

Research Article

Optimization of Asphalt Concrete Performance Using Waste Plastic Bottles (WPB) as a Sustainable Bitumen Modifier: A Comprehensive Rheological and Mechanical Assessment

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Abstract

This study investigated the potential of utilizing Waste Plastic Bottles (WPB) as a sustainable modifier in asphalt pavement mixtures, systematically examining the characteristics of aggregates, the WPB-modified bitumen binder, and the resulting asphaltic concrete mix. Detailed analysis of the aggregate gradation revealed the coarse fraction to be a well-graded gravel, characterized by a uniformity coefficient (C_u) of 2.47 and coefficient of curvature (C_c) of 1.14, indicative of optimal packing density for structural stability. These aggregates exhibited high durability, with an Aggregate Crushing Value (ACV) of 18.3% and Aggregate Impact Value (AIV) of 16.9%, ensuring resistance to abrasion and impact under traffic loads. In contrast, the fine aggregate was poorly graded ($C_c = 0.45$), highlighting the need for binder modification to enhance overall mix cohesion. Modification of pure bitumen (initial penetration 69 mm) with WPB progressively induced desirable hardening effects and superior high-temperature performance. Penetration values decreased markedly from 69 mm to 33 mm at 25% WPB incorporation, while the softening point rose substantially from 52 °C to 81 °C, demonstrating enhanced rutting resistance and thermal stability critical for tropical climates like Nigeria's Lagos region. Additional rheological improvements included increased viscosity (up to 2984 p.a.s), flash point (289 °C), and specific gravity (1.13), with minimal ductility loss, collectively affirming WPB's role in creating a more resilient binder. Marshall performance testing on the WPB-modified asphaltic concrete further validated these enhancements. The mixture achieved maximum Marshall Stability of 19.74 kN and peak Marshall Quotient of 4.32 kN/mm at 15% WPB content— a 78% stability increase and 34% quotient gain over the control mix (11.05 kN and 3.22 kN/mm). Flow values remained controlled (3.43–4.57 mm), balancing stiffness with workability. These outcomes, aligned with prior pelletized WPB concrete data showing optimal 10–15% thresholds, confirm WPB's efficacy in boosting stiffness, load-bearing capacity, and deformation resistance. Overall, WPB modification yields a mechanically superior, eco-friendly alternative to conventional asphalt, promoting waste valorization while meeting geotechnical standards for durable pavements in sustainable infrastructure projects.

Keywords

Waste Plastic Bottle, Bitumen, Asphalt, Pavement, Aggregate

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1. Introduction

The environmental impact of plastic waste in Nigeria is intricately linked to the country's ongoing infrastructure challenges, particularly within the road sector [1]. In recent decades, Nigeria has witnessed exponential growth in both population and urbanization, resulting in a significant increase in the consumption and disposal of plastic products, especially single-use plastics like polyethylene terephthalate (PET) bottles, low-density polyethylene (LDPE) bags, and sachet water bags [2, 3]. With an estimated annual generation of 2.5 to 3.5 million tonnes of plastic waste, Nigeria currently ranks as one of the world's largest contributors to plastic pollution, second only to India [4, 5]. The severity of this issue is further intensified by the lack of effective waste management systems, leading to the indiscriminate disposal of plastics in waterways, drainage systems, and urban areas [6-8].

The environmental consequences of this mismanagement are severe. Plastic waste clogs drainage systems, exacerbating urban flooding during the rainy season, and disrupts natural water channels, leading to the contamination of rivers and beaches [9, 10]. Studies have shown alarmingly high concentrations of microplastics in Nigerian water bodies, such as the Osun River, where contamination levels have exceeded 22,000 pieces per litre [11]. This pervasive plastic pollution threatens both aquatic and terrestrial ecosystems and poses significant risks to human health, as microplastics and the toxic substances they absorb can enter the food chain and infiltrate biological systems [12, 13]. Given the non-biodegradable nature of plastics, once they are released into the environment, they persist for centuries, accumulating in landfills, soils, and marine habitats, which further aggravates the issue [14].

The socio-economic ramifications of plastic pollution are equally severe. The accumulation of plastic waste in urban areas detracts from the aesthetic appeal of cities, diminishes property values, and undermines potential tourism revenue [8]. Furthermore, the blockage of drainage systems caused by plastic waste has led to recurrent flooding in major Nigerian cities, resulting in loss of livelihoods, damage to infrastructure, and an increase in waterborne diseases [15]. The prevalent practice of burning plastic waste, often due to the absence of formal waste collection systems, releases harmful toxins into the atmosphere, thereby contributing to air pollution and associated respiratory illnesses [8]. Despite the apparent and well-documented effects of plastic pollution, initiatives aimed at regulating single-use plastics and enhancing waste management have been hindered by weak enforcement, limited public awareness, and insufficient investment in recycling infrastructure [16].

Parallel to the environmental crisis posed by plastic waste, Nigeria's road network faces its own set of formidable challenges. The country's extensive road system, spanning approximately 200,000 kilometers, is plagued by poor maintenance, inadequate construction materials, and a heavy reliance

on imported bitumen, a key binder in asphalt production [17, 18]. As a result, Nigerian roads are characterized by frequent potholes, rutting, and cracking, conditions that severely impede economic activity and social mobility. Over 70% of roads, including those in semi-urban and rural areas, are in poor or deplorable condition, making transportation both difficult and hazardous [17]. The situation is further aggravated by the high cost and fluctuating availability of bitumen on the international market, which places additional strain on government budgets and often leads to the use of substandard materials in road construction [19].

The repercussions of Nigeria's inadequate road infrastructure are extensive. Subpar road conditions lead to increased vehicle operating expenses, extended travel times, and a rise in road accidents, all of which detract from economic productivity and social well-being [20, 21]. The agricultural sector, which heavily depends on road transport for moving goods from rural production centers to urban markets, is particularly impacted, as delays and spoilage during transit exacerbate post-harvest losses [22]. Furthermore, the absence of reliable road infrastructure restricts access to essential services such as healthcare, education, and emergency response, disproportionately affecting vulnerable populations in remote areas [23].

In response to the converging crises of plastic pollution and deteriorating road infrastructure, there is an increasing awareness of the necessity for innovative and sustainable solutions that address both issues simultaneously. One promising approach is utilizing plastic waste as a modifier in asphalt for road construction. This method involves integrating shredded plastic waste, such as PET and LDPE, into bitumen or asphalt mixtures, which not only enhances the mechanical properties of the pavement but also diverts plastic from landfills and the environment [24, 25]. International studies and pilot projects have shown that plastic-modified asphalt can improve road durability, increase resistance to deformation, and extend the lifespan of pavements, especially under the heavy traffic loads and harsh climatic conditions characteristic of Nigeria [26, 27].

The environmental advantages of this approach are noteworthy. By repurposing plastic waste for road construction, we significantly decrease the amount of plastic that ends up in landfills and natural ecosystems, thereby reducing the risks of flooding, pollution, and the loss of biodiversity [28]. Moreover, utilizing plastic-modified asphalt serves as a partial substitute for bitumen, which lessens Nigeria's reliance on expensive imports and supports the principles of a circular economy [29]. The incorporation of waste plastics into road materials also aligns with global trends promoting sustainable infrastructure development and resource efficiency, as emphasized by the United Nations Sustainable Development Goals (SDGs) [30].

2. Materials and Methods

The materials and methods used for the research are spelt out in the subsequent sections.

2.1. Materials

The subsequent materials were used for the study:

2.1.1. Bitumen

The bitumen utilized was sourced from BAL Engineering Limited, based in Ilorin, Nigeria. The Bitumen used was Grade 30 for Viscosity, or VG-30 based on [31]. The bitumen has a penetration grade of 60–70 mm and softening point ranging from 48 to 52°C in accordance to [32]. The specific gravity of the bitumen used is 1.05.

2.1.2. Coarse Aggregate

The coarse aggregate used for this research was purchased from Ijagbo, Kwara State, where manually polished natural coarse aggregate is supplied in bags. This is to ensure that the results of this study are as near as possible to those obtained with commercial natural coarse aggregate. The coarse aggregate that was used for the study consists of granite particulates which passes 19.5 mm sieves and remain on 12.5 mm BS sieves. This is in accordance with the specification stated in [33] for wearing course. The Coarse aggregate will be sorted by hand, and any impurities will be removed.

2.1.3. Fine Aggregate

Quarry stone dust was used as fine aggregate in the manufacturing of the Asphalt Mixes. The quarry stone dust employed in this study was obtained from same location as the coarse aggregate. The fine aggregate consists of quarry stone dust with portion passing 4.75 mm and retained on 75 µm BS sieves.

2.1.4. Waste Plastic Bottles

The waste plastic bottle (WPB) (PET) that were discarded were acquired from refuse production sites such as the residence halls and cafeteria of Federal Polytechnic, Offa (Lat: 8.1321° N Long: 4.7111° E), Nigeria. The WPB after been collected were thoroughly washed with distilled water to remove organic residues or impurities. After which the WPB were spread for sun drying. The WPB were shredded at the Ogbondroko plastic grinding milling in Offa, Nigeria.

2.2. Methods

2.2.1. Sample Preparation

Sample preparation was conducted in two stages;
Stages 1: Modified Bitumen

In this stage, the dry procedure of modification, which entails adding the shredded waste plastic bottles (WPB) to the bitumen without heating at a room temperature was used. The bitumen was modified with 0, 5, 10, 15, 20 and 25% shredded WPB so as to balance sustainability benefits with acceptable mechanical performance. The bitumen was improved by mixing shredded WPB into warm bitumen at temperatures over the melting point of the waste plastic bottles. The mixing temperature of the WPB with warm mix asphalt was 114 °C.

Stages 2: Plastic Modified Asphaltic Concrete

In this stage, the waste plastic bottle (WPB) modified bitumen was added into the already prepared aggregate to form asphaltic concrete by following the wet-mix method and using the Marshall method. An optimum binder content of 6.2% was used in samples of WPB modified with a plastic content of 5 – 20% by weight of mixes.

2.2.2. Experimental Program

Experiment or Test carried out in this research were done in three stages;

In the first stage, test such as sieve analysis, aggregate crushing value, aggregate impact value, flakiness index, Elongation index and specific gravity test were conducted on the coarse aggregate, fine aggregate and shredded waste plastic bottles. These tests were conducted in accordance to [34–38].

In the second stage, test such as penetration, softening point, Ductility, viscosity, flash and fire point and loss of heat test were conducted on the waste plastic bottle modified bitumen. These tests were conducted in accordance to [39–43].

Finally, in this stage, Marshall test was conducted on the plastic modified asphaltic concrete. These tests were conducted in accordance to [44].

3. Results and Discussions

3.1. Waste Plastic Bottles Properties

The waste plastic bottle was shredded into size ranging from 2.36 mm to 9.75 mm. The melting point of the waste plastic bottles is 225°C which is slightly less than the specified range of 250°C to 360°C. The reduction in temperature is as a result of the greater surface area and variation in plastic types. The specific gravity of the shredded waste plastic bottle is 1.33.

3.2. Aggregates Properties

The Particle distribution curve and physical characteristics of the coarse and fine aggregates are presented in Figure 1 and Table 1 respectively.

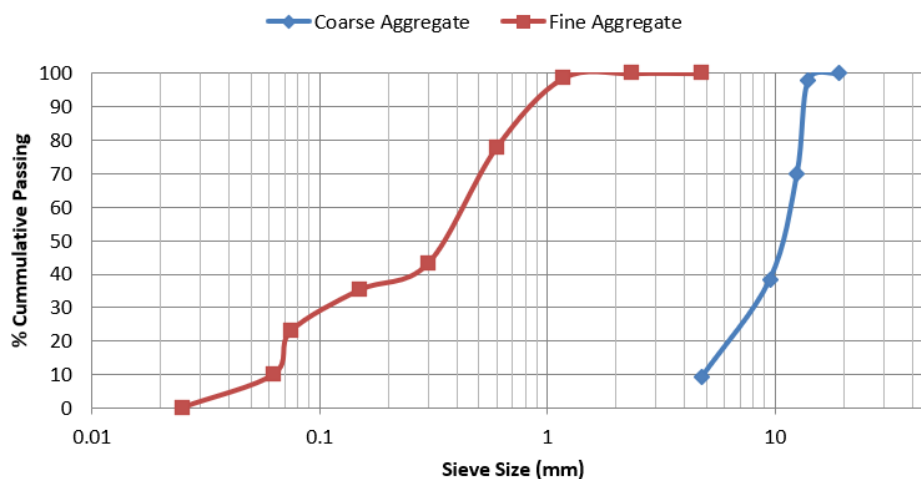


Figure 1. Particle size distribution of aggregate used.

Table 1. Physical Properties of Aggregates.

Physical Properties	Coarse Aggregates	Fine Aggregates
D ₁₀	4.77	0.063
D ₃₀	8.0	0.11
D ₆₀	11.8	0.42
Coefficient of Uniformity, C _u	2.47	6.67
Coefficient of Curvature, C _c	1.14	0.45
Aggregate Crushing Value (ACV)	18.3	-
Aggregate Impact Value (AIV)	16.9	-
Flakiness Index	23.3	-
Elongation Index	24.1	-
Specific Gravity	2.82	2.67
Water Absorption (%)	0.1	0.45

From Table 1, the coarse aggregate exhibits a maximum particle size D₆₀ of 11.8 mm and a characteristic effective size D₁₀ of 4.77 mm. The computed Coefficient of Uniformity (C_u) for the coarse aggregate is 2.47 and Coefficient of Curvature (C_c) is 1.14. Based on the Unified Soil Classification System (USCS) and common aggregate standards, the coarse aggregate can be classified as a well-graded gravel (GW), indicating a broad and smooth particle distribution suitable for achieving high packing density.

In Contrast to the coarse aggregate, the fine aggregate demonstrates a significantly finer gradation, with D₆₀ at 0.42 mm and D₁₀ at 0.063 mm. The higher C_u value of 6.67 for the fine aggregate suggests a wider range of particle sizes than the coarse aggregates. However, the associated C_c value of 0.45, which is less than the required range of 1 to 3 for well-graded material, strongly indicates a poorly graded or

gap-graded sand (SP or SW-SM borderline), potentially leading to less efficient packing in the sand matrix.

The mechanical durability of the coarse aggregate is quantified by several key tests such as Aggregate Crushing Value, Aggregate Impact Value, Elongation Index and Flakiness Index, providing insight into its resistance to degradation under applied stress. The relatively low Aggregate Crushing Value (ACV) of 18.3 and the Aggregate Impact Value (AIV) of 16.9 are both well within typical international standards (often capped near 30% or 45%, respectively), attesting to the material's high strength and resistance to crushing and sudden impact loads. Furthermore, the Flakiness Index (23.3%) and Elongation Index (24.1%) are close, signifying that a moderate proportion of the particles possess shape characteristics (i.e., being thin or long) that might negatively impact workability and strength if present in excessive

amounts; these values necessitate careful consideration, although they may meet some less stringent specifications. The inherent physical properties are completed by the Specific Gravity of 2.82 for the coarse aggregate and 2.67 for the fine aggregate. Notably, the Water Absorption for the coarse aggregate is exceptionally low at 0.1%, while the fine aggregate, exhibits a slightly higher but still moderate water absorption of 0.45%.

3.3. Bitumen and Waste Plastic Bottles Modified Bitumen Properties

The incorporation of waste plastic bottles into bitumen significantly alters its physical and rheological properties, as presented in Table 2 and Figures 2-9.

Table 2. Properties of bitumen and waste plastic bottles modified bitumen.

Properties	% of Waste Plastic Bottles Incorporated					
	0%	5%	10%	15%	20%	25%
Penetration (dmm) 25°C	69	67	61	49	37	33
Softening Point (°C)	52	58	63	72	75	81
Ductility (cm)	116	117	119	109	105	99
Viscosity (p.a.s)	2700	2800	2910	2970	2977	2984
Flash Point (°C)	255	262	274	281	284	289
Fire Point (°C)	310	322	339	347	352	360
Loss of Heat (°C)	0.15	0.18	0.23	0.25	0.24	0.23
Specific Gravity	0.99	1.01	1.04	1.08	1.11	1.13

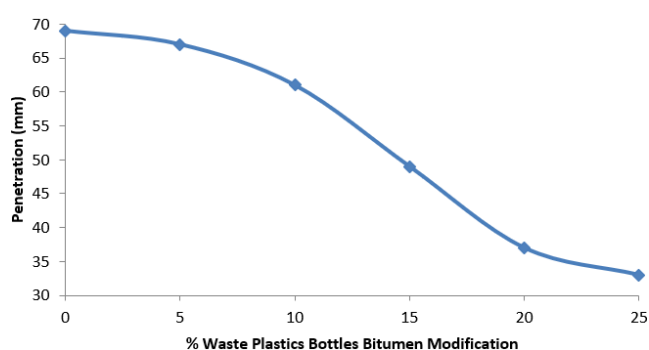


Figure 2. Effect of WPB on Penetration of Modified Bitumen.

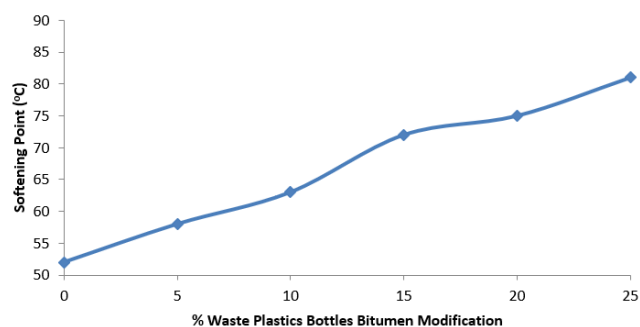


Figure 3. Effect of WPB on Softening Point of Modified Bitumen.

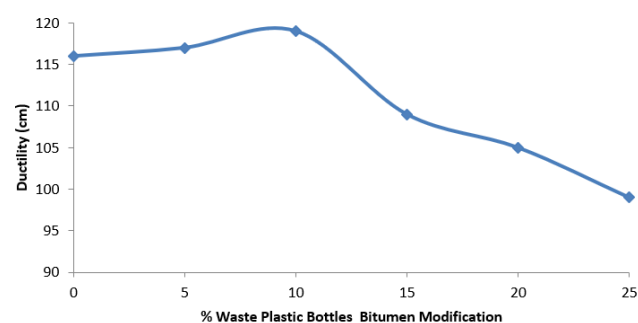


Figure 4. Effect of WPB on Ductility of Modified Bitumen.

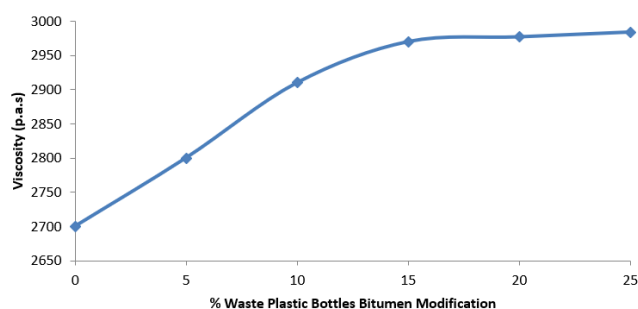


Figure 5. Effect of WPB on Viscosity of Modified Bitumen.

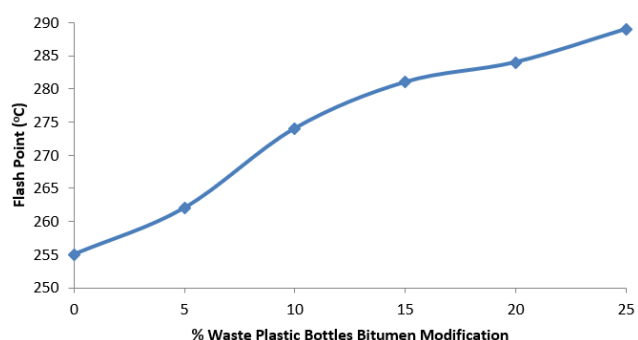


Figure 6. Effect of WPB on Flash Point of Modified Bitumen.

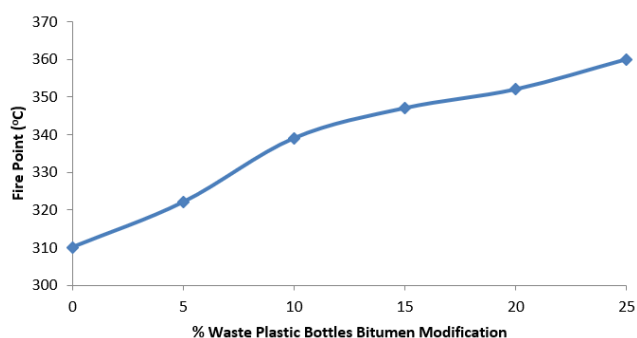


Figure 7. Effect of WPB on Fire Point of Modified Bitumen.

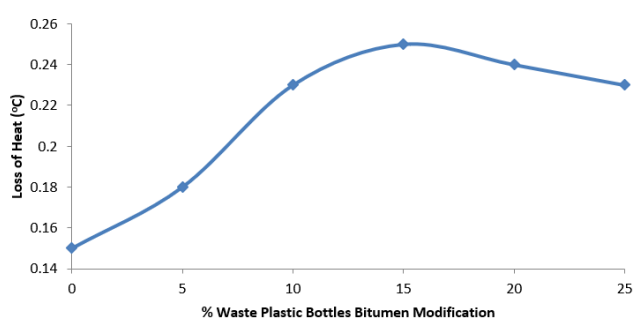


Figure 8. Effect of Loss of Heat on Ductility of Modified Bitumen.

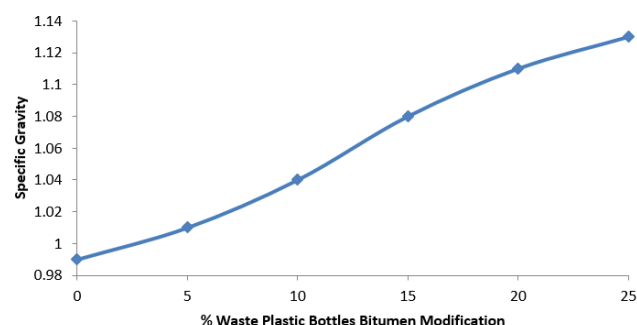


Figure 9. Effect of WPB on Specific Gravity of Modified Bitumen.

The penetration values exhibit a marked decrease from 69 dmm at 5% plastic content to 33 dmm at 25% as shown in Figure 2, signaling a substantial increase in hardness and stiffness of the modified bitumen compared to the unmodified state (0% with penetration of 25 dmm). This hardening effect corresponds well with the observed trend in softening point, which rises progressively from 52 °C in the base bitumen to 81 °C at the highest plastic dosage as shown in Figure 3. The increase in softening point indicates improved thermal resistance, enabling the bitumen to maintain structural integrity at elevated temperatures.

Ductility changes with plastic addition are relatively modest; values initially increase slightly from 116 cm at 0% to 119 cm at 10% plastic content but then decline to 99 cm at 25% as shown in Figure 4. Although higher ductility in the early dosage of waste plastic bottle suggests enhanced flexi-

bility, the eventual reduction could imply a trade-off between stiffness and extensibility as plastic content rises. The viscosity measurements provide further insight into the rheological changes: viscosity increases steadily from 2700 to 2984 p.a.s across the range of plastic incorporation as shown in Figure 5, reflecting a thicker binder mixture, which may influence workability and mixing temperatures during asphalt production.

Thermal safety, assessed through flash and fire points, improves with plastic content. The flash point increases consistently from 255 °C to 289 °C, and the fire point similarly rises from 310 °C to 360 °C, as shown in Figures 6 and 7 respectively, suggesting enhanced resistance to ignition and thermal degradation. These properties are crucial for safe handling and long-term performance in pavement applications.

The loss on heating values, a measure of binder volatiles and stability under heat, rises slightly with plastic addition, peaking at 0.25% at 15% plastic before marginally decreasing as shown in Figure 8. This pattern indicates an initial increase in potential volatility or mass loss due to thermal exposure, which stabilizes at higher plastic dosages. The specific gravity of the binder also shows a progressive increase, starting from 0.99 for pure bitumen to 1.13 at 25% plastic content as shown in Figure 9, indicating a denser material that may influence volumetric design in asphalt mixtures.

Overall, the modification of bitumen with waste plastic bottles enhances key performance attributes such as hardness, thermal stability, and viscosity, while modestly affecting ductility and thermal mass loss. These changes are consistent with improved resistance to deformation and thermal-related failures, making plastic-modified bitumen a promising material for sustainable pavement engineering.

3.4. Waste Plastic Bottles Asphaltic Concrete Properties

The performance characteristics of asphaltic concrete modified with varying percentages of waste plastic bottles, as summarized in Table 3, demonstrate notable improvements in mechanical strength and deformation resistance.

Table 3. Properties of Waste Plastic Bottles Asphaltic Concrete.

Properties	% of Waste Plastic Bottles Incorporated					
	0%	5%	10%	15%	20%	25%
Marshall Stability (kN)	11.05	13.16	17.39	19.74	17.45	16.25
Flow (mm)	3.43	3.71	4.12	4.57	4.18	4.05
Marshall Quotient (kN/mm)	3.22	3.55	4.22	4.32	4.17	4.01

Marshall Stability, which reflects the mixture's peak resistance to plastic flow, exhibits a significant and desirable enhancement with increasing modifier content as shown in Figure 10. For the control mix (0% WPB), the stability was recorded at 11.05 kN, yet this value dramatically improved to reach an optimum peak of 19.74 kN at the 15% WPB incorporation level. This substantial 78.6% increase in stability clearly indicates that the WPB acts as an effective stiffening and reinforcing agent within the mixture, which is critical for reducing rutting and permanent deformation under heavy traffic loading. Beyond this optimal threshold, however, the stability begins a declining trend, registering 17.45 kN and 16.25 kN at 20% and 25% WPB, respectively, suggesting that excessive plastic content may lead to coating difficulties or insufficient effective bitumen leading to a weaker structure.

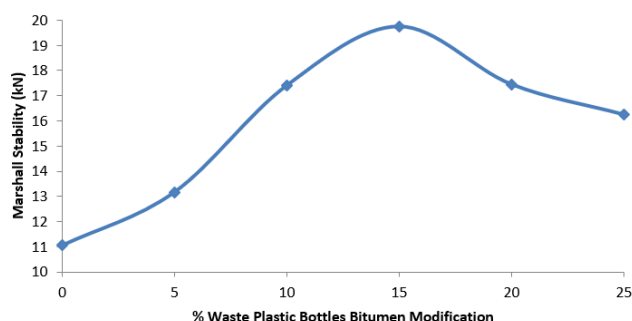


Figure 10. Marshall Stability of WPB Asphaltic Concrete.

Concurrent observation of the Flow values as shown in Figure 11 reveals that the material's flexibility, or its ability to deform before fracture, generally increased with initial modification, peaking at 4.57 mm at 15% WPB compared to 3.43 mm for the neat mix. This increase suggests that the presence of the thermoplastic material, particularly at the optimum dosage, may enhance the mix's resilience by promoting a moderate degree of ductile behaviour, preventing sudden, catastrophic failure, although the absolute value approaches the upper limits typically prescribed for dense-graded mixes.

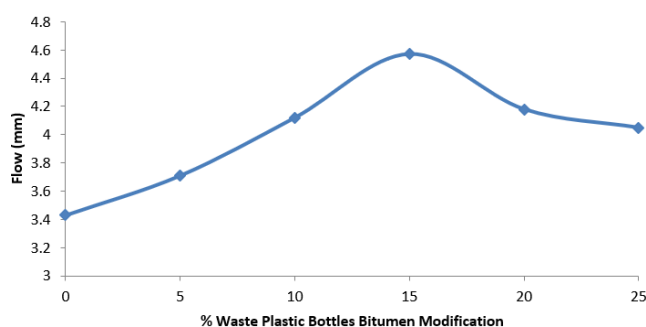


Figure 11. Flow Stability of WPB Asphaltic Concrete.

This necessary trade-off between stiffness and flexibility is most effectively captured by the Marshall Quotient (MQ) as shown in Figure 12, the ratio of stability to flow, which serves as a critical indicator of the mixture's shear stiffness and overall field performance. The MQ mirrors the stability trend closely, rising from 3.22 kN/m for the control mix to a maximum of 4.32 kN/m precisely at the 15% WPB inclusion rate. The attainment of the maximum Marshall Quotient at this 15% modification level confirms it as the most mechanically robust and stable composition, offering the best balance between high load-bearing capacity and controlled deformation, thereby signifying the ideal dosage for practical application in high-performance asphaltic concrete pavements.

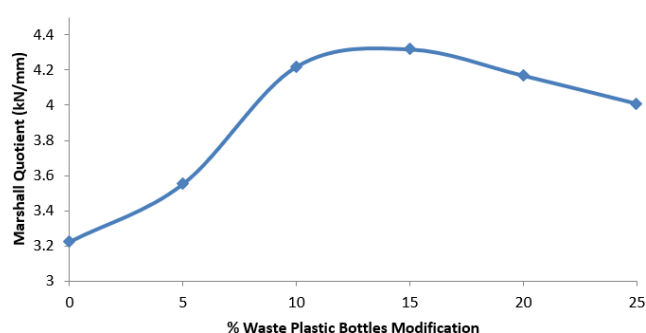


Figure 12. Marshall Quotient of WPB Asphaltic Concrete.

4. Conclusion

The comprehensive evaluation of the physical properties of aggregates and the performance characteristics of the Waste Plastic Bottles (WPB) modified bitumen and asphaltic concrete leads to a clear conclusion regarding the material's engineering viability. The inclusion of WPB successfully alters the rheological characteristics of the binder, leading to a harder material with significantly enhanced high-temperature stability, thereby mitigating the risk of rutting failure in service. Most critically, the mechanical testing of the asphalt mix demonstrated that the optimal modification level, determined to be 15% WPB by weight of bitumen, yields substantial improvements in both Marshall Stability and Marshall Quotient. Specifically, this optimum mix achieved an approximate 78% increase in stability over the control, confirming its superior resistance to permanent deformation. Consequently, the use of WPB in asphalt pavement construction represents a promising, sustainable engineering solution that improves the functional performance of the pavement layer while simultaneously addressing plastic waste management challenges.

Abbreviations

WPB Waste Plastic Bottle

Cu	Coefficient of Uniformity
Cc	Coefficient of Curvature
PET	Polyethylene Terephthalate
LDPE	Low Density Polyethylene
D10	Effective Diameter at 10% Finer
D30	Effective Diameter at 30% Finer
D60	Effective Diameter at 60% Finer
USCS	Unified Soil Classification System
GW	Well Graded Gravel
SP	Poorly Graded Sand
SW/SM	Gap Graded Sand

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Conflicts of Interest

The authors declare no conflicts of interest.

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