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Case Report

A comparative evaluation of the mechanical properties of PET and polystyrene modified asphaltic concrete containing rice husk ash filler

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ABSTRACT

The study evaluated and compared the influence of bitumen modification for sustainable asphalt using waste plastic (Polyethylene Terephthalate, PET) and waste Polystyrene (PS) at 5–50% modification levels. Rice husk ash (RHA) and desilted sand were used as filler and fine aggregate with crushed granite as coarse aggregate. Tests conducted include; penetration, viscosity, flash point, fire point, specific gravity, ductility and marshal stability test on asphalt. For PET modified-binder a decrease in penetration and ductility was observed while the specific gravity, viscosity, flash and fire points of the binder increased. For the PS modified-binder, the penetration, ductility, viscosity and specific gravity decreased with an increase in PS while the flash and fire point increased. Marshall Stability results showed an optimal of 20% PET modification was adequate for medium traffic surfing with stability, flow, density, air void, void in mineral aggregates (VMA), and Void filled with binder (VFB) of 4875N, 3.53 mm, 2.460 g/cm^3, 3.30%, 18.20%, and 81.87% respectively. For 10% PS modification content, the stability, flow, density, air void, void in mineral aggregates (VMA), and Void filled with binder (VFB) were found to be 6825N, 3.33 mm, 2.362 g/cm^3, 4.52%, 18.21%, and 75.18% respectively which was found to be adequate for heavy traffic surfacing. Hence, it was concluded that the investigated waste plastics could be used in Asphalt pavement courses. If applied, these results could provide low-cost materials for paving roads while also reducing waste-related pollution and environmental issues.

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1. INTRODUCTION

The world has avoided paying close attention to the consequences of rapid increases in plastic consumption for decades. As a result, the ecosystem has been inundated by unprecedented amounts of uncontrolled mixed plastic waste. Plastics used in packaging make up nearly half of all plastic waste globally Nchube et al. [1]. Plastic is a waste stream with recycling and recovery potential, Babayemi et al. [2], however, the recycling rates for plastic in African countries are low. Furthermore, use and production of virgin plastics are increasing. Therefore, a high proportion of plastic waste is being disposed of in landfills and dumpsites. Plastic serves as fuel for open burning at landfills/dumpsites with associated releases and constitutes a large fraction of marine litter, making it a major and growing global pollution concern.

Plastics consumption increased globally from about 330 million tons in 2016 to over 367 million tons in 2020 [3], these figures have increased over the past years. Combating the threat of plastic trash pollution has turned into a global en-

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vironmental issue. Plastic pollution has the potential to harm land, waterways, and oceans since a vast number of marine and land organisms have died as a result of plastic's non-biodegradability and soil danger. Plastic wastes are also hazardous to human health since they may contain toxic acids that can cause death Kehinde et al. [4]. It is not uncommon to encounter haze and poor air quality because of the burning of solid wastes (mostly plastic products) as a waste management method. It has been found that the emissions of CO_2 from incinerators are higher than those for coal, oil, or gas-propelled power plants. Incinerators produce 210 different types of toxic compounds, including mercury, fluorides, sulfuric acid, nitrous oxide, hydrogen chloride, and cadmium Bolden et al. [5].

The management of plastic waste in developing countries such as Nigeria is even more acute, where the infrastructures for collection, reuse, and recycling is often insufficient or lacking. For these countries, the development of effective plastic waste management strategies is imperative, and with such strategies geared towards addressing the technological, economic, environmental, and political challenges, Kehinde et al. [4].

Considering the enormous amount of construction work done annually and the quantity of waste produced each year, the concept of reusing and processing waste into raw materials in the construction industry is gaining traction among engineers, researchers, and government bodies. Past studies have tested the efficacy of different (Agro, Industrial, Mining, etc) waste as partial or full replacement of conventional construction materials. Results from such studies have shown great potentials. For example, Rice Husk (RH) is an abundantly available agricultural waste material in all rice-producing countries containing about 30%–50% of organic carbon Habeeb, and Mahmud [6]. When Rice Husk is burnt in the ambient atmosphere to any temperature within the range of 225–500 °C, Rice Husk Ash (RHA) is produced Kapur et al. [7]. The RHA has been researched as a partial replacement of cement in concrete with results showing it acted as a micro filler and enhancing cement paste pore structure Beagle [8]. Arabani et al. [9] studied the effects of RHA as an asphalt modifier on HMA using bitumen blends containing 5%, 10%, 15%, and 20% RHA modifier. The addition of RHA improved the rheological properties of bitumen, according to the findings. The MS, stiffness modulus, rutting strength, and fatigue performance of asphalt mixes were also improved by RHA modification. In an another study by Ewa et al. [10] the suitability of rice mill wastes in asphaltic concrete was reported. Quarry dust was partially and wholly replaced by rice husk and rice husk ash as filler up to 100% replacement levels. It was concluded that while, asphalt specimens with RH filler meets the requirement for binder course, samples with RHA filler met the requirement for both binder and waering courses.

One effective remedy to the problem of how to deal with plastic waste is to recycle it as an alternative road construction material since it can be used as a binder extender in asphalt binder Jamshidi and White [11]. Zoorob and Suparma [12] revealed that using recycled waste plastics materials mainly composed of Low-Density Polyethylene (LDPE) in bituminous mixtures resulted in a significant enhancement of its stability i.e. approximately 2.5 times greater than the stability of the control mixtures and durability while decreasing in density. In addition, the outcomes of the study showed that the asphalt fatigue life of the modified mixtures was longer than the control Casey et al. [13] studied the potential of recycled polymer to modify binder. The results of the experiments showed that 4% of recycled High-Density Polyethylene (HDPE) in a pen grader binder can result in the most promising outcome and improve the properties of the binder.

Figure 1. PET/PS blocked drains.

Polystyrene is a type of plastic that has long been used in packaging. Chemical recycling of discarded polystyrene into the equivalent monomers or hydrocarbons has been used in a number of studies Sato et al. [14]. The process is inefficient, however, because the cost of hydrocarbons and monomers is minimal when compared to the cost of recycling Nassar et al. [15]. As a result, finding an effective way to recycle waste polystyrene is beneficial Imene et al. [16].

Mousa et al. [17] reported on the production of sustainable asphalt mixes using recycled Polystyrene with the objectives of studying the effects of polystyrene on properties of bitumen and to investigate the feasibility of using the polystyrene as an additive to asphalt pavements. While penetration and ductility decreased, viscosity and softening point increased. The binder met the safety specifications for flash and fire points. It was concluded that the PS-modified binder had the potential of performing under hot climate conditions and can be used for playgrounds, parking lots, sidewalk pavements. Polystyrene in disposable food pack was recycled by Murana et al. [18] as a modifier for Bitumen in Hot Mix Asphalt. DFP derived from home trash was added to the bitumen in percentages of 2%, 4%, 6%, 8%, and 10%. DFP modified bitumen had lower penetration, ductility, and specific gravity, while its softening point increased. According to the Marshal Stability data, the DFP treated bitumen improved the stability value. It is recommended that the DFP content of the Optimum Bitumen Content (OBC) be 6.7 percent by weight.

A huge amount of plastic has infiltrated the Nigerian technosphere, Babayemi et al. [19] with only about 12% of the waste ending up in the recycling stream. This critical waste and resource category requires long-term management. Nigeria as a developing nation is currently faced with the challenge of handling plastic waste disposal and management, see Figure 1. This current study seeks to evaluate the comparative properties of eco-friendly and sustainable

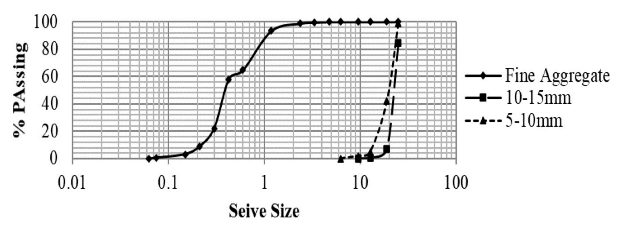

Figure 2. Particle Size Distribution curve of aggregate used.

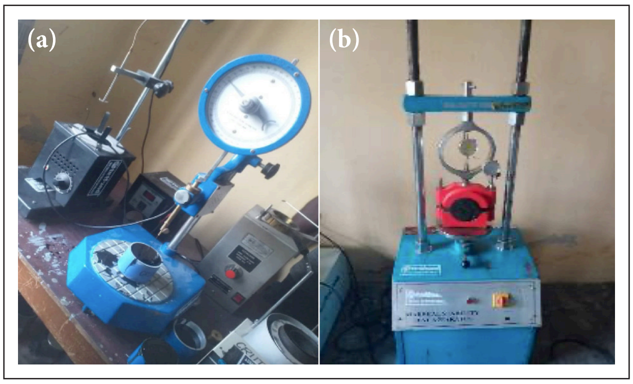

Figure 3. **(a, b)** Experimental set-ups.

asphalt having waste PET and PS as binder modifiers, rice husk ash as filler and de-silted sand (sediment sand blocking drain channels) as fine aggregate. Utilizing these waste will enhance cleaner engineering production of asphalt for road surfacing. The objectives of the study includes:

- To investigate the influence of waste PET and waste PS on the properties of modified binder.
- To investigate the influence of waste PET and waste PS on the properties of modified asphalt.
- Compare the influence of the modified-binder on asphalt properties.
- Determination of optimal PET and PS content on modified Binder

2. MATERIALS AND METHODS

2.1. Materials

Materials used in this study were bitumen grade 60 /70 penetration, waste plastic bottles (PET) and waste polystyrene (PS) as binder modifiers. Crushed granite with a size range of 5–15 mm was used as coarse aggregate, de-silted sand (sediment sand from gutters) was used as fine aggregate with a size range of 0–2 mm and Rice Husk Ash (ASH) as filler.

2.2. Methods

The aggregates were subjected to sieve analysis, specific gravity, and aggregate impact value (AIV) in accordance [20–22]. Figure 2 shows the particle size distribution curve of the aggregate while Table 1 is comparison of test results on aggregates with standards. The modified asphalt binders had partial replacement of bitumen with PET and PS at 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%. Penetration, viscosity, flash point, fire point, specific gravity, and ductility tests were carried out on the bitumen and the modified binders in accordance [23–27], see Figure 3a for experimental set-up. In Table 2, the mix proportion for binder modification is presented, while Table 3 shows the bitumen characterization against Standards. The propotion for asphalt mix design is shown in Table 4. Asphalt samples were prepared in accordance with ASTM D6927-15 [28] and IRC: 111 [29]. To determine the optimal bitumen content, a Marshall Stability test using the set-up of Figure 3b, was performed for each sample. The flow, bulk density, air void, void in mineral aggregate (VMA), and void filled by bitumen (VFB) were measured and compared to Table 5's typical Marshall mix design criteria. Equation 1 was used to estimate the Rigidity Ratio (RR) or Marshall Quotient (MQ), which measures a mix's resistance to permanent deformations and rutting.

$$RR = \frac{Stability}{Flow} \quad \left(\frac{KN}{mm^2}\right) \qquad \text{Eqn. 1}$$

3. RESULTS AND DISCUSSIONS

3.1. Modified Binder Properties

3.1.1. Penetration

The penetration behaviour of the modified binder is presented in Figure 4. The test result shows that the penetration values of the PET-modified binder increased up to 5% PET addition and thereafter, decreases as the polymer modifier

Table 1. Comparison of test results on aggregates with standards

Property	Limit	Result obtained	Code used	Code specification
AIR	%	14.7	BSEN 2620:2002	<30
Specific gravity (fine)	–	2.74	ASTM C128:2015	2.6–2.9
Specific gravity (coarse)	–	2.84	ASTM C128:2015	2.6–2.9
RHA	–	2.11	ASTM C136	–

Table 2. Mix proportions for asphalt binder modification

Bitumen	100	95	90	85	80	75	70	65	60	55	50
% PET	0	5	10	15	20	25	30	35	40	45	50
% PS	0	5	10	15	20	25	30	35	40	45	50

Table 3. Comparison of test results on pure bitumen with code specification

Test	Unit	Test method (ASTM)	Code specification for 60/70 penetration grade	Results obtained
Penetration@ 25 °C	mm	D5	60/70	69
Specific gravity@25 °C	–	D70	1.01–1.06	1.02
Flash and fire point	°C	D92	>250	262 and 285
Ductility@ 25 °C	cm	D113	>100	110
Viscosity@ 60 °C	Seconds	D4402	140–250	157

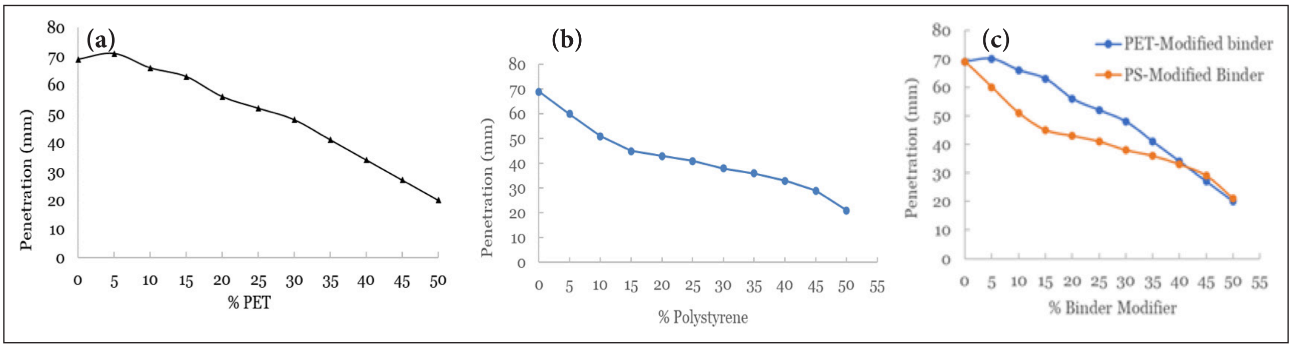

Figure 4. **(a)** Influence of PET on modified binder Penetration, **(b)** influence of PS on modified binder Penetration, **(c)** Comparative penetration curve.

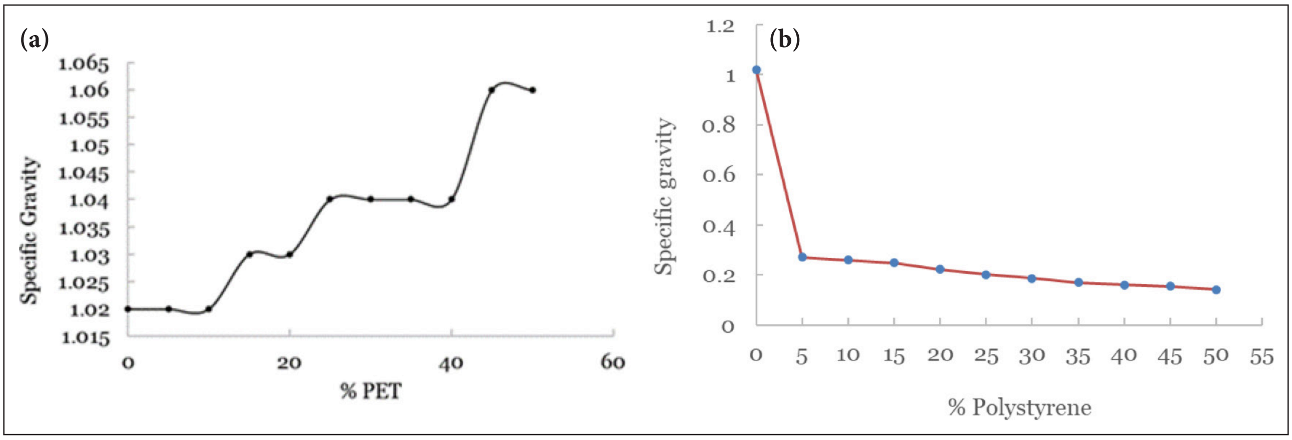

Figure 5. **(a)** Specific gravity of PET-Modified binder, **(b)** Specific gravity of PS-Modified binder.

increases. While the penetration of the PS-modified binder decreased with the increase in PS content as observed by Murana [18]. PET inclusion up to 15% gave acceptable penetration values in line with [23], while PS up to 5% gave acceptable value. It was observed that the addition of PET up to 5% makes the modified binder harder and more consistent which can lead to the improvement of rutting resistance of the mix, Esmaeil et al. [30] and Ramesh et al. [31]. From Figure 4c, PET-modified binder is stiffer than PS-modified binder within 0–40% binder addition, beyond this range, both modifiers behaved in similar ways. It is common for the consistency of modified asphalts to increase as a result of the inclusion of polymers, which implies a high resistance to deformation. This is most likely caused by swelling of maltenes (the oil fraction of bitumen) diffusing into the polymeric phase, as well as interactions between polar asphaltene molecules and polymer modifiers.

Table 4. Mix proportion used for asphalt

Type	Size in mm	% of constituents
Crushed sand	0–2 mm	59%
Crushed stone	5–10 mm	20%
Crushed stone	10–15 mm	10%
Filler	0–0.075 mm	5%
Bitumen	–	6%

3.1.2. Specific Gravity

The specific gravity of the PET-modified binder increases with the increase in the addition of the polymer as shown in Figure 5, while, the specific gravity of the PS-modified binder decreased with the inclusion of polystyrene Murana [18]. PS is a lighter weight waste compared to PET. Up to

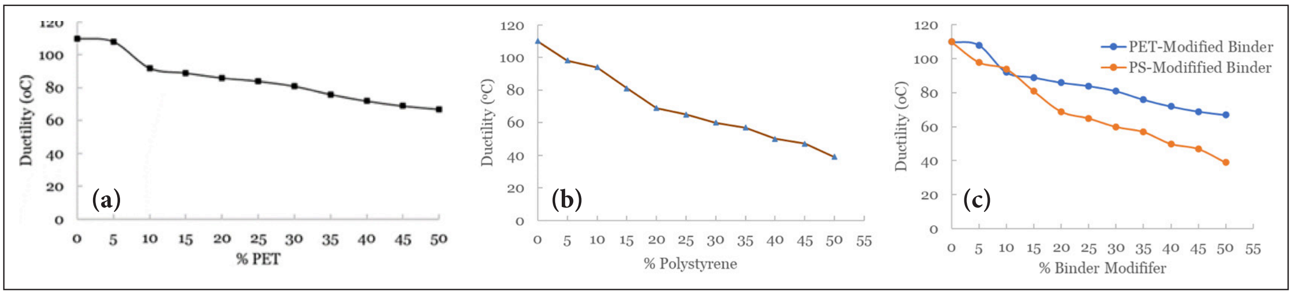

Figure 6. **(a)** Influence of PET on modified binder ductility **(b)** influence of PS on binder modified binder **(c)** Comparative ductility curve.

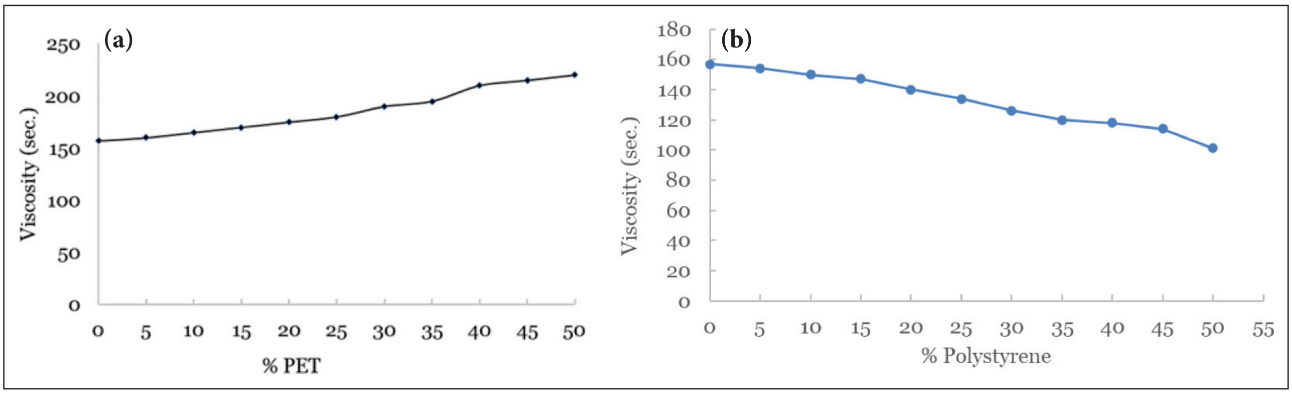

Figure 7. **(a)** Influence of PET on Viscosity **(b)** influence of PS on Viscosity.

Table 5. Typical Marshall mix design criteria [28]

Description	Base course		Binder course		Wearing course	
	Min.	Max.	Min.	Max.	Min.	Max.
Marshall specimens (ASTM D6927) No. of comp. Blows on each end of the specimen	75		75		75	
Stability (N)	2224		3336		6672	–
Flow (0.25 mm)	2	14	2	14	2	14
VMA (%)	13		14		15	–
Air voids (%)	3	8	3	8	4	6
VFB (%)	70		70		70	–

50% inclusion of PET gave acceptable values as required by [24]. Similar results were reported by Rahman et al. [32] and Akinleye et al. [33].

3.1.3. Ductility

Ductility is responsible for the internal cohesion of the binder. As seen in Figure 6, ductility decreased with the addition of the PET and PS. At 5% binder modification, PET-modified binder yielded acceptable ductility in line with [27] while PS-modified binder did not. Modified binder has reduced internal cohesion, resulting in lesser binder content and causing less ability for aggregates to adhere during asphalt mix. This mixture is suitable for usage in hotter climates, particularly in areas where temperature differentials are significant Akinleye et al. [33].

3.1.4. Viscosity

Figure 7 presents the influence of the PET on binder viscosity. The viscosity of the PET-modified binder increased as PET was added, indicating improvement in the adhesiveness of the modified binder. Up to 50% PET inclusion, viscosity values were within the specified limit in ASTM D4402 [26]. It can be concluded that PET-modified binder has higher workability than plain bitumen Akinleye et al [33]. On the other hand, the inclusion of polystyrene decreased viscosity as seen in Figure 5b. The optimal level of PS modification of binder is 20% while up to 50% PET addition, gave acceptable viscosity values as specified by [26].

3.1.5. Fire and Flash Point

The influence of polymer modification on the fire and flashpoints of the modified binder is shown in Fig-

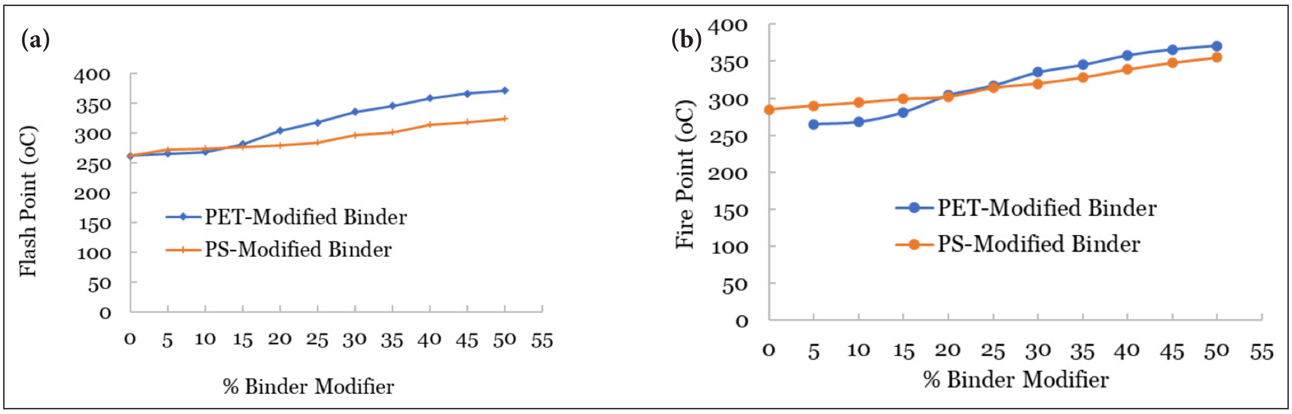

Figure 8. **(a)** Flash point, **(b)** fire point.

ure 8. Fire and flashpoints increased with the increased addition of both PET and PS with values failing within ASTM D 92 [25]. This implies a reduction in the risk of catching fire when the modified asphalt is being produced, with PET-modified binder having a better safety in terms of fire.

3.2. Influence of PET and PS on Asphalt Properties

3.2.1. Marshal Stability

As seen in Figure 9, the stability of the modified asphalt increased with percentage of the modifiers up to 20% optimal replacement level. The stabilities for PET and PS modified specimens at optimal modifier content were found to be 4525N and 6215N respectively. Beyond 20% inclusion of the modifiers, stability declined to 2238N and 3005N at 50% replacement level for PET and PS modified specimen respectively. While the stability value for PS-modified asphalt satisfied the requirement for wearing course (heavy traffic), PET-modified asphalt meet the requirement for binder course (medium traffic) [28]. The increased in stability of the modified asphalt mixture can be explained as a result of better adhesion development between asphalt binder and aggregate particles due to the addition of waste modifiers, Rasool et al. [34]. Due to the high rigidity of the modified PET and PS binder, the toughness and stability of the modified asphalt improved Jegatheesan et al. [35].This results in increased asphalt mixture strength, which helps to improve the asphalt mixture's stability.

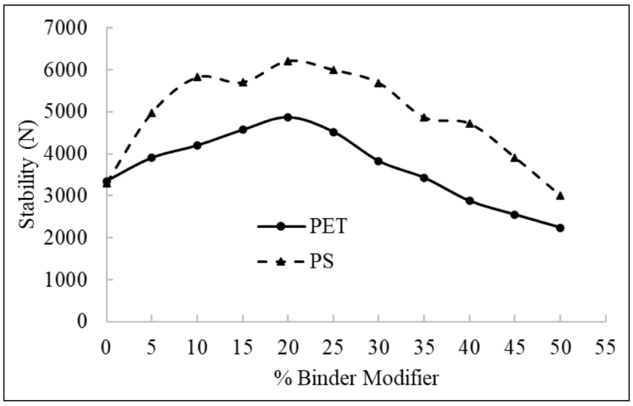

Figure 9. Stability of PET and PS modified asphalt.

3.2.2. Marshal Flow Values

The marshal flow value indicate asphalt deformation at the point when maximum load occurs. From Figure 10, the maximum flow value for both PET and PS modofied asphalt were 3.53 mm and 3.62 mm respectively, at 20% optimal modifier conetent. These values are within acceptabe flow values specified in [28]. Aliyu et al. [36] noted that a reduction in flow suggests that the polymer content has increased effects on the internal friction of the mix.

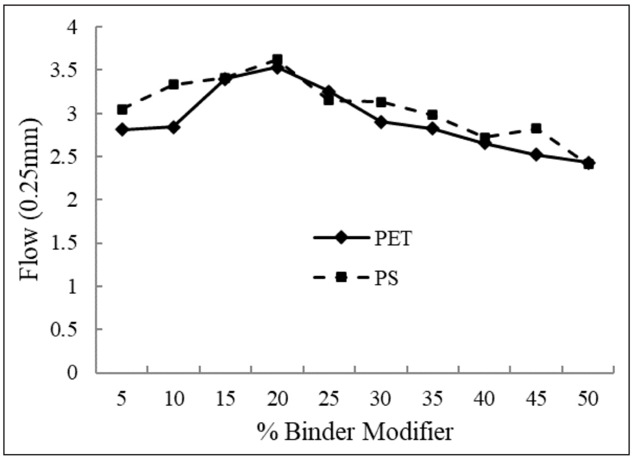

Figure 10. Inflence of modifiers on Marshal flow values.

3.2.3. Bulk Density

Bulk density of the modified asphalt mixes increase with the addition of modifiers as seen in Figure 11. PET-modified asphalt increased in density from 2.205 g/cm³ at 0% modifier content to 2.46 g/cm³ at 20%. Bulk desmity of PS-modified asphalt increased from 2.205 g/cm³ at 0% to 2.374 g/cm³ at 15%.

3.2.4. Air Voids

The air void for the PET and PS modified asphalt decreased with increased in the modifier content (MC) as seen in Figure 12. At 50% modifier conetent, airvoid for PET and PS-modified mixes were found to be 3.15% and 2.45% repectively. The value for PET-modified asphalt

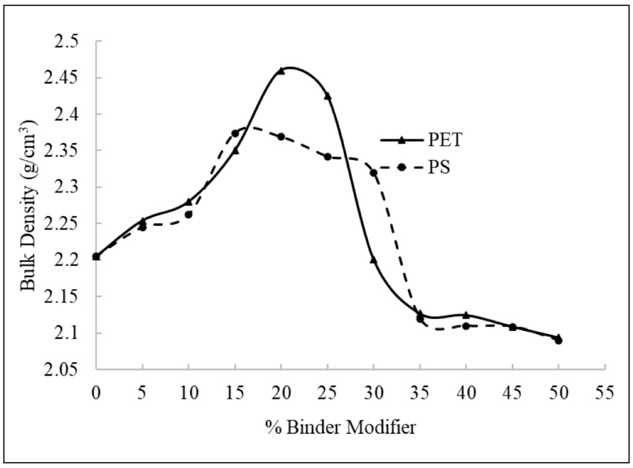

Figure 11. Inflence of modifiers on bulk density.

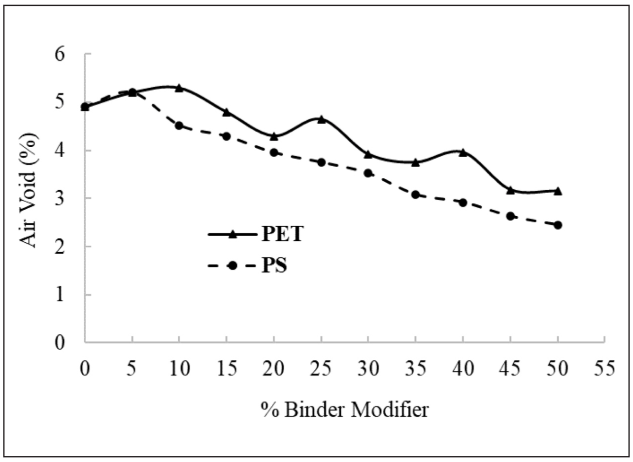

Figure 12. Inflence of modifiers on air voids.

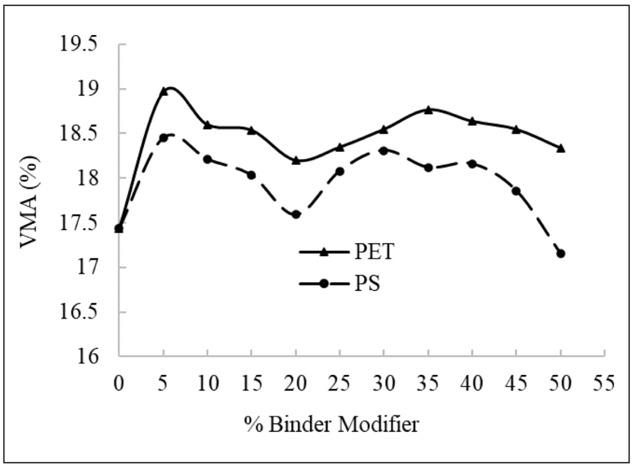

Figure 13. Inflence of modifiers on voids in mineral aggregate.

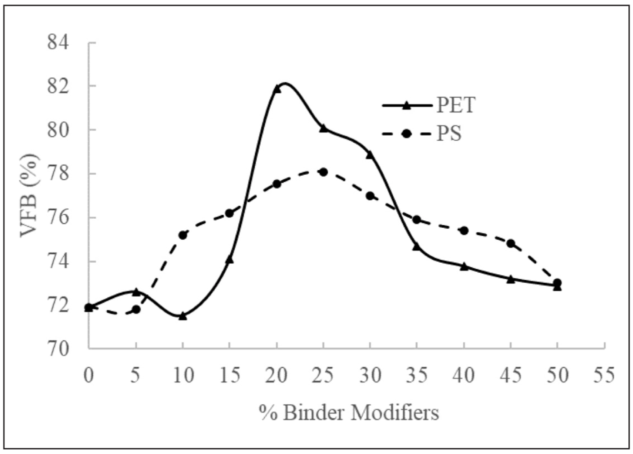

Figure 14. Inflence of modifiers on voids filled with binder.

is within the acceptable range for binder course while PS-modified asphalt did not meet the air void requirement at 50% replacement level. At 20% optimal modifier content, air void values were 4.3% and 3.95% for PET and PS modified asphalt respectively. These air void values are within acceptable range for binder and wearing course [28].

3.2.5. Voids in Mineral Aggregates (VMA)

In Figure 13, the influence of the modifiers on voids in mineral aggregate is presented. The amount of void space between the aggregate particles of compacted asphalt (VMA) increased first to maximum values at 10% OMC, then decreased sharply as the modifier content increased to 20% MC for both PET and PS samples. VMA values for both asphalt mixes satisfied the minimum requirements of 14% and 15% for binder and wearing courses respectively [28].

3.2.6. Voids Filled with Binder (VFB)

The result of VFB variation with PET and PS addition can be seen in Figure 14. The maximum VFB values obtained for PET and PS modified asphalt are 81.87% and 78.10% respectively both of which are greater than the minimum value of 70% recommended by [28].

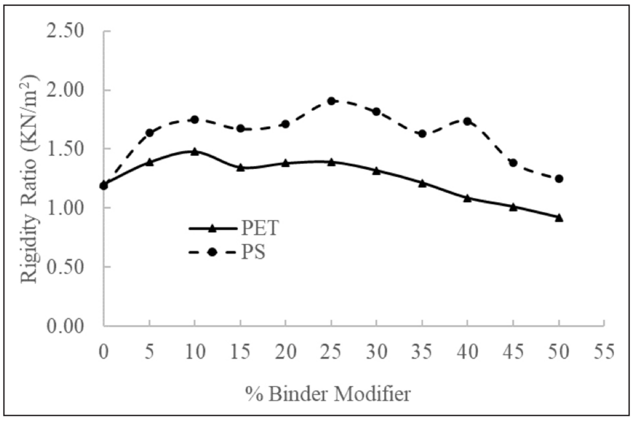

Figure 15. Influence of binder modificstion of rigity ratio.

3.2.7. Rigidity Ratio (RR)

Figure 15 depicts the mix's resistance to permanent deformations as evaluated by the Rigidity Ratio (RR) or Marshall quotient. The highest RR of 1.48 KN/m^2 for PET modified asphalt occurred at 10% MC while that of PS modified asphalt was 1.91 KN/m^2 at 25% MC. Rigidity ratio of PS modified asphalt is higher than PET modified asphalt. In service, RR values can be used to assess a material's resistance to shear stress, permanent deformation, and rutting Aliyu [36].

4. CONCLUSION

Waste management is a serious challenge in Nigeria and other developing countries. Plastic bottles and waste polystyrene being a major non-biodegradable waste. The modification of bituminous binder for asphalt purposes using waste plastic bottles (PET), waste Polystyrene and waste rice husk ash was studied. De-silted sand (sediment sand from gutters) was utilized as fine aggregate, reducing the menance of flood innblocked concrete channels. Waste rice husk ash served as asphalt filler. After comparing the results, the following conclusion was made:

1. Both polymers modified binders fell within acceptable ASTM Standards for use as asphalt paving materials. Waste plastic bottle inclusion up to 15% gave acceptable penetration values in line with ASTM Standard, while polystyrene up 5% gave acceptable value.
2. While PET increases the specific gravity of the modified binder, PS decreases the specific gravity of the modified binder. At 5% binder modification, PET-modified binder yielded acceptable ductility while PS-modified binder did not.
3. Viscosity increased with the PET modifier while it decreased with the PS modifier. The optimal level of PS modification of binder is 20% while up to 50% PET addition, gave acceptable results. PET-modified binder has a better safety in terms of fire due to higher flash/fire point temperatures.
4. Marshall Stability results showed an optimal of 20% PET modification was adequate for medium traffic surfacing with stability, flow, density, air void, void in mineral aggregates (VMA), and Void filled with binder (VFB) of 4875N, 3.53 mm, 2.460 g/cm^3, 3.30%, 18.20%, and 81.87% respectively.
5. For 10% PS modification content, the stability, flow, density, air void, void in mineral aggregates (VMA), and Void filled with binder (VFB) were found to be 6825N, 3.33 mm, 2.362 g/cm^3, 4.52%, 18.21%, and 75.18% respectively which was found to be adequate for heavy traffic surfacing.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

PEER-REVIEW

Externally peer-reviewed.

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