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Utilization of Bitumen Modified with Pet Bottles as an Alternative Binder for the Production of Paving Blocks

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Abstract

This study considers the utilization of bitumen modified with molten polyethylene terephthalate (PET) waste bottles as an alternative binder in paving blocks. PET waste was used at 2, 4, 6, 8, and 10% to modify bitumen in the production of paving blocks. Compressive strength test and skid resistance test were conducted on the paving block samples to evaluate their mechanical strength properties, while water absorption and the Cantabro abrasion tests were carried out to ascertain the durability of the paving block samples. The PET-modified bitumen paving blocks (PMBPB) have enhanced compressive strength and skid resistance compared to unmodified bitumen paving blocks. Also, a significant reduction in water absorption rate of up to 56% was achieved in PET-modified bitumen paving blocks (PMBPB) compared to the unmodified sample. The abrasion loss in the PMBCB samples was the least compared to that in normal cement paving blocks and unmodified bitumen paving blocks. The maximum compressive strength and least water absorption for the PET-modified bitumen concrete paving blocks were obtained at a 10% PET replacement level. It can be concluded that enhanced compressive strength and durability in cement paving blocks and unmodified bitumen paving blocks could be achieved with the use of PET modified bitumen in concrete paving block production, and this will also encourage PET waste recycling and contribute meaningfully to sustainability in concrete paving block production.

Keywords: PET-Modified Bitumen; Paving Blocks; Skid Resistance; Compressive Strength; Abrasion Loss.

1. Introduction

In recent years, there has been an increasing tendency to recycle waste generated by human activities through different effective solid waste management practices. Polyethylene terephthalate (PET) is a common plastic used as a raw material for making plastic bottles, containers for packaging food products, and other consumer goods [1]. PET is the chemical name for polyester; it's a clear, strong, and lightweight plastic with good engineering properties. [2]. Waste from PET bottles constitute a significant component of total solid waste generated in any populated environment [3]. This has been attributed to the fact that PET bottles are swiftly becoming the most preferred packaging material for drinks, foods, and beverages globally [4] and consequently pose a serious disposal problem [5].

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On the other hand, bitumen is one of the oldest identified construction materials, especially in road construction [6]. Other areas of bitumen application include roofing, pipe coating, environmental protection, electrical insulation, soundproofing, landslip containment, textiles, and medicine [7]. The properties of bitumen vary with its production and processing procedures. Likewise, the engineering properties of any modified bitumen mix largely depend on the type of materials used for the modification [8]. It has been acknowledged in the literature that the use of neat bitumen would not provide all the needed engineering characteristics for paving and industrial applications, which include resistance to climate and more demanding traffic loads, enough stiffness at high temperatures to resist rutting, and the ability to remain soft and elastic enough at low temperatures to resist thermal cracking [9, 10]. To meet some of these specific required properties, bitumen is usually modified with different additives [11]. Several studies have improved the properties of bitumen using different types of additives and modifiers, such as polymers, chemical modifiers, extenders, oxidants and antioxidants, hydrocarbons, and anti-stripping additives. Lewandowski [12] used polymer-modified asphalt binder in the production of asphalt pavement to achieve asphalt pavement with reduced load-associated fatigue and increased low-temperature thermal cracking resistance.

The review conducted by Porto et al. [13] reveals several benefits of polymer-modified bitumen, such as enhanced resistance to abrasion and fatigue, thermal susceptibility, and increased softening point. However, high susceptibility to cracking due to reduced elasticity at low temperatures and some compatibility problems, especially in plastomers, have limited their applications in concrete/asphalt pavement. Likewise, Bitumen modified with thermosetting polymers produced a polymer-modified bitumen with good adhesive ability, excellent resistance to deformation, excellent fatigue performance, and high stiffness modulus, however, they are not commonly used for pavement application due to rapid deterioration of their technological properties, higher thermal sensitivity, high prices and high quantity of thermosetting polymer (above 10%) that is required to meet standard mechanical properties [8].

PET waste is hugely generated in many parts of the world, the global demand for PET packaging consumption has continued to rise and this has contributed to the enormous waste PET generated globally. Data from the Smithers Market report shows that the global demand for PET packaging materials was 22.65 million tonnes in 2020 and will continue to grow at an annual average rate of 3.7% to 27.1 million tonnes in 2025 [14, 15]. The report also shows that PET bottles for water and other drinks constitute up to 45% of the global PET packaging consumption. This has generated concern for researchers as they search for viable ways to effectively utilize PET waste. Bitumen modified with PET has increasingly gained the attention of researchers due to its good engineering properties, including good mechanical strength properties, rigidity, and high performance against permanent deformation and fatigue cracking [16]. PET has also been observed to have high creep and heat distortion resistance [17]. In addition, PET possesses good oil and solvent resistance.

Atta et al. [18] prepared Imidazolium Ionic Liquid (IIL) used as a hardener for epoxy resin with polyethylene terephthalate (PET) waste and pentaethylenehexamine (PEHA). They were able to obtain epoxy resin with higher thermal stability and balanced strength, as well as flexible epoxy films with high resistance to corrosion in seawater fog environments. Since pavement blocks are subjected to different loading and environmental conditions, it is important to understand the mechanical and durability properties of any new form of paving block produced. A review of the literature has shown that there is still very limited knowledge of PET application on asphalts concrete and pavement block properties. Gopinath & Kumar [19] used modifiers to improve the rheological behaviour of bitumen, and they concluded that Polymer (PET)-modified bituminous binders offered better resistance against permanent deformations due to their higher phase angle and a higher softening point when compared to conventional binders. In the experimental study of Ogundipe [20], PET waste was used as a modifier for asphalt concrete, and he obtained a significantly reduced stability of 20.4% in PET modified asphalt concrete and improved permanent deformation resistance of the PET modified asphalt compared to unmodified asphalt concrete. This is a good pointer that PET-modified bitumen could be used in paving applications. It can be observed that there is no information available on the skid resistance properties and water absorption of PET modified paving blocks in literature. These properties are important for paving blocks with good mechanical and durability properties.

In order to solve the highlighted problems associated with polymer-modified bitumen, which make them unsuitable for pavement applications as well as make proper use of PET waste generated in the environment, this study has carried out laboratory investigations to assess the mechanical and durability properties of PMBPB samples produced. The information about its compressive strength was used to measure its load-bearing capacity, the skid resistance helps to understand the tyre breaking effect on the PMBPB surface. Likewise, their permeability to liquid in contact with the paving block surface is measured by their water absorption rate, and the rate of removal of particles from the PMBPB surface was determined through the abrasion test.

2. Materials and Methods

2.1. Materials

The following materials were used in this study.

2.1.1. Cement

Ordinary Portland cement (Dangote 3X brand, 42.5R grade) conforming to BS 12:1991 was used for preparing the concrete mix.

2.1.2. Aggregate

The aggregate type used was quarry dust. Grey fine rock particles retained on 150 µm aperture sieve size with maximum particle passing 4.75mm. The quarry dust used was in dry condition and was sourced locally at a granite quarry site in Omu-Aran, Kwara State. The physical properties of the quarry dust used are presented in Table 1 and Figure 1.

Table 1. Physical properties of Quarry dust

S/N	Physical Properties	Quarry dust
1	Specific gravity	2.70
2	Fineness modulus	2.85
3	Bulk Density (kg/m^3)	1780
4	Fine particles less than 0.0075 mm (%)	13

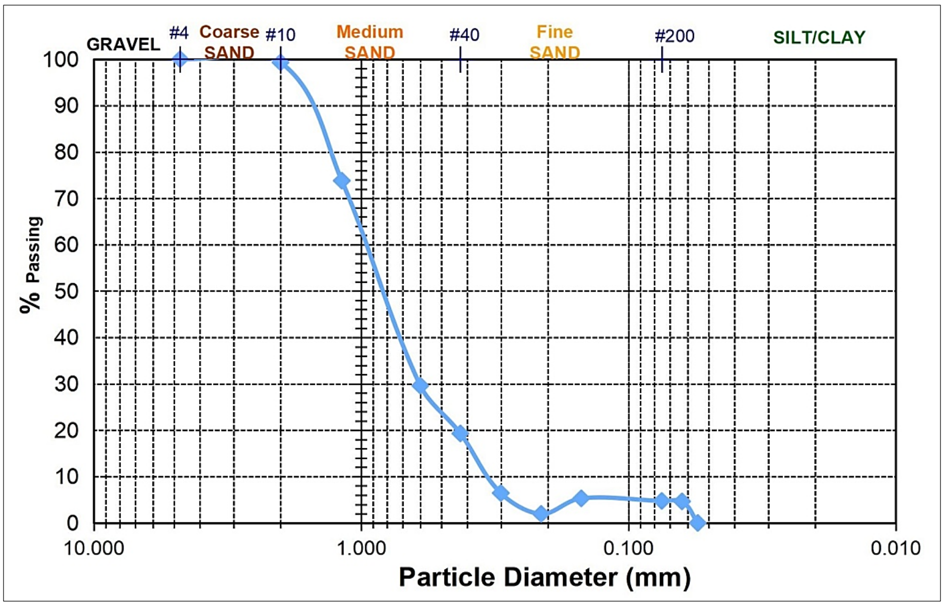


Figure 1. Particle Size Distribution of Quarry Dust

2.1.3. Bitumen

Bitumen of grade 60/70 was used for this research. It was sourced from a petroleum company. The properties of the bitumen are shown in Table 2.

Table 2. Bitumen properties

Parameters	Value	Specification	Standard
Penetration @ 25^{0}C	66	60-70	AASTHO D-5
Ductility @ 25^{0}C	121	100 Min	AASTHO D-113
Solubility	107	99.5 Min	AASTHO D-4
Viscosity (seconds)	2753	2400 Min	ASTM D-2171
Flash Point (C)	287	≥ 250	ASTM D-70
Softening Point	56	55-65	ASTM D36
Specific gravity @ 25^{0}C	1.04	1.01-1.06	ASTM D-92

2.1.4. PET Bottles

The polymeric material used for modification was waste polyethylene terephthalate (PET) bottles collected within Landmark University campus (see Figure 2). The labels on the bottles were removed and the bottles were then washed and oven-dried drying at a temperature ranging from 20 ℃ to 25 ℃ to remove water in the collected material and to enable easy melting. The PET bottles were melted at a temperature of 270 ℃.

Figure 2. Samples of collected waste PET bottles

2.2. Mix Proportions

The mix proportion used for laboratory work is shown in Table 3 and the mixing process is shown in Figure 3. Using the same content of cement for the bitumen, the bitumen was used to totally replace the cement. Thereafter, the bitumen content was then modified with molten waste PET bottles at 2, 4, 6, 8, and 10% by weight to determine their effect on the strength, skid resistance, abrasion and water absorption of the paving blocks.

Table 3. Specimen mix proportion

Mix ID	% PET replacement	Bitumen (g)	PET (g)	Cement(g)	Quarry dust (g)
C100	0	0	0	342	2048
B100	0	342	0	0	2048
PMB-2	2%	335.2	6.8	0	2048
PMB-4	4%	328.3	13.7	0	2048
PMB-6	6%	321.5	20.5	0	2048
PMB-8	8%	314.6	27.4	0	2048
PMB-10	10%	307.8	34.2	0	2048

Remark: Mix ID: **C100**, is 100% Cement base concrete paving block; **B100**, is unmodified bitumen paving blocks; and **PMB-a**, PMB = PET modified bitumen paving blocks – while '**a**' is the percentage replacement of bitumen with PET.

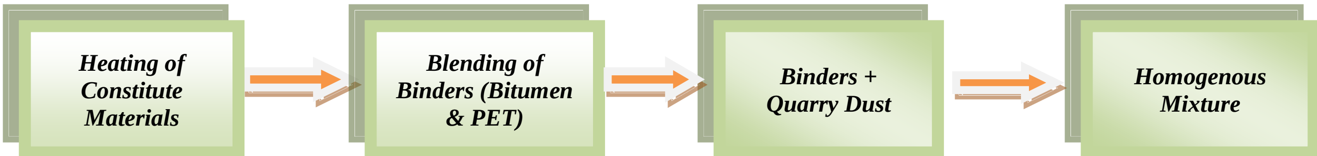


Figure 3. Stepwise procedure for the paving block production

2.3. Laboratory Test

2.3.1. Compressive Strength

The compressive strength of the samples was measured at 7, 14, and 28 days according to ASTM C39 [21] and ALCONPAT [22] guidelines, using the Universal Testing Machine. The Paving block sample was loaded on its entire side as shown in Figure 4 and the compressive strength value was taken as the quotient of the maximum test load (until rupture) over the cross-section of the paving block specimen.

Figure 4. Compressive Strength Measurement of Paving block

2.3.2. Water Absorption

Water absorption test was conducted to determine the amount of water absorbed under specified conditions in accordance with BS 1881-122 [23]. The paving block samples after 28 days were oven-dried at a temperature of 105^0C for 6 hours. The oven-dry weight of the paving block was measured and subsequently wholly immersed in water for 24hours. The weight after water immersion is also measured.

2.3.3. Skid Resistance

The skid resistance of the samples was measured using the Portable Skid Resistance Tester (British Pendulum tester) shown in Figure 5 in accordance with British Standard 812 [24]. The pendulum released from the horizontal position hit the surface and the needle position indicates the reading of the pointer to the nearest whole number [25]. This approach focuses on the pavement surface micro-texture which refers to the small-scale texture of the pavement aggregate component that controls contact between the tire rubber and the pavement surface [26]. Three (3) runs of British pendulum tester (BPT) were conducted over each of the samples produced and the mean value is recorded. Before running the BPT, A 24-hour curing period was taken into account and the surface was properly wet as per wet condition specifications.

Figure 5. Skid Resistance Measurement with British Pendulum Tester

2.3.4. Cantabro Loss

The Cantabro abrasion resistance test was carried out on the specimen using Los Angeles abrasion (LAA) testing machine in accordance with ASTM C1747 standards [27]. Durability is a vital requirement of any type of pavement surface. Hence, it is imperative that the loss of particles on bitumen pavement surface when subjected to abrasive load be minimum for structural reliability [28]. In this test, each sample of the paving block was placed in LAA machine. The initial weight of each specimen is measured (w_1) and recorded before placing it into the machine. The LAA machine was allowed to rotate at a speed of 30–33 revolutions per minute for 300 revolutions. After the revolution, the abraded sample (see Figure 6) was cleaned from any loose rubbles and weighed (w_2). Equation 1 is used to compute the abrasion loss.

$$\text{Cantabro Loss (\%)} = \frac{(W_1 - W_2)}{W_1} \times 100 \quad (1)$$

where,w_1 is initial weight of the sample in grams, and w_2 is Final weight of the sample in gram.

Figure 6. Abraded paving block samples

3. Results and Discussion

3.1. Compressive Strength

Figure 7 presents the compressive strength results of the cement and PET-modified bitumen paving blocks. As expected, the compressive strength increases with curing days in the range of 8.18 to 17 Nmm^{-2}, 11.67 to 20.49 Nmm$^{-2,}$ and 11.78 to 23.64 Nmm^{-2} for 7, 14, and 28-days curing period respectively. Considering the different mix of paving blocks used in this study, those with cement binder had the highest compressive strength when compared to the other mixture. This indicates that bitumen and PET-modified bitumen binder do not significantly improve the compressive strength. The reduction in compressive strength for unmodified and PET-modified paving blocks compared to cement pavement blocks is attributed to the development of a weaker interfacial transition zone (ITZ) formed at the interface of bitumen binder and aggregates. However, PET-modified paving blocks show increased compressive strength compared to unmodified Bitumen paving block samples. The highest compressive strength obtained for PET-modified paving blocks was 16 Nmm^{-2} at 10% PET replacement. Awodiji et al. [29] observed reduced strength for sand-PET paving blocks. Likewise, Agyemam et al. [30] also considered the use of PET as an alternative binder for paving blocks and the result obtained indicates compressive strength values below 10 Nmm^{-2}. In comparison to previous studies, the strength values obtained using PET modified paving blocks have demonstrated an improvement in the performance of PET as an alternative construction material. According to Udawattha et al. [31], the minimum strength requirement for 'class 4' for use of pedestrian walkways is 15 N/mm^2, therefore, the pavement block produced with 10% PET-modified bitumen with curing period of 28-days is suited for the construction of pedestrian pavement.

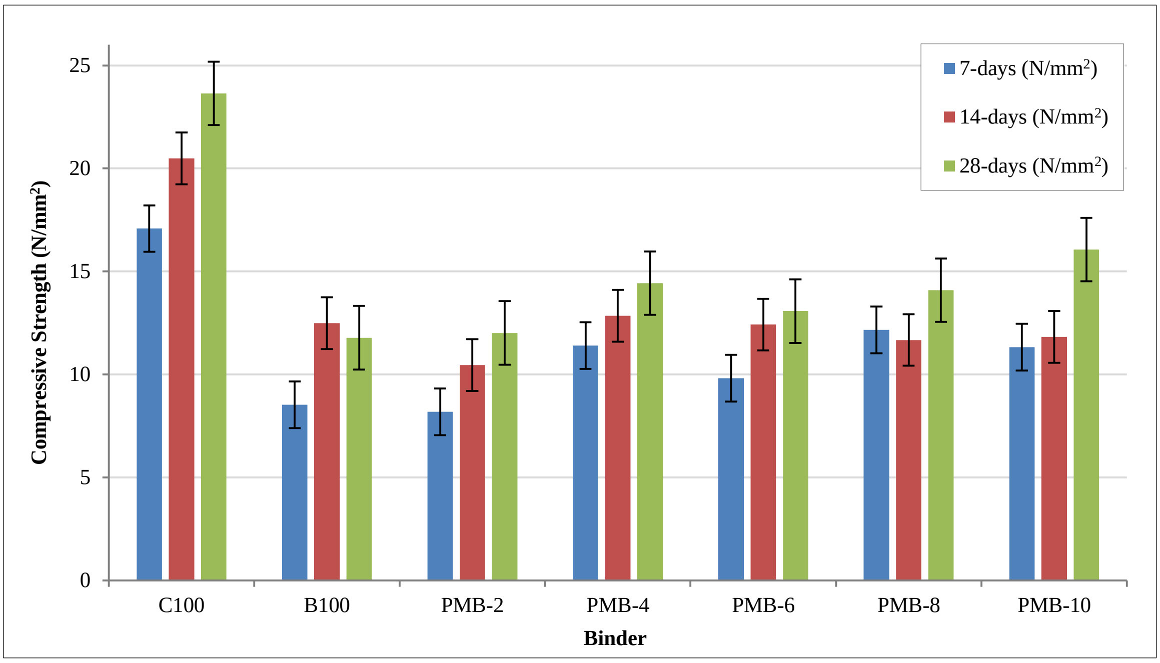


Figure 7. Compressive Strength value for pavement blocks

A one-way analysis of variances (ANOVA) was performed to determine if the effect of curing age and percentage of PET bottles on the compressive strength is significant or not. The results of the ANOVA analysis are summarized in Table 4. As seen from Table 4, the statistical p-value computed is 1.0805E-6; hence, it can be concluded that the influence of curing age and percentage of PET bottles on the compressive strength is significant.

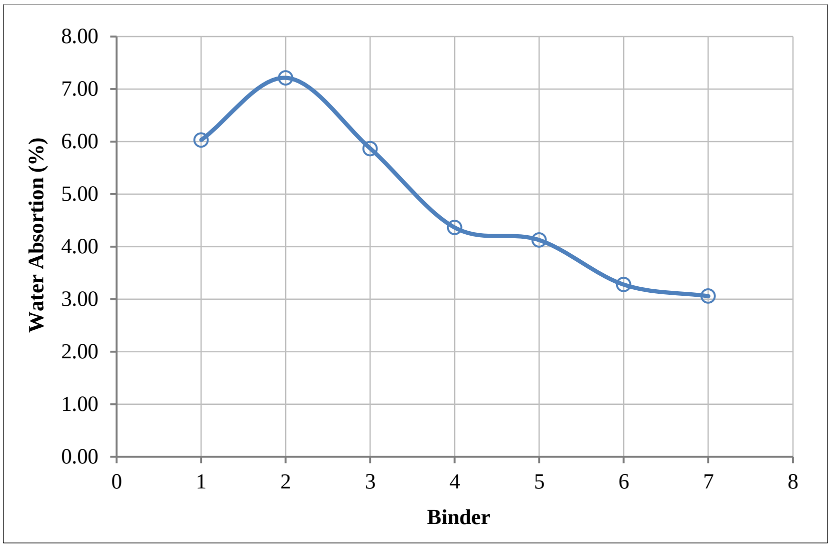
Table 4. ANOVA analysis for the relationship between Compressive strength, curing age and percentage of PET bottles

Source	DF	Sum of Squares	Mean Square	F-Value	Prob>F
Model	2	1175.00083	587.50042	18.20345	1.0805E-6
Error	51	1645.98005	32.27412	-	-
Total	53	2820.98088	-	-	-

3.2. Water Absorption

Moisture damage of pavements is a significant problem affecting the durability of pavements. The amount of water absorbed for each paving block sample is shown in Figure 8. There is an observed decrease in water absorption with increasing PET contents in paving blocks. The water absorption for unmodified bitumen paving block of 7.2% decreased by about 56 % when the bitumen content is modified with 10% PET. Hence, PET addition significantly reduces the affinity of bitumen paving blocks to water as observed in paving block sample PMB-10 having the lowest water absorption value. This assertion of reduced water absorption for paving units incorporating PET is supported by

Awodiji et al. [29] and Agyemam et al. [30]. Their previous research has indicated a significant reduction in the water absorption of PET paving blocks. This can be attributed to the good water-repellent characteristics of PET due to its hydrophobic properties [32]. The low water absorption characteristics exhibited by the PET-modified bitumen is key to ensuring that the mixture is protected from moisture damage during the service stage.



1	Cement
2	Bitumen
3	2% PET
4	4% PET
5	6% PET
6	8% PET
7	10% PET

Figure 8. Water Absorption for the pavement blocks

3.3. Skid Resistance

The skid resistance value measured for samples is shown in Figure 9. Skid resistance is quantified using a skid number (SN), which measures the ratio of frictional resistance to motion in the plane of the interface 'F' to load perpendicular to the interface 'L' (the higher the SN, the better) TRRL Road Note 27 [33]. Among all samples tested, the 2% PET-modified bitumen samples had the least skid number of '34' while the 6% PET-modified bitumen sample had the highest skid number of 85. The skid numbers obtained in PET modified paving blocks with 2, 4, 6, 8, and 10 % PET replacement were 34, 56, 85, 84, and 84, respectively. It was observed that 4% PET-modified bitumen has no significant effect on PMBPB skid resistance, with only a 0.1% increase in skid number compared to unmodified bitumen paving block samples. Also, there was a slight reduction in the PMBPB skid resistance above 6% PET replacement, the skid number reduced slightly from 85 in 6% PMBPB to 84 in 8% and 10% PET-modified bitumen paving blocks. It can be concluded that there is improved skid resistance in the PET-modified bitumen paving block sample compared to the unmodified bitumen paving block sample. All tested samples meet the Category C minimum skid resistance value (45) based on TRRL Road Note 27 specifications [34], except for samples having 2% PET-modified bitumen, which has a lower SN of 34.

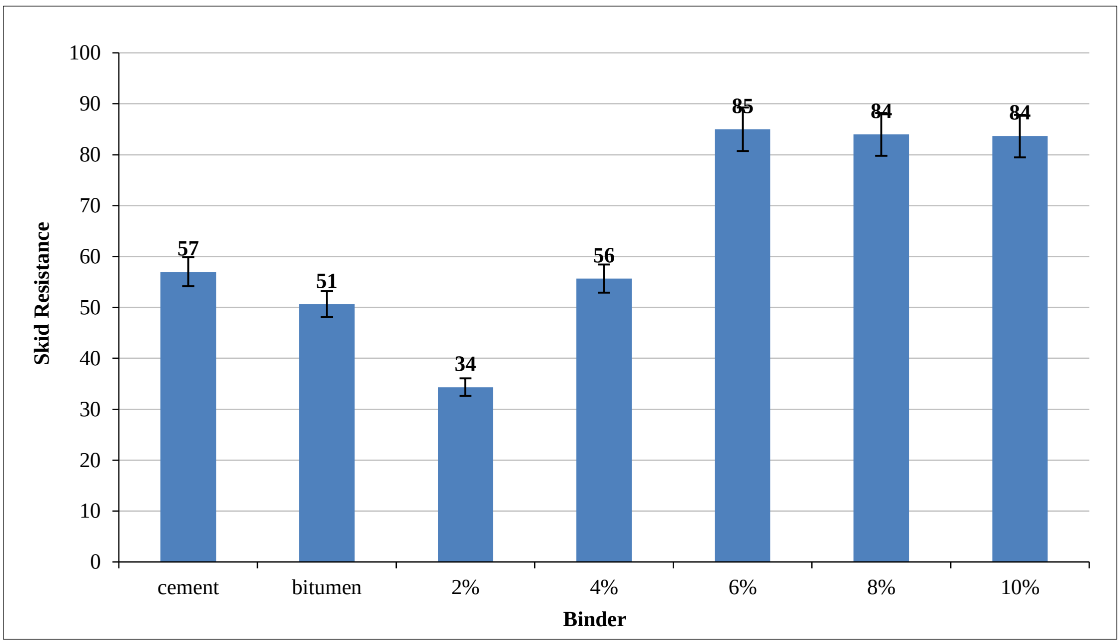


Figure 9. Skid resistance for pavement blocks with different binder content

3.4. Cantabro Abrasion Loss

The Cantabro test was used to evaluate the particle loss on the paving block samples' surface, and the result obtained is shown in Figure 10. The effect of various binder compositions on the abrasion loss showed a decreasing trend of abrasion value with increasing PET content. The Cantabro loss in the unmodified PET paving block sample (B100) was reduced by 25.7, 58.8, 70.27, 73.2, and 73.5% when modified with 2, 4, 6, 8, and 10%, respectively. The correlation between compressive strength and Cantabro loss of the paving block is presented in Figure 11. The Cantabro loss demonstrated a clear negative linear relationship with compressive strength. This is attributed to the enhanced binder characteristics and aggregate packing force of aggregates within PET modified bitumen paving blocks, resulting in enhanced compressive strength and less abrasion loss. This result is also in agreement with Saboo et al. [28] and Rao et al. [35].

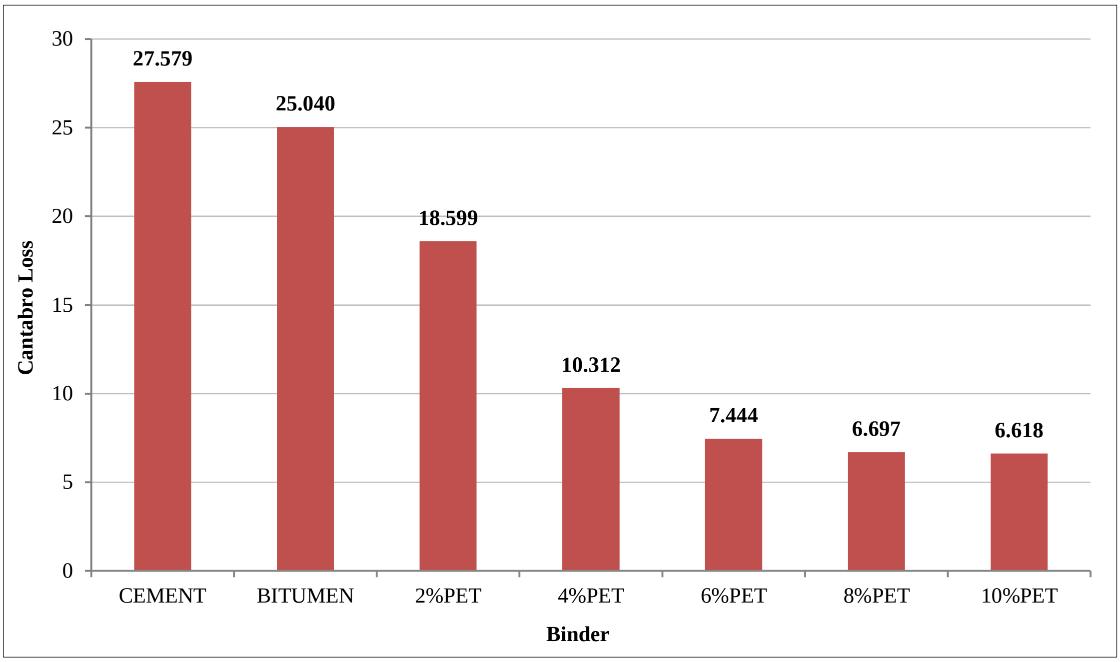


Figure 10. Cantabro abrasion loss for different binder compositions

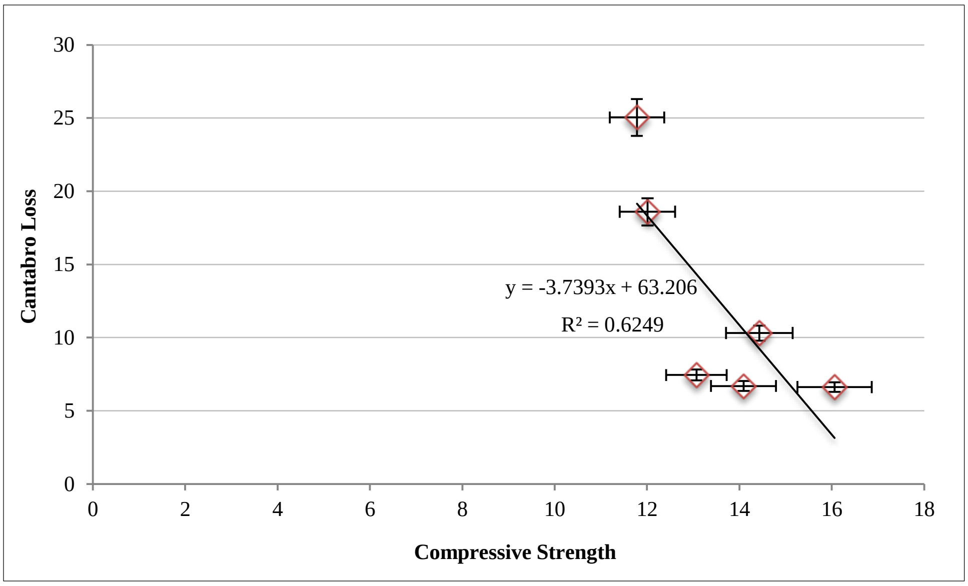


Figure 11. Relationship between Cantabro loss and Compressive Strength

4. Conclusions

One way to reduce the cost of road construction and make it more sustainable is by utilizing waste materials. This study considers using bitumen modified with polyethylene terephthalate (PET) waste as an alternative binder in paving blocks. The experimental results have demonstrated significant performance in terms of skid resistance, compressive strength, and abrasion loss. Based on the experimental investigation, the following conclusions are drawn:

- PET-modified bitumen is found to have the highest skid number, indicating that PET can significantly improve the skid resistance of paving blocks.
- The utilization of unmodified bitumen in paving blocks reduces its compressive strength; however, PET-modified paving blocks show increased compressive strength compared to unmodified bitumen paving block samples. The highest compressive strength was obtained at the 10% PET modified bitumen level.
- Abrasion loss decreased as PET content increased. A clear negative correlation was obtained between abrasion loss and compressive strength, which further confirms that the PET modified bitumen pavement block performs well in terms of durability and strength requirements.
- There was a significant reduction in water absorption with increasing PET contents. This indicates that PMBPB is less permeable and protected from moisture or chemical ingress and damage during its service stage, hence enhancing its durability performance.

5. Declarations

5.1. Author Contributions

Conceptualization, T.A., D.O., F.N., and O.A.; methodology, T.A., D.O., F.N., and O.A.; formal analysis, T.A., D.O., F.N., and O.A.; resources, T.A., D.O., F.N., and O.A.; writing—original draft preparation, T.A., D.O., A.F.D., E.B., F.N., O.A., and M.A.; writing—review and editing, T.A., D.O., A.F.D., E.B., F.N., O.A., and M.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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