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Palm Oil Fuel Ash, Garnet Waste and Sawdust as Modified Asphalt Mixture: A Critical Review

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Palm Oil Fuel Ash, Garnet Waste and Sawdust as Modified Asphalt Mixture: A Critical Review

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Abstract. The addition of palm oil fuel ash (POFA), garnet waste, and sawdust as a modified asphalt binder and mixture for paving materials show that recycling materials from industrial and agricultural waste have been implemented with environmental concern, increasing the proper handling of this waste product. The use of POFA, garnet waste, and sawdust as a modifier to improve the properties of binder and mixture is critically evaluated in this study. The review focuses on the evaluation of POFA, garnet waste, and sawdust in asphalt binder and mixture modification. In essence, the combination of POFA, garnet waste, and sawdust offer a promising waste materials potential to enhance the rheological and mechanical performance of the modified binder and mixture. The use of this modification in the binder and mixture is expected to improve performance and be on par with the traditional asphalt binder and mixture.

1. Introduction

Waste generation in the world had been increasing year by year. The sources came from various fields such as municipal solid waste, agricultural waste, and industrial waste. By 2050, the amount of this worldwide trash is anticipated to rise by 3.4 billion tonnes, in according with United States Environmental Protection Agency (EPA) regulations [1]. The world had witnessed an alarming increase in the production of waste, leading to significant environmental and social consequences. Therefore, a significant portion of waste ends up in landfills or in incinerated, leading to environmental pollution and the release of greenhouse gases into the atmosphere. Addressing these complex issues requires concerted efforts at local, national, and international levels to promote sustainable waste management practices, reduce waste at the sources, and encourage the adoption of a circular economy strategy to reduce waste production and increase resource efficiency. Malaysia had become one of the waste manufacture quantities and highest bestowal country for about 19.15 million metric tonnes according to Malaysia Palm Oil Board (MPOB) [2] produced in 2020. The utilization of waste materials in pavement construction presents a promising solution to address both the environmental and economic challenges associated with waste management. Incorporating waste materials into pavement construction offers a sustainable alternative to traditional construction practices. Over the years, researchers had found a solution to recycle the waste in pavement construction. Previous researchers had used palm oil fuel ash (POFA), garnet waste, and sawdust for asphalt modification to reduce the environmental impact. These three types of different waste materials are frequently used as substituent elements in the utilization of modified asphalt binder and mixture [3, 4, 5].

1.1 Asphalt Binder and Mixture

The field of asphalt modification plays a crucial role in the development of pavement and road materials. Road materials that can reduce fracturing at low temperatures and increase resilience to deformation at high temperatures are urgently needed. Asphalt's main function is to bind aggregate together and protect it from water and other harmful substances. Initially, asphalt served this purpose effectively, however, with the increase in traffic loads and accelerated environmental deterioration, its performance has been compromised. When crude oil is refined, a complex and heterogeneous mixture of hydrocarbons called asphalt is produced. As a result, research on asphalt modification has become important, using a variety of techniques and cutting-edge materials as modifiers. When compared to the conventional binder, modified asphalt offers feature enhancement in the decrease of pavement deterioration and lowers life cycle costs. Arising issues in pavement performance, one efficient way to solve the problem is using asphalt modification. Numerous studies had been explored for asphalt modification using waste materials, bio-oil, and other recycling sources [6, 7, 8]. The next section will expand on the previous researchers using POFA, garnet waste, and sawdust in asphalt modification. Based on this, this review intends to quantitatively analyse the previous researchers that had done asphalt modification using POFA, garnet waste, and sawdust. Then, the chemical composition of each material. Finally, the performance properties of physical and mechanical especially the Marshall stability test. The review work is shown in Figure **1**.

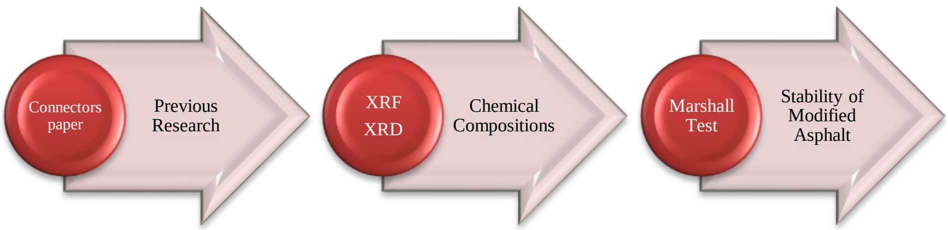

Figure 1. Review roadmap.

2. Use of Palm Oil Fuel Ash, Garnet Waste, and Sawdust in Modified Asphalt Mixture

2.1 Palm Oil Fuel Ash

Palm oil fuel ash (POFA) is a byproduct waste of burning palm oil husk and palm kernel shells as biomass fuel in palm oil mills. During the combustion process, the biomass fuel undergoes complete or partial burning, resulting in the formation of ash. This ash, known as POFA, is a byproduct of the combustion process. POFA is collected from the boiler systems of palm oil mills and is often regarded as waste material. Tons of garbage that harm the environment are produced during the manufacture of palm oil alone. In addition to the use of polymers, agricultural wastes such as POFA is one of the waste materials that can utilised to modify bitumen. In asphalt modification, POFA can be utilized as a mineral filler in the binder and mixture for asphalt. The fine particle of POFA can fill the gaps between aggregate particles, improving the asphalt mixture's stability. As a result, the pavement becomes stronger, more resilient, and less likely to rut or crack [3]. Figure **2** shows the POFA sample taken from agricultural sources. Figure **3** indicates the POFA usage as an asphalt modifier seized in the connectors paper mapping. This mapping provides further support for the researchers to find out POFA usage in modified asphalt from 2005 until 2022. Previous research has shown that asphalt modified with POFA shows a significant influence of chemical composition on performance [8]. Table **1** shows the POFA's chemical composition from earlier studies that perform a very rich content of silica oxide (SiO_2), followed by aluminium oxide (Al_2O_3) and ferum oxide (Fe_2O_3). The high content of silica can increase the stability and durability of modified asphalt mixture [6, 7, 8]. Based on the findings of the chemical composition of POFA, the high content of this oxide suggests the overall performance of asphalt by providing increased resistance to rutting, cracking, and fatigue.

Figure 2. POFA sample.

Table 1. Chemical compositions of POFA comparison with previous studies.

Chemical composition (%)	Hamada *et al.* [9]	Abid *et al.* [10]	Hamada *et al.* [11]	Khalid *et al.* [12]	Khankhaje *et al.* [13]	Mohammadhosseini *et al.* [14]	Sukaimi *et al.* [15]	Olivia *et al.* [16]
SiO_2	21.00	57.80	26.10	53.30	43.60	62.60	43.60	64.30
Al_2O_3	5.90	2.30	8.54	1.90	8.50	4.65	11.40	4.36
Fe_2O_3	3.40	9.60	4.09	-	10.10	8.12	4.70	3.41
CaO	64.70	3.60	54.8	9.20	8.40	5.70	8.40	7.92
MgO	0.03	1.40	0.358	4.10	4.80	3.52	4.80	4.58
Na_2O	0.03	0.56	0.186	-	-	-	0.40	-
K_2O	0.01	3.50	0.97	-	3.50	9.05	3.50	5.57
SO_3	2.40	-	2.40	-	2.80	1.16	2.80	0.04

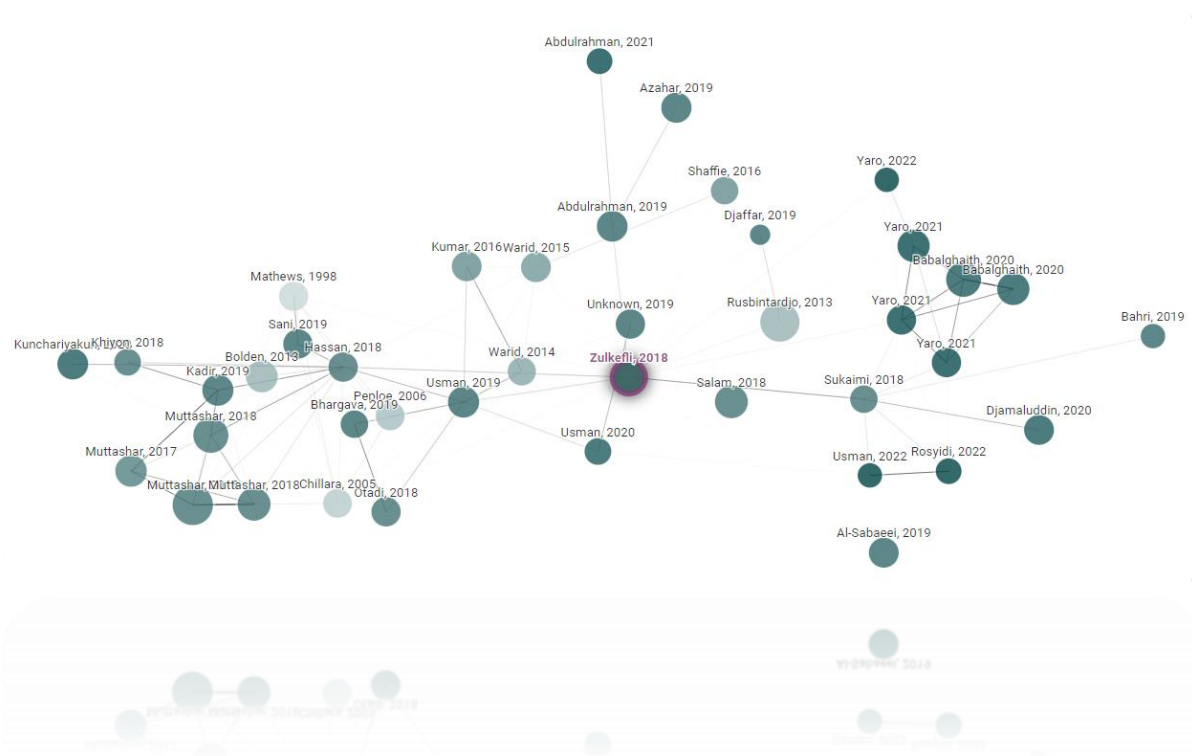

Figure 3. Connectors paper mapping for POFA usage as asphalt modifier [17].

2.2 Garnet Waste

Garnet is a group of silicate minerals that have angular fractures, relatively high specific gravity, and decomposition resistance, making it appealing for use in variety of industrial applications. Garnet waste is an industrial waste generated in the mining and explosives industries. Additionally, garnet waste also originates from industrial applications where garnet is used as an abrasive material. In industries like metal fabrication, waterjet cutting, sandblasting, and abrasive blasting, garnet is used for its high hardness and durability to remove unwanted materials from surfaces. The use of garnet abrasive becomes waste after it has been used and required proper management and disposal. Garnet waste not only poses an environmental problem but also offers the possibility of obtaining efficient construction material through appropriate recycling [18]. Figure **4** shows the garnet waste sample from the blasting pipe in the industrial area. Many researchers had done asphalt modification using garnet waste [4, 19, 22]. Connectors paper mapping as can be seen in Figure **5** indicates the researcher had begun to utilize garnet waste in asphalt modification whether as a filler or additive in binder and mixture. Table **2** shows the chemical compositions of garnet waste compared with previous studies. The highest chemical found in garnet waste is Fe_2O_3 where 100% of overall studies contain iron on the samples, followed by SiO_2 and Al_2O_3. Ferum oxide may lead to improved resistance to permanent deformation. Therefore, it can be noticed that the use of garnet waste ferum oxide is higher in comparison with silica oxide. The particle size distribution of garnet waste, surface properties, and similarity with asphalt binders are factors other than the chemical composition for asphalt modification.

Figure 4. Garnet waste sample.

Table 2. Chemical compositions of garnet waste comparison with previous studies.

Chemical composition (%)	Muttashar *et al.* [19]	Muttashar *et al.* [20]	Aletba *et al.* [21]	Huseien *et al.* [22]	Mior Sani *et al.* [18]	Kunchariyakun and Sumak [23]	Usman *et al.* [24]	Jamaludin *et al.* [25]
Fe_2O_3	42.06	43.06	43.06	43.10	34.87	33.10	43.40	40.23
SiO_2	34.76	33.76	33.76	33.71	13.61	36.00	28.30	39.04
Al_2O_3	14.88	13.88	13.88	13.90	6.39	17.70	14.30	13.40
CaO	3.15	4.15	4.15	4.15	2.43	5.48	4.45	-
MgO	2.91	2.91	2.91	2.91	1.42	5.97	4.68	4.08

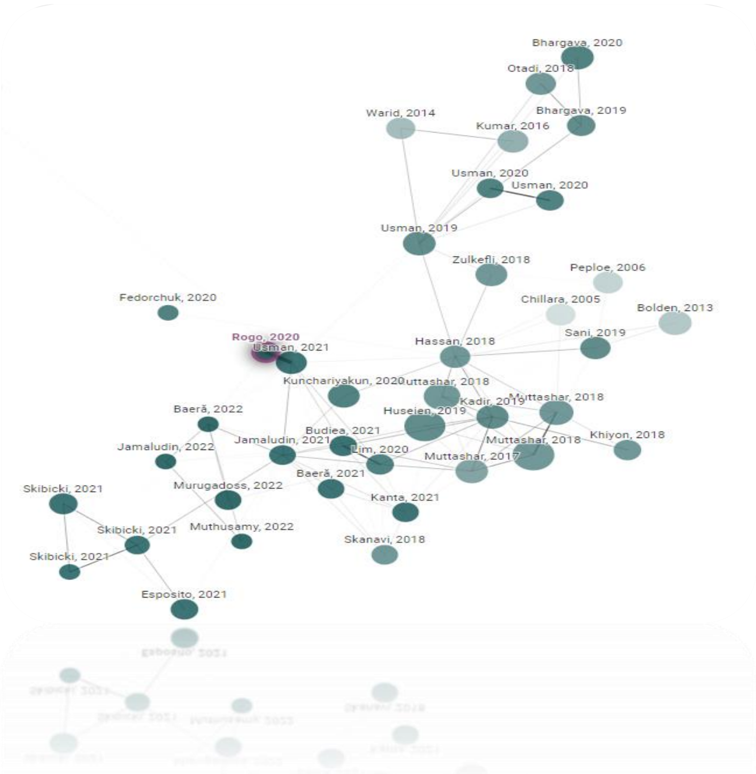

Figure 5. Connectors paper mapping for garnet waste usage as asphalt modifier [17].

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2.3 Sawdust

Sawdust is a byproduct of the woodworking industry and is composed of fine particles or shavings of wood. It is generated during various wood-cutting, sawing, and milling processes. Figure **6** shows the sawdust waste from word working operation of sawing, milling, and sanding school furniture. Sawdust is organic waste produced during the mechanical reduction of wood into numerous shapes and sizes [26]. Sawdust is an organic waste product created when wood is mechanical milled into different sizes and forms [27]. Sawdust is produced as a waste product from small, erratic chips or powdery materials [28]. Sawdust is generated in vast quantities every year, and managing it has a major problem. To address these issues, sawdust has found application as a material used in asphalt modification. Figure **7** shows the researchers from all over the world who underwent asphalt modification using sawdust, sawdust ash, wood ash, and related wood waste products. Sawdust ash is a lightweight material containing the oxides of calcium, silica, alumina, iron, sulphur, potassium, magnesium, tungsten, and phosphorus (Table **3**) and has a specific gravity of 2.29 [5]. From the table, it can be seen that the highest chemical compound found is calcium oxide which indicates the strong adhesion between asphalt binder and aggregate. The suitability of the calcium oxide will enhance the adhesion and cohesion of asphalt modification.

Figure 6. Sawdust sample.

Table 3. Chemical compositions of sawdust ash comparison with previous studies.

Chemical composition (%)	Ikeagwuani [29]	Osuya and Mohammed [30]	Bi and Jakarni [31]	Karati and Roy [32]	Moura *et al.* [33]	Akter *et al.* [28]
SiO_2	53.39	5.30	28.11	6.54	2.93	72.58
Al_2O_3	14.30	1.90	5.14	5.77	-	0.79
Fe_2O_3	2.64	1.65	2.91	10.38	0.73	0.99
CaO	7.20	49.70	29.53	57.56	73.8	12.40
MgO	3.30	4.06	5.14	1.20	3.58	1.68
P_2O_5	0.40	2.95	2.48	-	4.14	2.58
K_2O	21.72	8.43	9.64	-	11.07	6.74
TiO_2	1.00	0.05	-	-	0.15	0.17

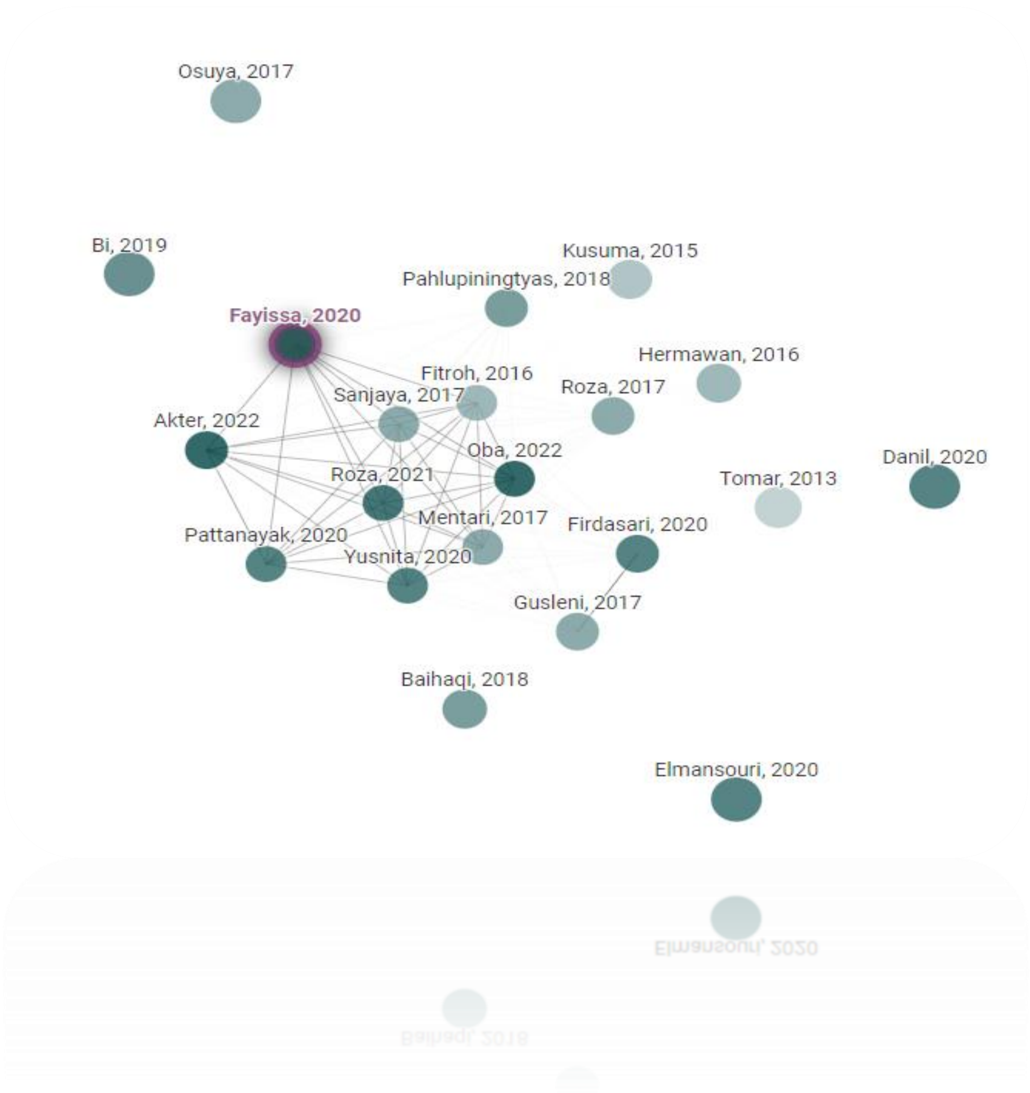

Figure 7. Connectors paper mapping for sawdust ash usage as asphalt modifier [17].

3. Palm Oil Fuel Ash, Garnet Waste, and Sawdust in Modified Asphalt Mixture

3.1 Palm Oil Fuel Ash Application

Borhan et al. [34] conducted research on the effects of palm oil fuel ash (POFA) on asphalt mixtures. This study uses optimum asphalt content of 5.35% with 4 different percentages of POFA: 1, 3, 5, and 7% (Figure **8**). The samples were analysed using mechanical properties that are Marshall stability test, static and dynamic creep, resilient modulus, and fatigue test. The findings show that SiO_2 with 43.6% is the highest percentage in the chemical composition. Fe_2O_3 (11.4%), Al_2O_3 (8.4%), and MgO (4.8%) also play crucial roles as significant chemical components in the POFA asphalt mixture, contributing to mixture resistance, stability, and durability. The replacement of POFA up to 5% can be used as a modified asphalt mixture. The result indicates that the value of Marshall stability as long as in the range of specification, can improve the performance of the asphalt mixture. It also confirms that performance results in higher resistance to permanent deformation compared to the control mixes. The use of POFA increased the asphalt mixtures' elastic modulus and stability.

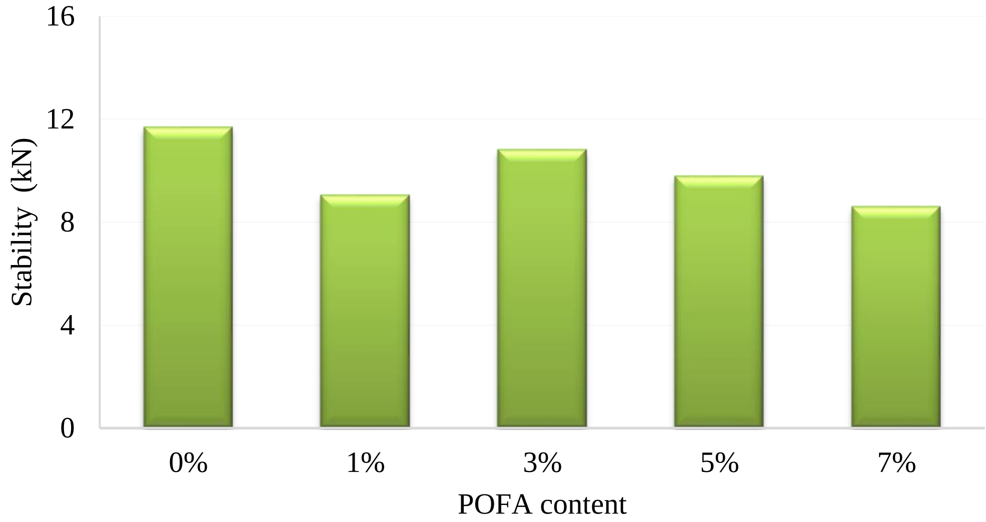

Figure 8. Effect of POFA.

Ahmad et al. [35] studied on the use of POFA in asphalt pavement as a filler. POFA with passing 75 µm mix with ACW20 and variety of percentage (3, 5, 7 and 10%). Figure **9** shows the Marshall result from different asphalt content; 4.6%, 5.10% and 5.6%. Marshall stability and resilient modulus were also conducted in this study. The findings shows that 3% amount of POFA with optimum asphalt content of 5.10% improved the stability and tensile strength of the asphalt mixture. However, excessive POFA content may lead to the formation of deleterious compounds and reduce the overall strength of the blends. The modified POFA blends also obtained better mechanical properties. In summary, the addition of an appropriate amount of POFA boosts rutting resistance throughout the pavement's service life and notably reduces temperature susceptibility.

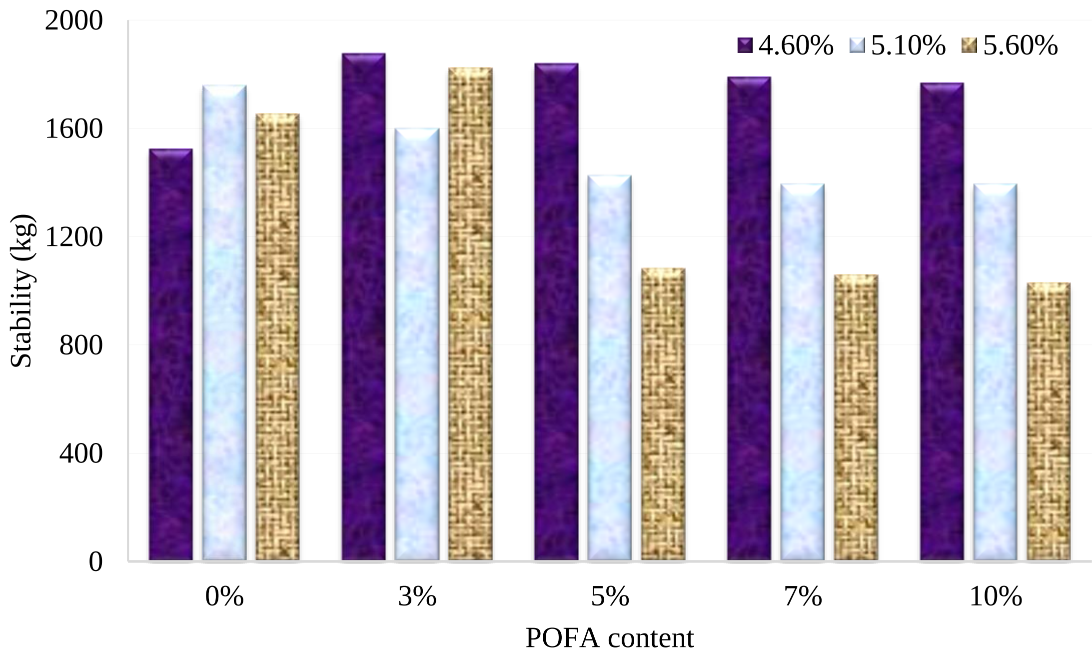

Figure 9. Marshall results from different asphalt content.

Hainin et al. [3] had a study on the influence of POFA in different percentages and under different aging conditions. To assess the penetration and softening point of bitumen, two procedures–RTFO and PAV tests were used. By reducing the penetration value and raising the softening temperature for both unaged and aged samples, the results show that the inclusion of POFA increased the durability of the binder. Bitumen that has been POFA-modified is more resistance to long-term deformation at high temperatures. After short-term aging, POFA mixtures also exhibited higher stiffness due to less binder penetration. A study by Raja Zulkefli et al. [36] assessed the physical and rheological characteristics of POFA-modified bitumen with 5 and 7 % POFA, which was sieved through a 0.075 mm sieve and ground at different time periods (1 and 4 hours). The fineness of POFA had a significant impact on the properties of the bitumen and decreased the penetration value and softening temperature (Figure **10**). POFA with a size of 7 % between 500 nm and 3 μm is the most suitable blend for modified bitumen. The result indicates that an increase in penetration index (PI) shows less susceptibility to temperature. Therefore, decreasing penetration and softening values indicate that the modified bitumen becomes harder than the conventional.

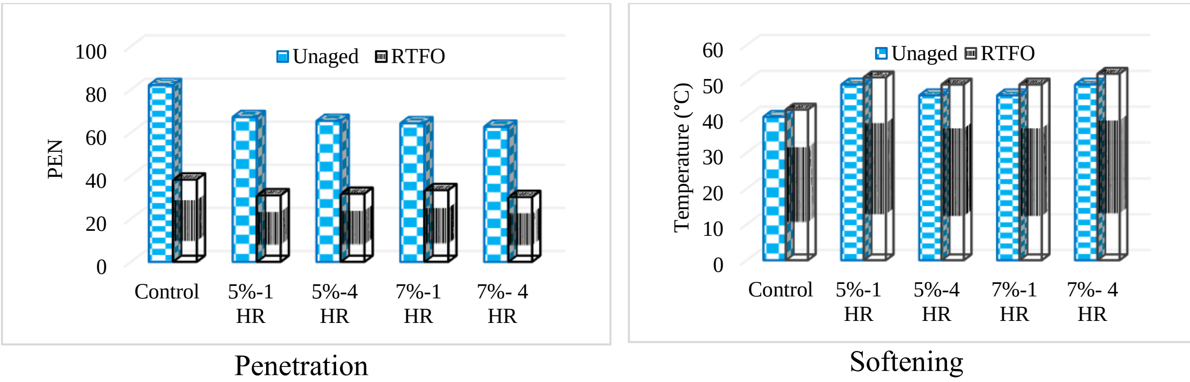

Figure 10. Graph of penetration and softening at different size of POFA.

Abdulrahman et al. [37] performed a study of moisture damage and rutting of warm mix asphalt containing POFA-modified bitumen. This study used 5% POFA with 0.75% evotherm to produce warm POFA-modified bitumen. This study also investigates Marshall flow and stability, dynamic creep, asphalt pavement analyser, and tensile strength ratio using boiling water test. The optimum bitumen content found at 5.2% indicates the stability of hot mix asphalt (HMA) had more stability than warm mix asphalt (WMA). Figure **11** summarises the findings of the Marshall tests for HMA and WMA at the optimum bitumen content which both exceed the standard level for both asphalt modifications using POFA. As can be seen, the usage of POFA in asphalt modification improves higher than the standard value which further investigation with this waste materials are very promising in road industry.

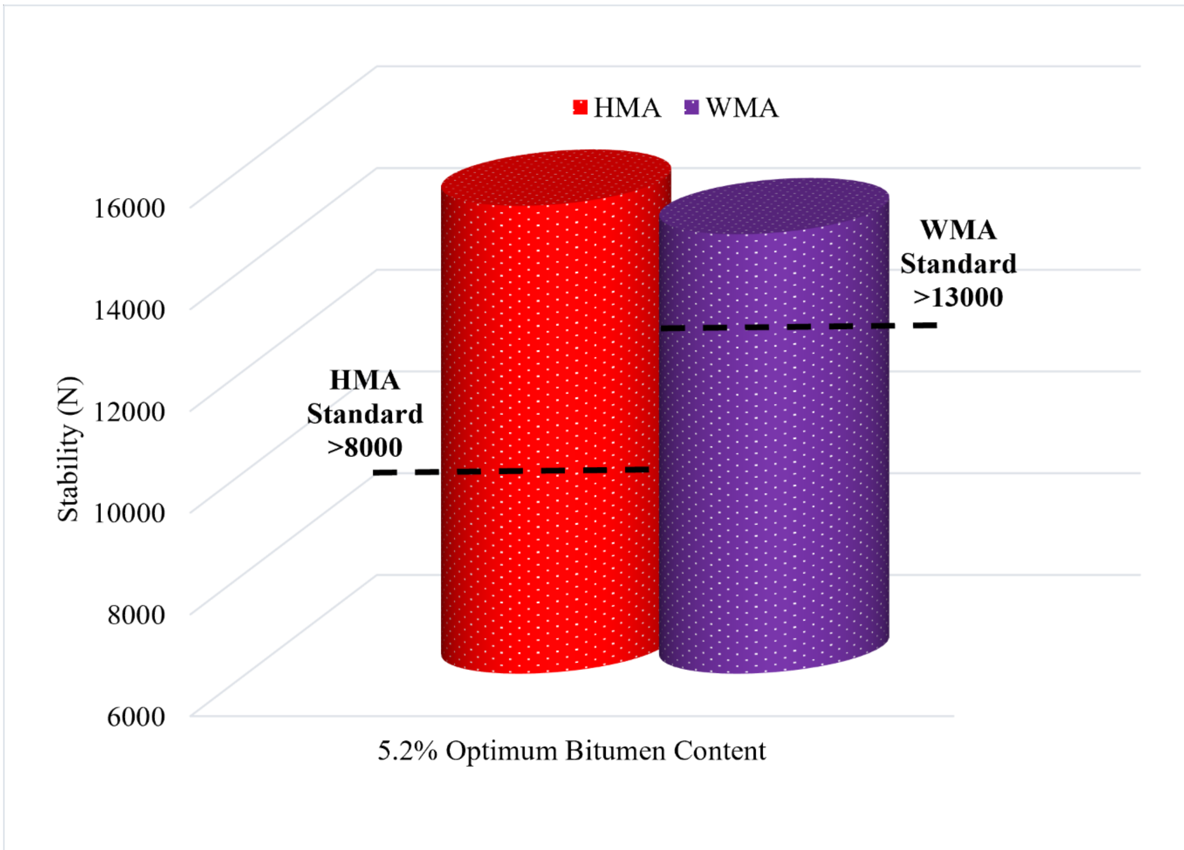

Figure 11. Summary of Marshall test result for HMA and WMA.

3.2 Garnet Waste Application

Previously, Muttashar et al. [19] revealed in terms of environmental issues, financial effectiveness, and resource conservation, spent garnet is a potential candidate for sand replacement up to 25%. The highest chemical composition is ferum oxide (Fe_2O_3) with a percentage of 43.06 %. Next researchers, Aletba et al. [20] investigated the possibility of employing garnet waste as fine aggregate replacement in asphalt modification of hot mix asphalt (HMA). The garnet waste was created with the intention of replacing up to 25% aggregate in the asphalt mixture of AC14 and contrasting it with granite aggregate as a traditional asphalt sample. They both [19, 21] found 25% of garnet waste from aggregate replacement improved the performance of HMA. Figure **12** shows the Marshall result for this replacement. It can be seen that the optimum bitumen content using garnet waste is 4.8% less 0.2% from conventional asphalt. Replacement of garnet waste increases the specific gravity, voids filled with bitumen (VFB), and voids in the total mix (VTM). The result also shows that an increment of stability will lessen the flow, higher value the stiffness, and better resistance to permanent deformation.

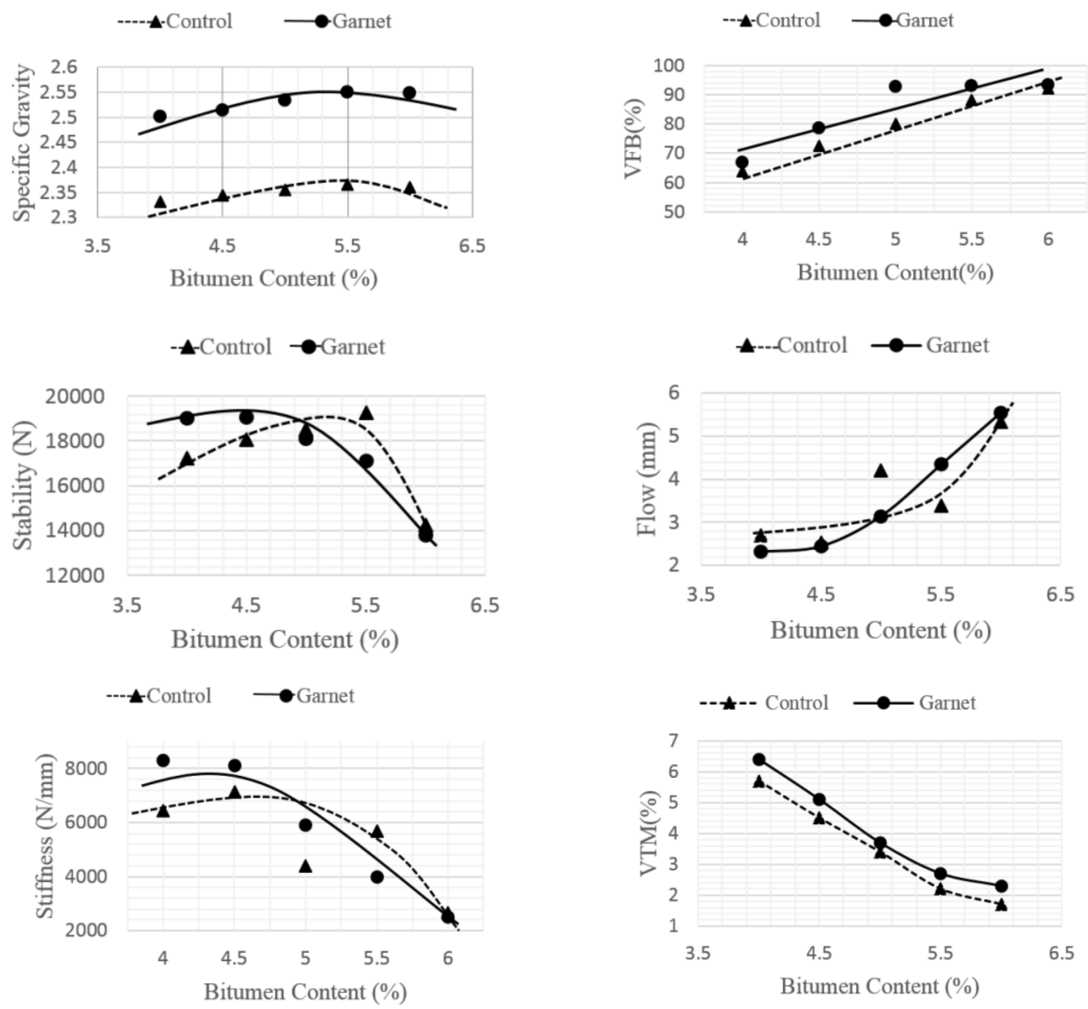

Figure 12. Marshall Properties of 25 % garnet waste [21].

Other investigation by Usman et al. [24] compared the physical and microstructural properties of waste garnet materials gathered through automated and manual blasting techniques. In this study, wasted garnet used in cold mix asphalt (CMA) was substituted with garnet produced manually generated (MG) and automatically (AG). According to the reports, spent garnet can be utilise in emulsified asphalt repair mixtures since its chemical composition is compatible with cationic type emulsions. It is advisable that the use of spent garnet as fine aggregates for producing cold mix asphalt construction. The researcher reported that granite and garnet have a high proportion of quartz in the XRD pattern (Figure **13**). The high quartz content is confirmed by the chemical composition result which shows Fe_2O_3 is 43.4% (Table **2**). This implied that ferum oxide content quartz along with silica oxide can enhance the stability, and Marshall's stability result indicates that a 25% addition of garnet waste increases the up to 3% stability of CMA. Figure **14** demonstrates how the FTIR analysis complements the XRD analysis and Table **4** shows the Marshall stability results of this study. The improvement of stability also increases the stiffness and VFB and VTM of the modified asphalt containing waste garnet. Another interpretation indicated that adding waste garnet increases the stability and rutting resistance of the asphalt mixture.

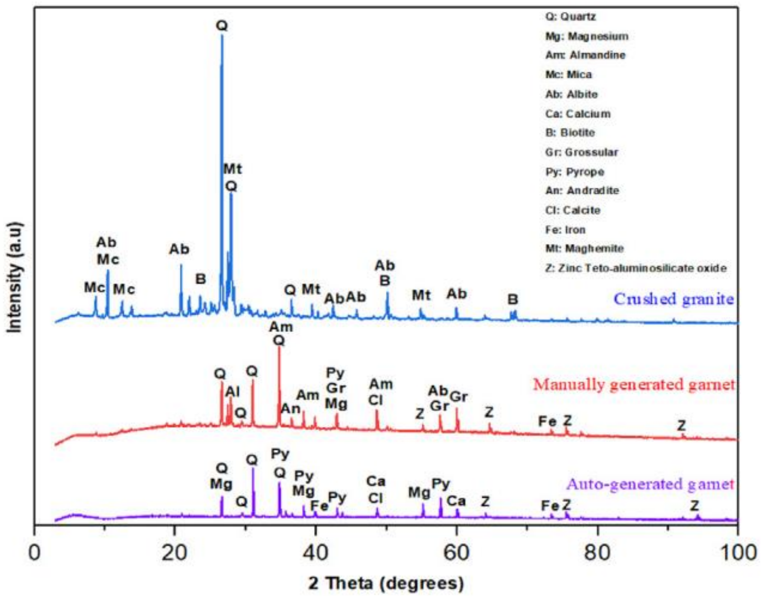

Figure 13. XRD results of spent garnet [24].

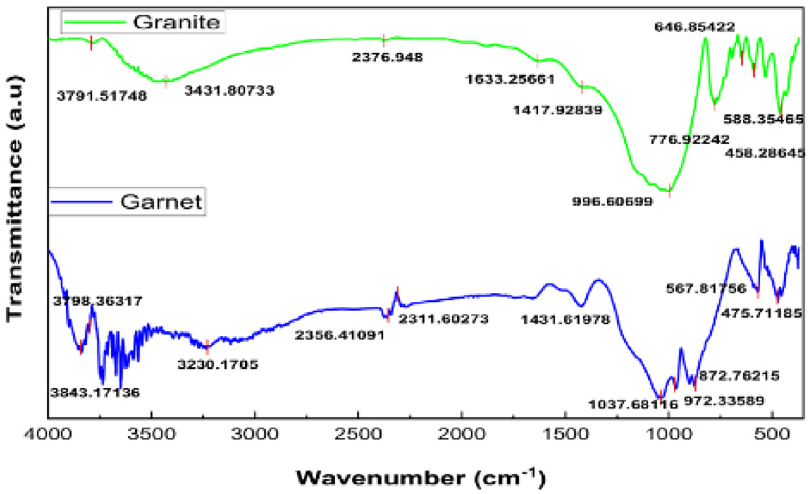

Figure 14. FTIR results of granite and garnet [24].

Table 4. Results of Marshall properties and OBC [24].

Properties	Results	
	Control	25% Garnet
Stability (N)	18502	19000
Flow (mm)	4.2	2.9
Stiffness (N/mm)	4405	6551
Voids in total mix, VTM (%)	3.4	4.1
Voids filled with bitumen, VFB (%)	80.2	85.0
Optimum Bitumen Content (%)	5	4.8

3.3 Sawdust Application

A laboratory evaluation conducted by Osuya and Mohammed [30] reported the characteristics of asphaltic concrete by evaluating the effects of sawdust ash (SDA) suitability as an additive. After being burned into ash in a furnace at 800°C, the sawdust was allowed to cool and sieved through a 75 µm mesh. Samples were prepared with SDA of 5, 10, 15, 20, and 25% subjected to Marshall stability and flow test. The research revealed that adding sawdust ash to asphaltic concrete enhanced its characteristics (Figure **15**). It can be seen that 15% of SDA had the highest stability (18.2 kN) and the increase in stability was attributed to the high percentage of CaO (49.70%) as depicted in Table **3**. In contrast, with the decreasing flow value, the trend of the composition strength in stability and flow was found to have influenced the use of SDA in the asphalt mixture. This strong potential was predicted since an increasing up to 15% SDA positively affected the stability.

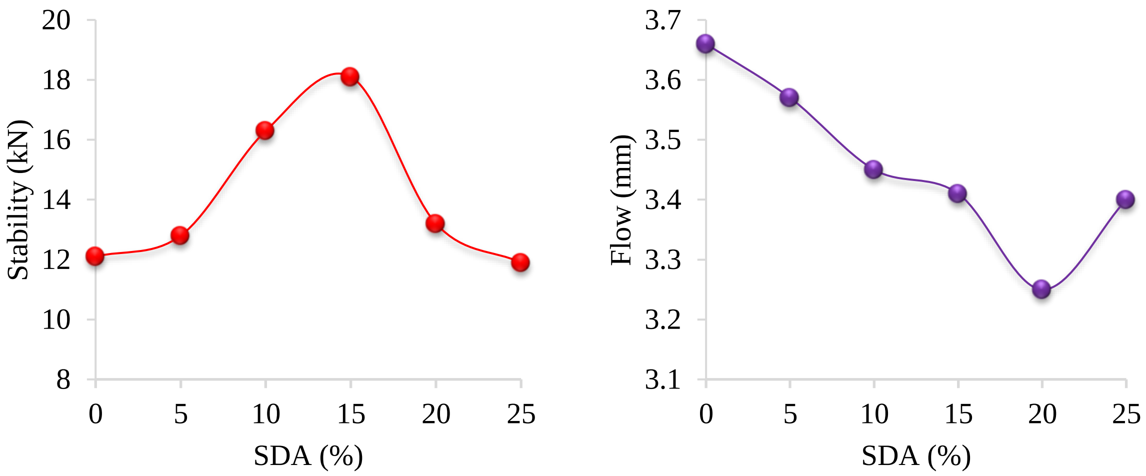

Figure 15. Stability and flow with different percentages of sawdust ash.

Fayissa et al., [5] investigated the use of sawdust ash in asphalt concrete as a filler. A fatigue, tensile strength, and deformation resistance test was carried out while substituting 3, 6, 9, and 12% of the sawdust ash with basaltic dust. Sawdust ash in this study is a physically lightweight material that contains calcium oxide, silica, alumina, iron oxide, sulphur oxide, potassium oxide, magnesium oxide, tungsten oxide, and phosphorous oxide and has a specific gravity of 2.29. Figure **16** indicates the Marshall properties of sawdust ash. The results showed that the use of sawdust ash a mineral filler improved the permanent deformation and fatigue life at different temperatures. Sawdust ash can replace 12% of the filler, which contributes to lower moisture susceptibility in the production of asphalt concrete. The high content of calcium carbonite reduced rutting and moisture damage potentials. When compared to traditional fillers used in the construction of asphalt concrete. Yasanthi's et al. [38] study found that the replacement and addition rates of carbonized wood sawdust were determined by taking into account the Marshall characteristics, which also resulted in lower filler material costs of about 9.5% from the original cost. They claimed that using sawdust, it should be burnt as sawdust ash (SDA) as a filler decreased the strength performance of asphalt concrete. It was observed that SDA in less-oxygen conditions can be used to replace the conventional filler in HMA up to 2.74% of the weight of aggregate. Marshall stability results show the SDA addition from 4 to 7% was lower than the conventional, however, the best SDA content is at 30g. According to Awolusi et al. [39], the properties of asphalt concrete as an admixture using sawdust are suitable for evaluating the effects. The sawdust was heated to 800°C in a kiln, burned to ash, cooled, and sieved using a 75 µm BS sieve. The results indicate that the addition of sawdust ash to asphalt concrete improved its properties. Oba and Ugwu [40] reported that the optimum binder content using the standard Marshall curves (Figure **17**) was 4.88% using sawdust ash. Overall, the study using sawdust resulted in a finding it can resist permanent deformation because of good stability.

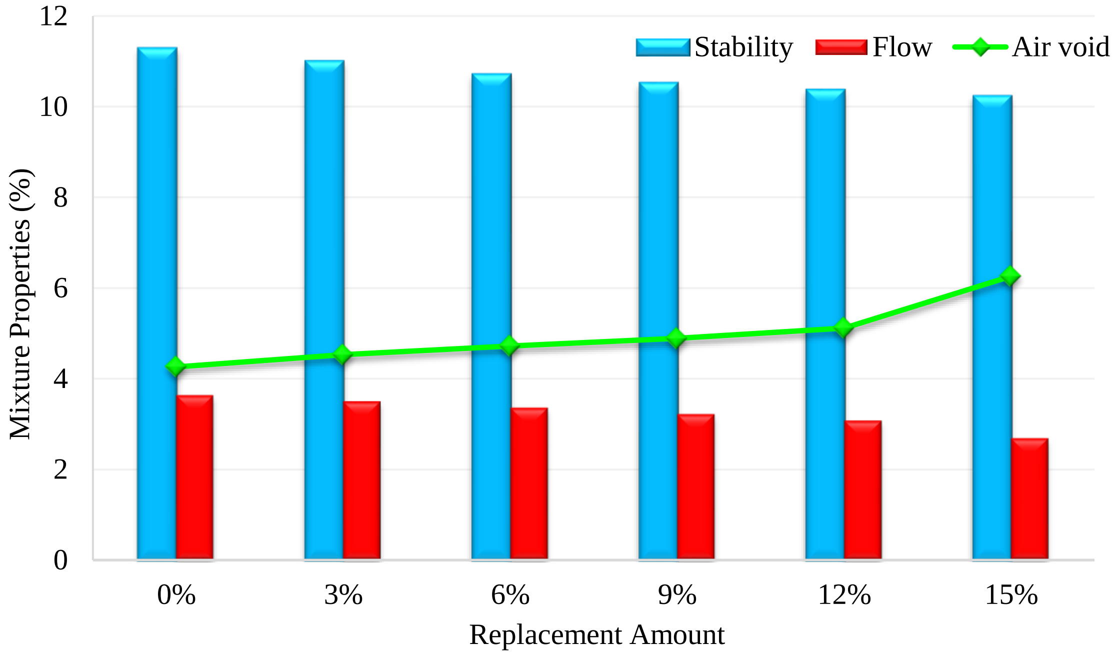

Figure 16. Marshall properties of sawdust ash.

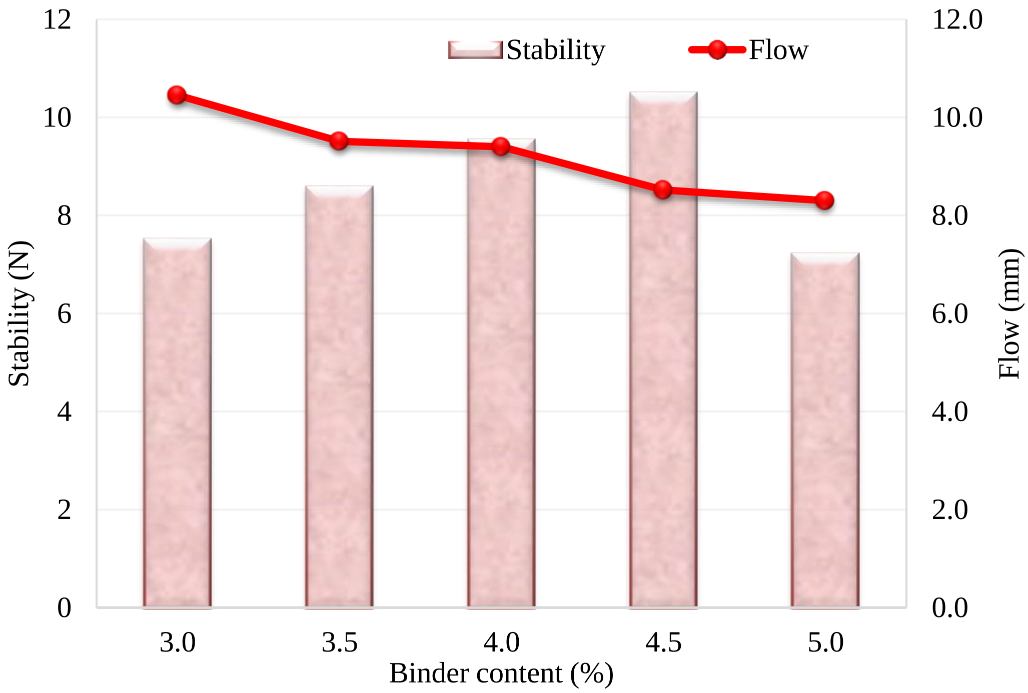

Figure 17. Stability vs flow using sawdust ash.

The effectiveness of coal dust and wood powder ash as a substitute to traditional filler in asphalt concrete was investigated by Akter et al. [28]. A total of 90 samples altogether were produced and tested for chemical, physical, and mechanical properties of an asphalt mixture including 4 to 8% of coal dust, wood powder ash and ordinary stone. The investigation was conducted to determine the applicability of coal dust and wood powder due to the high amount of SiO_2, Fe_2O_3, and Al_2O_3 as mineral fillers. The result showed that 6% wood powder and 4% coal dust satisfied better durability, fatigue, and moisture-induced damages to the asphalt concrete. Marshall properties of wood powder ash are shown in Figure **18**. It shows that the highest stability using wood powder is at 6% content. The effective content for wood powder is 6% and the other properties of the Marshall test look promising using as filler in the asphalt modification. Sawdust is going to be one that contributes to a sustainable waste management system and enhances pavement performance in the asphalt mixture.

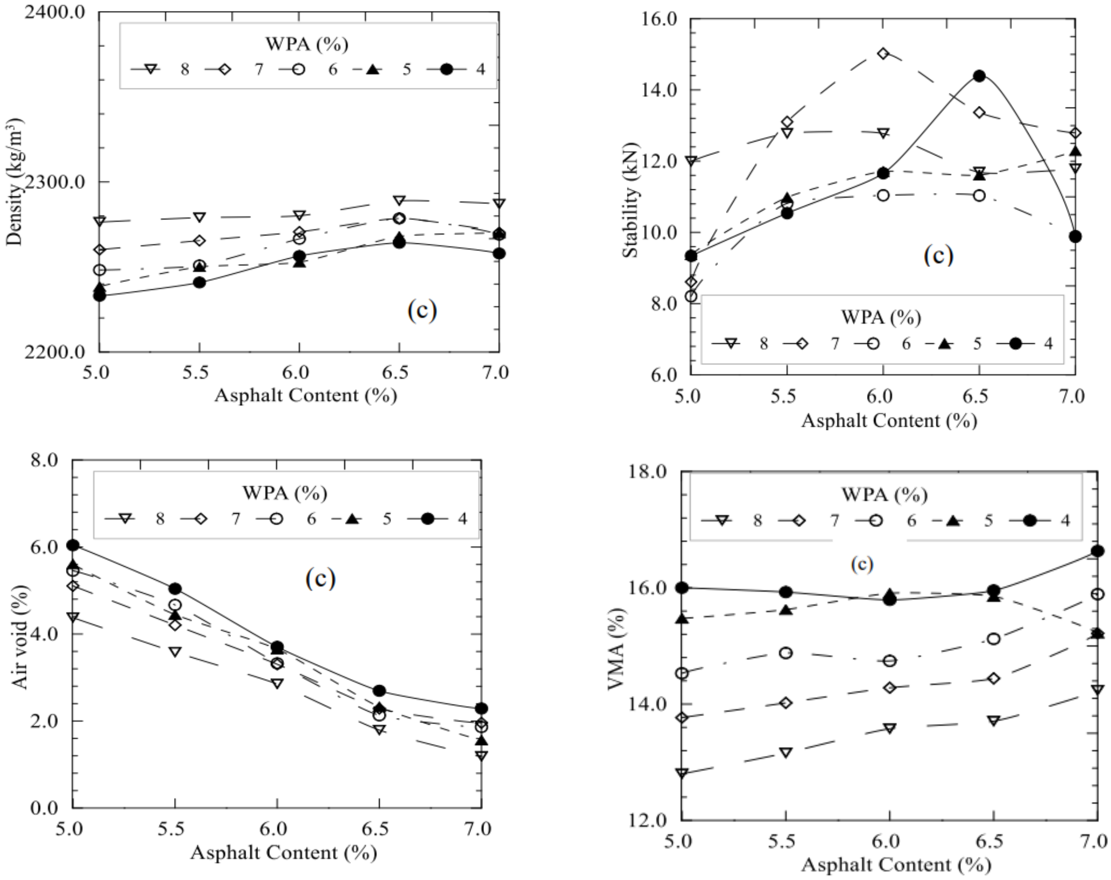

Figure 18. Marshall properties result of wood powder ash [28].

Meanwhile, Bi and Jakarni [31] discovered that wood ash can be used as a filler in asphalt mixture because of the similarity in physical and chemical characteristics of the conventional fillers. The study designs a range of percentages of 25, 50, 75, and 100% by weight. The samples were tested for Marshall stability and flow, indirect tensile fatigue, asphalt permanent deformation, and resilient modulus tests. The chemical composition showed the highest percentage is at CaO and SiO_2 where 29.53% and 28.11%, respectively. As a result, the asphalt mixture's gaps are reduced and the adherence of the aggregate to the asphalt binder is improved. The standard specification for stability is 8000 N, flow between 2 to 4 and stiffness is > 2000 N. The highest stability is shown at 25% wood ash content which indicates better permanent deformation (Figure **19**).

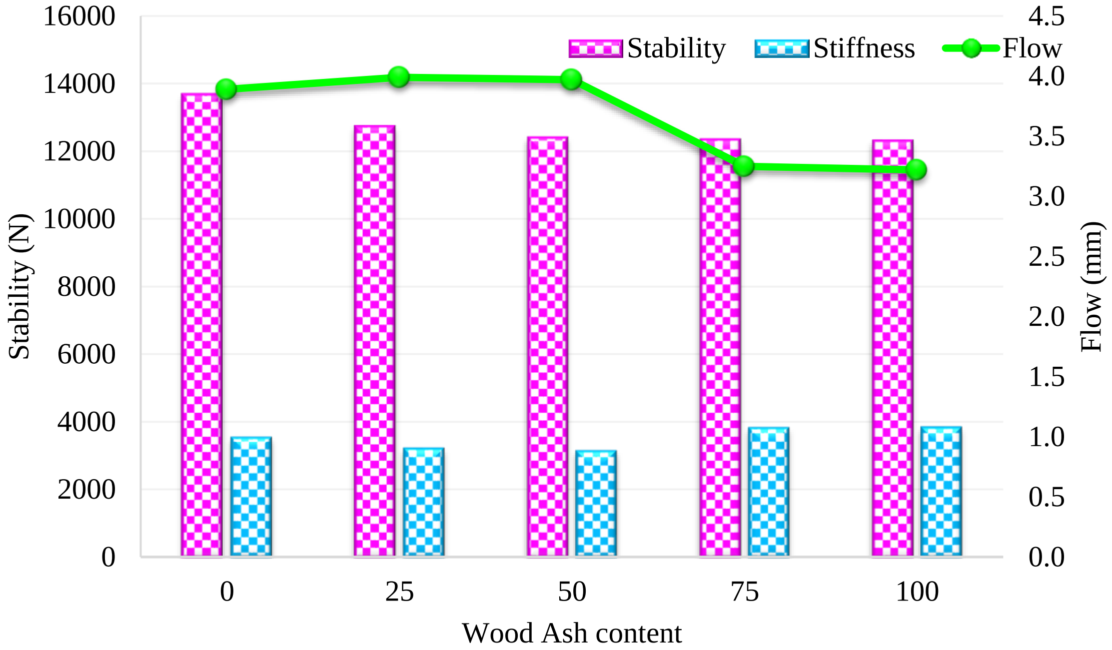

Figure 19. Result stability of wood ash addition.

Nassef et al. [41] conducted a study of the effects of sawdust and rice husk on the effectiveness of asphalt binders and mixtures. A mechanical mixer was used to blend the 10, 15, and 20% of asphalt binder. They conducted a Marshall test, on tensile strength, and loss of stability. The result confirms that 15% rice husk with 15% sawdust perform softening point temperature and viscosity increases, and penetration decreases. In contrast to other mixes, the HMA-containing SD mixture had the lowest stability because it had the lowest density, highest VMA, and most air voids. Figure **20** depicts a loss of stability results employed in this study using three asphalt mixtures. It can be seen; sawdust had a lower value of maximum loss stability compared to limits of 25% and it is acceptable as the high strength of stability.

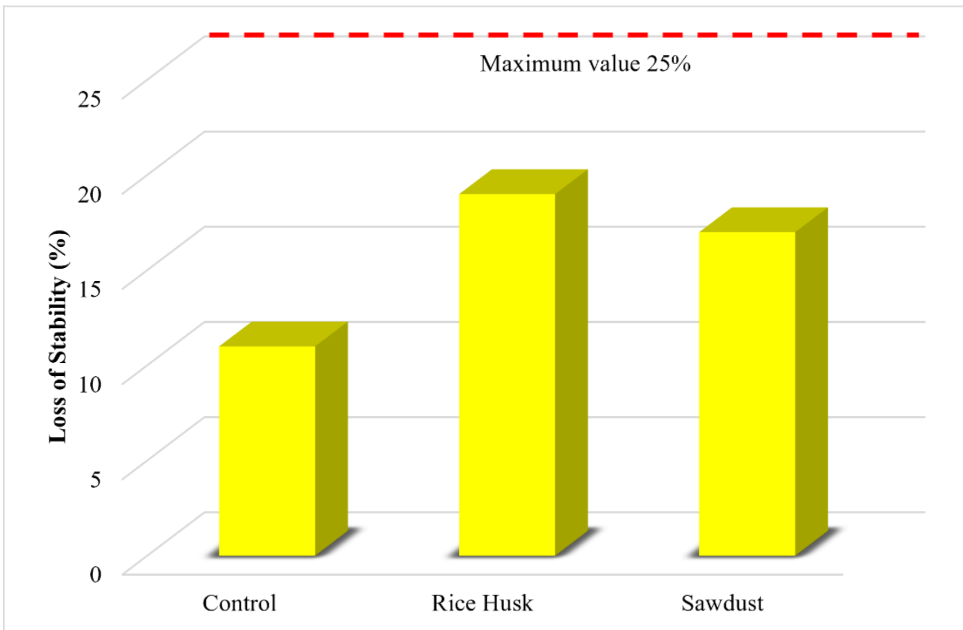

Figure 20. Loss of stability.

4. Discussions

The findings reported that POFA, garnet waste, and sawdust may all be classified as waste materials that are primarily used for complete substitution as modifier in binder and mixture modification, as stated in prior work. Figure **21** displays a summary usage of POFA, garnet waste, and sawdust modified asphalt mixture reviews pertaining to this research. POFA, a byproduct of palm oil industry, possesses a chemical composition rich in silica oxide (SiO_2), aluminium oxide (Al_2O_3), ferum oxide (Fe_2O_3) and calcium oxide (CaO). Through the incorporation of POFA into asphalt mixtures, improvements in Marshall stability can be observed between 3-7% potential replacement. Marshall stability is a common test used to evaluate asphalt mixtures' strength and deformation characteristics. The results showed that adding POFA enhances the stability and rutting resistance of asphalt mixtures, and improves their durability and stiffness, thereby suggesting its potential as a sustainable and effective modifier in asphalt pavement construction. Contrarily, garnet waste, one of the industrial wastes produced by waterjet cutting, has a chemical predominantly composition that is primarily made up of greater value in Fe_2O_3, Al_2O_3, and SiO_2. The incorporation of garnet waste into asphalt mixtures has been studied to assess its impact on Marshall stability, which is a crucial parameter for evaluating the strength and deformation characteristics of asphalt mixtures. The stability findings showed a promising outcome, indicating that adding garnet waste can improve the stability, rutting resistance, and tensile strength of the asphalt mixtures. Based on these findings, garnet waste has the potential to be used as a sustainable modifier (up to 25% replacement) and an eco-friendly solution for the utilization of industrial waste materials. The asphalt modification of sawdust and sawdust ash is composed of calcium oxide, silica-alumina, iron oxide, and potassium oxide. The addition of sawdust to asphalt mixtures aims to enhance its properties and performance. The evaluation of the strength and stability of the asphalt mixtures revealed that the inclusion of up to 12% sawdust, resulted in improved stability, resistance to deformation, and lower moisture susceptibility. This modification technique shows promise for sustainable asphalt production by utilizing a waste material and enhancing the performance of the asphalt mixture.

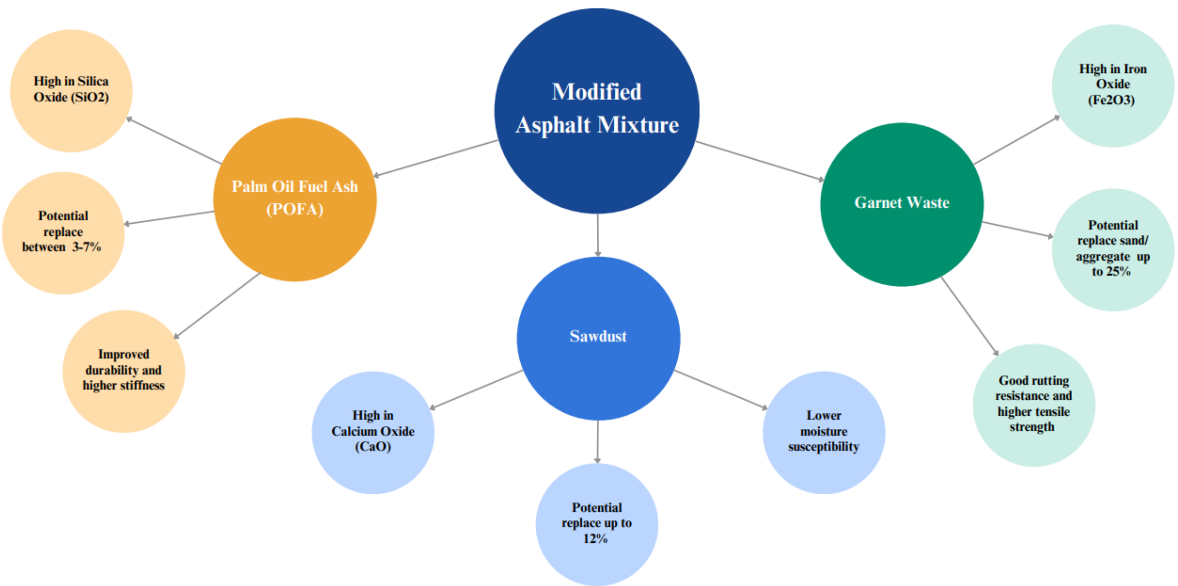

Figure 21. Summary of usage POFA, garnet waste and sawdust in modified asphalt mixture.

5. Conclusions

This review suggests further investigation and applications of POFA, garnet waste, and sawdust as alternative modifiers and substitute materials in the pavement industry. However, prior research has only addressed the ingestion of residue from a single source. Therefore, the research gap that need to be addressed for future study is to use these three waste component in combination as a modifier. Continued efforts are needed to make the three waste combination asphalt mixtures require further investigation of their mechanical and rheological properties. The use of residue in the paving industry might slash emissions associated with waste disposal and further lower the cost of wasteland. Additionally, using such waste materials in the construction of pavement will lighten the burden on conventional resources. Furthermore, there is a need to expand research work in the future to prove the superiority of POFA, garnet waste, and sawdust applications in pavement materials.

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