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SUSTAINABLE ASPHALT FROM WASTE PLASTIC BOTTLES (WPB), RICE HUSK ASH (RHA) AND DESILTED SAND

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Abstract.

The study evaluated the influence of bitumen binder modification for sustainable asphalt using waste plastic (Polyethylene Terephthalate, PET) 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. The PET modified-binder a decrease in penetration and ductility was observed while the specific gravity, viscosity, flash and fire points of the bitumen increased. Marshall Stability results showed an optimal of 20% PET modification was adequate for binder course with stability, flow, density, air void, void in mineral aggregates (VMA), and Void filled with bitumen (VFB) of 4875N, 3.53mm, 2.460g/cm^3, 3.30%, 18.20%, and 81.87% respectively. Hence, it was concluded that the investigated waste plastics could be used in Asphalt pavement courses.

Keywords: Bitumen, Binder, PET, Sustainability, Marshall Stability, Asphalt.

1.0 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. In addition, more virgin plastic is being produced and used. As a result, a sizable portion of plastic garbage gets dumped in landfills and other areas. Plastic is a major and expanding source of worldwide pollution because it is used as fuel for combustion at landfills and dump sites with the resulting emissions and makes up a sizable portion of marine pollution.

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 environmental 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. The emissions of CO2 from incinerators have been found to be higher than those from power plants that are powered by coal, oil, or gas. Mercury, fluorides, sulfuric acid, nitrous oxide, hydrogen chloride, and cadmium are just a few of the harmful substances that are produced by incinerators, 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.

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 225-500ºC, 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]. In another study, Arabani and Tahami [9] reported on the effects of RHA as an asphalt modifier on Hot Mix Aspahle (HMA) using bitumen blends containing 5%, 10%, 15%, and 20% RHA modifier. Testing was done on the penetration grade, ductility, softening point, rotational viscosity, and dynamic shear rheometer to assess the rheological characteristics of asphalt binders. The mechanical parameters of asphalt mixtures were also evaluated, including Marshal Stability (MS), stiffness modulus, rutting resistance, and fatigue behavior. 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. Desmond et al., [10] investigated 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 wearing 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]. Using recycled waste plastics materials mainly composed of Low-Density Polyethylene (LDPE) in bituminous mixtures, Zoorob and Suparma [12] revealed significant enhancement in stability of LDPE-modified asphalt, (approximately 2.5 times greater) than the stability of the control mixtures and durability while decreasing in density. In addition, the outcome 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. Basic tests were prepared and conducted on bitumen to evaluate the impact of the recycled polymer on the properties of the bitumen. 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.

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, Yoshiki 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 (DFP) was recycled by Murana et al., [18] as a modifier for Bitumen in Hot Mix Asphalt. In the study, 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, Joshua 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(a) and (b). This current study seeks to evaluate the properties of eco-friendly and sustainable asphalt having waste PET as binder modifiers, rice husk ash as filler and de-silted sand (sediment sand blocking drain channels) as fine aggregate. Utilizing this waste will enhance cleaner engineering production of asphalt for road surfacing. The objectives of the study include:

i. To investigate the influence of waste PET on the properties of modified bitumen binder.
ii. To investigate the influence of waste PET on the properties of modified asphalt.
iii. Determination of optimal PET content on modified Binder

2.1 Materials and Methods

2.1.1 Materials.

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

Figure 1: PET blocked drains

2.0 Methods.

The aggregates were subjected to sieve analysis, specific gravity, and aggregate impact value (AIV) in accordance [20], [21], [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 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], [24], [25], [26], and [27], see Figure 1b for experimental set-up. In Table 2, the mix proportion for binder modification is presented, while Tables 3 shows the bitumen characterization against Standards. The proportion 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 1c, 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.

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

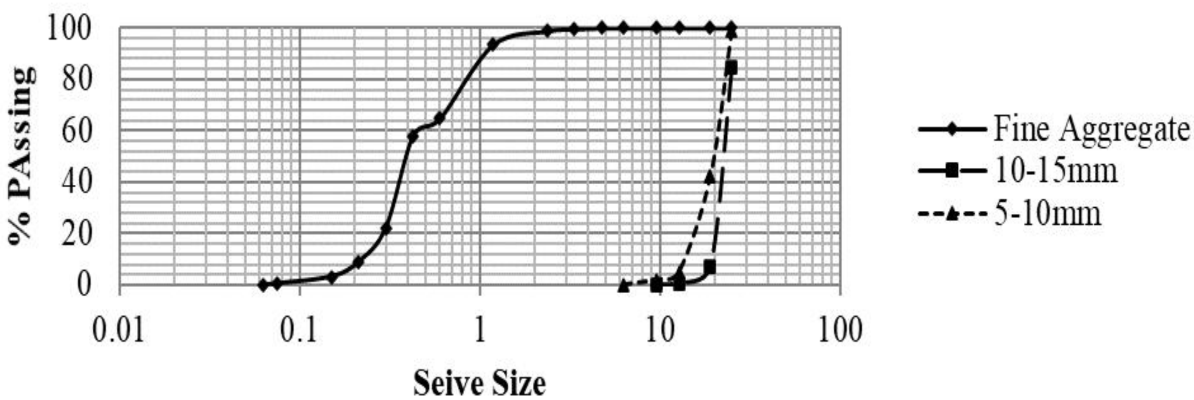

Figure 1: Particle Size Distribution curve of aggregate used

Table 1: Comparison of Test Results on Aggregates with standards

Property	Limit	Result obtained	Code used	Code specification
AIV	%	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	-

a *b*

Figure 2: (a)/(b) Experimental set-ups

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

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@ 25ºC	mm	D5	60-70	69
Specific Gravity@25ºC	-	D70	1.01-1.06	1.02
Flash and Fire Point	ºC	D92	>250	262 and 285
Ductility@ 25ºC	cm	D113	>100	110
Viscosity@ 60ºC	Seconds	D4402	140-250	157

Table 4: Mix proportion used for asphalt

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

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 (0.25mm)	2	14	2	14	2	14
VMA (%)	13		14		15	-
Air voids (%)	3	8	3	8	4	6
VFB (%)	70		70		70	-

3.0 Results and Discussions

3.1 Modified Binder Properties

3.1.1 Penetration

The penetration behaviour of the modified binder is presented in Figure 2. 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 increases. PET inclusion up to 15% gave acceptable penetration values in line with [23]. 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., [31] and Ramesh et al [32].

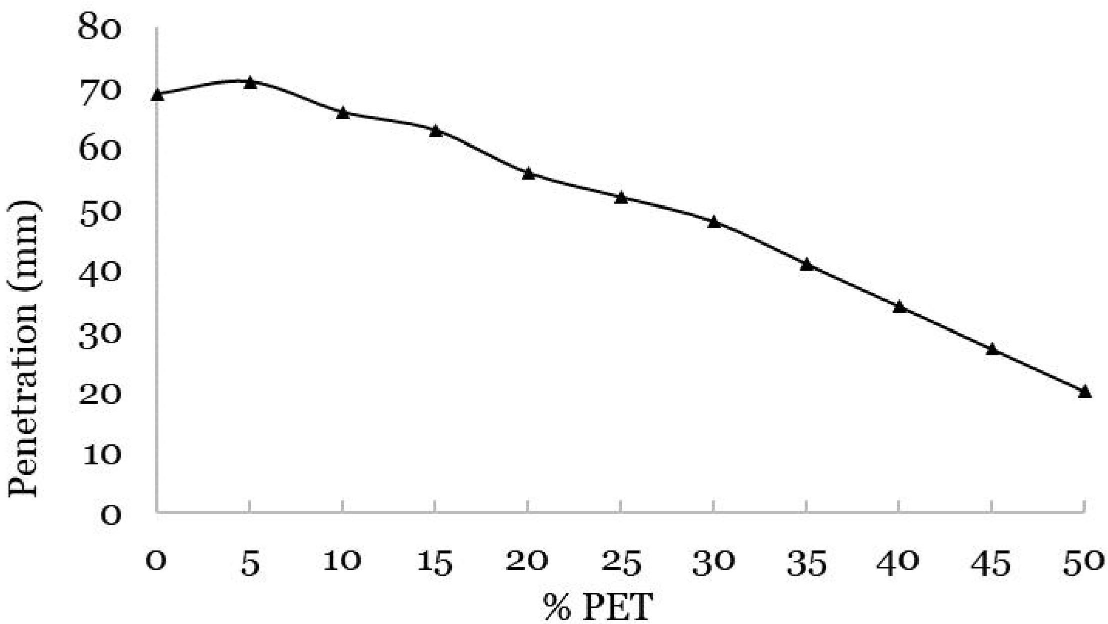

Figure 2: Influence of PET on modified binder Penetration

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 3, this is a reverse trend for Polystyrene-modified binder reported by Murana [18]. Polystyrene is a lighter weight waste compared to PET. Up to 50% inclusion of PET gave acceptable values as required by [24]. Similar results were reported by Rahman et al., [33] and Akinleye et al [34].

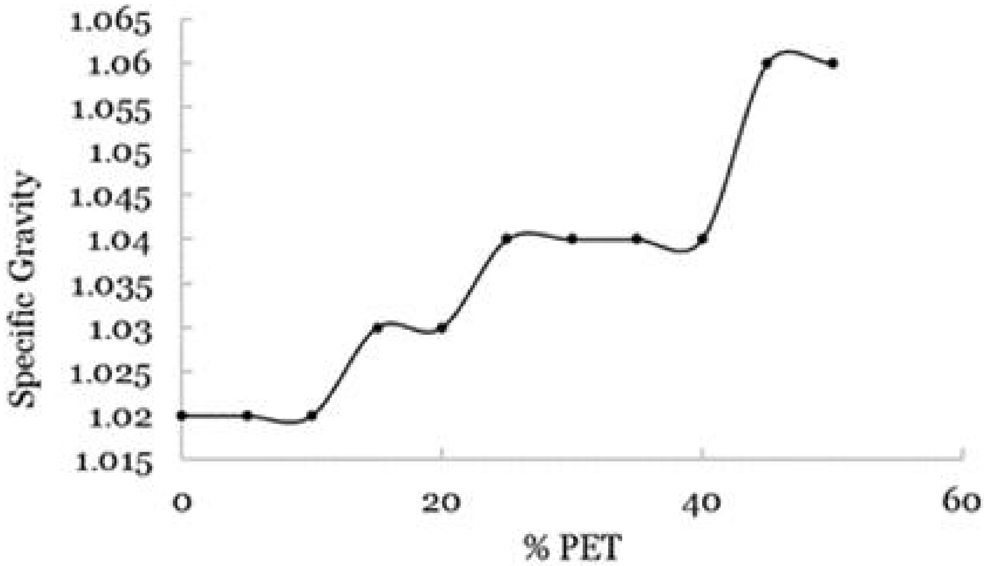

Figure 3: Specific gravity of PET-Modified binder

3.1.3 Ductility

Ductility is responsible for the internal cohesion of the binder. As seen in Figure 4, ductility decreased with the addition of the PET. At 5% binder modification, PET-modified binder yielded acceptable ductility in line with [27]. 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. Baghaee et al [31], [32], and Akinleye et al [34].

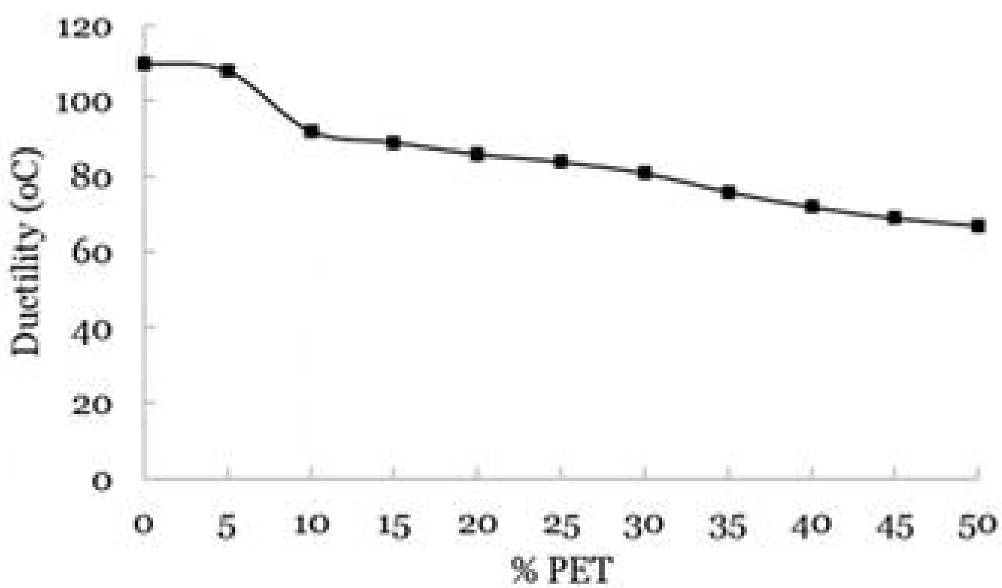

Figure 4: Influence of PET on modified binder ductility

3.1.4 Viscosity

Figure 5a 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 [34]. The optimal level of 50% PET addition, gave acceptable viscosity values as specified by [26].

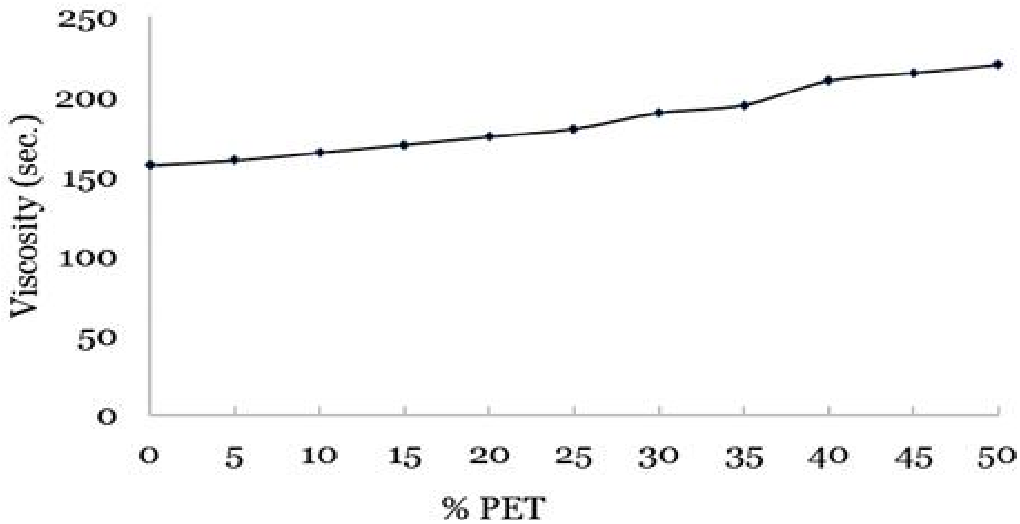

Figure 5: Influence of PET on Viscosity

3.1.5 Fire and Flash Point

The influence of polymer modification on the fire and flashpoints of the modified binder is shown in Figure 6. Fire and flashpoints increased with the increased addition of PET with values falling 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.

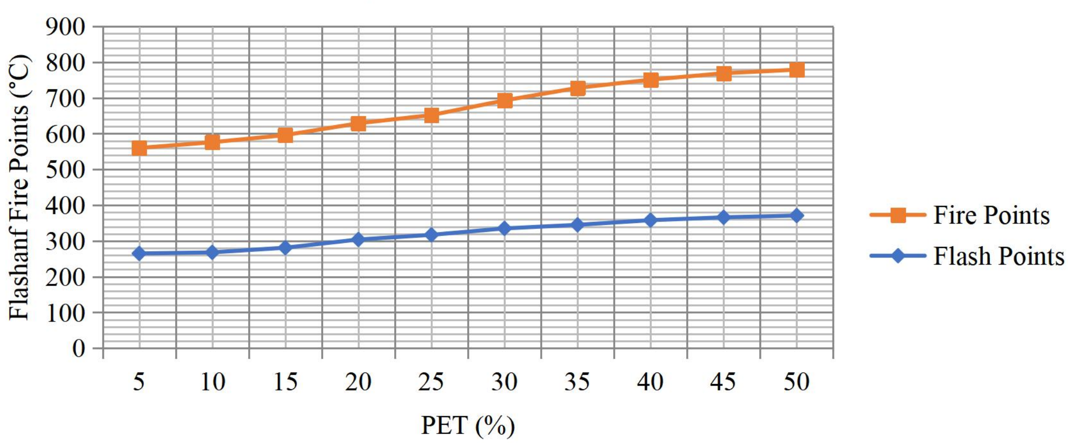

Figure 6: Flash Point and Fire Point

3.2 Influence of PET on Asphalt Properties

3.2.1 Marshal Stability

The stability of the modified asphalt increased with percentage of the modifier up to 20% optimal replacement level. The stability for PET-modified specimen at optimal modifier content was found to be 4525N. Beyond 20% inclusion of the PET modifier, stability declined to 2238N at 50%. The stability value for PET-modified asphalt met 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.,[35]. Due to the high rigidity of the modified PET binder, the toughness and stability of the modified asphalt improved Jegatheesan et al., [36]. This results in increased asphalt mixture strength, which helps to improve the asphalt mixture's stability.

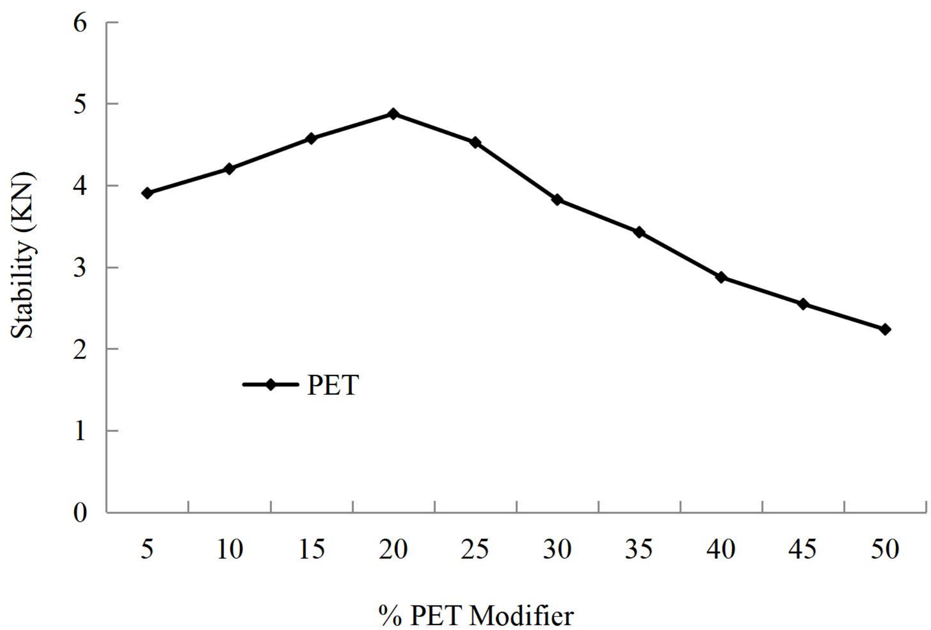

Figure 7: Stability of PET-modified asphalt

3.2.2 Marshal Flow Values

The marshal flow value indicates asphalt deformation at the point when maximum load occurs. From Figure 8, the maximum flow value for both PET-modified asphalt was 3.53mm, at 20% optimal modifier content. This value is within acceptable flow values specified in [28]. Aliyu et al. [37] noted that a reduction in flow suggests that the polymer content has increased effects on the internal friction of the mix.

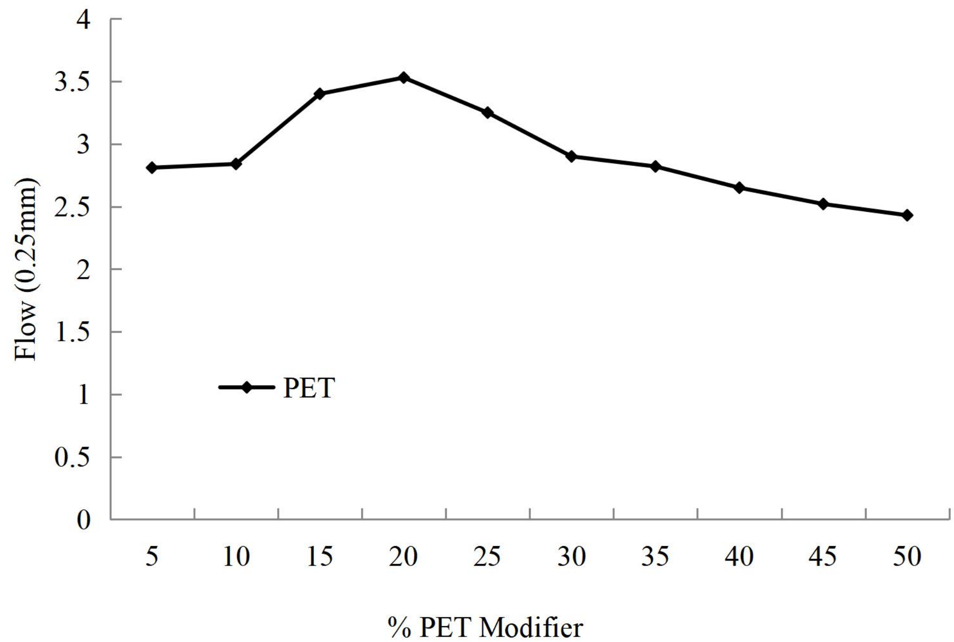

Figure 8: Influence of Modifier on Marshal Flow Values

3.2.3 Bulk Density

Bulk density of the modified asphalt increased with the addition of modifier as seen in Figure 9. PET- modified asphalt increased in density from 2.205g/cm^3 at 0% modifier content to 2.46g/cm^3 at 20%. Improvement in the density of asphalt impact better durability properties to the modified asphalt.

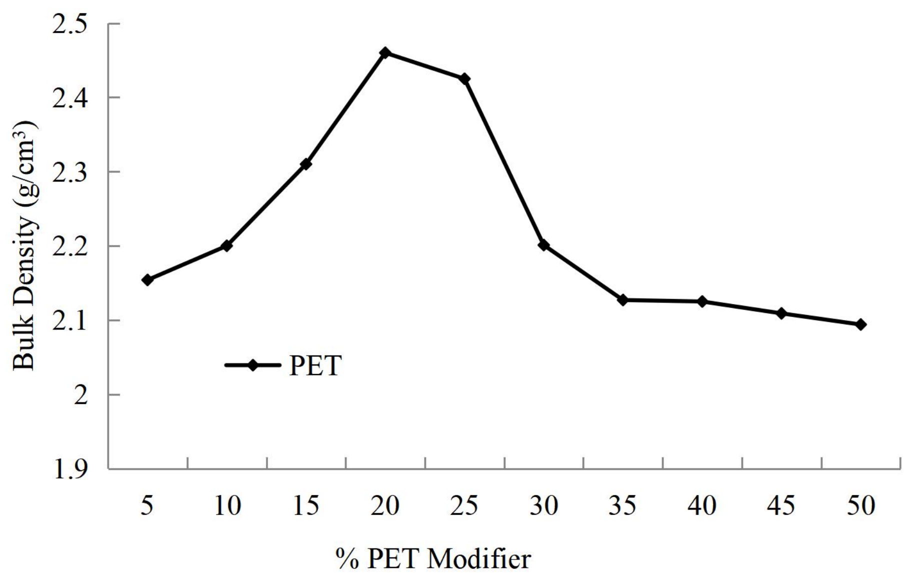

Figure 9: Influence of Modifier on Bulk Density

3.2.4 Air Voids

The air void for the PET-modified asphalt decreased with increased in the modifier content (MC) as seen in Figure 10. At 50% modifier content, air void for PET-modified mix was found to be 3.15%. The value for PET-modified asphalt is within the acceptable range for binder course. At 20% optimal modifier content, air void values were 4.3%. This air void value is within acceptable range for binder and wearing course [36].

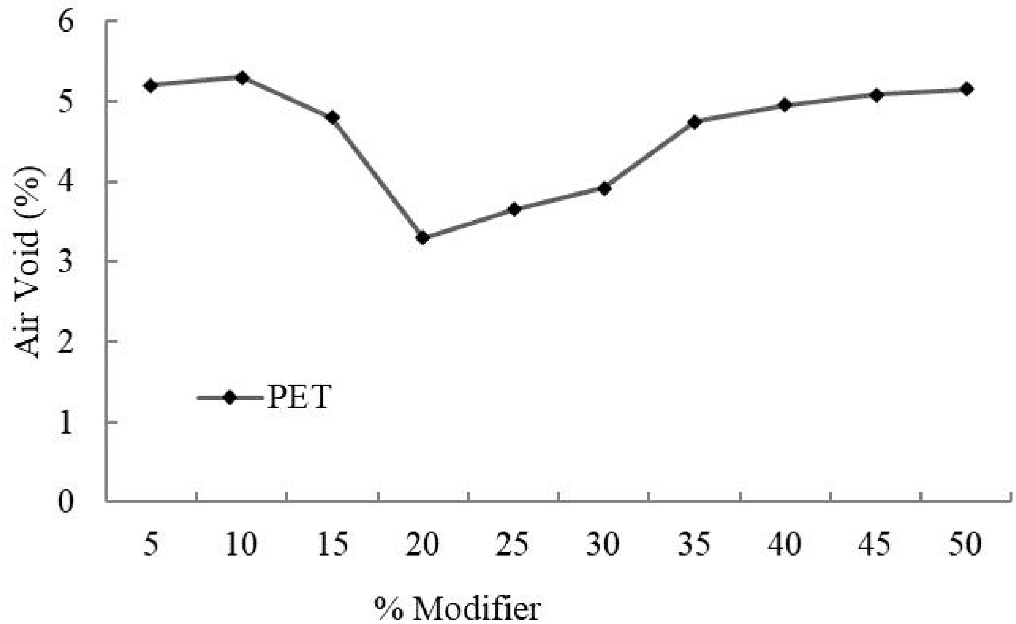

Figure 10: Influence of Modifier on Air Voids

3.2.5 Voids in Mineral Aggregates (VMA)

In Figure 11, the influence of the modifier on voids in mineral aggregate is presented. The amount of void space between the aggregate particles of compacted asphalt (VMA) decreased first from 0% to a minimum value at 20% OMC, then increased sharply as the modifier content increased to 50% MC. VMA value of the modified asphalt satisfied the minimum requirements of 14% and 15% for binder and wearing courses respectively [36].

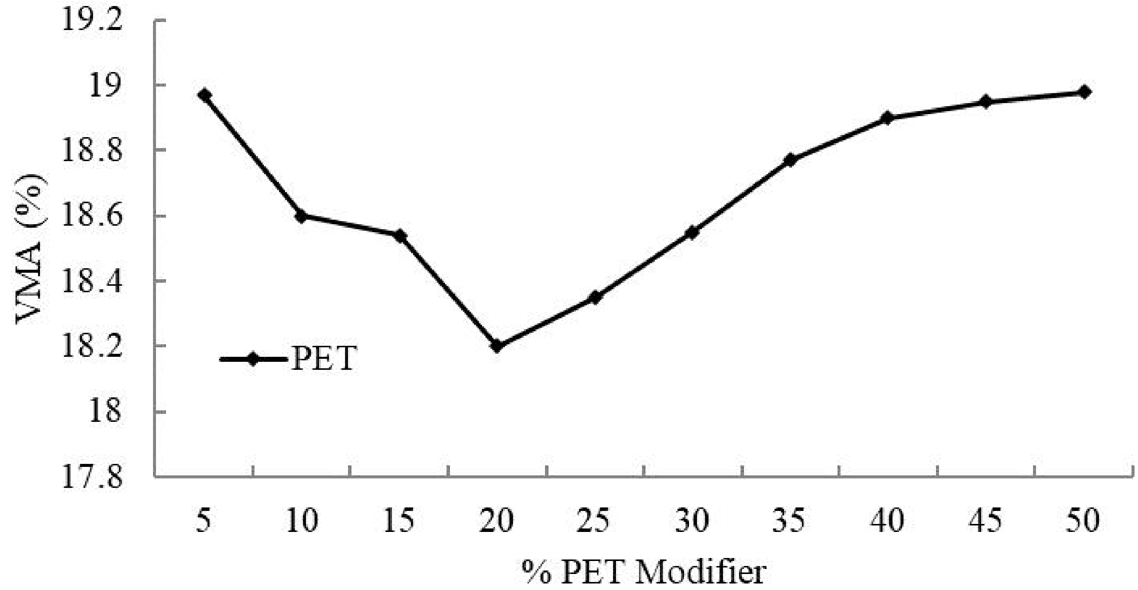

Figure 11: Influence of Modifier on Voids in Mineral Aggregate

3.2.6 Voids Filled with Bitumen (VFB)

The result of VFB variation with PET addition can be seen in Figure 12. The maximum VFB value obtained for PET-modified asphalt was 81.87% which are greater than the minimum value of 70% recommended by [36].

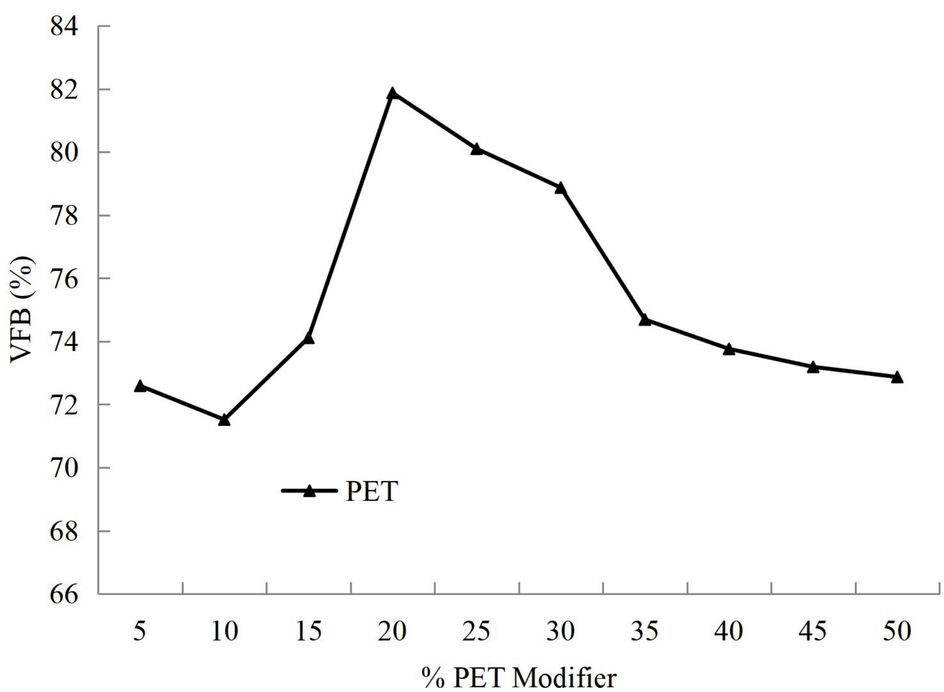

Figure 12: Influence of Modifier on Voids Filled with Bitumen

3.2.7 Rigidity Ratio (RR)

Figure 13 depicts the mix's resistance to permanent deformations as evaluated by the Rigidity Ratio (RR) or Marshall quotient. The highest RR of 1.48KN/m^2 for PET modified asphalt occurred at 10% MC. In service, RR values can be used to assess a material's resistance to shear stress, permanent deformation, and rutting. Abdalla [30].

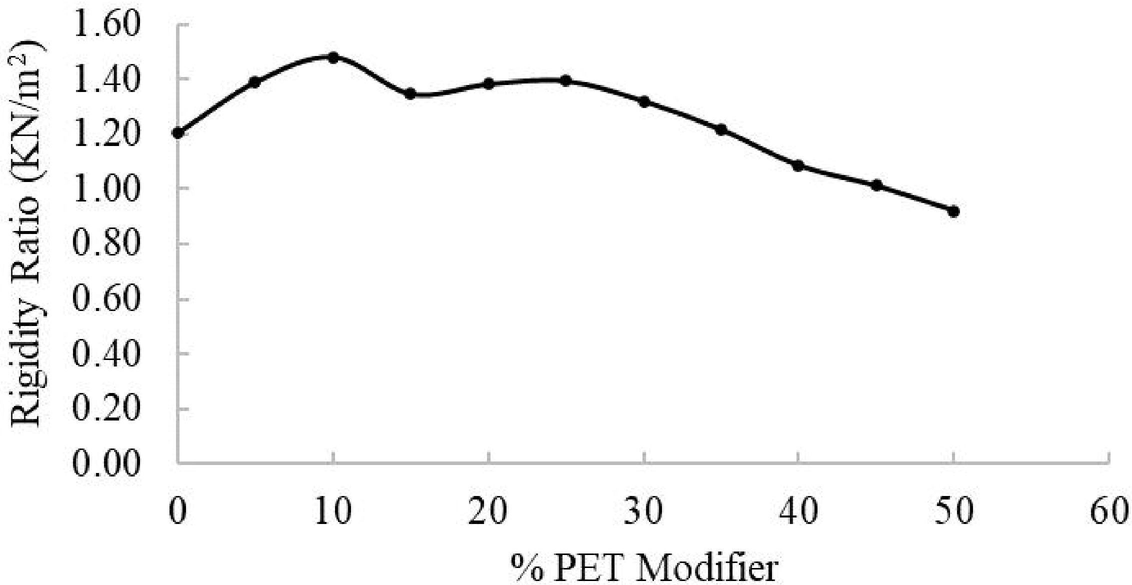

Figure 13: Influence of Binder Modification of Rigidity ratio

4.0 Conclusion

1. Waste management is a serious challenge in Nigeria, with Plastic bottles being a major non-biodegradable waste.
2. The modification of bituminous binder for asphalt purposes using waste plastic bottles (PET) was studied. The polymer modified bitumen was 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.
3. While PET increases the specific gravity of the modified binder. At 5% binder modification, PET-modified binder yielded acceptable ductility.
4. Viscosity increased with the PET modifier. The optimal level of PET modification of binder was 50%. PET-modified binder has a better safety in terms of fire due to higher flash/fire point temperatures.
5. From sustainability point of view, cheap asphalt has been produced from the study as the binder, filler and fine aggregate were all modified from various waste.

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