LAUTECH Journal of Engineering and Technology 20 (2) 2026: 168-176
10.36108/laujet/6202.02.0251

# Performance Evaluation Of Crushed PET Bottles In Highway Pavement Construction

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**Article Info**

*Article history:*

**Received: June 1,** 2026
**Revised: July 17,** 2026
**Accepted: July 18,** 2026

***Keywords:***

Polyethylene Terephthalate, Waste, Stability, Flow, Asphalt Concrete.

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**ABSTRACT**

***Although waste polyethylene terephthalate (PET) from discarded plastic bottles serves as a promising and economical additive for the enhancement of asphalt concrete's mechanical properties, conventional asphalt concrete is still at risk of permanent deformation (rutting) and early failure due to heavy traffic and environmental stress, thus requiring an investigation into the potential benefits of partially replacing bitumen with crushed waste PET to improve stability and flow and reduce maintenance costs for pavements. This study examines modifying asphalt concrete using crushed waste polyethylene terephthalate (PET) from crushed PET bottles. Marshall stability measures the maximum load an asphalt sample can support before failing. It is tested by compacting cylindrical asphalt specimens, soaking them in a water bath at 60°C, and then loading them in a Marshall machine until they fail. The peak load (stability) and deformation (flow) are recorded. The Marshall test was performed on the samples after the optimum bitumen content of asphalt concrete was substituted with 0%, 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% of PET waste. When the unmodified and PET-modified asphalt concrete were compared, it was apparent that the modified asphalt concrete showed improved stability and flow. At a PET waste percentage of 7.5%, the asphalt concrete modified with PET waste showed the highest stability. This suggests that adding PET waste could increase asphalt's resistance to permanent deformation and also reduce the cost and maintenance of flexible pavement.***

## INTRODUCTION

The growing problem of plastic waste has become a major global environmental issue, especially in developing countries like Nigeria. Out of the different types of plastics, Polyethylene terephthalate (PET) is commonly used in packaging drinks due to its lightweight and economical properties. However, the biodegradation-resistant property of PET has led to many environmental issues, such as blockage of drainage systems, floods, and pollution of both terrestrial and aquatic environments (Obianyo *et al.,* 2024). In addition, waste management issues in Nigeria have worsened the issue of PET waste generation, thus necessitating effective recycling approaches (Oladunni *et al*., 2024). This challenge may be addressed through an innovative approach that involves the use of waste PET material in highway pavement development. The road pavements in Nigeria tend to suffer premature failures due to reasons such as high traffic loading, poor construction quality, and harsh weather conditions (Abdulazeez and Sani, 2024). There is a possibility for conventional asphalt mixes to have problems such as rutting, cracking, and moisture susceptibility, which make their lifespan shorter than expected. As a result, the modification of asphalt mixes with waste materials like PET has been gaining more attention recently.

Polyethylene terephthalate (PET) materials have desirable engineering characteristics such as high tensile strength, resistance to chemical breakdown, and toughness, making them appropriate to be included in pavement construction. The inclusion of PET materials from recycled plastic bottles in asphalt mixtures as an aggregate or as a bituminous modification has been shown to improve the structural characteristics of the pavement (Obianyo *et al.,* 2024). According to previous research, asphalt concrete mixtures with PET modifications have higher rigidity and Marshall stability, and better resistance to permanent deformation than the traditional ones (Shah *et al.,* 2023). Likewise, Ramire *et al.* (2025) found that PET inclusion in asphalt mixtures improves load-bearing capacity and reduces rutting. In Nigeria, various works have been conducted on the use of waste plastics in the construction of roads. For instance, Obianyo *et al*. (2024) studied the effectiveness of stabilizing lateritic soils using plastic waste and found that there were considerable improvements in strength parameters of the soil, thereby suggesting that the use of plastic waste could boost the subgrade pavement performance. In addition, Choudhary *et al*. (2020) found that incorporating plastic waste in asphalt mixtures improves the durability of the mixture and reduces its vulnerability to water damage. Ahmadinia *et al*. (2011) examined the influence of integrating waste PET bottles at varying percentages of 0%, 2%, 4%, 6%, 8%, and 10% into stone mastic asphalt (SMA), concluding that 6% by weight of bitumen represented the optimal PET content, which significantly enhanced the volumetric and mechanical characteristics of the mixture.

The performance improvement achieved by adding PET into asphalt mixtures is mainly attributed to the effect generated by the polymer-binder interaction. PET serves as a reinforcement agent that increases the viscosity and stiffness of the binder, thus increasing its deformation resistance at high temperatures (Bilema *et al.,* 2024). PET additives also help fill up the air voids present in the asphalt mixture, causing densification of the asphalt matrix. Such densification contributes to lower levels of air voids, increased adhesion between the aggregates and binder, and improved stripping resistance (Sofo *et al.,* 2024). Numerous studies conducted across the world have shown the effectiveness of adding PET to asphalt to improve pavement characteristics. According to Ghodrati *et al.* (2025), use of recycled plastics in asphalt mixes results in enhanced performance characteristics of engineering materials while simultaneously reducing the environmental burden. It was also shown that PET-modified asphalt mixes have greater resistance to fatigue and thus a longer lifespan than conventional asphalt. Additionally, LCA studies suggest that using PET in road construction results in lower emissions and conserves resources (Rispoli and Ajibade, 2024).

Despite all these benefits, there are still some constraints to the use of PET bottles in pavements. These include the problem of achieving consistent distribution of the material in the mix, establishing optimum levels of PET to be used, and possible interactions of the PET and the bitumen. There is also a lack of guidelines concerning the use of plastic materials in paving, particularly in Nigeria, thus limiting the practice (Oladunni *et al*., 2024). The utilization of pavement materials reinforced with polyethylene terephthalate (PET) aligns with sustainable development and the concept of a circular economy. The recycling of waste PET bottles to produce useful construction materials will help address issues related to environmental degradation, resource depletion, and high construction costs. In Nigeria, where waste management of plastics and road construction are key issues, such an innovation becomes highly relevant.

The focus of this investigation is on the performance of waste PET bottles as a bitumen modifier in highway pavements. It is aimed at understanding the influence of waste PET bottles on the behavior of asphalt mixtures in terms of strength and durability. These results can be useful in developing literature concerning sustainable paving materials and serve as groundwork for the use of waste PET in roads.

## MATERIALS AND METHODS

### Materials Used and their Sources

The materials used in this study include normal highway pavement materials and waste polyethylene terephthalate (PET) bottles. This material selection was made to examine the effect of using PET bottles on asphalt pavement performance. In this study, penetration grade bitumen 60/70 was used as the binder. Penetration grade 60/70 bitumen is one of the materials that are commonly used in Nigeria in the construction of flexible pavements. Bitumen was obtained from Slava Yeditepe Construction Company, a firm based in Osogbo, Osun State, Nigeria and its physical properties were determined based on ASTM and AASHTO standards. Aggregates that ranged from fine to coarse were sourced locally from a quarry section of Slava Yeditepe Construction Company. The aggregates were analyzed to establish their fitness for use in the production of asphalt. Tests conducted on the aggregates included sieve analysis, specific gravity, aggregate impact value and crushing value. Used polyethylene terephthalate (PET) bottles were obtained from dumping sites and business areas within Elizade University, Ilara-Mokin, Ondo State. The used PET bottles were subjected to cleaning and drying processes, and then mechanical processing to obtain small pieces that normally have sizes between 2 mm and 6 mm. The processed PET was used for modifying the asphalt mixture. The properties of PET, such as density and melting point, were considered while preparing the mixture. Mineral fillers such as stone dust and

Portland cement were added to the asphalt mix to provide stability and these were also sourced from Slava Yeditepe Construction Company.

### Sample Preparation

The asphalt binder containing PET was produced using the wet technique, whereby PET shreds were first added into the bitumen before adding the aggregates. In this case, bitumen was melted at temperatures of 160–180 °C, while the aggregates were heated up to about 160–170 °C. Different proportions of PET 0%, 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% by weight of bitumen were gradually added to the heated bitumen, then stirred well using the mechanical stirrer until a homogeneous product was obtained. Stirring continued for a long time until melting occurred and allowed interaction between the bitumen and PET to create the modified bitumen.

### Physical Characterization of PET-modified Bitumen

The physical properties of PET-modified bitumen were determined using standard laboratory tests in accordance with ASTM and AASHTO specifications. The tests carried out were penetration (ASTM D5 / D5M), softening point (ASTM D36 / D36M), ductility (ASTM D113) and flash and fire point (ASTM D92) tests.

### Physical Characterization of Aggregates and Chemical Characterization of PET

The physical characterization of aggregates was analysed using American Society for Testing and Materials standards. Specific gravity, aggregate impact test, aggregate crushing test and moisture content test were carried out. The chemical properties of PET were analysed using X-ray fluorescence (XRF) and X-ray diffraction(XRD) tests in accordance with ASTM specifications.

### Marshall Mix Design

Aggregates and Optimum bitumen content of 6% were mixed inside a steel bowl and stirred vigorously at a temperature of about 185 ºC. This mixture was compacted using a fore-heat Marshall mold by applying 50 blows to both faces of the specimen. The specimen was then turned around and subjected to another 50 blows on the other face. In total, 14 samples of asphalt concrete were made with the inclusion of shredded PET to determine its influence on the material. Different quantities of PET were used to replace bitumen in six samples, that is, 2.5%, 5%, 7.5%, 12.5% and 15%. Tests such as Marshall stability (ASTM D1559) and flow (AASHTO T245) were carried out on the samples.

**Microstructural Properties of the PET-modified Asphalt Concrete**

A scanning electron microscope was used to examine the microstructure, bonding, and morphology of PET-modified asphalt mixtures in accordance with ASTM standards

## RESULTS AND DISCUSSION

**Physical Characterization of Bitumen and Modified Bitumen**

The physical characterization of bitumen and modified bitumen is discussed in the following subheading.

**Penetration Test**

It is apparent from Figure 1that modified bitumen has a lower penetration value than unmodified bitumen. It also demonstrates that the penetration value falls as the amount of PET in bitumen increases. When 2.5%, 5%, 7.5%, 10%, 12.5% and 15% of PET were added, the decrease from the original bitumen was 63 mm, 52 mm, 46 mm, 41 mm, 35 mm, 26 mm and 14 mm, respectively. This indicates that the modified bitumen was made harder and more uniform by the addition of PET. These results agreed with FGN (1997) standards.

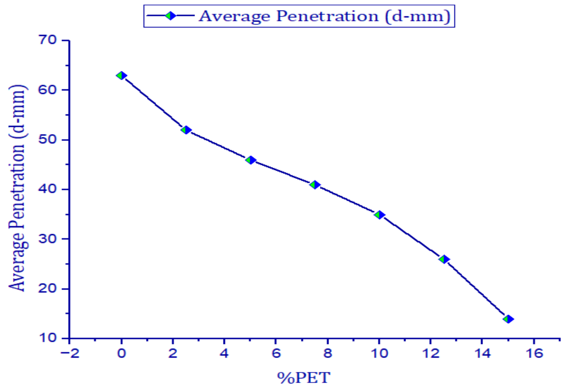



**Figure 1:** Penetration test against %PET content

**Softening Point Test**

The softening point increased as the PET content increased, as shown in Figure 2. The findings unequivocally demonstrate that adding PET to bitumen raises the softening point value, and that the softening point rises in tandem with PET content. This phenomenon suggests that the binder is less likely to weaken in hot conditions and is more resistant to the effects of heat. Therefore, the improved binder will be less vulnerable to temperature variations with the inclusion of PET. These results agree with Choudhary *et al*. (2020).

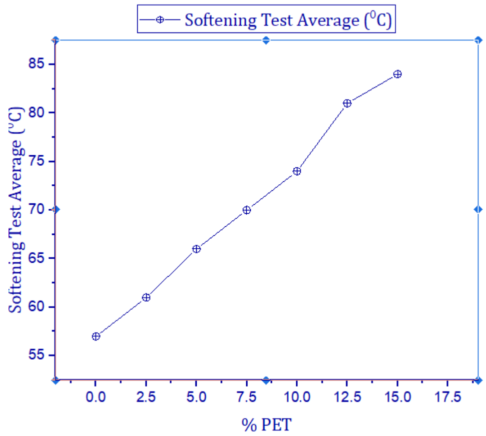



**Figure 2:** Softening point test against %PET

**Ductility Test**

The result of the ductility test is presented in Figure 3. The ductility value kept decreasing as the percentage of PET increased. Compared to 0% PET, which has the highest ductility, according to Figure 3, a PET content beyond 5% progressively decreased the ductility. The remaining values obtained were also above the recommended minimum value of 100cm according to AASHTO T 51.

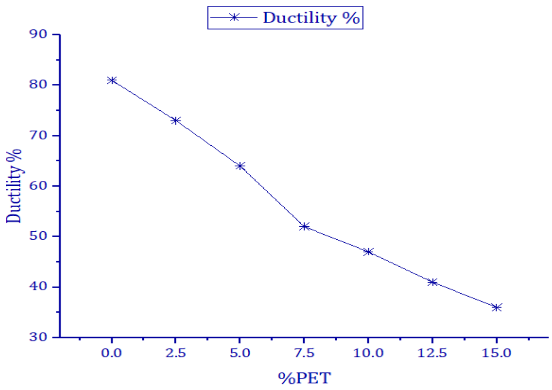
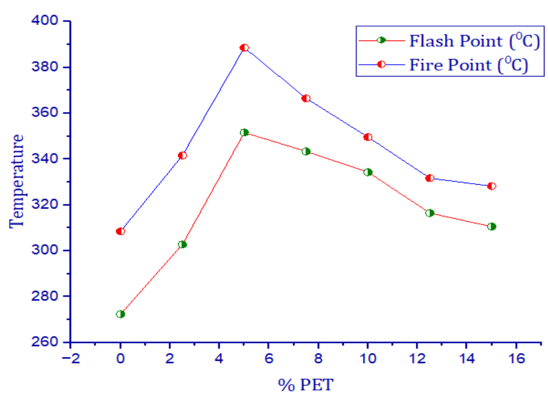



**Figure 3:** Ductility against % PET

**Flash and Fire Point Test**

Figure 4 indicates that adding PET content initially increased both the flash and fire points of the substance, suggesting that the material became less volatile and safer to handle at elevated temperatures. The highest thermal stability is achieved at a 5% PET content, where both the flash and fire points reach their maximum values. Beyond this concentration, the thermal stability began to decrease. The consistent difference between the flash point and fire point, with the fire point being higher, is expected and confirms the validity of the test results. The result is consistent with the findings of Bilema *et al.* 2024.




. **Figure 4:** Flash and fire point against %PET

**Physical Characterization of Aggregates**

The physical properties of the aggregates: Sieve analysis and additional physical properties of aggregate results are discussed in the following sub-sections.

**Sieve Analysis**

Figure 5 displays the aggregate and aggregate mixture's particle size distribution curves for the asphalt concrete. According to the General Specifications for Roads and Bridges (FGN, 1997), the aggregate mixture's curve shows that it falls inside the envelope.

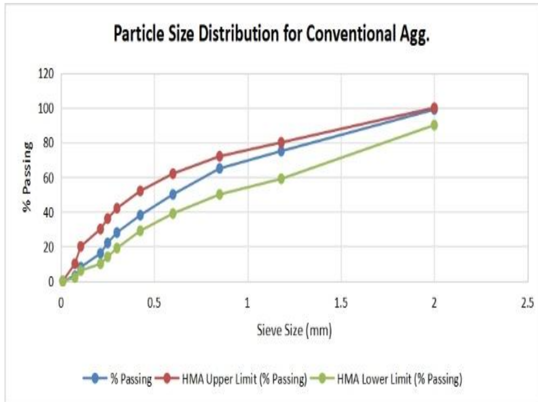



**Figure 5:** Gradation Curve of Sieve Analysis

**Additional Physical properties of aggregate results**

The physical characteristics of the aggregates: moisture content, aggregate impact value (AIV), aggregate crushing value (ACV) and specific gravity (Gs) are as indicated in Table 1. The values found for each parameter fall within the designated range for road surfacing, according to the FGN (1997).

**Table 1:** Results of Physical Characterization of the Aggregates

| 1 | Materials | Moisture Content (%) | AIV %() | ACV (%) | Gs (g) |
|---|---|---|---|---|---|
| 2 | Aggregates | 0.8% | 21.8 | 27.5 | 3. |
| 3 | FMWHM, 2013 Specifications | Max 5% | 20-30 | 27-35 | -- |

**Chemical Characterization of Crushed PET Bottles**

**X-ray Diffraction Analysis**

The X-ray diffraction (XRD) results are as indicated in Figure 6. The high content of urea ($CH_4NO_2$), which is an organic compound, influenced the chemical interactions involving the binder, thereby potentially modifying the polarity. Silvialite content indicates the presence of significant aluminosilicate material, as shown in Figure 7, which can improve the stiffness and load-bearing capacity of the rejuvenated asphalt. XRD corroborated this by identifying dolomite as the principal crystalline phase, with minor quartz and calcite. This carbonate-rich, low-alumina filler was selected/used alongside PET-modified bitumen because of its favorable chemical compatibility with the binder.

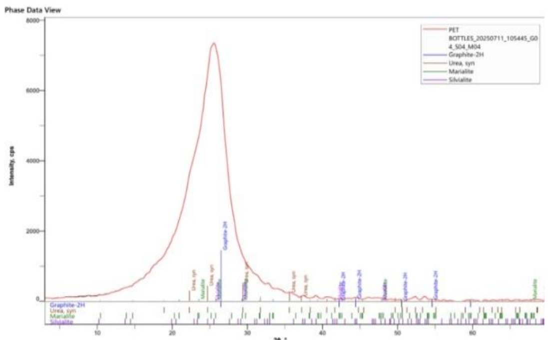



**Figure 6:** XRD diffractogram graph of PET-modified asphalt sample

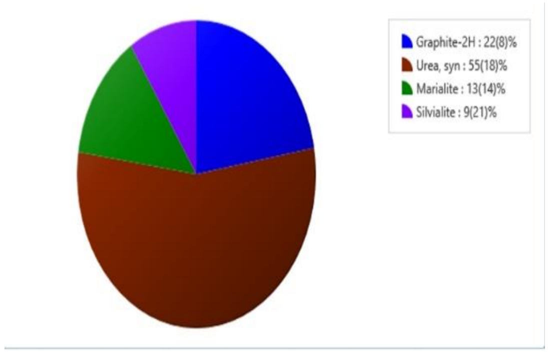



**Figure 7:** XRD diffractogram of sample with phase identification.

**X-ray Fluorescence (XRF) analysis**

Table 2 displays the sample's XRF data. MgO, $AlO_3$, and $SiO_2$ are the main oxides; $FeO_3$, CaO, and $SO_3$ are present in trace levels. The oxide composition, which is dominated by MgO, $Al_2O_3$, and $SiO_2$, verifies the presence of substantial mineral materials in the sample. These minerals may increase the asphalt mix's stiffness and resilience to long-term deformation by serving as micro-fillers. While the presence of CaO is beneficial for adhesion, the presence of $FeO_3$ indicates a possible need for ageing resistance treatments. XRF confirmed the filler is dominated by CaO and MgO oxides (~58% combined), consistent with a dolomitic limestone material

**Table 2:** X-ray Fluorescence analysis of the PET (%)

| Oxide | MgO | $Al2O_3$ | CO | $SiO_2$ | $SO_3$ | $FeO_3$ | CaO | $P_2O_5$ | $TiO_2$, ZnO $V_2O_5$, $Cr_2O_3$, MnO |
|---|---|---|---|---|---|---|---|---|---|
| Weight | 27.39 | 3.36. | 31.10 | 23.50 | 3.36 | 1.78 | 2.40 | 0.71 | < 0.25 each |

**Marshall Mix Design Results**

Stability and flow results were obtained from the Marshal mix design, which are discussed in the following subsections.

**Stability Results**

Figure 8 shows that the stability values of the PET-modified asphalt concrete were 15.5 KN, 17.8 KN, 20.2 KN, 25.6 KN, 18.7 KN, 15.8 KNand13.2kN, respectively, at percentages of 0%, 2.5%, 5%, 7.5%, 10%, 12.5% and 15% replacement of bitumen. It clearly shows that the optimum value of 25.6KN were obtained from 7.5% replacement of bitumen. The addition of crushed PET bottles improved the adhesion development between the aggregate particles and the asphalt binder, which increased the strength of the asphalt mixture and helped to improve its stability. Other values were compared with standards such as the General Specifications for Roads and Bridges (FGN, 1997). All the results obtained were within the specifications. This finding of 7.5% as optimum PET content agrees with Ahmadinia *et al.* (2011), who reported improved stability at PET contents between 6–8%.

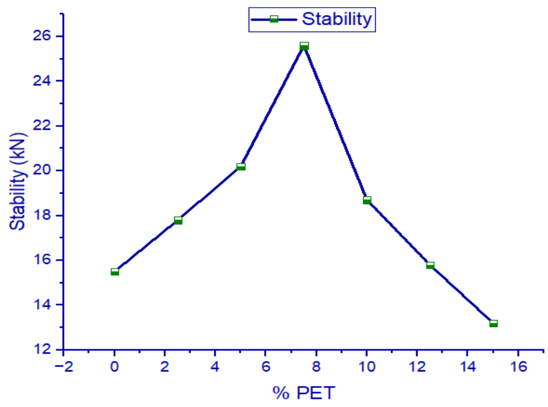



**Figure 8**: Marshal stability against %PET

**Flow Results**

The flow values obtained are indicated in Figure 9. The values were 3.4 mm, 3.2 mm, 3.1 mm, 3.0 mm, 3.2 mm, 3.3 mm and 3.5 mm. According to the General Specifications for Roads and Bridges (FGN, 1997), the flow values for 2.5%, 5%, 7.5%, 10%, 12.5%, and 15% fall between 2 and 6 mm. The PET-modified asphalt's enhanced stiffness, which improved its permanent deformation resistance, may be the cause of the decrease in flow values. This result conforms with (Sofo *et al.,* 2024).

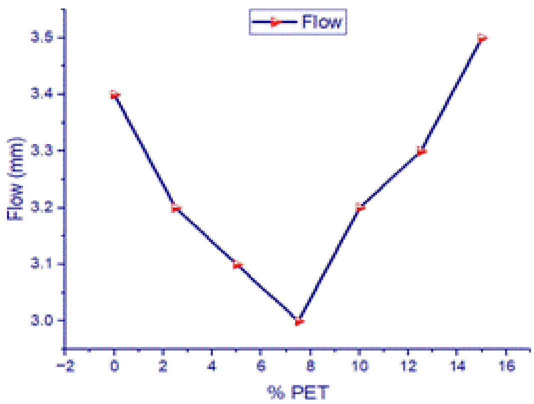



**Figure 9:** Marshal flow against %PET

**SEM/EDS Analysis of PET-modified Bitumen**

Figure 10 shows the mixture of asphalts and PET, describing a mixture of angular, irregular particles of various sizes which corresponds to the mineral aggregates(Silicon, Iron and Aluminum) from the elemental analysis. Figure 10 demonstrates that the PET particle is embedded within, and partially surrounded by, the bitumen-aggregate matrix, rather than sitting as a separate, unbonded phase. This is a positive indicator of some degree of physical interfacial bonding/adhesion between the plastic modifier and the binder. The elongated, angular shape of the PET fragment (rather than a fully melted/rounded droplet) suggests the PET was incorporated in solid/crushed particulate form (dry process) rather than being fully melt-blended into the bitumen. The surface texture around the PET particle (whether there are visible gaps/debonding at the edges or tight embedding) is often used qualitatively to argue for good vs. poor bitumen–PET adhesion. From Figure 10, the PET fragment appears reasonably enclosed within the surrounding mastic with no major visible gap. The general porosity and grain packing of the matrix visible elsewhere in the image can also be discussed in terms of compaction density/void in the mix

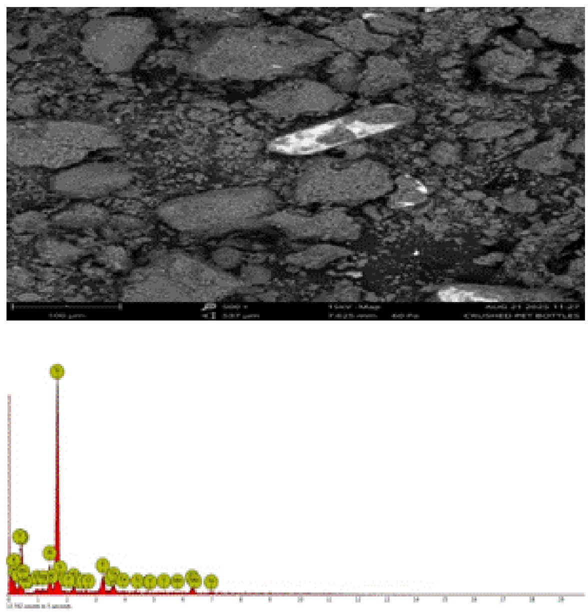


**Figure 10:** Results for SEM/EDS analysis

## CONCLUSION

This study investigated the modification of asphalt concrete using polyethylene terephthalate (PET) derived from used plastic bottles, motivated by the need for sustainable management of the large volumes of plastic waste generated daily. This study has demonstrated that the addition of crushed PET to asphalt concrete improves stability and flow, thereby enhancing resistance to rutting under heavy traffic loading, though this gain came at the cost of reduced fatigue resistance, revealing a stiffness-related trade-off that underscores the need for optimized rather than excessive PET dosage. SEM analysis confirmed that PET particles were physically embedded within the bitumen-aggregate matrix, while the carbonate-rich mineral filler used further supported adhesion and moisture resistance, together accounting for the observed improvement in mechanical stability. Based on these findings, it is concluded that crushed PET bottles offer a technically viable strategy for improving asphalt concrete performance, simultaneously addressing the challenges of premature pavement failure and unmanaged plastic waste in Nigeria and similar developing regions.

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