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Research Article

Assessing the Viability of Wood Ash as a Filler in Asphalt Mixtures

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Abstract

Waste management is increasingly crucial worldwide, and integrating agro-waste into pavement construction offers a promising approach for sustainability and enhanced material properties. This research investigates the use of wood ash as a filler in asphalt mixtures, using varying proportions of 0%, 2%, 4%, and 6% replacement by weight of asphalt. Experimental tests, including softening point, penetration, Marshall stability and flow, indirect tensile strength, and abrasion loss, were conducted to assess the influence of wood ash on asphalt mixture properties. The findings reveal that wood ash can improve certain performance aspects such as stability, flow and density at an highest content of 6%, balancing tensile strength and stiffness properties. These results underscore the importance of optimizing wood ash content to enhance asphalt performance. This study demonstrates that wood ash is a sustainable alternative to conventional fillers in asphalt production, contributing to environmental conservation and waste management. Further research is recommended to explore various aggregate gradations, binder types, and the potential of wood ash as an asphalt modifier for quality improvement. Such studies are vital for advancing pavement technology, improving infrastructure quality, and addressing environmental challenges.

Keywords: Wood Ash, Asphalt Mixtures, Stability, Strength, Abrasion Loss

Introduction

The disposal of agro-industrial waste poses a significant environmental challenge in Asia, with the region producing around 1.3 billion tons of such waste annually [1]. However, only a small portion of this waste is currently recycled or composted. Malaysia, a key agricultural producer in Southeast Asia, contributes significantly to this issue through the substantial waste generated from various agricultural activities [2]. Common agricultural wastes in Malaysia include coconut husk, empty fruit bunches (EFB), rice husks, and bagasse [3]. Improper disposal of these wastes can result in water pollution, soil contamination, and the release of harmful gases into the atmosphere, posing risks to both human and animal health.

Nevertheless, agricultural wastes possess the potential to become valuable resources in the future. By conducting thorough research and development, these wastes can be repurposed to generate a range of products that provide societal advantages [4]. In Malaysia, there is a growing inclination towards the utilization of agricultural waste, supported by government agencies that provide financial incentives to businesses exploring innovative applications for such waste [5, 6, 7]. Numerous research institutions in Malaysia are actively engaged in devising creative methods to leverage agricultural waste. With ongoing research and development efforts, it is plausible to harness Malaysia's agricultural waste for the creation of a more sustainable future ecosystem.

Wood ash has been the subject of research due to its potential in modifying bitumen, displaying encouraging outcomes in boosting the performance of asphalt. Studies have delved into the utilization of wood ashes in both asphalt binder and mixes, suggesting that increased concentrations of wood ashes notably enhance the adhesion and moisture resistance of the altered materials [8, 9, 10, 11]. Moreover, the integration of fly ash into bitumen has been examined, revealing enhanced performance in terms of viscosity and complex modulus at elevated temperatures, albeit with a detrimental effect on resistance to cracking at lower temperatures [12]. Additionally, the enhancement of wood ash through polymer modification has been proven to elevate its characteristics, such as hydrophobicity and antibacterial properties, providing avenues for the development of functional hybrid materials for diverse industries [13]. In conclusion, the utilization of wood ash in bitumen modification offers a sustainable and eco-friendly approach with the potential to enhance the performance and longevity of asphalt.

Zahid et al., [8] examined the adhesion and moisture susceptibility of wood ashes known as chip board ash (CBA) in modified asphalt using bitumen bond strength (BBS) and rolling bootle test (RBT). The findings were conclusive, and they indicate that employing higher wood ashes concentration led to improved the adhesion and moisture resistance. The bitumen coverage was increased up to 30% when 5% of CBA were added to the base binder of 60/70 grade bitumen. Meanwhile, study from [9] using wood biomass combustion ash (CRBA) as a filler in hot mix asphalt (HMA). The results depicted that CBRA of 3.5% and 4.0% can be used as filler which improved Marshall stability of 27% compared to the conventional asphalt mixture. [14] found 50% wood ash content as a filler in asphalt concrete mixtures for the base-wearing layers increased the Marshall stability and asphalt's resistance to the appearance of plastic deformation and

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indicated greater tensile strength. Similarly with study by [11] which used wood powder ash as altenates of the conventional filler in the asphalt concrete. Their findings showed that 6% wood powder was satisfied with most of the Marshall criteria.

These studies have provided valuable insights into the potential of waste materials, including sawdust and charcoal ash, as modifiers of bitumen mixtures. This research aims to address this gap by investigating the effects of incorporating sawdust ash and charcoal ash on key bitumen properties, including Marshall stability, indirect tensile strength, and resistance to abrasion loss. Figure 1 depict the various methodology stages in this study.

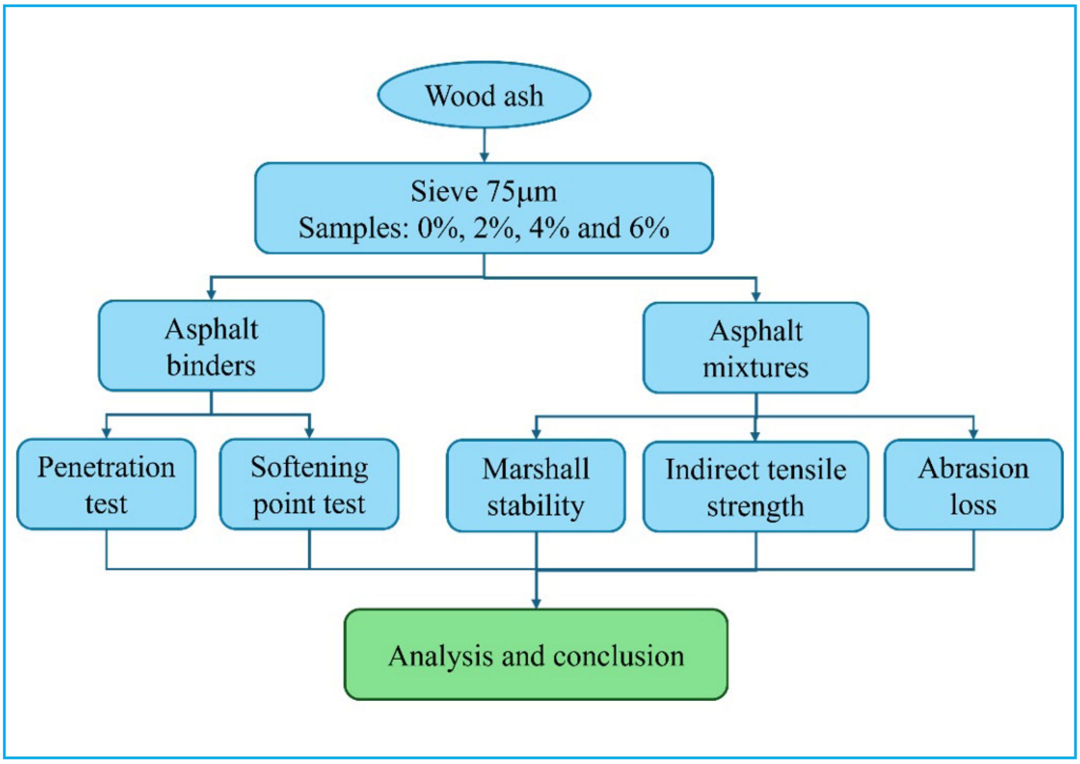

Figure 1. The flowchart in this study

Materials and Methodology

Asphalts

This study utilized 60/70 grade of asphalt, with the properties of the asphalt binders detailed in Table 1. The mixtures included a control mix (0%) and four modified asphalt mixtures incorporating varying proportions of wood ash: 0%, 2%, 4%, and 6%. There were three rational behind choosing the 60/70 grade asphalt that were the compatibility with wood ash, the performance in the tropical climate and consistency in modification results. Meanwhile, the percentage used were based on the previous study using wood ash as the filler in asphalt mixture [8, 11]. The wood ash was incorporated into the asphalt prior to mixing with the aggregate through a process called wet mixing.

Table 1. Characteristics of asphalt binders

Test	Standard	Limitations	Results
Penetration	ASTM D5	60-70	65 dmm
Softening Point	ASTM D36	49-56	50°C
Specific Gravity	ASTM D70	1.01-1.06	1.01
Viscosity	ASTM D4402	< 3 Pa.s	0.5 Pa.s at 135 °C

Aggregate

The gradation of aggregates employed in this research adhered to the specifications outlined in JKR/SPJ/2008-S4 for asphaltic concrete (AC 14). The aggregates were segregated into batches based on the percentage passing for each size. Figure 2 represent the gradation limits for AC 14.

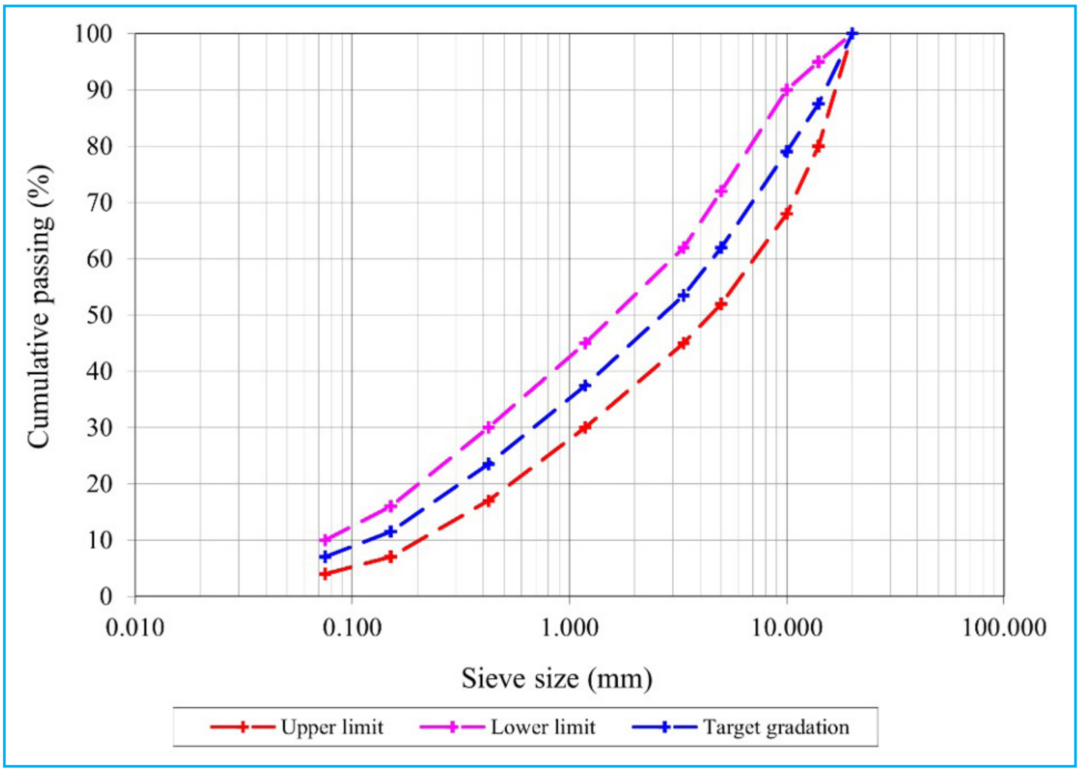

Figure 2. Gradation limits of AC 14

Wood Ash

The wood ash (Figure 3) was acquired from Eng Part Supply (M) Sdn Bhd, Pahang, Malaysia. Before application, the wood ash underwent a drying process in an oven at 110 °C. Subsequently, it was sifted through a 425 μm sieve to eliminate debris and other foreign materials. The remaining wood ash was then subjected to milling and further sieving through a 75 μm sieve. The additive used was encapsulated wood ash with increment 0%, 2%, 4% and 6% of wood ash. The chemical composition of the wood ash are detailed in Table 2. Specific gravity of wood ash was 2.52 g/cm^3.

Figure 3. Wood ash

Table 2. Chemical composition of wood ash

Chemical Compositions	Value (%)
CaO	36.13
K_2O	9.33
SiO_2	27.17
MgO	6.24
SO_3	0.95
Al_2O_3	5.32
Fe_2O_3	3.21
P_2O_3	2.15
Na_2O	0.22
LOI	9.28

Experimental Works

Sample Preparation

The modified asphalt binder was prepared by heating asphalt 60/70 to 160 °C in a steel container until liquefied. Furthermore, wood ash were added to the asphalt in proportions of 0%, 2%, 4% and 6% by weight of the original asphalt. A high-speed shear mixer operating at 1500 rpm for 60 minutes was used to mix the materials. The blending process was performed at 160 °C to avoid asphalt aging at high temperatures. To achieve a full mixing time with regard to the wood ash and asphalt, approximately 60 minutes was used to produce a homogeneous binder. Here, the JKR standards [15] were used to establish the optimum amount of asphalt. Five specimens were constructed under each experimental condition and sample type.

Asphalt Binder Tests

Penetration test

This test is designed to evaluate the consistency of penetration grade bitumen in accordance with the ASTM D5 standards [16]. The standard penetration needle underwent cleaning before insertion into the needle holder. Subsequently, the needle was gradually lowered until its tip made contact with the specimen's surface. Simultaneously, the dial reading on the penetrometer was reset to zero, and an electric timer was connected to it. The timer button was then pressed, initiating the release of the needle holder for a duration of 5 seconds conducted at a consistent temperature of 25 °C. The resulting penetration value was utilized for determining the depth of penetration. To obtain an average penetration score, this process was iterated three times on the same specimen.

Softening point test

For the softening point test, the asphalt binder was placed in ring molds while still warm. The specimens were allowed to cool at room temperature for at least thirty minutes in open air. During this time, water was poured into a beaker and placed in a water bath, which was then set on a magnetic stirrer. A thermometer was used to monitor the water temperature, maintaining it at 5 ± 2 °C for 15 minutes. Once the temperature stabilized, the specimens were placed in the ring holder. After another 15 minutes, steel balls were positioned in the ball-centering guides using forceps. The water was then heated with an electric heater at a rate of 5 ± 2 °C per minute. The temperature and time were recorded when the ball dropped to the base plate of the suspended ring holder. This procedure followed ASTM D36 standards [17].

Asphalt Mixture Tests

Marshall stability test

The Marshall stability test as in Figure 4, conducted following ASTM D6927 [18], was employed to assess the reliability of the mixture. Marshall stability played a crucial role in determining traction strength, while Marshall flow was indicative of the specimen's resistance to rutting. Specimens were weighed in air, water, and saturated surface dry conditions. The weight of specimens in the air condition was recorded. In the water state, the specimens were fully immersed in a water bath at 25 °C for 15 to 30 minutes, and the weight was measured underwater. After promptly cleaning the sample with a wet towel until the air weight was determined, the specimens were submerged in a water bath at 60 °C for 40 minutes. Following this, the sample was stripped and gently cleaned with a towel before being positioned between the lower and upper segments of the breaking head. This investigation provided data on parameters such as stability, flow, stiffness, and bulk density.

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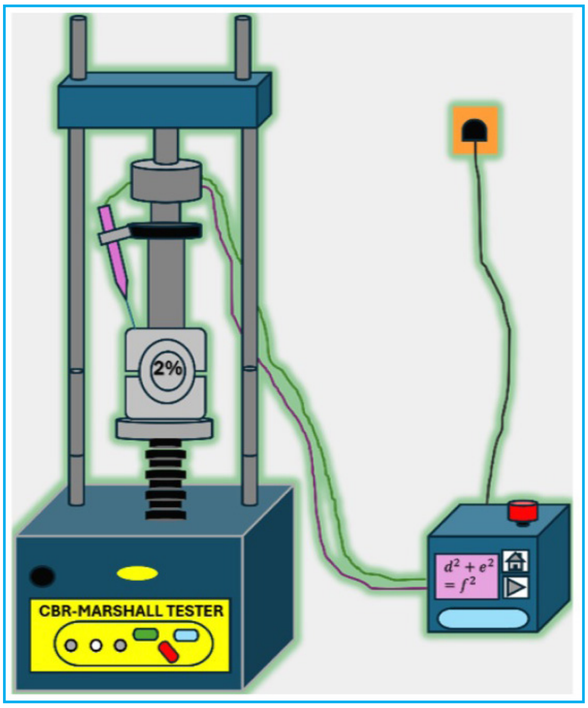

Figure 4. Marshall stability equipment

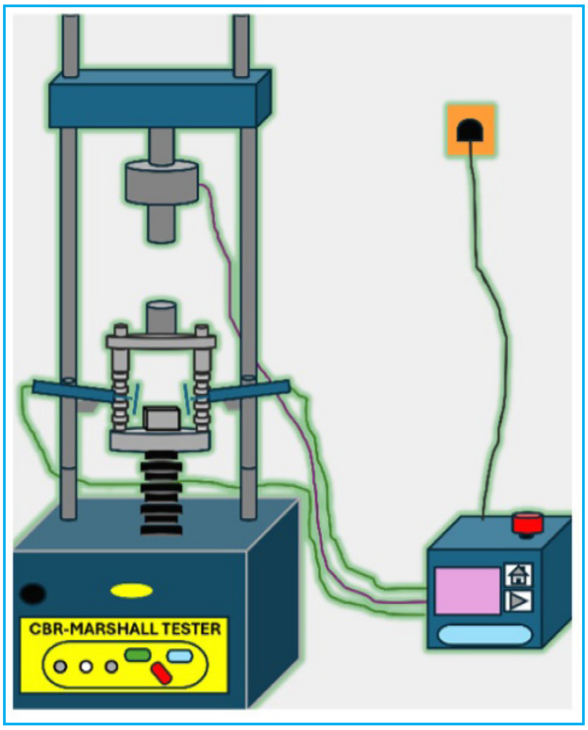

Figure 5. Indirect tensile strength equipment

Indirect tensile strength

The evaluation of indirect tensile strength involves a destructive test on the vertical diameter plane of the sample to assess its resistance to cracking due to ambient temperature. The Marshall design method was employed for sample preparation, following the guidelines outlined in ASTM D6391 [19].

Before testing, the samples underwent conditioning at 25 °C in a Universal Testing Machine (UTM) for a duration of 4 hours. Subsequently, the Universal Compression Machine with an indirect tensile loading fixture was used for the actual testing, as illustrated in Figure 5. The calculation of the indirect tensile strenght value was performed using Eq. (1). Where the P denotes peak load (kN), D denotes diameter of specimen (mm) and T denotes height of specimen (mm).

$$S = \frac{2P}{\pi T D}$$

Abrasion loss test

The abrasion loss test aimed to evaluate the resistance of asphalt concrete specimens to abrasion caused by traffic loads. The assessment involved calculating the percentage loss after 500 revolutions [20]. Two sets of asphalt mixture were prepared for each percentage of wood ash content. Prior to the measurement, the specimens were weighed. Subsequently, each sample, without a steel ball, was placed into the abrasion loss system. The drum underwent rotations at 100, 200, 300, 400 and 500 revolutions. After every 100 revolutions, the drum was stopped, and the specimen was weighed. This process was repeated for two specimens at each wood ash percentage. After completion, the samples were taken out and weighed to recorded the weight after abrasion (Wi) using Eq. (3). Where Wo represents the weight before abrasion and Wi represents weight after abrasion.

$$Abrasion\ loss = \frac{Wo - Wi}{Wo}$$

Results and Discussions

Asphalt binders properties

Figure 6 shows the penetration value versus the different percentages of wood ash. Result depicts the penetration value was decreased from 64 °C to 50 °C with almost 16% decrement. The penetration value indicating its consistency or hardness. A higher penetration value suggests a softer or more fluid bitumen, while a lower penetration value indicates a harder or more viscous bitumen [21]. There were several factors that impact the decrement of the penetration values. First, wood ash acts as a fine filler material that occupies the voids within the asphalt mixture, resulting in a denser and more compact structure. This reduces penetration values as the mixture becomes harder and more resistant to deformation. Second, the chemical interaction between the constituents of wood ash, such as calcium and silica compounds, and the bitumen could enhance the overall stiffness of the mixture. Lastly, the particle size and distribution of wood ash may contribute to its effectiveness as a filler, with finer particles

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enhancing the interlocking of aggregates and thus reducing penetration values. The consistent decrease in penetration values with increased wood ash content highlights the significant impact of wood ash on the mechanical properties of the asphalt mixture. However, it is crucial to consider the practical implications, such as potential changes in workability and durability, which require further investigation.

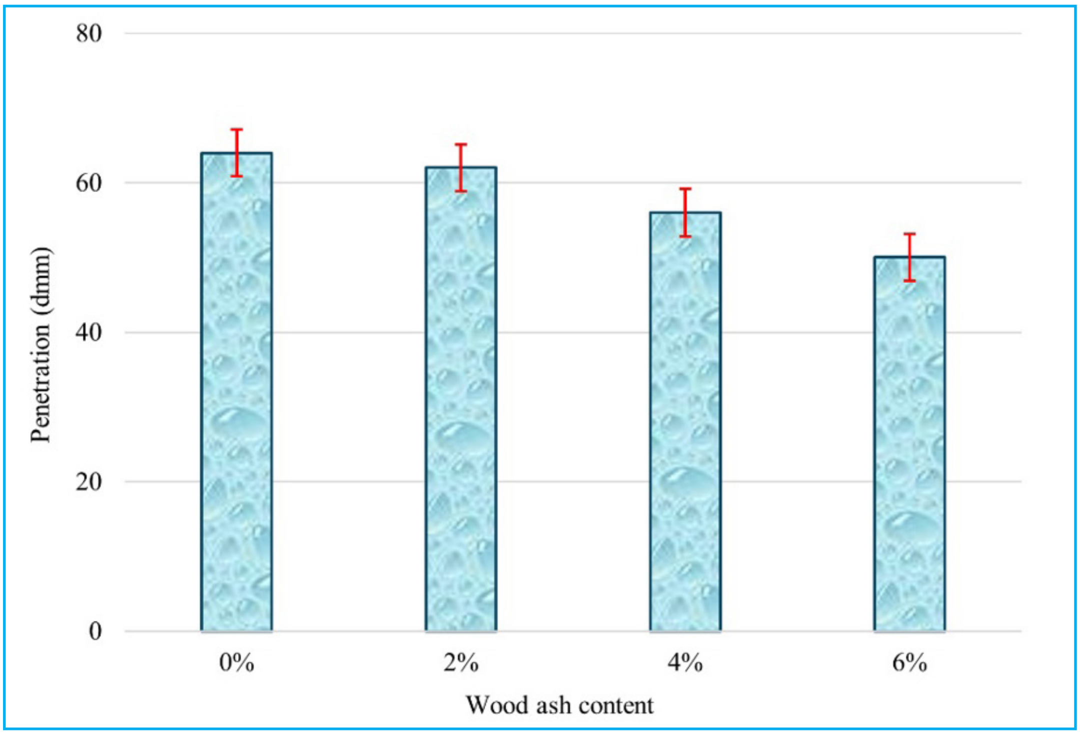

Figure 6. The penetration value of wood ash modified bitumen binders

The results from Figure 7 shows a clear trend as the percentage of wood ash in the asphalt mixtures increased from 0% to 6%. Initially, there is a slight increased in the softening point from 49.2 °C for the control (0% wood ash) to 50.5 °C for 2% wood ash, suggesting potential enhancement of initial softening characteristics due to physical and chemical properties of wood ash particles. However, with higher percentages (4% and 6% wood ash), the softening point begins to rise again, reaching 52.8 °C and 54.1 °C respectively. This suggests that increased wood ash content may start to alter the asphalt binder's rheological properties, affecting its thermal stability and resistance to deformation at higher temperatures. Based on the Figure 7, with higher percentages of wood ash (4% and 6%) in the asphalt mixture, the observed increase in the softening point suggests several potential reasons why this alteration in the asphalt binder's rheological properties occurs. As the amount of wood ash increases, there may be changes in the packing density and distribution of particles within the asphalt binder matrix [22]. This altered packing arrangement can affect how the binder behaves under thermal stress, potentially leading to an increase in the softening point.

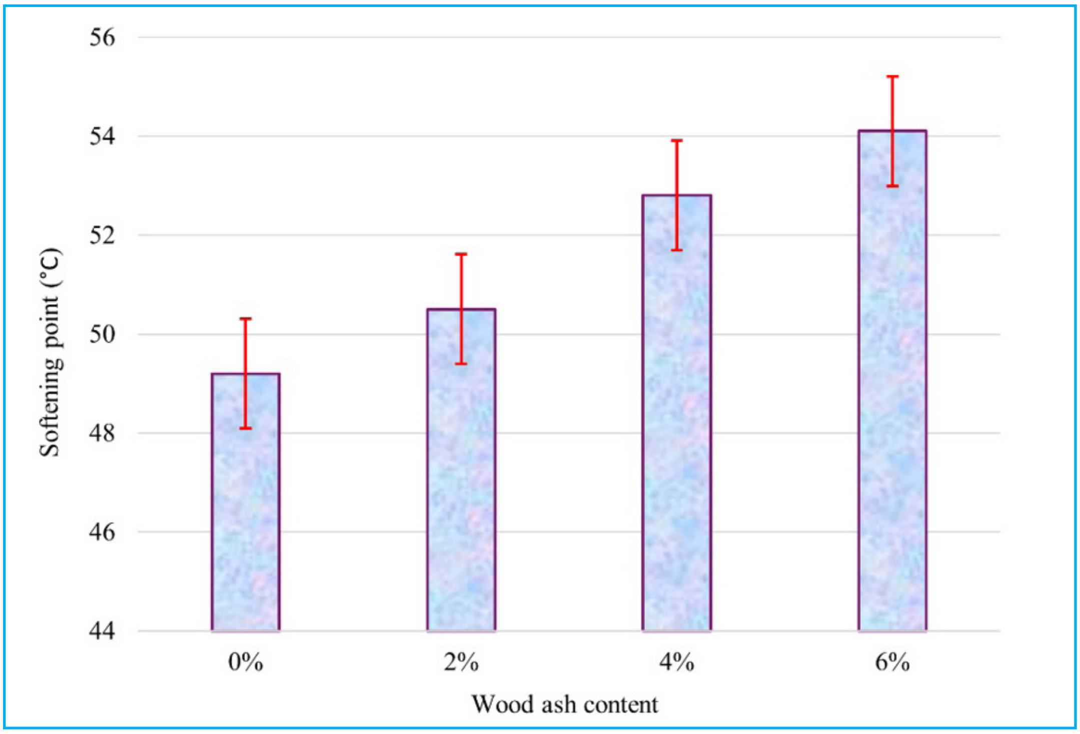

Figure 7. The softening point value of wood ash modified bitumen binders

Marshall stability properties

Stability

The control sample (0% wood ash) exhibited a Marshall stability of 8464 N, serving as a baseline for comparison. As the percentage of wood ash increased, the stability values showed varied trends. The sample with 2% wood ash demonstrated a notable decrease in stability, recording 4925 N, suggesting a potential adverse impact on the strength characteristics of the asphalt mixture. However, with higher percentages of wood ash (4% and 6%), the stability values improved to 5262 N and 8140 N, respectively, approaching or exceeding the stability of the control mix. Figure 8 shows the graph of stability of asphalt mixture at different percentage of wood ash. Several factors may contribute to these observed changes. Wood ash, known for its pozzolanic properties, likely interacts chemically with the asphalt binder, influencing its adhesive and cohesive properties. The initial decrease in stability at 2% wood ash could indicate inadequate mixing or an unfavourable effect on binder-aggregate interaction. Conversely, the higher percentages of wood ash may have positively impacted mixture stability by enhancing binder stiffness and reducing susceptibility to moisture.

Furthermore, the particle size distribution and specific surface area of wood ash particles could affect the packing density and internal friction angles of the asphalt mix, influencing Marshall stability. The interaction between wood ash particles and asphalt binder is crucial in understanding the variations observed in stability across different mix designs. In conclusion, incorporating wood ash as a filler in asphalt mixtures shows variable effects on Marshall stability based on the percentage used. Initial addition of 2% wood ash reduced stability, but subsequent 4% and 6% additions improved or matched stability compared to the control mix without wood ash. This indicates wood ash could be a beneficial additive in asphalt, especially in higher concentrations, potentially enhancing resistance to rutting and moisture damage. At 6% addition of wood ash content suggest the best result for enhancing the stability of the modified asphalt mixtures.

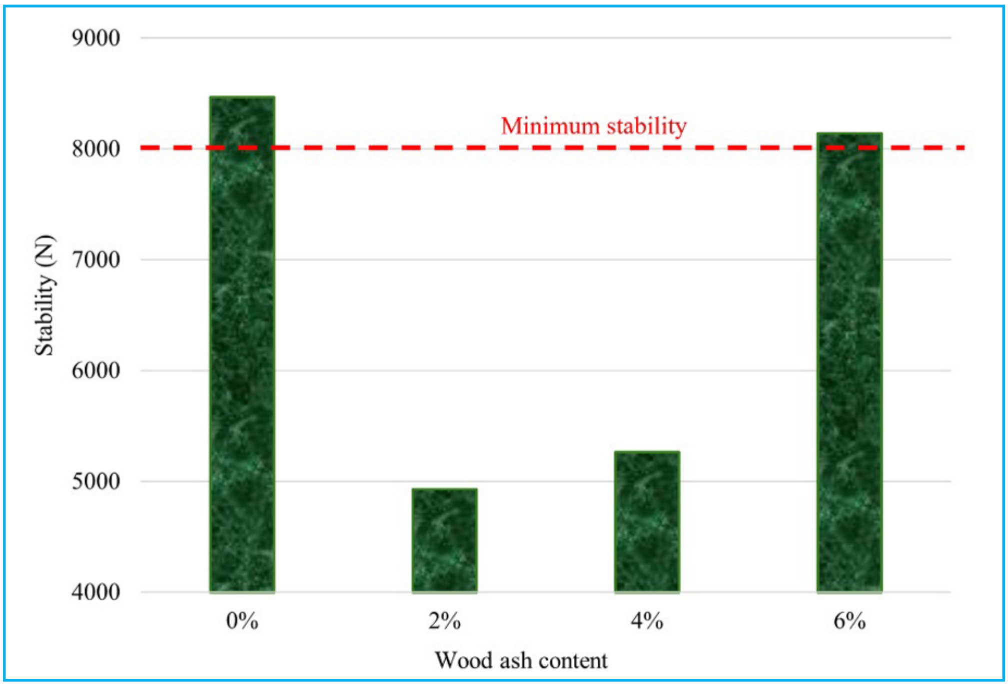

Figure 8. Stability of wood ash modified asphalt mixtures at different percentages

Flow

Based on Figure 9, the flow of asphalt mixture at different percentage of wood ash was shown. Initially, without any wood ash (0% content), the flow value was measured at 5.789 mm. As the percentage of wood ash increased to 2%, 4%, and 6%, the flow values decreased to 3.056 mm, 3.331 mm, and 3.666 mm, respectively. This trend suggests that incorporating wood ash into the asphalt mixture reduces flow, indicating potential enhancements in asphalt stability. The decrease in flow values with higher wood ash content can be attributed to its ability as a pozzolanic material to alter the rheological properties of the asphalt binder. This alteration likely improves binder cohesion and viscosity, thereby reducing flow and enhancing stability.

Nevertheless, it is essential to note that excessive wood ash content may lead to diminishing returns or negative effects on asphalt performance. Further research should focus on determining the optimal wood ash content to maximize benefits while maintaining overall mixture performance. According to the Malaysian Standard Specification for Road Works, the acceptable flow range is between 2.0 mm and 4.0 mm. Only the modified asphalt mixture met the JKR specifications. The conventional asphalt mixture failed to meet JKR standards due to its high flow value, indicating a higher risk of road defects and permanent deformation, such as rutting or shoving, under load.

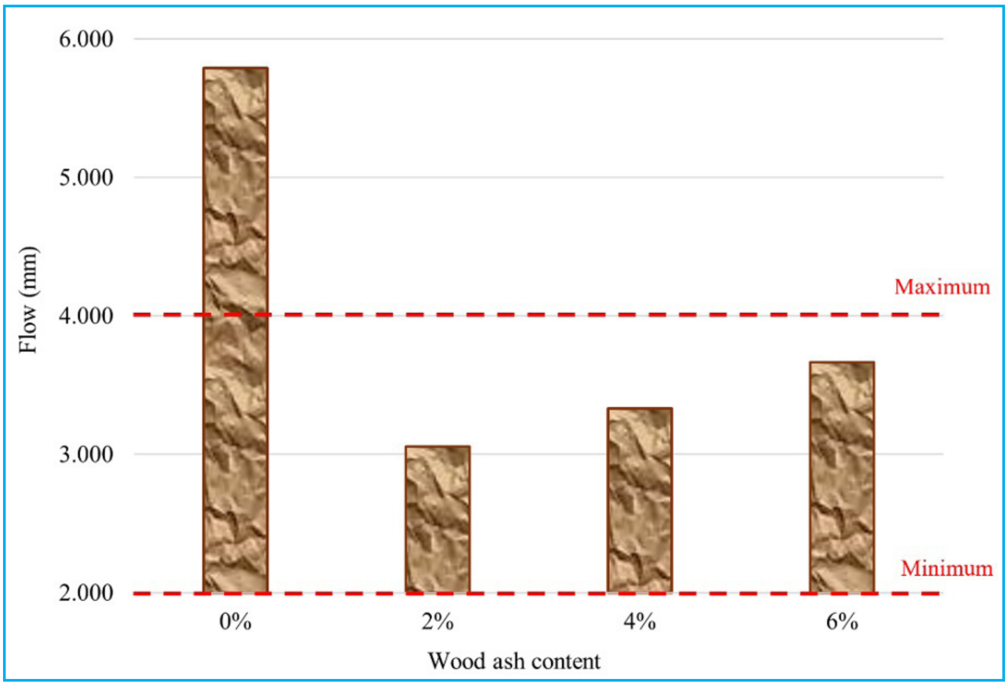

Figure 9. Flow of wood ash modified asphalt mixtures at different percentages

Stiffness and flow

As the wood ash content increases, the flow values generally decrease, indicating reduced deformation under load based on the Figure 10. For instance, the flow value drops from 5.789 mm in the control mixture (0% wood ash) to 3.056 mm in the mixture with 2% wood ash. This significant reduction in flow corresponds to a substantial increase in stiffness from 1490.89 N/mm to 2683.64 N/mm. This inverse relationship suggests that the asphalt mixture becomes more resistant to deformation as stiffness increases. At 4% wood ash, the flow value slightly increases to 3.331 mm, while the stiffness decreases to 1665.96 N/mm compared to the 2% mixture. This indicates that beyond a certain point, additional wood ash may not contribute proportionally to stiffness and may allow more deformation under load. Similarly, at 6% wood ash, the flow value is 3.666 mm with a stiffness of 2216.12 N/mm, suggesting that while the mixture is still stiffer and less deformable than the control, it does not out perform the 2% mixture. In conclusion, there is a clear inverse relationship between stiffness and flow in asphalt mixtures with wood ash filler: as stiffness increases, flow decreases, indicating enhanced resistance to deformation. The optimal balance is observed at 2% wood ash content, which achieves the highest stiffness and the lowest flow.

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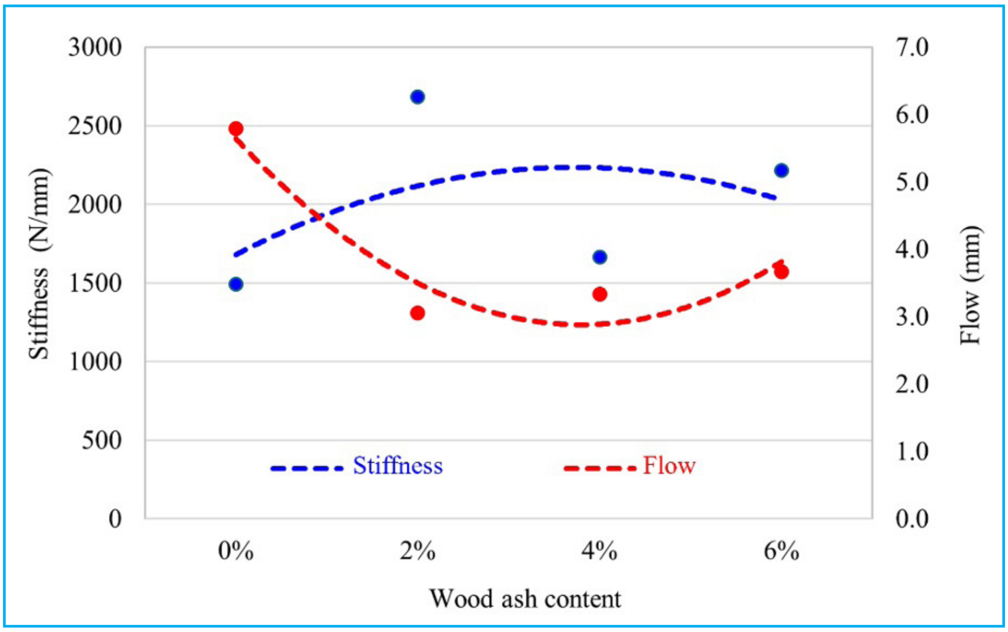

Figure 10. Stiffness vs flow of wood ash modified asphalt mixtures at different percentages

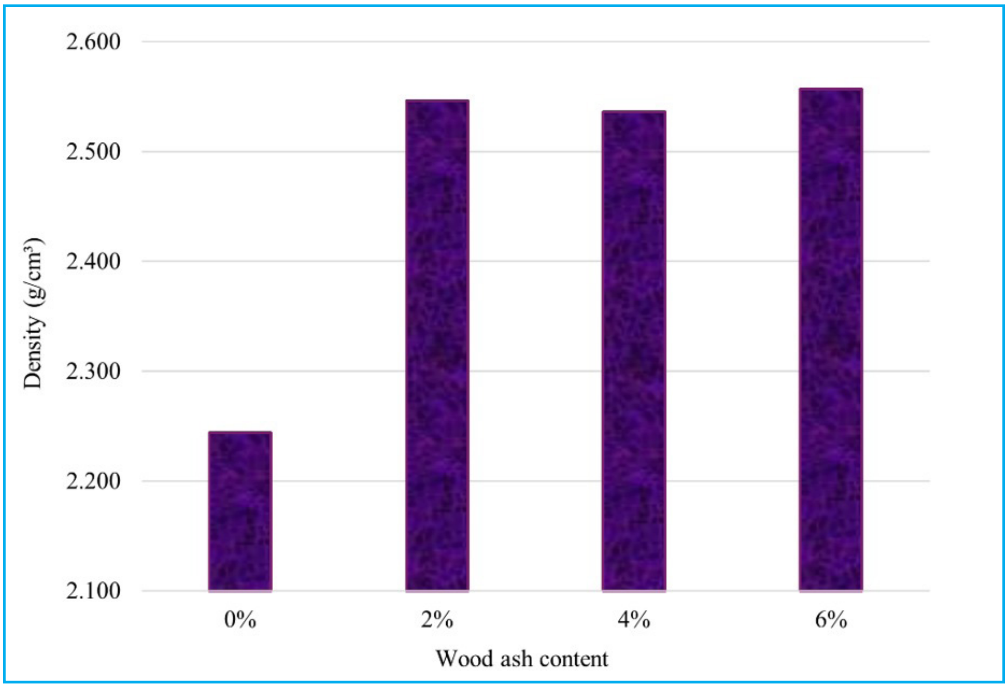

Figure 11. Density of wood ash modified asphalt mixtures at different percentages

Density

Figure 11 depicts the density of asphalt mixture at different percentage of wood ash. The base asphalt mixture (0% wood ash) had a density of 2.244 g/cm^3. When 2% wood ash was added, the density increased significantly to 2.546 g/cm^3. At 4% wood ash, the density slightly decreased to 2.536 g/cm^3, indicating a minor drop compared to the 2% wood ash mixture. Finally, the 6% wood ash mixture showed the highest density at 2.557 g/cm^3. The increase in density from

0% to 2% wood ash indicates that wood ash contributes to filling the voids within the asphalt mixture more effectively than the base mixture alone, leading to a denser material. This trend suggests that wood ash has a beneficial filling effect up to a certain point. However, the slight decrease in density at 4% wood ash compared to 2% could imply an optimal concentration range for wood ash addition, where beyond a certain percentage, the filler effect might be slightly counteracted by the potential for ash particles to create internal voids or alter the mixture's compaction characteristics. The highest density observed at 6% wood ash suggests a further improvement in filling capacity, yet this might also point to the potential limit where additional wood ash no longer contributes to significant density increases but stabilizes the density improvement.

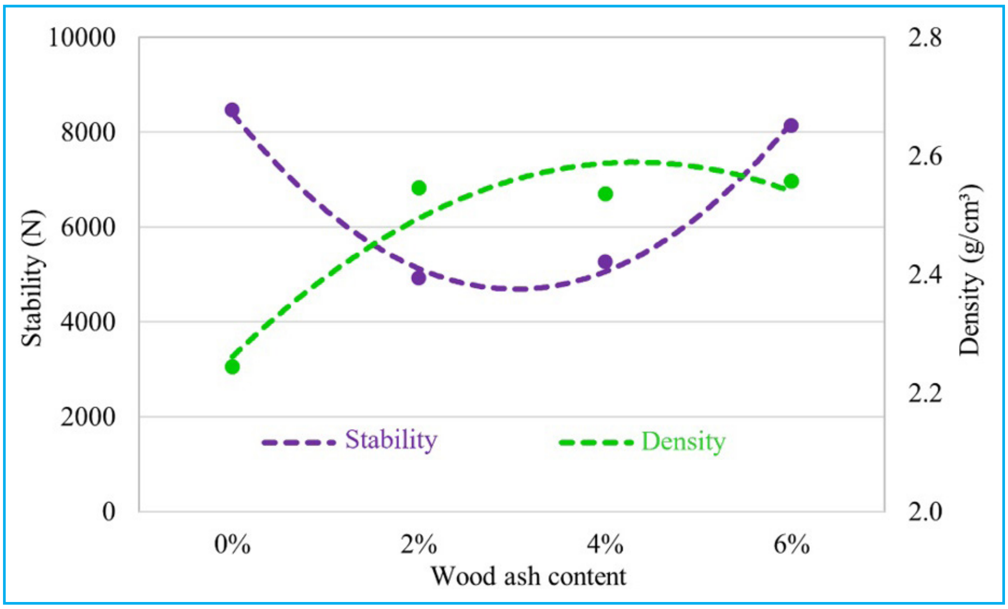

Figure 12. Stability vs density of wood ash modified asphalt mixtures at different percentages

Stability and density

Figure 12 illustrates the impact of wood ash on stability and density. Generally, stability decreases as the percentage of wood ash increases. The conventional asphalt mixture showed a highest stability of 8464 N, while the lowest stability, at 2% wood ash, was 4925 N. Stability indicates how well an asphalt mixture performs under load. According to [23] stability depends on the cohesion of the asphalt, which increases with higher asphalt content. It is evident that at 2% wood ash, the mixture becomes very prone to cracking, is brittle, cannot withstand high loads, and has low strength. Additionally, the results show that bulk density decreases with increasing wood ash content, as the bitumen fills the void spaces between aggregate particles.

The interaction between stability and density underscores the need for careful consideration in optimizing asphalt mix designs with wood ash fillers. While higher density generally correlates with increased stability, observed prominently at 6% wood ash, this relationship was disrupted at lower concentrations. Here, despite density gains, stability decreased, highlighting the critical role of filler content and distribution in achieving optimal performance. Therefore, balancing these factors becomes crucial to maximize both density and stability effectively across the range of wood ash concentrations tested.

Indirect tensile strength

Figure 13 presents that the mixture with 0% wood ash exhibited the highest indirect tensile strength at 375.7 kPa. As the percentage of wood ash increased to 2%, 4%, and 6%, the indirect tensile strength values decreased to 285.82 kPa, 332.20 kPa, and 268.96 kPa, respectively. On the other hand, indirect tensile strength can be seen increased with the increase in wood ash content and started to decrease at 6% wood ash which recorded the tensile strength of 4% wood ash asphalt mixture as an optimum performance. This finding broadly supports the work of other studies [9] that also found 4% wood ash content. The decrease in indirect tensile strength with increasing wood ash content suggests that while wood ash can act as a filler in asphalt mixtures, excessive quantities might negatively impact the strength properties of the mixture. This observation could be attributed to several factors such as the particle size distribution of wood ash, its chemical composition affecting the asphalt binder, and the interfacial bonding between wood ash particles and the asphalt binder [24].

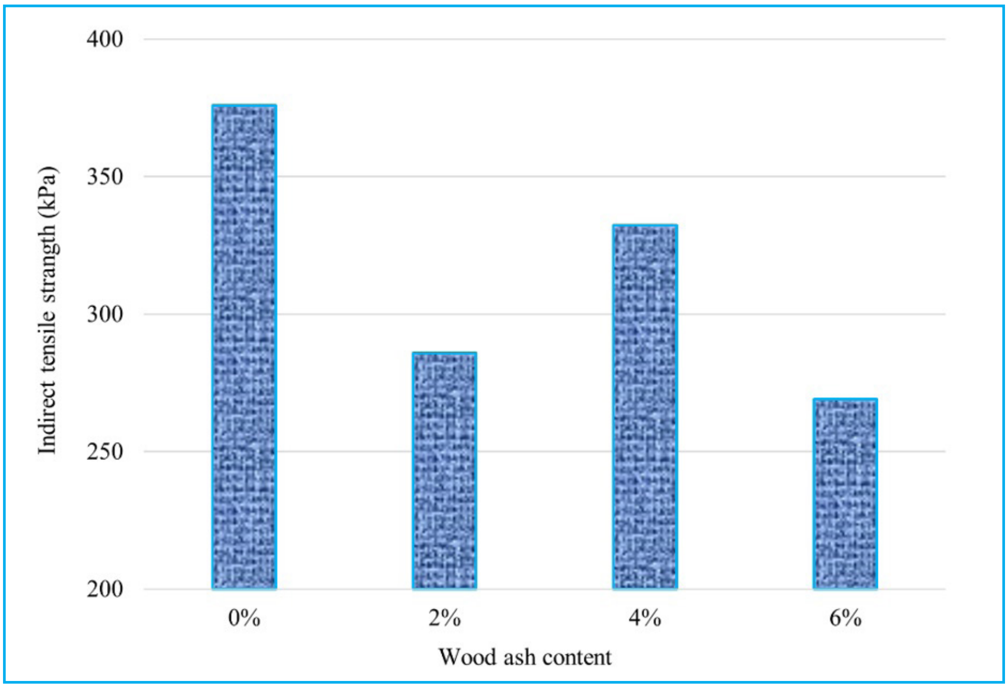

Figure 13. Indirect tensile strength of wood ash modified asphalt mixtures

It is also essential to consider the practical implications of using wood ash as a filler in asphalt mixtures. While it may offer environmental benefits by recycling waste material and reducing the demand for natural aggregates, careful optimization of wood ash content is crucial to ensure that it enhances rather than compromises the performance of asphalt pavements.

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Abrasion loss

According to Figure 14, the results indicate a notable trend in abrasion resistance with increasing wood ash content. At 0% wood ash, the asphalt mixture exhibited an abrasion loss of 1.25%. This baseline measurement serves as a reference point for comparing the effects of wood ash inclusion. As the wood ash content increased to 2%, 4%, and 6%, the abrasion losses were recorded as 7.94%, 41.34%, and 47.50% respectively. The significant increase in abrasion loss at 4% wood ash content suggests that beyond a certain threshold, the benefits of using wood ash as a filler diminish. This observation aligns with prior research indicating that excessive filler content can negatively impact the performance of asphalt mixtures. The sharp rise in abrasion loss at 4% wood ash content may be attributed to reduced bonding between the wood ash particles and the asphalt binder, leading to decreased cohesion and increased susceptibility to abrasion. Based on the results of abrasion loss testing, it is evident that up to 4% wood ash content can potentially improve abrasion resistance without significantly compromising the integrity of the asphalt mixture. It is important to highlight that, according to JKR standards [15], the maximum permissible range for abrasion loss generally falls between 35% and 45%. However, beyond this threshold, particularly at 6% wood ash content, there is a considerable increase in abrasion loss, indicating a decrease in the mixture's durability.

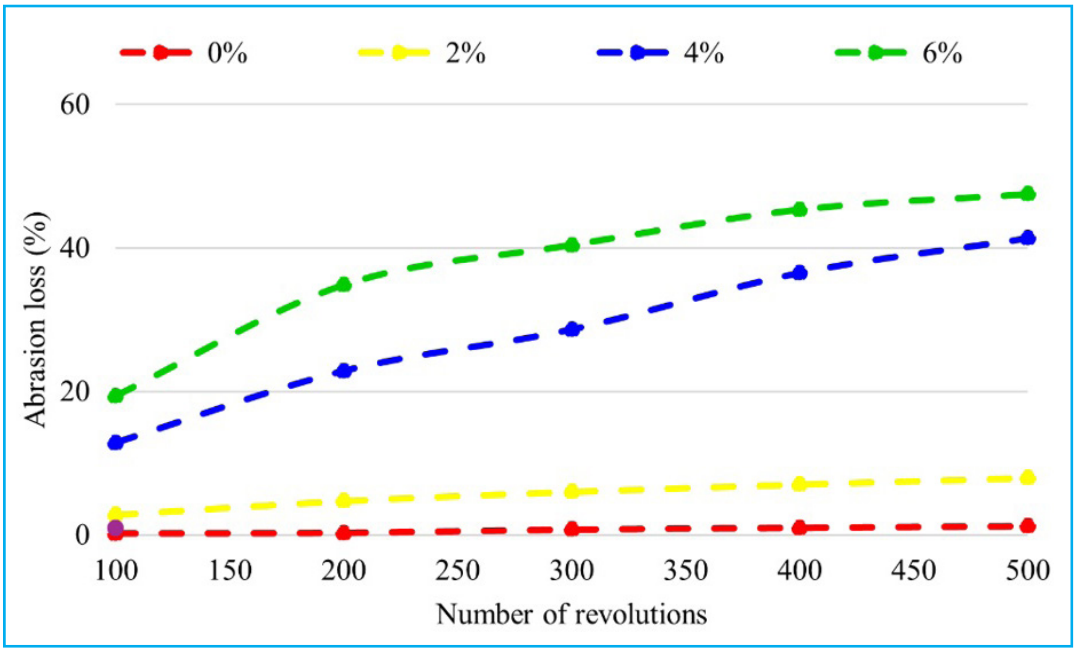

Figure 14. Effect of abrasion loss for 0%, 2%, 4% and 6% wood ash modified asphalt mixtures

Correlation of Marshall stability, indirect tensile strength and abrasion loss

Correlation analysis of stability and indirect tensile strength

Figure 15 presents the effect of different wood ash percentages on Marshall stability and abrasion loss in asphalt mixtures. At 0% wood ash, the mixture exhibits the highest stability of 8464 kN and the lowest abrasion loss of 1.249%. As the wood ash content increases to 2%, the stability significantly decreases to 4925 kN, while the abrasion loss increases to 7.94%. For the mixture with 4% wood ash, stability slightly improves to 5262 kN, but the abrasion loss dramatically rises to 41.344%. At 6% wood ash, the stability reaches 8140 kN, and the abrasion loss further increases to 47.496%. Conversely, Marshall stability generally decreases with higher wood ash content, suggesting reduced resistance to deformation and potential structural integrity under traffic loading. The observed inverse relationship between abrasion loss and Marshall stability with increasing wood ash content in asphalt mixtures can be attributed to several factors which are abrasion resistance.

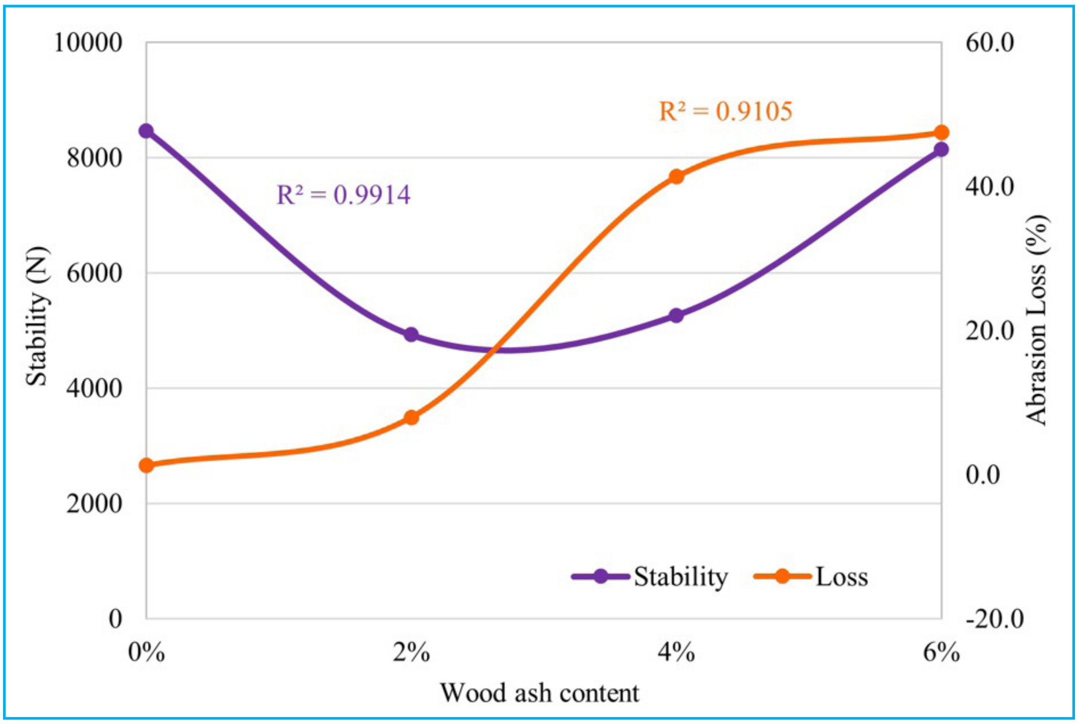

Figure 15. Stability vs abrasion loss of wood ash modified asphalt mixtures

Wood ash particles may not provide the same level of resistance to wear and abrasion as mineral fillers. Higher abrasion loss rates with increased wood ash content suggest that the asphalt surface may wear down more quickly, exposing the underlying layers and reducing pavement durability over time. Other than that, wood ash particles, depending on their size distribution and shape, may not integrate as effectively with the asphalt binder compared to traditional mineral fillers. This incomplete bonding can lead to weaker interfacial adhesion and increased susceptibility to abrasion, where particles may detach more easily under frictional forces. In conclusion, while the stability shows some fluctuations with increasing wood ash content, the abrasion loss consistently increases, indicating a trade-off between stability and durability with higher wood ash percentages.

Correlation analysis of density and abrasion loss

Figure 16 illustrates the relationship between wood ash content in asphalt mixtures and their corresponding density and abrasion loss. At 0% wood ash, the mixture has a density of 2.244 g/cm³ and an abrasion loss of 1.249%. Increasing the wood ash content to 2% results in a notable rise in density to 2.546 g/cm³ and a significant increase in abrasion loss to 7.94%. At 4% wood ash, the density slightly decreases to 2.536 g/cm³, while the abrasion loss escalates dramatically to 41.344%. Finally, with 6% wood ash, the density reaches its highest value of 2.557 g/cm³, and the abrasion loss peaks at 47.496%. This escalation in abrasion loss indicates a decrease in the asphalt mixtures' resistance to wear and potential deterioration under traffic and environmental conditions as wood ash content rises.

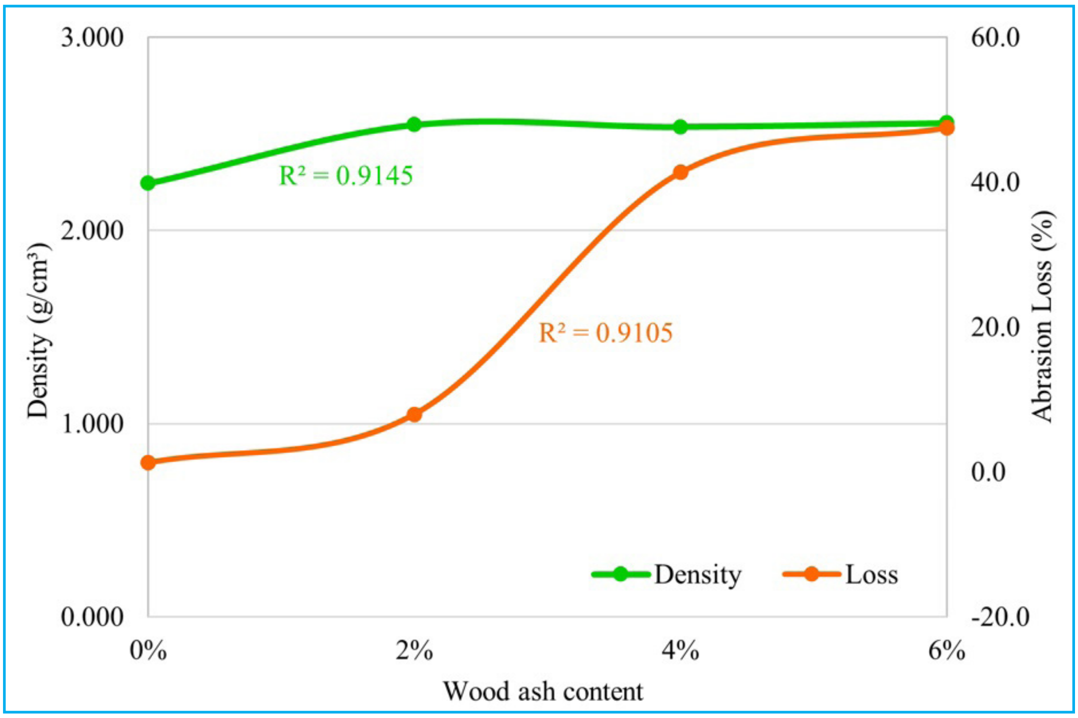

Figure 16. Density vs abrasion loss of wood ash modified asphalt mixtures

The relationship between density and abrasion loss underscores the complex interplay between structural integrity and surface durability in asphalt pavements. While higher density generally correlates with improved resistance to abrasion, the study highlights the importance of carefully balancing filler content to optimize both density and durability. As the percentage of wood ash increased, abrasion loss also increased, indicating potentially reduced durability. Higher density generally correlates with better compaction, which tends to enhance the overall durability and resistance of the asphalt mixture to surface abrasion. A well-compacted mixture with higher density can form a dense surface that resists wear and extends pavement life. In summary, the data indicates that while the density of the asphalt mixtures generally increases with higher wood ash content, there is a corresponding and substantial increase in abrasion loss, suggesting a compromise between density and durability.

Conclusions

In conclusion, while wood ash as a filler in asphalt mixtures shows potential in certain performance aspects such as stiffness and density, it also introduces challenges in terms of stability and abrasion resistance. The optimal performance was observed at a wood ash content of 6%, which balanced tensile strength and flow properties. These findings highlight the importance of optimizing wood ash content to enhance the performance of asphalt mixtures in practical applications. Thus, wood ash is a sustainable material suitable for replacing conventional fillers in asphalt mixture production, reducing environmental pollution. Further studies are recommended to explore different gradations and binder types and to investigate wood ash as an asphalt modifier for quality improvement. By exploring different aggregate gradations, binder types, and incorporating innovative materials like wood ash, researchers aim to develop asphalt mixtures that are more durable, sustainable, and cost-effective. Such studies are essential for advancing pavement technology, improving infrastructure quality, and addressing environmental concerns. The practical implications in real-world applications can be addressed by (i) ensuring supply chain efficiency and material availability in the region, (ii) conducting a lifecycle cost analysis, including the reduction in wood ash disposal costs, and (iii) evaluating long-term performance, focusing on durability and aging through field trials.

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Conflicts of Interest

The authors declare no competing interest.

Author Contributions

Wan Noor Hin Mior Sani: writing, original draft preparation. **Nur Shahirah Shahrom:** writing, reviewing and editing. **Rozalina Ab Rashid:** reviewing and editing. **Norhidayah Abdul Hassan:** reviewing and editing. **Zaid Hazim Al-Saffar:** reviewing and editing. **Mohd Hazree Hashim:** funding and reviewing.

Data Availability Statement

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

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