SINERGI Vol. 30, No. 1, February 2026: 263-272
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2026.1.024

Utilization of teak wood powder waste as eco-friendly filler in HRS-WC asphalt: a comparative analysis of dry and wet Marshall mix methods

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Abstract
With the increasing demand for road durability driven by rapid economic development, innovative and sustainable approaches are essential to improve the strength and service life of road pavements. This study investigates the use of teak wood powder waste (TWPW) as a cost-effective and environmentally friendly filler material in Hot Rolled Sheet – Wearing Course (HRS-WC) asphalt mixtures. Utilizing bio-waste not only supports circular economic principles but also offers economic benefits by reducing reliance on conventional, more expensive fillers. The research evaluates various TWPW concentrations (0%, 0.3%, 0.6%, and 0.9%) and their effects on key Marshall test parameters, including stability, flow, Marshall Quotient (MQ), Voids in Mineral Aggregate (VMA), Voids in Mix (VIM), and Voids Filled with Asphalt (VFA). Samples were prepared using both dry and wet methods in accordance with Bina Marga (2018) specifications. The results indicate that the optimum filler content was 0.9% for the dry method (stability: 1042.68 kg) and 0.6% for the wet method (stability: 1161.14 kg). SEM analysis confirmed that filler dispersion significantly influences the internal structure and porosity of the mixture. At 0.3% and 0.6%, the filler was more evenly distributed, leading to improved compaction and mechanical performance. Conversely, agglomeration at 0.9% increased voids and reduced compaction quality. This study demonstrates that TWPW can serve as a viable low-cost filler alternative, maintaining pavement performance while reducing material costs and environmental impact. The findings support the adoption of sustainable waste utilization practices in road construction.

Keywords:
Filler;
HRS-WC;
Marshall Test;
Stability;
Teak Wood Powder;

Article History:
Received: June 28, 2025
Revised: August 27, 2025
Accepted: September 16, 2025
Published: January 8, 2026

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INTRODUCTION

The increasing demand for durable, sustainable road infrastructure has led to the exploration of innovative materials to improve the strength and lifespan of road pavements [1]. Roads play a crucial role in transportation networks and must withstand the growing traffic while maintaining safety and efficiency. As economic growth accelerates [2], the durability of road surfaces becomes increasingly critical, particularly in regions with heavy traffic and harsh environmental conditions [3]. This has prompted the need for advanced materials that enhance the performance of asphalt mixtures while remaining environmentally responsible [4].

In the field of Traffic Engineering and Safety, ensuring road durability and structural integrity is essential to maintaining road safety for all users [5], particularly amid rising traffic volumes and loads [6]. One promising solution to this challenge is the use of bio-waste materials, specifically Teak Wood Powder Waste (TWPW), a byproduct of the furniture industry. Teak wood sawdust is often found in rural areas because teak trees grow abundantly in these areas. Forestry Statistics of Indonesia (2020) stated that Indonesia's total log production in 2020 will reach 61.02 million m^3, where Indonesia's total sawn wood production will reach 2.6 million m^3 per year. The furniture industry produces sawdust, accounting for 12-15% of the wood raw materials used [7].

TWPW is an abundant, sustainable filler [8] that can improve the properties of asphalt mixtures while addressing growing environmental concerns about waste disposal. Traditionally discarded or burned, this waste can now be repurposed in asphalt mixtures, providing an environmentally friendly alternative to conventional fillers. Using TWPW as a filler can reduce road construction costs while advancing the principles of a circular economy by recycling waste materials [9][10]. By using TWPW, the asphalt industry reduces reliance on costly mineral resources and supports waste recycling, in line with the principles of the circular economy [11].

TWPW, rich in lignin and cellulose, can enhance the stability and stiffness of asphalt mixtures, making it both an economically viable and performance-effective option for road construction. Although research specifically on TWPW is limited, studies such as those by Zhang et al. (2020) have shown that lignin, a byproduct of biomass, can improve the mechanical performance of asphalt mixtures, including resistance to deformation and thermal cracking [12].

This study focuses on the use of TWPW in Hot Rolled Sheet – Wearing Course (HRS-WC) asphalt mixtures. HRS-WC mixtures are commonly used in tropical climates, such as Indonesia, due to their high flexibility and durability under heavy traffic [13]. However, the potential to enhance these mixtures with sustainable, cost-effective fillers, such as TWPW, remains largely unexplored. The study aims to evaluate the effect of varying filler contents of TWPW on the performance of the asphalt mixture. The key parameters of interest, as measured by the Marshall stability test, include stability, flow, Marshall Quotient (MQ), Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). These parameters are essential for assessing the quality and durability of asphalt mixtures, particularly their ability to withstand traffic loads, resist deformation, and maintain long-term performance [14].

Recent studies have highlighted the benefits of incorporating bio-waste materials, such as sawdust and biomass ash, into asphalt mixtures [15][16]. These materials have been found to improve stability, workability, and rutting resistance of asphalt mixtures, while also contributing to sustainability by reducing the environmental impact of road construction [17]. Wood-based fillers, particularly those with high lignin content, such as teak wood, have shown promise for enhancing adhesion between the asphalt binder and aggregates [18], thereby improving the mixture's stiffness and stability [19]. The use of these materials not only helps in reducing waste but also decreases the carbon footprint associated with traditional road construction materials [20].

Previous research has demonstrated that, for example, sawdust can increase the Marshall stability of asphalt, making it more resistant to deformation under traffic loads [21]. Other studies have examined the impact of filler content on asphalt performance, suggesting that there is an optimal filler proportion that maximizes the mixture's mechanical properties without compromising its workability [22]. Furthermore, the method of incorporating the filler—whether dry or wet—can influence the final properties of the asphalt mixture. It has been observed that, in the wet method, where moisture is added to the filler-aggregate mixture, uniform filler distribution can enhance compaction and stability [23].

Despite the promising results of using bio-waste fillers, further research is needed to assess their long-term performance, especially under varying environmental conditions such as temperature fluctuations, moisture exposure, and heavy traffic. Additionally, economic feasibility studies are essential for evaluating the cost-effectiveness of large-scale use of these bio-waste materials, particularly in countries with abundant agricultural and industrial waste. This study aims to fill this gap by investigating the use of TWPW in HRS-WC asphalt mixtures, focusing on its effects on key performance parameters under both dry and wet mixing conditions. The findings from this research will provide valuable insights into the potential of TWPW as a sustainable, cost-effective filler for asphalt mixtures, thereby contributing to the development of greener, more durable road construction technologies.

METHOD

This study investigates the utilization of Teak Wood Powder Waste (TWPW) as a filler in Hot Rolled Sheet – Wearing Course (HRS-WC) asphalt mixtures. The primary objective was to evaluate the impact of different TWPW concentrations on key asphalt properties, using two different mixing methods: dry and wet. The analysis focused on evaluating the Marshall test parameters, including stability, flow, Marshall Quotient (MQ), Void in Mix (VIM), Void in Mineral Aggregate (VMA), and Void Filled with Asphalt (VFA). The research procedure followed standard practices outlined by Bina Marga (2018) and involved preparing asphalt mixtures with varying filler contents (0%, 0.3%, 0.6%, and 0.9% by weight). These mixtures were then tested to assess changes in their mechanical properties and determine the optimal filler content for enhanced stability and performance.

Material

The primary material used in this study was Teak Wood Powder Waste (TWPW), sourced from a local furniture manufacturing facility. The asphalt binder used was a commercial-grade binder. The coarse and fine aggregates used in the mixtures were locally sourced and conformed to the specifications outlined in Bina Marga (2018) standards. The primary equipment used in this research was the FEI INSPECT S50 Scanning Electron Microscope (SEM), which was used to observe the microstructure and filler distribution in the asphalt mixtures. The SEM was set at a magnification of 2500x for optimal imaging.

Density measurements were performed according to ASTM D792. The specimens were prepared by compacting the asphalt mixtures and then weighing them to determine the bulk density.

Methods

The TWPW was processed by sieving the powder to a fine consistency. The various filler contents (0%, 0.3%, 0.6%, and 0.9% relative to the aggregate's total weight) were then mixed into the asphalt mixture. The TWPW was added in dry form for the dry method and mixed with water for the wet method.

For the dry method, the coarse aggregates, fine aggregates, and TWPW filler were dry-mixed to ensure uniform distribution of the filler. The asphalt binder was then added, and the mixture was heated to 140°C. These temperatures guarantee that the asphalt binder's viscosity is sufficiently low to allow effective coating of the aggregate particles [24]. After thorough mixing, the asphalt mixture was compacted at 121°C. In the wet method, water was first added to the dry mixture of coarse aggregates, fine aggregates, and TWPW filler. The addition of water increases expansion and improves workability [25]. The mixture was thoroughly stirred for 10 minutes at room temperature to ensure proper hydration of the filler. The asphalt binder was then added to the mixture, heated to 140°C, and compacted at 121°C.

RESULTS AND DISCUSSION

The determination of the optimum asphalt content (OAC) is based on the Marshall test specification requirements. The Marshall parameters used as reference are VIM, VMA, VFA, stability, flow, and Marshall Quotient. Table 1 summarizes the Marshall test results, with asphalt contents that meet all Marshall parameters of 7.14% and 7.54%, resulting in an Optimum Asphalt Content (OAC) of 7.33% (Figure 1).

The density is the ratio of the test specimen's weight to its volume, reflecting the compactness of the asphalt mixture. In the analysis, the variables used to determine density include dry weight, saturated weight, and surface-dry weight (SSD). According to results from both the dry and wet methods, the density values show a consistent pattern: density decreases with increasing filler content. Other research found that mixtures with higher density can withstand greater loads and exhibit greater resistance to water and air infiltration [26]. Therefore, if the density decreases, the mixture tends to soften.

In the dry method, the density decreases from 0% filler content to 0.6%, then increases at 0.9% filler (Figure 2). The highest density in the dry method is at 0% filler content, with a value of 2.417 gr/cm^3, and the lowest density is at 0.6% filler content, with a value of 2.385 gr/cm^3. In the wet method, the density decreases steadily with increasing filler content (Figure 2). The highest density is at 0% filler content, with a value of 2.417 gr/cm^3, and the lowest density is at 0.9% filler content, with a value of 2.338 gr/cm^3.

VIM (Void in Mix) represents the percentage of air voids in the mixture, determined by the aggregate material present in the mixture. According to the Bina Marga (2018 Revision 2), the VIM value that meets the HRS-WC specifications is between 3% and 5%. Figure 3 shows that the VIM value increases with increasing filler content.

Table 1. Summary of Marshall Test Parameters for Optimum Asphalt Content

No	Asphalt Content Variation	Bulk Density (gr/cm³)	Void in Mix (VIM)	Void in Mineral Aggregate (VMA)	Void Filled with Asphalt (VFA)	Stability (kg)	Flow	Marshall Quotient (MQ)
1	6.0	2.335	8.505	20.341	58.203	1301.398	3.460	391.945
2	6.5	2.350	7.186	20.238	64.623	1371.955	2.163	536.768
3	7.0	2.372	5.610	19.931	71.920	1345.823	3.040	447.193
4	7.5	2.416	3.141	18.895	83.383	1011.327	3.000	342.266
5	8.0	2.440	1.408	18.506	92.403	974.742	3.680	266.277

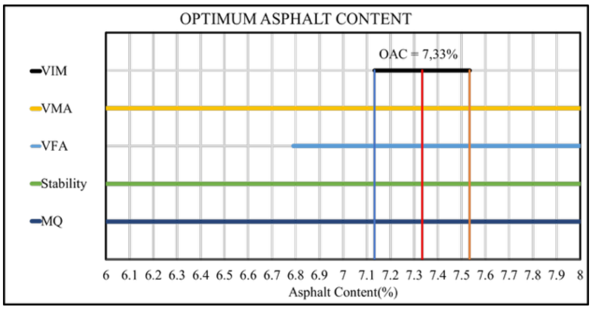

Figure 1. Graph of optimum asphalt content values

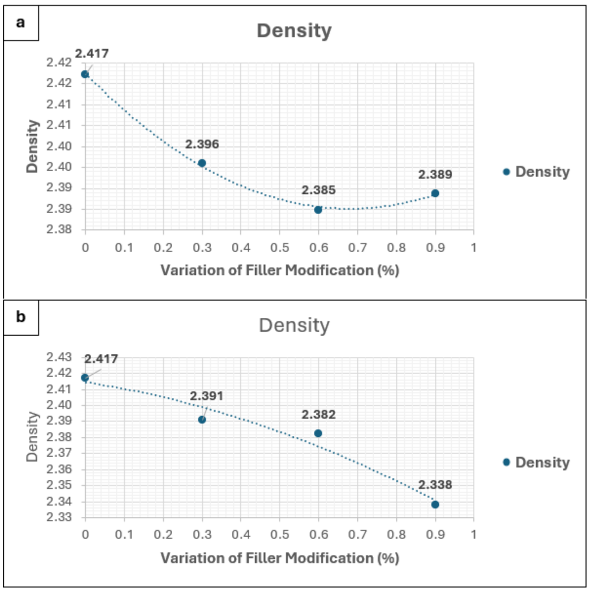

Figure 2. Graph of (a) Density results for the dry method and (b) Density results for the wet method

In the dry method, the VIM value increases from 0.3% to 0.6% filler content, then decreases by 0.2% to 0.9% filler content. In the dry method, all filler variations meet the Bina Marga (2018 Revision 2) specification requirements, with the highest VIM value at 0.6% filler (4.62%) and the lowest at 0% filler (3.328%). Meanwhile, in the wet method, the VIM value steadily increases up to 0.9%. In the wet method, the highest VIM value is at 0.9% filler, which does not meet the Bina Marga 2018 Revision 2 specification requirements, with a value of 6.486%.

Previous research found that a high VIM value reduces the impermeability of dense asphalt concrete, increases asphalt oxidation, and accelerates its aging, thereby reducing the durability of the asphalt concrete [27]. However, if the VIM value is too small, it will cause bleeding when the temperature rises. The VIM specification limit, according to Bina Marga (2018 Revision 2), is 3% to 5%.

In line with the study on crumb rubber modified asphalt mixtures, the current study finds similar trends when comparing the wet and dry methods of incorporating TWPW into the asphalt mixture. A previous study found that the dry method—in which crumb rubber is added directly to the aggregate—can enhance the mixture's stiffness. However, they also observed that this method may reduce the adhesion between the rubber and the asphalt binder, leading to greater moisture susceptibility and a decrease in mechanical properties after ageing and moisture conditioning [28].

Similarly, in our study, the dry method showed greater stability at lower filler content (0.3%), but agglomeration of TWPW particles at higher filler contents (0.6% and 0.9%) compromised the mixture's uniformity. This resulted in decreased compaction and increased voids (VIM), particularly at the highest filler content, where the dry process led to lower resistance to moisture damage in rubberised asphalt [28].

The VMA (Void in Mineral Aggregate) value represents the percentage of voids in the mineral aggregate particles of the asphalt mixture that has been compacted. The VMA value is a determining factor in the durability and rutting performance of asphalt mixtures. According to the Bina Marga (2018 Revision 2), the VMA value that meets the HRS-WC specifications is at least 17%. Below are the calculated VMA values for the modified test specimens.

The VMA value, as shown in Figure 4, for each variation of filler content is close to each other and fluctuates with the increasing filler content. The VMA value is a determining factor in the durability of a mixture; as it increases, the volume of voids filled in the mixture also increases.

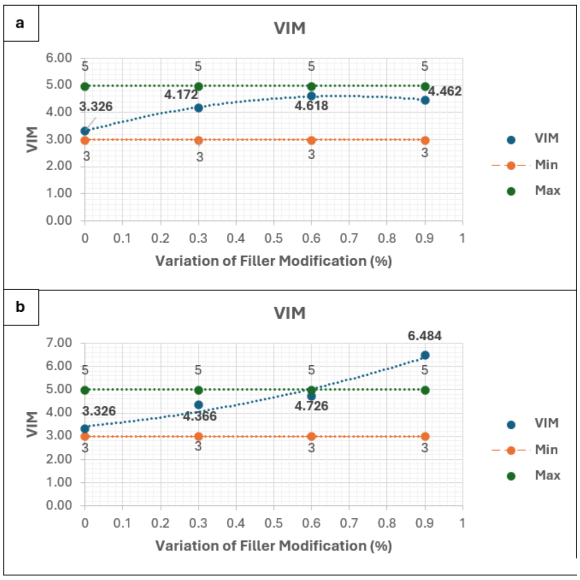

Figure 3. Graph of (a) VIM results for the dry method and (b) VIM results for the wet method

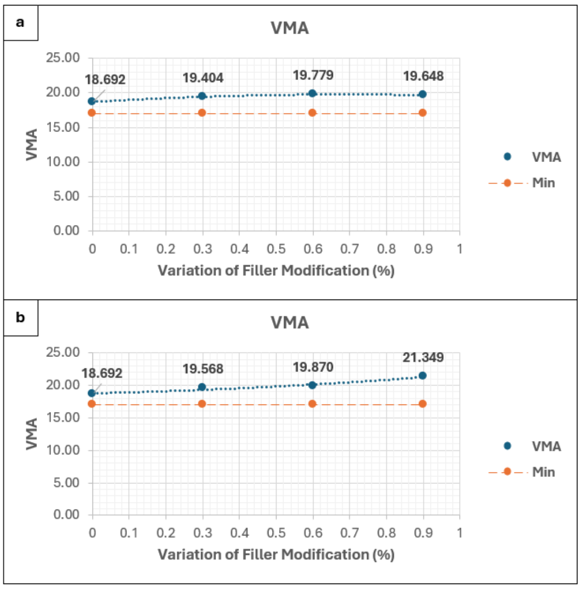

Figure 4. Graph of (a) VMA results for the dry method and (b) VMA results for the wet method

In the dry method, the VMA value increases from 0% to 0.6% filler, then decreases by 0.13% to 0.9% filler. The highest VMA value in the dry method is 0.6% filler content (19.781%), and the lowest is 0% filler content (18.694%). Meanwhile, in the wet method, the VMA value steadily increases with increasing filler content. In the wet method, the highest VMA value is 21.351% at 0.9% filler, and the lowest is 18.694% at 0% filler. In this study, the VMA values for all test specimens meet the Bina Marga (2018 Revision 2) specifications, with a minimum VMA value of 17%.

The VFA (Void Filled with Asphalt) value represents the percentage of air voids in the aggregate that are filled with asphalt. According to the Bina Marga (2018 Revision 2), the VFA value that meets the HRS-WC specifications is at least 68%. In Figure 5, the VFA value tends to decrease with each increase in filler content. However, in the dry method, the VFA value increases by 0.7% at 0.9% filler content. The highest VFA value in the dry method is 82.203% at 0% filler content, and the lowest is 76.654% at 0.6% filler content.

Meanwhile, in the wet method, the VFA content decreases with increasing filler content. The highest VFA value in the wet method is 82.203% at 0% filler content, and the lowest is 69.636% at 0.9% filler content. In this study, the VFA values for all test specimens in both methods meet the specifications set by Bina Marga (2018 Revision 2), with the minimum VFA for HRS-WC asphalt being 68%. The stability value represents the mixture's ability to withstand load pressure in the Marshall test apparatus.

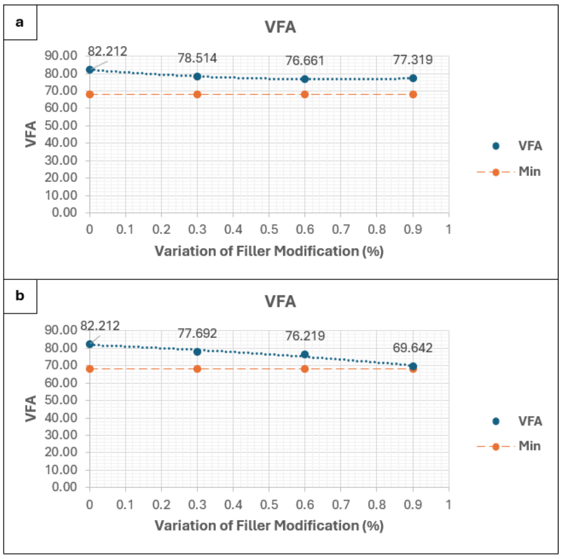

Figure 5. Graph of (a) VFA results for the dry method and (b) VFA results for the wet method

The stability value is obtained by multiplying the dial reading by the calibration factor of the Marshall Test apparatus. According to the Bina Marga (2018 Revision 2), the stability value required to meet the HRS-WC specifications is a minimum of 600 kg. Based on Figure 6, the stability value for all test specimens increases with increasing filler content. In the dry method, the highest stability value is 1042.68 kg at 0.9% filler content, and the lowest is 857.145 kg at 0% filler content. For the wet method, the highest stability value is also at 0.9% filler content (1185.552 kg), and the lowest is at 0% filler content (857.145 kg). In this study, the stability values for all test specimens meet the Bina Marga (2018 Revision 2) specifications, with a minimum stability value of 600 kg.

In general, the current findings indicate a consistent relationship between Marshall parameters. An increase in density and asphalt saturation tends to result in higher stability, while void in mix (VIM) and voids in mineral aggregate (VMA) tend to decrease. This correlation aligns with the statistical analysis presented by other research, which demonstrated that optimal compaction and binder content significantly improve Marshall stability by enhancing particle interlock and reducing air voids, thereby improving load resistance [29].

Furthermore, research has investigated the effects of mineral fillers on asphalt mixtures. The study concluded that adding filler not only increases the binder's stiffness but also enhances the mixture's overall mechanical strength. However, excessive filler content can lead to increased retained air voids and increased moisture susceptibility, which, in turn, may negatively affect long-term durability [30]. This implies that while higher filler content may improve stability, it must be carefully optimized to prevent unintended impacts on VIM and VMA values.

The flow value represents the change that occurs in the test specimen due to a load during the Marshall test. The flow value is obtained from the dial reading on the Marshall test apparatus. Bina Marga (2018 Revision 2) states that flow refers to the amount of plastic deformation of the asphalt mixture test specimen that occurs due to a load until the maximum limit, expressed in length units. Flow indicates the deformation of the asphalt mixture specimen caused by the applied load. Below are the flow values obtained from the dial readings for the modified test specimens.

For all modified test specimens, the flow value decreased with increasing filler content. In the dry method, according to Figure 7, the flow value decreases from 0% to 0.3% filler content, then stabilizes at 0.6% filler content, and decreases again at 0.9% filler content. The highest flow value in the dry method is at 0% filler content (3.3 mm), and the lowest is at 0.9% filler content (3.0 mm). In the wet method, the flow value decreases from 0% filler content (3.3 mm) to 0.9% filler content (3.0 mm). A flow value that is too high indicates a plastic mixture that can better follow deformation under load. At the same time, a flow value that is too low suggests the mixture has a higher volume of unfilled voids or a lower asphalt content, potentially leading to early cracking and low durability. In this study, the flow values for all test specimens meet the specifications, with a minimum flow value of 3 mm.

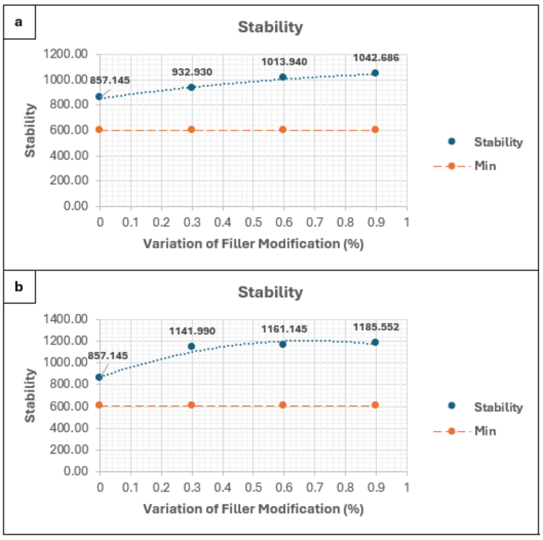

Figure 6. Graph of (a) stability value, dry method, and (b) stability value, wet method

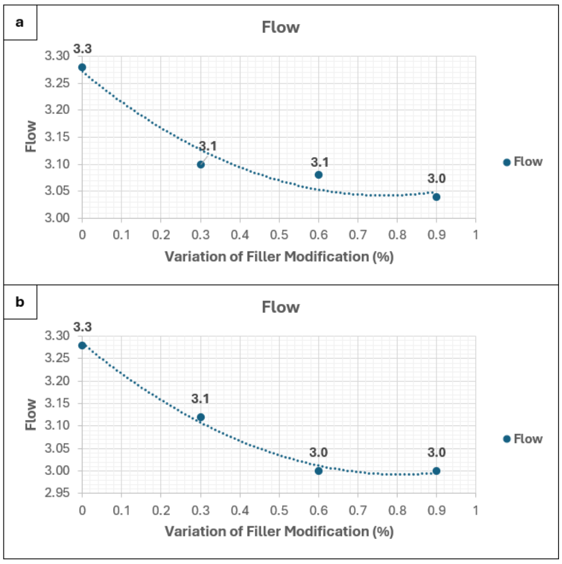

Figure 7. Graph of (a) flow results for the dry method and (b) flow results for the wet method

The Marshall Quotient (MQ) is the ratio of stability to flow. A high Marshall Quotient indicates a high degree of stiffness in the hardened layer. A hardened layer with an excessively high Marshall Quotient will easily crack under repeated traffic loads. According to the Bina Marga (2018 Revision 2), the MQ value that meets the HRS-WC specifications is a minimum of 250 kg/mm. Below are the Marshall Quotient values for the modified test specimens.

According to Figure 8, the Marshall Quotient values tend to be close to each other, with some slight fluctuations as filler content increases. The MQ value indicates the stability and strength of the asphalt mixture in bearing loads.

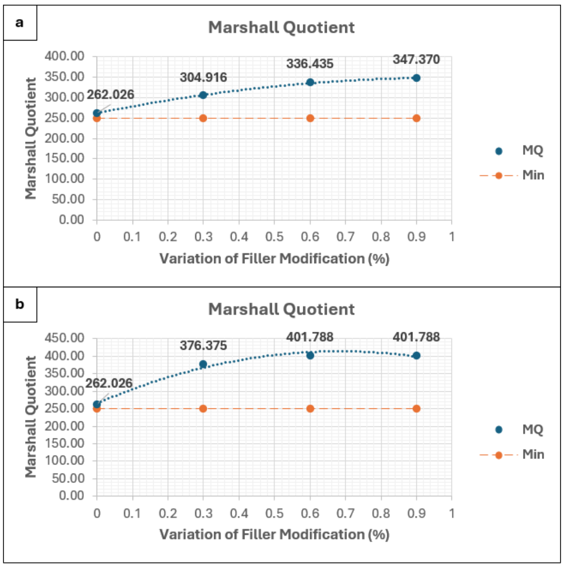

Figure 8. Graph of (a) MQ results for the dry method and (b) MQ results for the wet method

In the dry method, MQ values generally increase with increasing filler content, with the highest at 0.9% (319.018 kg/mm) and the lowest at 0% (283.365 kg/mm). In the wet method, the MQ value increases from 0% filler content to 0.6%, then decreases slightly to 0.9%. The highest MQ value in the wet method is 368.770 kg/mm at 0.6% filler content, and the lowest is 283.365 kg/mm at 0% filler content. A high MQ value indicates a high degree of stiffness in the hardened layer. A hardened layer with an excessively high MQ value is prone to cracking under repeated traffic loads [31]. Conversely, a very low MQ value indicates the mixture is too flexible (plastic), causing the hardened layer to deform under traffic loads easily. In this study, the MQ values for all test specimens meet the Bina Marga 2018 Revision 2 specifications, with a minimum MQ value of 250 kg/mm.

In this study, SEM (Scanning Electron Microscopy) was used to visualize filler distribution in the asphalt mixture, providing further insights into the relationship between the mixture's microstructure and Marshall test results. The SEM results show varying filler distributions at each filler content, affecting the physical and mechanical characteristics of the asphalt mixture. The distribution of TWPW within the asphalt mixture significantly influences its physical properties, particularly stability and VIM.

SEM analysis at 0.6% filler reveals less homogeneous filler distribution, which causes a decrease in density (2.385 gr/cm³). At 0.9% filler, SEM shows filler agglomeration (Figure 9c), which reduces the mixture's density due to increased porosity and voids (Figure 2). The increase in VIM with increasing filler content is evident in the SEM results, which show that voids or air pockets in the mixture increase at higher filler contents. SEM shows that at 0.9% filler agglomeration (Figure 9c), more voids remain unfilled, which correlates with the increase in VIM observed in the Marshall test. The VIM result for the wet method with 0.9% filler is higher than that for the dry method (Figure 3b) because, in the wet method, the filler distribution is more even and fills gaps between aggregates more effectively.

In the wet method, although the filler is more evenly distributed, the efficiency of filling voids with asphalt is lower, resulting in larger voids and an increase in VIM. In contrast, in the dry method, despite higher filler agglomeration, the mixture structure is more compact with fewer unfilled voids, resulting in a lower VIM at the duplicate filler content. This result is the same as the VMA and VFA results, where 0.9% filler with the dry method also shows a decrease compared to the wet method, which is still related to the agglomeration that occurs.

Agglomeration reduces the efficiency of void filling in the mineral aggregate, as reflected in the decrease in VMA (Figure 4), and reduces the volume of Voids Filled with Asphalt, thereby lowering the VFA value (Figure 5). These results align with the previous research [32]. At 0.3% and 0.6% filler, SEM shows more even distribution of filler particles, leading to better compaction and filling of voids between aggregates, which increases stability in both the dry and wet methods (Figures 9 and 10).

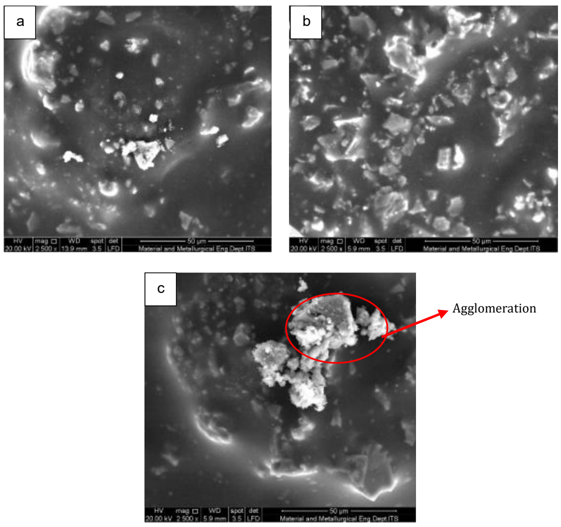

Figure 9. SEM results on fillers with compositions of (a) 0.3%, (b) 0.6%, and (c) 0.9% using the dry method

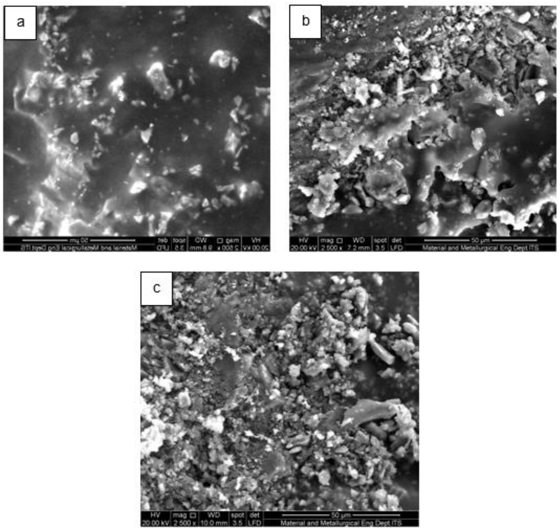

Figure 10. SEM results on fillers with compositions of (a) 0.3%, (b) 0.6%, and (c) 0.9% using the wet method

This enhanced compaction helps the mixture resist deformation under load. At 0.9% filler, SEM shows agglomeration of filler particles, especially in the dry method (Figure 9), which creates larger voids but also increases the mixture's rigidity. Despite the reduced compactness, the overall structure becomes stiffer, improving stability.

In the wet method, the filler remains more uniformly distributed, enhancing stability by effectively filling voids (Figure 6b). Thus, across all filler contents, increased filler content creates a denser, stiffer mixture, contributing to higher stability. For flow, the SEM shows that at 0.3% and 0.6% filler, the filler particles are more evenly distributed, allowing the mixture to retain some plasticity while avoiding excessive deformation. However, at higher filler contents (0.9%), agglomeration of filler particles begins to reduce the mixture's flow (Figure 7), as the filler particles restrict the asphalt's movement and decrease its ability to deform plastically under load.

The increase in Marshall Quotient (MQ) observed in both the dry and wet methods with increasing filler content (0.3%, 0.6%, and 0.9%) can be explained by the SEM results, which show that as the filler content increases, the distribution of filler particles becomes more uniform, and the mixture becomes more compact. At 0.3% and 0.6% filler, SEM reveals that the filler particles effectively fill the voids between aggregates, improving the packing density and overall structure of the mixture. This leads to an increase in MQ, as the mixture becomes stiffer and more resistant to deformation under load, reflecting higher stability relative to flow. At 0.9% filler, although SEM shows some agglomeration of filler particles, especially in the dry method, which creates larger voids, the overall mixture still becomes stiffer due to the increased filler content.

This agglomeration increases the mixture's rigidity, leading to higher MQ despite a slight reduction in flow. In the wet method, where the filler is more evenly distributed, the mixture's overall structure is more compact, resulting in a much greater increase in MQ. Thus, in both methods, increasing filler content leads to better compaction and stiffness, resulting in a higher Marshall Quotient (MQ) and indicating improved stability relative to flow.

CONCLUSION

The addition of teak wood powder waste as a filler to Hot Rolled Sheet – Wearing Course (HRS-WC) mixtures improved stability and the Marshall Quotient (MQ). In the dry method, the 0.9% filler content resulted in a stability value of 1042.68 kg, a flow value of 3 mm, VIM of 4.46%, and VFA of 77.31%. Meanwhile, in the wet method, the 0.6% filler content resulted in a stability of 1161.14 kg, a flow value of 3 mm, VIM of 4.72%, and VFA of 76.72%. In both methods, increased stability led to reduced flow and increased VIM.

SEM analysis confirmed that the distribution of filler plays a significant role in the formation of voids and the compactness of the asphalt mixture. At 0.3% and 0.6% filler, the uniform distribution of the filler contributed to better compaction and increased stability. However, at 0.9% filler, SEM revealed filler agglomeration, leading to larger voids and reduced mixture density, thereby increasing VIM. The VMA and VFA values followed a similar trend, with higher values observed in the wet method due to more even filler distribution. Despite the increased filler agglomeration, the overall structure became stiffer, contributing to higher stability. The values for stability, flow, VIM, and Marshall Quotient met the Bina Marga 2018 standards, indicating that the use of teak wood powder waste as a filler can still produce a functional asphalt mixture, despite some changes in the parameters.

ACKNOWLEDGMENT

This research was supported/partially supported by ITS Surabaya through its research and publication grant program. In addition, we thank our colleagues from Institut Teknologi Sepuluh Nopember for their insights and expertise, which greatly assisted the research.

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