The results highlight the importance of optimizing waste dosage to balance strength and flexibility. While all modified mixtures meet the standard requirements, excessive flow values near the upper limit (4 mm) suggest the need for further evaluation of rutting resistance to prevent premature pavement failures.

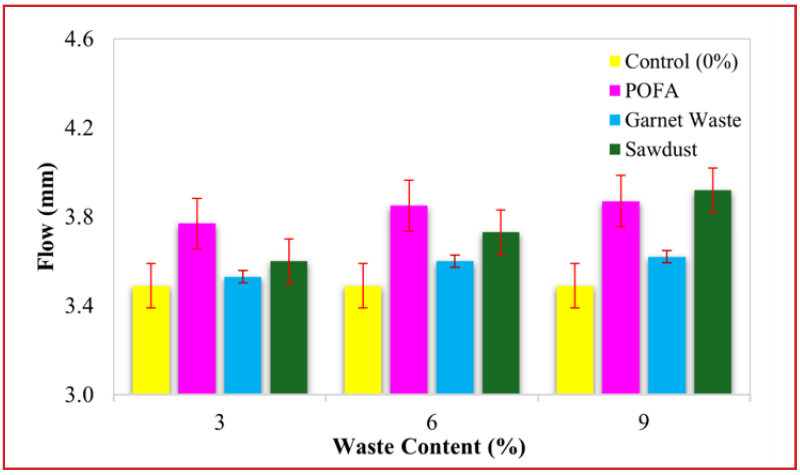

Figure 5. Flow result for different waste materials and contents

Volumetric Properties Evaluation

Figure 6 illustrates the correlation between asphalt air voids (VTM) and the percentage of waste materials; POFA, garnet waste, and sawdust in the modified asphalt mixture. The results indicate that the VTM values for all modified mixtures fall within the 3-5% range specified by the Malaysian Standard Specification for Road Works [18], ensuring adequate durability and resistance to deformation. Maintaining air voids within this range is crucial to preventing issues such as flushing, shoving, and rutting on the pavement surface. Among the modified mixtures, the lowest VTM value of 4.5% was observed at 9% POFA, while the highest value of 4.92% occurred at 3% POFA. For garnet waste, increasing its content resulted in a gradual decline in VTM values, from 4.86% at 3% to 4.60% at 9%. Similarly, sawdust showed a decreasing trend, with the highest VTM recorded at 3% (4.91%) and the lowest at 9% (4.55%). This trend suggests that higher waste content contributes to a denser asphalt mixture with reduced air voids.

The reduction in VTM with increasing waste content indicates a potential improvement in mixture compactness and cohesion, which can enhance durability and load-bearing capacity. However, excessively low VTM values may pose challenges such as poor permeability and increased susceptibility to moisture damage, which could lead to premature failure. On the other hand, mixtures with higher VTM may have insufficient binder coverage, making them more prone to cracking and oxidation.

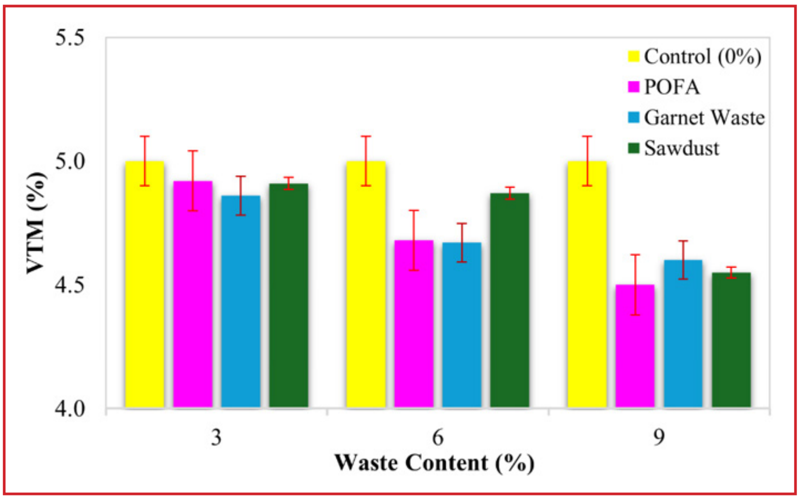

Figure 6. VTM result for different waste materials and contents

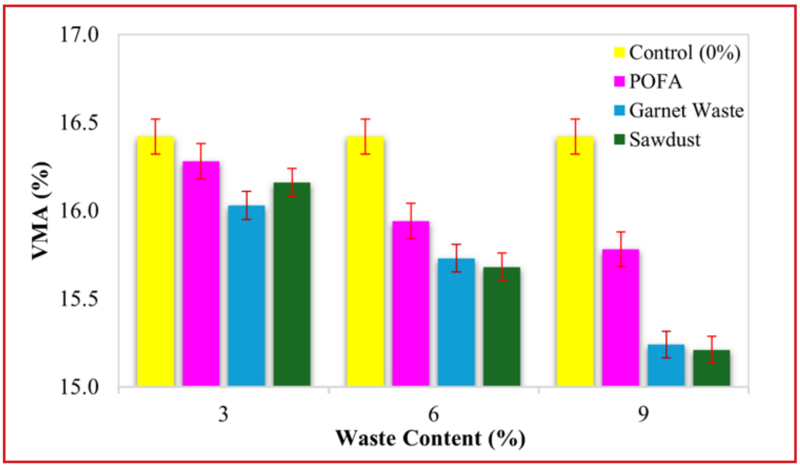

Figure 7. VMA result for different waste materials and contents

Figure 7 illustrates the VMA values of modified asphalt mixtures incorporating different percentages of POFA, garnet waste, and sawdust. The graph indicates a decreasing trend in VMA values with the addition of these waste materials. Among the modified mixtures, the highest VMA value of 16.28% was observed at 3% POFA, whereas the conventional asphalt mixture exhibited a VMA of 16.42%. Notably, the Malaysian Standard Specification for Road Works [18] does not specify a limitation for VMA in modified asphalt mixtures containing waste materials. A higher VMA generally indicates increased void space within the mixture, which can impact the asphalt binder's ability to coat aggregate particles effectively. In contrast, a lower VMA suggests better coating and improved mix performance [26].

From a critical perspective, the reduction in VMA with increasing waste content implies that the modified mixtures become denser, potentially enhancing durability. However, excessively low VMA values could restrict adequate binder film thickness, leading to durability concerns such as premature aging or cracking. While a moderate decrease in VMA is beneficial for ensuring good aggregate-binder interaction, it is essential to balance VMA levels to maintain proper workability, resistance to moisture damage, and long-term performance of the asphalt mixture.

Figure 8 depicts the VFA values for modified asphalt mixtures containing varying percentages of POFA, garnet waste, and sawdust. VFA represents the percentage of air voids within an asphalt mixture that are filled with asphalt binder, influencing its overall durability and resistance to deformation. The conventional asphalt mixture recorded a VFA of 70%. For the modified asphalt mixtures, the inclusion of 3%, 6%, and 9% POFA resulted in VFA values of 70.06%, 70.24%, and 70.30%, respectively, all of which meet the minimum 70% requirement set by the Malaysian Standard Specification for Road Works [18]. A higher VFA value within the 70–80% range is generally desirable, as it suggests enhanced resistance to deformation, particularly against rutting.

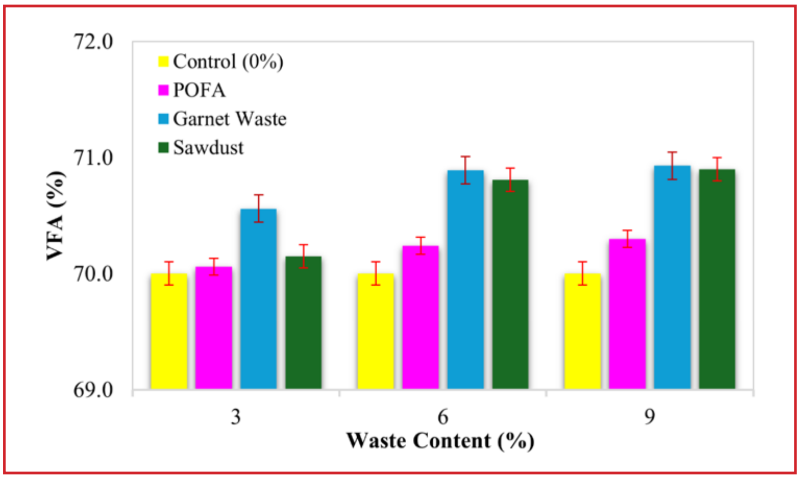

Figure 8. VFA result for different waste materials and contents

The addition of garnet waste showed an increasing trend in VFA, with values ranging from 70.56% at 3% to a peak of 70.93% at 9%. Similarly, sawdust-modified mixtures exhibited VFA values of 70.15% at 3% and 70.90% at 9%, indicating a positive correlation between waste content and VFA. These results suggest that incorporating waste materials contributes to an optimal binder-void relationship, reducing the mixture's susceptibility to premature failure. However, while maintaining a VFA above 70% ensures adequate binder coverage and mix cohesion, excessive values may indicate overfilling of voids, potentially leading to bleeding or reduced mixture stiffness. Hence, a balanced VFA is crucial to achieving an asphalt mix that offers both durability and resistance to permanent deformation.

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Effect of Waste Modification on Volumetric Performance

The air voids (VTM) results indicate a consistent reduction in void content with increasing waste modification. The control mixture (0% waste) exhibits a VTM of 5%, aligning with the typical range of 3–5% recommended by Malaysian Standard Specification for Road Works [18]. With the blending of individual waste materials, a noticeable decline in VTM is observed, with POFA, garnet waste, and sawdust. This trend suggests improved compaction and better binder adhesion due to the finer particle size and filler effect of the waste materials, which reduce the presence of interconnected air voids. The slightly lower VTM in garnet waste and POFA-modified mixtures compared to sawdust implies that these materials contribute more significantly to densification, potentially due to their higher mineral content. These findings align with the study by Al-Hadidy et al. [27], which reported that the addition of pozzolanic and fibrous waste materials enhances binder coating and compaction, reducing air voids while maintaining adequate workability. However, it is crucial to balance void reduction, as excessive compaction may lead to reduced permeability and premature moisture damage.

The voids in the mineral aggregate (VMA) results further support the effect of waste modification on mixture densification. The control mixture has a VMA of 16.42%, which gradually decreases with increasing waste content, reaching the lowest values at 9% modification: 15.78% for POFA, 15.24% for garnet waste, and 15.21% for sawdust. The reduction in VMA suggests that the waste fillers effectively occupy the void spaces within the aggregate structure, enhancing particle interlocking and binder-filler interaction. Among the modified mixtures, sawdust and garnet waste result in the lowest VMA values, possibly due to their higher particle cohesion and better distribution within the mix. These results are in line with previous studies, which demonstrated that biomass-derived fillers contribute to improved aggregate packing, thereby lowering VMA. However, while a decrease in VMA generally enhances mixture strength, a significant reduction below the standard threshold (14%) may compromise binder film thickness, leading to durability concerns.

The voids filled with asphalt (VFA) values demonstrate a slight increase with increasing waste content, reinforcing the improved compaction and bitumen distribution observed in the VTM and VMA results. The control mixture exhibits a VFA of 70%, while at 9% waste modification, the values rise slightly to 70.3% (POFA), 70.93% (garnet waste), and 70.9% (sawdust). These results indicate that more binder is occupying the available void spaces, improving mix cohesion and potentially enhancing fatigue resistance. The trend aligns with findings from Wang et al. [28], who reported that waste fillers such as sawdust enhance binder absorption, thereby increasing VFA without causing excessive bleeding. However, the moderate increase in VFA suggests that the modified mixtures retain a balanced level of binder film thickness, avoiding excessive softening effects. Overall, the results demonstrate that the incorporation of waste materials contributes to a more compact, well-structured asphalt mix, reinforcing the sustainability and performance benefits of utilizing waste-derived fillers.

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Conclusions and Recommendations

This study investigated the influence of individual waste materials: POFA, garnet waste, and sawdust on the volumetric and mechanical properties of asphalt mixtures. The findings demonstrated that these three waste materials individually enhanced the Marshall stability, reduced air voids, and improved voids filled with asphalt, indicating better compaction and binder adhesion. Among the tested modifications, 6% waste content exhibited the most balanced performance, yielding the highest stability while maintaining optimal volumetric properties. The results confirmed that POFA, garnet waste, and sawdust act as effective fillers, enhancing the interlocking structure and reducing permeability while still maintaining compliance with standard specifications. The study also highlighted the importance of selecting an appropriate waste percentage to prevent excessive densification, which could negatively impact long-term durability and moisture resistance.

The practical implications of these findings suggest that waste-modified asphalt mixtures offer a sustainable alternative for pavement construction, reducing reliance on virgin materials while enhancing mechanical properties. The observed improvements in stability and volumetric performance support the feasibility of integrating these waste materials into asphalt pavements, contributing to environmental sustainability and resource conservation. However, further research is recommended to assess the long-term performance of these mixtures under various climatic conditions, particularly in terms of aging, rutting resistance, and moisture susceptibility. Future studies should also explore hybrid waste combinations to determine synergistic effects and optimize mix design for different traffic and environmental conditions. Implementing these insights can advance sustainable road construction practices, aligning with global initiatives for waste utilization and green infrastructure development.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Wan Noor Hin Mior Sani: conceptualization, writing - original draft, methodology, investigation, formal analysis and data curation.

Data Availability Statement

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

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