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Evaluation of Bitumen-PET content in Asphalt for Road Construction

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Abstract: *The incorporation of waste plastics such as polyethylene terephthalate (PET) into asphalt binders presents a sustainable approach to enhance pavement performance while addressing environmental concerns. This study aims to evaluate PET-modified bitumen content for road construction applications. PET in form of plastic bottles ground into powder form was added to bitumen in varying percentages (2%, 4%, 6%, 8% and 10%) by weight of the bitumen. Both the control and modified bitumen were then subjected to standard tests such as penetration, ductility, softening point, viscosity, flash and fire point and loss on heating to determine their properties. The optimum PET content was then evaluated as 8% by weight of the bitumen which corresponded to the maximum penetration index value and was used to prepare the asphalt concrete in which the bitumen+PET content was varied in percentages of 5%, 6%, 7% and 8% by weight of the asphalt. The Marshall stability and flow, percent air voids, bulk density, voids in mineral aggregate (VMA) and voids filled with bitumen (VFB) of the asphalt concrete samples were determined and used to evaluate the optimum bitumen+PET content as 5.9% by weight of asphalt which can be used to produce high performance asphalt pavement.*

Keywords— Polyethylene terephthalate, sustainable, penetration index, Marshall stability, flow.

1. INTRODUCTION

Road infrastructure plays a critical role in economic development and social connectivity necessitating the construction of durable pavements. Asphalt concrete, composed primarily of bitumen and aggregates, is the most commonly used material for flexible pavement construction due to its favorable mechanical properties and ease of maintenance. However, conventional bitumen exhibits limitations such as temperature susceptibility, oxidative aging and poor resistance to deformation under heavy traffic loads which often lead to premature pavement failures such as rutting, cracking and potholes. To address these challenges, PET polymer wastes have been proposed for modifying bitumen used in asphalt concrete production [1].

The increasing accumulation of plastic waste, particularly polyethylene terephthalate (PET) from discarded plastic bottles and packaging materials, poses significant environmental challenges worldwide due to its non-biodegradable nature [2]. Conventional asphalt pavements, primarily composed of bitumen, can be modified with various polymers to enhance their performance characteristics such as rutting resistance, flexibility and durability [3]. Recently, the use of waste plastics including PET as modifiers in bitumen has gained attention due to their availability, cost-effectiveness and potential to improve pavement properties [4].

PET being a thermoplastic polymer with excellent mechanical strength and chemical stability, has been shown to improve the viscoelastic properties of asphalt binders when incorporated appropriately [5]. Several studies have reported that PET-modified bitumen exhibits increased softening points, higher stiffness and better resistance to deformation [6]. However, the optimal PET content for maximizing performance without compromising workability remains to be fully established.

Determining the optimum PET content and optimum bitumen+PET content involves evaluating the physical and rheological behavior of modified bitumen and asphalt mixtures. Prior research indicates that PET contents typically range between 2% and 10% of the binder weight [7]. Excessive PET content can lead to increased viscosity and processing difficulties in the asphalt whereas insufficient PET content may cause the desired performance benefits not to be realized. This study aims to systematically evaluate the effects of varying PET contents on the properties of the modified bitumen and to identify the optimum PET and the optimum bitumen+PET contents for road construction applications.

2. METHODOLOGY

2.1 Materials

- Bitumen: A 60/70 penetration grade bitumen (as shown in Figure 1) was used and it was obtained from Omuo-Ekiti in Ekiti state.

Fig. 1. Bitumen

- Polyethylene Terephthalate (PET): Waste PET bottles collected from FUTA campus (as shown in Figure 2) were cleaned, dried, shredded into small pieces and then ground into powder form (Figure 3)

Fig. 2. The PET waste bottles

Fig. 3. PET waste after conversion to powder

- Fine and coarse aggregates: The fine aggregate used was river sand (shown in Figure 4; with size of particles less than 4.75mm) while the coarse aggregate was crushed granite (shown in Figure 5; with particles sizes greater than 4.75mm). Both aggregates were obtained from a sales point in Omu-Aran, Kwara state.

Fig. 4. Fine aggregate (sand)

Fig. 5. Coarse aggregate (granite)

- Filler: The filler material used was quarry dust (as shown in Figure 6) also obtained from a sales point in Omu-Aran, Kwara state.

Fig. 6. Filler (quarry dust)

2.2 Methods

- The physical properties of the materials namely specific gravity and particle size distribution were determined.
- The chemical properties (elemental and oxide composition) of the PET powder were obtained through X-ray fluorescence (XRF) test
- The modified bitumen was prepared by adding the PET as replacement in varying percentages namely 2%, 4%, 6%, 8% and 10% by weight of bitumen. The process involved heating the bitumen to 180^{o}C and gradually adding the PET powder while stirring at 1000 revs per minute for 2 hours to ensure uniform dispersion.
- The control and PET-modified bitumen were subjected to laboratory tests namely penetration, ductility, softening point, viscosity, flash and fire point and loss on heating tests.
- The optimum PET content was evaluated by applying the Penetration Index (PI) which was calculated by using two bitumen properties namely penetration and softening point.
- The Optimum Bitumen+PET content was evaluated from the stability, bulk specific gravity and 4% air voids of the asphalt concrete samples.

3. ANALYSIS AND DISCUSSION OF RESULTS

3.1 Determination of the Physical Properties of the Materials

The physical properties of the Coarse Aggregate (Granite), Fine Aggregate (Sand), Filler (Quarry dust) and polyethylene terephthalate (PET) such as specific gravity and particle size distribution were obtained through the following steps:

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3.1.1 Specific Gravity test

The specific gravity of a material is defined as the ratio of the mass of a given volume of material to the mass of an equal volume of water. The specific gravity of each material was measured using a pycnometer according to a specified standard range from 2.5 to 3.0 [8].The specific gravities are as shown in Table 1.

Table 1: The materials and their corresponding Specific Gravities

Materials	Specific Gravity
Coarse Aggregate (Granite)	2.79
Fine Aggregate (Sand)	2.64
Filler (Quarry dust)	2.14
PET	1.94

Based on Table 1, it can be observed that the granite and sand recorded specific gravities of 2.79 and 2.64 respectively which are within the standard range of 2.5 to 3.0, indicating their adequacy for use in asphalt mixtures. The quarry dust and PET with lower specific gravities of 2.14 and 1.94 respectively are lightweight making them suitable for applications where reduced weight is desired.

3.1.2 Particle Size Analysis test

Particle size analysis or sieve analysis was carried out on the granular materials so as to determine their particle size distribution (PSD) [9]. Figure 7 shows the PSD curves for the granite, sand, quarry dust and PET. Some key parameters are required to characterize such materials namely:

D_{10}, D_{30} and D_{60} – the particle sizes where 10%, 30% and 60% of the particles are smaller respectively

C_u – Coefficient of Uniformity

$$\text{where } C_u = \frac{D_{60}}{D_{10}} \quad (1)$$

C_c – Coefficient of curvature

$$\text{where } C_c = \frac{(D_{30})^2}{D_{10} * D_{60}} \quad (2)$$

So, for well graded gravel: $C_u > 4$ and $1 < C_c < 3$
and for well graded sand: $C_u > 6$ and $1 < C_c < 3$ [10]

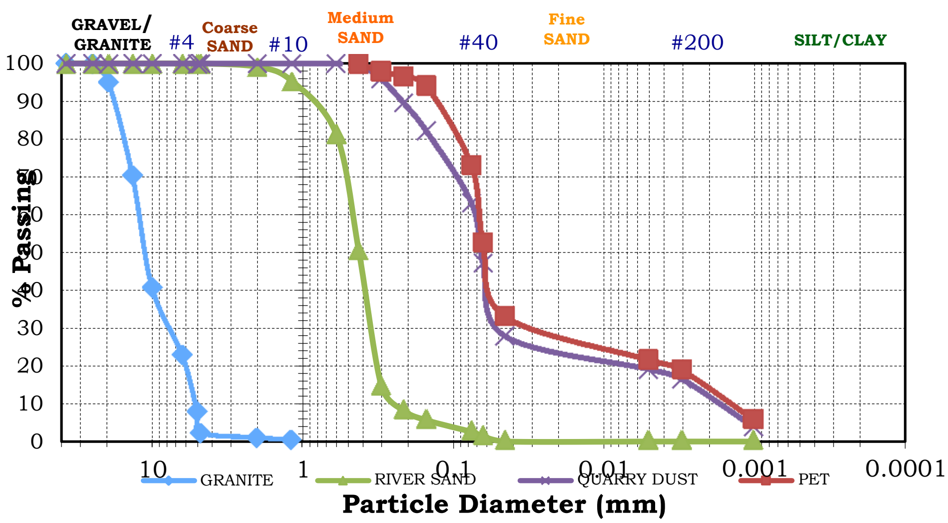

Fig. 7. Particle size analysis graphs for the granite, sand, quarry dust and PET

On calculating the C_u and C_c for the materials, the parameters in Table 2 and the corresponding grading were obtained.

Table 2: Calculated C_u and C_c parameters for the materials and the corresponding grading

Parameter	Granite	Sand	Quarry Dust	PET
Coefficient of Uniformity (C_u)	2.5	2.35	8.75	44
Coefficient of curvature (C_c)	0.9	1.16	5.21	11.68
Grading	Poorly graded	Poorly graded	Poorly graded	Poorly graded

Even though these materials are poorly graded individually, mixing them helps to fill the void spaces thereby improving the overall grading of the mix.

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3.2 Determination of Chemical Properties

The chemical properties of the Polyethylene terephthalate (PET) were obtained through X-ray fluorescence (XRF) test. This test was carried out to determine the elemental and oxide composition of the PET [11]. It involves illuminating the PET sample with X-rays, which causes the sample to emit its own characteristic X-rays. By analyzing the intensity and wavelengths of these emitted X-rays, the elements and oxides present in the sample and their concentrations can be identified.

3.2.1 Elemental Composition of the PET

Table 3 shows the elements present in the PET as well as their corresponding concentrations.

Table 3: Elemental Composition and Concentration

Element	PET (%0	Element	PET (%)
O	46.467	Fe	0.281
Al	1.380	Co	0.002
Si	0.627	Ni	0.000
P	0.000	Cu	0.019
S	22.032	Zn	0.003
Cl	0.569	Zr	0.061
K	0.008	Nb	0.006
Ca	28.408	Sn	0.044
Ti	0.039	Ba	0.000
V	0.000	Ta	0.014
Cr	0.007	W	0.007
Mn	0.026		

Based on the results in Table 3, it can be observed that the PET powder contains considerable amount of oxygen (46.467%). Oxygen significantly affects asphalt concrete, primarily through oxidative aging. This process, influenced by oxygen concentration, temperature and moisture, leads to changes in asphalt's properties, including increased stiffness, brittleness and reduced durability. Oxygen also plays a role in the combustion of asphalt, affecting the pyrolysis and combustion stages [12].

The sulphur component in the PET is also considerable. This component can have both positive and negative effects on asphalt concrete. Generally, it can enhance certain properties like Marshall Stability, stiffness and resistance to rutting, especially at higher temperatures. However, it can also negatively impact the environment and health due to the potential release of sulfur dioxide during production and use [13] [14].

The calcium component in the PET is also high. This reacts with carbonates to form Calcium Carbonate which can improve various properties like moisture resistance, stiffness and rutting resistance, although optimal dosage is crucial to avoid negative impacts on properties like fracture resistance. The calcium component also reacts with chlorides to form Calcium chloride, a different calcium compound, which is used in recycled asphalt to reduce voids and improve compaction leading to increased maximum dry density (MDD) and enhanced strength properties like unconfined compressive strength (UCS) and California bearing ratio (CBR). When used in the reconstruction of asphalt roads, it can help control the drying rate during compaction and curing, leading to increased structural stability [15] [16].

3.2.2 Oxide Composition of the PET

Table 4 shows the oxides present in the PET as well as their corresponding concentrations.

Table 4: Oxide Composition and Concentration

Oxide	PET [%]	Oxide	PET [%]
SiO_2	1.342	CaO	39.748
Cr_2O_3	0.01	K_2O	0.01
MnO	0.034	BaO	0.000
Fe_2O_3	0.402	Al_2O_3	2.608
Co_3O_4	0.002	Ta_2O_5	0.017
CuO	0.024	TiO_2	0.065
Nb_2O_3	0.007	ZnO	0.004
WO_3	0.008	Cl	0.569
P_2O_5	0.000	ZrO_2	0.082
SO_3	55.012	SnO_2	0.056

Based on Table 4, it can be observed that the PET contains high lime (CaO) content (39.748%). This concentration especially in the hydrated form can increase the moisture resistance, stiffness and durability of the asphalt concrete. It can also improve the adhesion between the asphalt binder and aggregates thereby producing a stronger and more resilient pavement [17].

The Trioxosulphate in the PET having the highest concentration (55.012%) can improve several key properties of asphalt concrete. It can increase Marshall stability, stiffness and ductility at low temperatures while also enhancing resistance to water infiltration [18].

3.3 Evaluation of the Optimum PET Content

Thereafter, the optimum PET content for modifying the bitumen was evaluated. This involved subjecting the control bitumen and the modified bitumen to the following laboratory tests to ascertain their mechanical properties:

3.3.1 Penetration Test

This test measures the hardness or softness of bitumen by measuring the depth in tenths of a millimeter to which a standard loaded needle will penetrate vertically in 5 seconds. The penetrometer consists of a needle assembly with a total weight of 100g and a device for releasing and locking in any position. The test was carried out at a specified temperature of 25° C [19]. In hot climates, a lower penetration grade is preferred. Table 5 shows the penetration values obtained for the bitumen with varying PET contents.

Table 5: Penetration values for Bitumen with varying PET contents

PET Content (%)	Penetration @ 25°C (mm)	Specification	Test Method
0	72	60-75	ASTM D5
2	69		
4	66		
6	63		
8	61		
10	54		

3.3.2 Ductility Test

This test is a standard method used to evaluate the flexibility and elongation properties of bitumen. It measures the distance in centimeters to which a standard briquette of bitumen can be stretched before it breaks. The test provides valuable information about the ability of bitumen to withstand deformation under varying temperature conditions, as well as its suitability for different applications such as road construction [20]. Table 6 shows the ductility values obtained for the bitumen with varying PET contents.

Table 6: Ductility values for Bitumen with varying PET contents

PET Content (%)	Ductility @ 25°C (cm)	Specification	Test Method
0	115	100 Min.	ASTM D113/D113M
2	112		
4	108		
6	105		
8	105		
10	103		

3.3.3 Softening Point Test

This test measures the temperature at which the asphalt binder softens. Bitumen does not suddenly change from solid to liquid state, but as the temperature increases it gradually becomes softer until it flows readily. All semi-solid state bitumen grades need sufficient fluidity before they are used in pavement construction. The softening point is the temperature at which the substance attains a particular degree of softening under specified conditions of test for bitumen; it is generally determined by the Ring and Ball test [21].Table 7 shows the softening point values obtained for the bitumen with varying PET contents.

Table 7: Softening point values for Bitumen with varying PET contents

PET Content (%)	Softening Point (°C)	Specification	Test Method
0	53	52-60	ASTM D36
2	53		
4	54		
6	56		
8	58		
10	58		

3.3.4 Viscosity Test

Viscosity is a measure of the resistance to flow of a liquid. The higher the viscosity of liquid bitumen, the more nearly it approaches a semi-solid state in consistency. Bitumen binders of low viscosity, simply lubricate the aggregate particles instead of providing a uniform thin film for binding action, similarly, high viscosity does not allow full compaction and the resulting mix exhibits heterogeneous character and thus low stability values. The viscosity of bitumen was measured with a viscometer [22]. Table 8 shows the viscosity values obtained for the bitumen with varying PET contents.

Table 8: Viscosity values for Bitumen with varying PET contents

PET Content (%)	Viscosity @ 120°C (MPa.s)	Specification	Test Method
0	2743	2400 Minimum	ASTM D2171
2	2648		
4	2625		
6	2597		
8	2546		
10	2512		

3.3.5 Flash and Fire point test

The flash point of bitumen is the temperature at which its vapors ignite momentarily when exposed to a flame while the fire point is the temperature at which the bitumen ignites and continues to burn for at least five seconds [23]. These points are important for safety considerations during bitumen handling and use, indicating the temperature at which precautions are needed to prevent fire hazards. Table 9 shows the flash and fire point values obtained for the bitumen with varying PET contents.

Table 9: Flash and fire point values for Bitumen with varying PET contents

PET Content (%)	Flash and Fire point (°C)	Specification	Test Method
0	284	250 Min	ASTM D92
2	278		
4	270		
6	269		
8	260		
10	255		

3.3.6 Loss on heating test

The loss on heating test for bitumen determines the amount of volatile components that evaporate when the material is heated [24]. This test is crucial for assessing bitumen's suitability for hot climates and its stability over time, as excessive volatile loss can negatively impact pavement performance. Table 10 shows the loss on heating values obtained for the bitumen with varying PET contents.

Table 10: Loss on heating values for bitumen with varying PET contents

PET Content (%)	Loss on Heating (%)	Specification	Test Method
0	0.14	0.2 Max	ASTM D6
2	0.14		
4	0.16		
6	0.16		
8	0.19		
10	0.2		

3.3.7 Penetration Index (PI)

The penetration index (PI) of bitumen is a dimensionless number that indicates its temperature susceptibility, which reflects how much its consistency changes with temperature variations. It's a calculated value derived from the bitumen's penetration and softening point, and a lower PI indicates greater temperature sensitivity. Bitumen with a low PI may become too soft in hot weather and too brittle in cold weather, leading to pavement distress. The formula used for calculating PI is as shown in Equation 1 [25].

$$\frac{((20\times SP)+(500\times \log P)-1952)}{(SP-(50\times \log P)+120)} \quad (3)$$

G_b - specific gravity of bitumen
Air voids percent,

where
SP - softening point (in °C) and
P - penetration value (in 0.1 mm) at 25°C

Table 11 shows the penetration indices obtained for the bitumen with varying PET contents. The PET content corresponding to the highest PI, 8%, was regarded as the optimum for the bitumen used in this study.

Table 11: Penetration indices for bitumen with varying PET contents

PET Content (%)	Penetration Index
0	0.46
2	0.34
4	0.45
6	0.79
8	1.13
10	0.81

3.4 Evaluation of the Optimum Bitumen+PET Content

The next step was to evaluate the optimum bitumen + PET content for producing the asphalt samples. The bitumen content in Asphalt concrete should be between 5% and 8% [26]. Hence, asphalt concrete test samples were produced with bitumen + PET content varying from 5% to 8% and subjected to laboratory tests to determine the corresponding parameters namely: Bulk specific gravity of the samples (G_M), Specific gravity of the compacted samples (G_T), bulk density value of the specimens (G_B), Air voids content (V_v), percent volume of bitumen (V_b), Voids in mineral aggregate (VMA) and Voids filled with bitumen (VFB). The stability and flow of the asphalt concrete specimens were also obtained using the Marshall Stability apparatus. The corresponding formulae for calculating these parameters are as given in equations 4 to 9 [10].

Bulk specific gravity, $G_M = \frac{W_M}{W_M - W_W}$ (4)

where,
W_M - weight of mix in air
W_W - weight of mix in water
Specific gravity of compacted samples:

$$G_T = \frac{W_1+W_2+W_3+W_b}{\left(\frac{W_1}{G_1}+\frac{W_2}{G_2}+\frac{W_3}{G_3}+\frac{W_b}{G_b}\right)} \quad (5)$$

where,
W_1 = weight of coarse aggregates (CA) in the total mix
W_2 - weight of fine aggregates (FA) in the total mix
W_3 - weight of filler (FL) in the total mix
W_b - weight of bitumen in the total mix
G_1 - specific gravity of coarse aggregate
G_2 - specific gravity of fine aggregate
G_3 - specific gravity of filler material

$$V_v = [(G_T - G_M)/G_T] \times 100 \quad (6)$$

Percent volume of bitumen:

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$$V_b = [\frac{W_b}{G_B} / (\frac{W_1 + W_2 + W_3 + W_b}{G_M})] \times 100 \quad (7)$$

$$\text{Voids in mineral aggregate, } VMA = V_v + V_b \quad (8)$$

$$\text{Voids filled with bitumen, } VFB = (\frac{V_b}{VMA}) \times 100 \quad (9)$$

The calculated values for these parameters are as shown in Table 12 along with the stability and flow values at 5%, 6%, 7% and 8%.

Table 12: Calculated values for asphalt concrete parameters

SAMPLE NO	(B + P) C (%)	WEIGHT IN AIR	WEIGHT IN H_2O	G_T	G_M
1	5	1222.7	675	2.390	2.232
2	6	1244.7	698.6	2.359	2.279
3	7	1203.2	655	2.329	2.195
4	8	1265.4	680.4	2.299	2.163

Table 12: Calculated values for asphalt concrete parameters (cont'd)

SAMPLE NO	VOLUME OF VOID (V_V)	%VOLUME OF BITUMEN (V_b)	VMA (%)	VFB (%)	STABILITY (KN)	FLOW (mm)
1	6.611	11.388	17.999	63.270	7.411	3.9
2	3.391	13.953	17.344	80.449	10.855	4.5
3	5.754	15.679	21.433	73.154	8.943	4.9
4	5.916	17.657	23.573	74.903	6.595	5.3

where (B + P)C - bitumen + PET Content

The weights and the specific gravities of the materials used in producing the asphalt concrete are as shown in Table 13.

Table 13: Weights and apparent specific gravities of asphalt concrete materials

(B + P) C (%)	WEIGHT OF CA (W_1)	WEIGHT OF FA (W_2)	WEIGHT OF FILLER (W_3)	WEIGHT OF BITUMEN (W_b)	SPECIFIC GRAVITY OF MATERIALS	
5	600	300	240	60	BITUMEN (G_b)	0.98
6	600	300	228	72	FILLER (G_3)	2.14
7	600	300	216	84	FA (G_2)	2.64
8	600	300	204	96	CA (G_1)	2.79

Thereafter, the optimum bitumen+PET content was obtained as the average of the sum of bitumen+PET contents corresponding to maximum stability (6.2%), maximum bulk specific gravity (5.8%) and air voids at 4% (5.6%) of the asphalt samples. In this case, a value of 5.86% was obtained which to one decimal place gives 5.9%. Figures 8 to 13 show the graphs of stability, flow, bulk specific gravity, % Air voids, % voids filled with bitumen and % voids in mineral aggregate against % Bitumen + PET content. In Figure 8, the maximum stability of the asphalt is 10.9kN which is greater than the recommended minimum (3.34kN) and corresponds to a bitumen+PET content of 6.2% [27]. All the values of stability used to plot the graph against bitumen content are also higher than the minimum specified. This indicates that the asphalt concrete can support considerable loading before failure.

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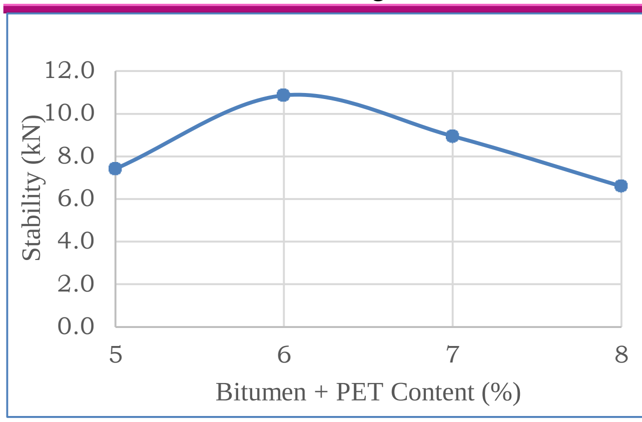

Fig. 8. Graph of Stability against Bitumen + PET content

Figure 9 shows that the flows of the modified asphalt increase continuously for all the bitumen+PET contents and the highest value was recorded at 8% bitumen content. However, only the flow value of 3.9mm at 5% bitumen+PET content falls within the specified standard range of 2.0mm to 4.25mm [27]. Consequently, the asphalt has more flow values higher than the range indicating greater flexibility and resistance to cracking but a higher susceptibility to rutting (which is a depression on a pavement surface due to repeated loading at a spot).

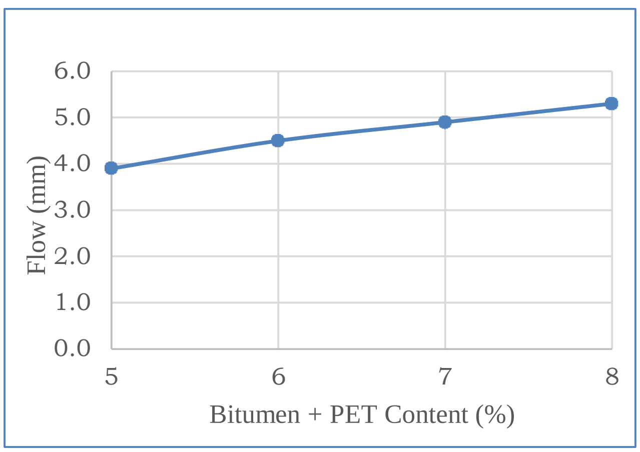

Fig. 9. Graph of flow against Bitumen + PET content

Figure 10 shows that the maximum bulk specific gravity of the asphalt is 2.28 at 5.8% bitumen+PET content. The specified standard range of acceptable bulk specific gravity of asphalt is 2.2 to 2.5 [26]. Two of the values plotted fall within this range at 5% and 6% bitumen+PET contents. The bulk specific gravity is a crucial property for asphalt mix design because it is used to calculate essential volumetric properties such as voids in mineral aggregate (VMA), voids filled with bitumen (VFB) and percentage air voids (V_v).

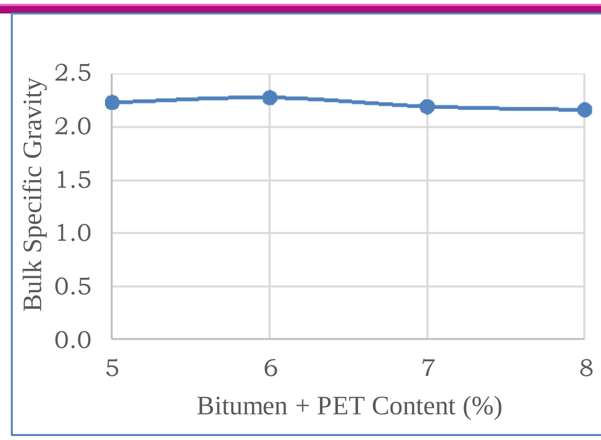

Fig. 10. Graph of Bulk specific gravity against Bitumen+PET content

The percent air voids indicates the amount of airspace between aggregate particles and binder that allows for some additional compaction from traffic and space for binder to flow during this densification process. Too high an air void content reduces pavement durability and strength leading to water intrusion, frost damage (in cold climates) and cracking. Too low a void content can result in bleeding and rutting. Figure 11 indicates that the bitumen+PET content corresponding to 4% air void is 5.6%. The specified standard range of percent air voids is 3% to 5% [26] and only one of the plotted values (3.391%) falls within this range at 6% bitumen+PET content.

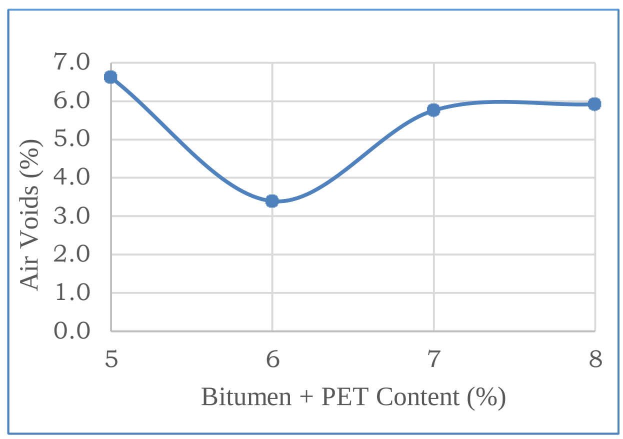

Fig. 11. Graph of Air voids (%) against Bitumen+PET content

The voids filled with bitumen (VFB) is a measure of how much space between aggregate particles in an asphalt mix is occupied by bitumen. A high VFB indicates a good asphalt film thickness leading to a more durable pavement while a low VFB can result in thin films, reduced durability and premature pavement failure. Figure 12 shows that only two of the plotted VFB values (73.154% and 74.903% with corresponding bitumen+PET contents of 7% and 8%

respectively) fall within the specified standard range of 65% to 75% [26].

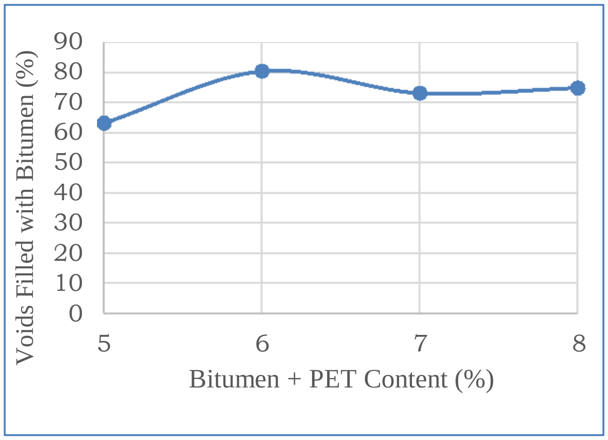

Fig. 12. Graph of Voids filled with bitumen (%) against Bitumen+PET content

The voids in mineral aggregate (VMA) indicates the available space within a compacted asphalt mix that can be filled by bitumen binder and air voids. An inadequate VMA results in thin asphalt films leading to a dry, low durability mix susceptible to rutting and cracking. Figure 13 shows that all the VMA values plotted are above the specified standard minimum value of 15% [26] with the lowest value being 17% with corresponding bitumen+PET content of 5.8%.

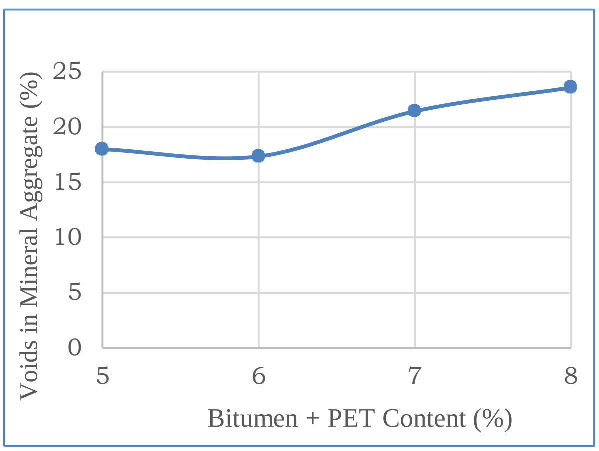

Fig. 13. Graph of Voids in mineral aggregate (%) against Bitumen+PET content

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

Based on the chemical properties of the PET powder used in this study which were determined through X-ray fluorescence (XRF) test, it was observed that the oxygen, sulphur and calcium components were highest with concentrations of 46.467%, 22.032% and 28.408% respectively. Oxygen affects asphalt concrete primarily through oxidative aging which leads to increased stiffness, brittleness and reduced stability.

The presence of sulphur in the PET at high concentration has both beneficial and unfavorable impact on the asphalt concrete. It can enhance the stability, stiffness and resistance to rutting at high temperatures. It can also be harmful to the environment and human health through potential release of sulphur dioxide during production process and use. The calcium component can react with carbonates to form calcium carbonate which is capable of improving asphalt properties such as moisture resistance, stiifness and rutting resistance. It can also react with chlorides to form calcium chloride capable of reducing void, improving compaction and increasing structural stability.

In terms of the oxides in the PET, the lime (CaO) and the trioxosulphate (SO_3) components are highest with concentrations of 39.748% and 55.012% respectively. CaO in hydrated form can increase the moisture resistance, stiffness and adhesion (of the binder and aggregates) of the asphalt concrete. SO_3 can increase the ductility and resistance to water infiltration even though the presence of sulphur can cause ageing and hardening of the bitumen over time.

The laboratory tests to evaluate the mechanical properties of the bitumen revealed the following: The penetration test showed that any PET content in the bitumen that exceeds 8% by weight of bitumen will yield penetrations that would fall outside the standard specification of 60 to 75 penetration grade [19] and the bitumen would become too hard and brittle. In terms of the ductility test, all the values of ductility obtained were above the specified standard minimum of 100cm [20] indicating that the bitumen does not break at any PET content applied while it is drawn. The softening point test showed that all the softening point values were within the 52°C to 60°C standard specified [21] indicating that the bitumen softens at moderately high temperatures.

The viscosity test showed that all the resistance to flow values were well above the specified standard minimum of 2400 MPa.s [22] indicating good resistance to flow. The flash and fire point values obtained were also above the specified standard minimum of 250°C [23] meaning that the bitumen has safe operating temperature for heating, mixing and application. The loss on heating test showed that the amounts of volatile contents that evaporate when the bitumen is heated fall below the specified standard maximum of 0.2% [24] indicating that the bitumen is moderately volatile. The PET content (8%) corresponding to the highest penetration index (PI) value (1.13) was identified as the optimum PET content. This PI indicates low temperature susceptible bitumen. It also confirms the grading of the bitumen as 60/70 penetration grade.

The Marshall stability test on the modified asphalt concrete showed that the maximum stability obtained was 10.9kN (with corresponding bitumen+PET content of 6.2%)

which is greater than the standard minimum specification of 3.34kN [27]. This indicates that the asphalt has greatly increased in strength on the addition of the PET powder and can support considerable load before failure. The corresponding flow values increased continuously for all the bitumen+PET contents and the highest value was obtained at 8% content. However, only the flow value of 3.9mm at 5% bitumen+PET content falls within the specified standard range of 2.0mm to 4.25mm [27] with other values being higher than the range. This indicates greater flexibility and resistance to cracking but a higher susceptibility to rutting.

The specified standard range of percent air voids and voids filled with bitumen (VFB) are 3% to 5% and 65% to 75% respectively [26]. In the case of the percent air voids, only one of the plotted values (3.391%) falls within the specified range at 6% bitumen+PET content. This situation may lead to increased porosity and weakening of the aggregate interlock. With regards to the VFB, only two of the plotted values (73.154% and 74.903% with corresponding bitumen+PET contents of 7% and 8% respectively) fall within the specified range. Values of the VFB within the specified range usually indicate durable asphalt. An adequate void in mineral aggregate (VMA) value is a minimum of 15% [26]. All the VMA values plotted were above this minimum value indicating that much of the available space within the asphalt concrete is filled with bitumen and air.

The optimum bitumen+PET content was thereafter calculated as 5.9% based on the average of the sum of bitumen+PET contents corresponding to the maximum stability, maximum bulk specific gravity and 4% air void of the asphalt concrete samples. This optimum value can be used to produce high performance asphalt pavement.

This research supports the sustainable utilization of recycled PET in road pavement infrastructure thereby contributing to environmentally friendly and durable road pavements as well as supporting the advancement of Sustainable Development Goals (SDGs) 9 (Industry, Innovation, and Infrastructure) and 11 (Sustainable Cities and Communities).

4.2 Recommendations

Field performance studies should be carried out to validate the laboratory results obtained in this study. Long-term aging and durability assessments of the asphalt concrete produced using PET modification should be conducted. Lastly, the environmental benefits and cost implications of PET-modified asphalt should be investigated and quantified

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6. CONFLICT OF INTEREST

The authors confirm that there is no conflict of interest related to this manuscript.

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