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Investigating the Mechanical Properties of Warm Mix Asphaltic Concrete Modified with Crumb Rubber and Waste Plastic Bottle

Akindele A. E.[a, c], Salami L. O.[b*], Akinleye M. T.[c], Salami, M. O.[c], Adeoti F. R.[d], Ajadi E.O.[c] and Ipaye M. A.[c]

[a*]Department of Civil Engineering, Federal Polytechnic, Ede, Nigeria
[b]Department of Civil Engineering, Osun State University, Osogbo, Nigeria
[c]Department of Civil Engineering, Adeleke University, Ede, Nigeria
[d]Department of Civil Engineering, University of Ilorin, Ilorin, Nigeria

***Corresponding Author E-mail:**lukman.salami@uniosun.edu.ng

Abstract: *Warm Mix Asphalt (WMA) technology, recognized for its reduced production temperatures and environmental benefits, serves as a sustainable alternative to conventional asphalt. This study evaluates the combined use of crumb rubber from end-of-life tyres and polyethylene terephthalate (PET) from waste plastic bottles as modifiers in WMA. Crumb rubber and PET, both non-biodegradables, pose significant environmental risks through improper disposal and combustion. In this research, comprehensive laboratory analyses were conducted, including sieve analysis, specific gravity, aggregate crushing and impact values for both fine and coarse aggregates, alongside key bitumen tests such as flash and fire point, penetration, ductility, and softening point. The asphalt mixes were modified with crumb rubber and PET in 2% intervals from 0% to 20% by bitumen weight. Marshall Stability, flow, and quotient were evaluated to assess performance. The results demonstrated compliance with specification standards, with optimal Marshall Stability of 17.6 kN and flow of 6.0 mm at 10% modification, and a maximum Marshall quotient of 5.0 kN/mm at 0%. The incorporation of waste rubber and plastic improved the mechanical performance of WMA, confirming its potential in sustainable pavement engineering.*

Keywords: *Warm Mix Asphalt, Crumb Rubber, Waste Plastic Bottles, Asphalt, Modification, Marshall Stability, Sustainable Pavement, Bitumen Properties*

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1. INTRODUCTION

Asphalt concrete, primarily composed of asphalt binder and aggregates, is central to flexible pavement construction, especially in countries like Nigeria where Hot Mix Asphalt (HMA) is commonly employed (Akinleye and Tijani, 2023). However, the traditional HMA process involves high production temperatures above 150°C, resulting in significant energy consumption and greenhouse gas emissions (Calabi-Floody *et al.,* 2020). This has led to a shift toward Warm Mix Asphalt (WMA), which operates at lower temperatures (100–140°C) and offers up to 30% fuel savings while reducing environmental impact (Akinleye *et al.,* 2020; Milad *et al.,* 2022). WMA still requires further performance optimization to handle the stresses experienced by pavement layers, including wear, rutting, and fatigue cracking (Fan *et al.,* 2019). A promising enhancement approach involves the integration of polymers such as crumb rubber and plastics into the asphalt binder, which improves mechanical performance while addressing waste management challenges (Mahida *et al.,* 2023). Given that aggregates form about 85% of the asphalt mix volume and binders only 10%, modifying the binder significantly influences the entire mixture's behavior under stress (Alemu *et al.,* 2023; Nigatu, 2020).

Waste polymers, especially from tyres and plastic bottles, present severe environmental threats due to their non-biodegradability and harmful emissions when incinerated (Adeniran et al., 2022). Crumb rubber, derived from scrap tyres, helps tackle landfill overflow and environmental hazards while enhancing asphalt performance by increasing viscosity and improving resistance to rutting and fatigue cracking (Li *et al.,* 2021; Sitepu *et al.,* 2020). Studies affirm that rubber particles' elasticity helps absorb traffic-induced stress and contributes to quieter pavement surfaces (Wang *et al.,* 2020). Likewise, waste plastic bottles, mainly made of polyethylene terephthalate (PET), are major contributors to global waste (Ajagbe *et al.,* 2020). Their integration into asphalt increases binder softening points and deformation resistance (Assefa, 2020; Awaeed *et al.,* 2022). Shredded PET acts as a binder modifier when blended with asphalt at elevated temperatures, enhancing pavement strength, flexibility, and longevity (Xu *et al.,* 2021; Ullah et al., 2024). Additionally, using plastic in asphalt supports circular economy principles by transforming waste into valuable construction inputs, thereby reducing reliance on virgin materials and lowering emissions (Raj *et al.,* 2021).

Despite the potential benefits, concerns remain regarding the long-term durability, compatibility, and mechanical behavior of WMA when modified with crumb rubber and plastic bottles (Capitao *et al.,* 2022; Ongel and Hugener, 2020). Traditional HMA poses environmental and energy consumption challenges, while growing waste from tyres and PET bottles exacerbates pollution and landfill pressures (Geyer *et al.,* 2021; Sienkiewicz *et al.,* 2021). This study, therefore, seeks to explore the performance of WMA modified with crumb rubber and plastic waste, focusing on mechanical properties such as strength, elasticity, rutting resistance, and moisture susceptibility. It also evaluates the environmental implications of integrating these materials into WMA, including potential emissions and overall sustainability. The aim is to contribute to sustainable infrastructure development by leveraging waste materials to enhance asphaltic concrete performance, reduce environmental impact, and promote green construction solutions aligned with global sustainability goals (Zaumanis *et al.,* 2024).

The primary aim of this study is to investigate the effect of incorporating crumb rubber and waste plastic bottles into warm mix asphaltic concrete (WMA). To achieve this, the study evaluates the index properties of the aggregates and bitumen, examines the Marshall properties of the modified WMA, and determines the optimal proportion of crumb rubber and plastic bottle content for enhancing performance. The research encompasses both field and laboratory work, with the field phase involving the collection of bitumen, aggregates, crumb rubber, plastic bottles, and filler materials. In the laboratory, standardized tests based on AASHTO, ASTM, BS, and Federal Ministry of Works (2016) specifications were conducted to assess the engineering properties of the mix. The modification levels ranged from 0% to 20% of the bitumen weight in 2% increments. These varying proportions enabled a detailed analysis of the material's mechanical behavior under different modification scenarios.

The justification for this study lies in addressing two pressing concerns: environmental pollution from non-biodegradable waste and the need for more sustainable road construction materials. End-of-life tyres and polyethylene terephthalate (PET) bottles contribute significantly to landfill overflow and pollution, and their reuse in WMA aligns with circular economy goals by converting waste into valuable resources (Geyer *et al.,* 2021; Sienkiewicz *et al.,* 2021). At the same time, WMA reduces energy use and emissions compared to traditional hot mix asphalt (Zaumanis *et al.,* 2024), though concerns about its long-term durability remain (Capitao *et al.,* 2021). Incorporating crumb rubber can enhance the mix's elasticity and deformation resistance, while PET plastic bottles improve its strength and durability under traffic loads and environmental stress (Ongel and Hugener, 2020; Ali *et al.,* 2023). By reducing reliance on virgin bitumen, this study promotes resource conservation and supports international sustainability targets. Ultimately, the findings may inform infrastructure policies that encourage the use of recycled materials in road construction, contributing to greener and more resilient urban development.

II. METHODOLOGY

2.1 Sample Collection and Preparation

The materials used in this study include both conventional and waste-based components sourced locally within Nigeria. Crushed granite, with particle sizes ranging from 15 mm to 21 mm, was used as the coarse aggregate and obtained from a quarry in Ede, Osun State. Quarry dust served as both the fine aggregate and the filler; for fine aggregate, it was sieved to a maximum size of 4.75 mm, while for filler, it was further sieved through a U.S. No. 200 sieve (75 µm) to achieve the required fineness. Sasobit, a warm mix asphalt additive, was procured from Reynolds Construction Company in Ibadan, Oyo State. Crumb rubber with a particle size of 1 mm was sourced from Free Recycling Limited located at Wire and Cable Apata, Ibadan. Waste plastic bottles, primarily PET, were collected from dumpsites around Adeleke University, Ede, and were shredded and melted before use. The binder used in the mix was grade 60/70 bitumen, sourced from a bitumen plant in Ogun State.

2.2 Aggregate Testing

The quality of aggregates used in asphaltic concrete was determined through several standardized laboratory tests. First, a sieve analysis was carried out following BS 812–103.1 (1985) to classify the particle size distribution of both coarse and fine aggregates. Aggregates were oven-dried at 105°C for 12 hours, weighed, and mechanically sieved to determine the percentage passing and retained on each sieve size. The Coefficient of Uniformity (Cu) and Coefficient of Curvature (Cc) were calculated using standard formulas to assess grading characteristics. Next, the specific gravity of aggregates was determined using the pycnometer method in accordance with BS 1377–2 (1990). A dried 10 g sample was weighed in a pycnometer bottle before and after being filled with distilled water, and the specific gravity was computed using recorded mass values. These measurements are essential for volumetric mix design calculations. Furthermore, the Aggregate Crushing Value (ACV) test, conducted according to BS 812–110 (1990), evaluated the aggregate's resistance to gradual compressive loads. A sample retained between the 10 mm and 12.5 mm sieves was compacted in a cylinder and subjected to crushing, after which the percentage of fine particles (passing through 2.36 mm sieve) was used to compute ACV. A lower ACV indicates higher resistance to crushing, a desirable property for pavement aggregates.

Lastly, the Aggregate Impact Value (AIV**)** test was performed in compliance with BS 812–112 (1990) to assess the toughness and impact resistance of the aggregates. Oven-dried samples were sieved and compacted into a standard cylindrical mould in three layers. A 14 kg hammer was dropped from a height of 38 cm to simulate impact loads, and the material passing through the 2.36 mm sieve was measured. The AIV was then calculated as the percentage of fines formed relative to the original sample weight. This test is particularly relevant for assessing the ability of aggregates to withstand sudden impacts during construction activities such as roller compaction. These series of aggregate tests ensure that the materials selected for the modified warm mix asphalt meet structural performance standards and are suitable for use in durable pavement construction.

2.3 Material Testing

i. Penetration Test: The penetration test of bitumen assesses its hardness or softness by measuring the depth, in millimetres, to which a standard loaded needle penetrates vertically within five seconds, while maintaining the temperature of the bitumen sample at 25 °C. The penetration values were obtained using a Penetrometer manufactured in accordance with ASTM D1321, which has a high precision temperature controller, a cold light source, a magnifying glass, and a needle assembly weighing 100 grams total. A graduated dial was connected so that the penetration value could be read. This dial was used to read penetration values up to 0.1 mm.

ii. Flash and Fire Point Test: The Flash and Fire Point Test was conducted to determine the safe temperature range for heating and applying bitumen. In line with ASTM D92 (Cleveland Open Cup Method), the bitumen was heated until fully liquefied and poured into a clean test cup. A test flame was applied at intervals starting 28°C below the expected flash point, with temperature increments of 2 °C. The flash point was recorded as the lowest temperature at which vapours ignited briefly, while the fire point was the temperature at which sustained ignition occurred for at least 5 seconds. Results were corrected for ambient pressure using the formula: *Flash or Fire Point = C + 0.033 × (P – 760)*, where *C* is the observed temperature and *P* is the atmospheric pressure in mmHg.

iii. Ductility Test: The ductility of the bitumen used was also be tested and measured as the distance in centimetres that a standard bitumen briquette can be stretched before the thread snaps. The experiment was performed at 27°C, with the pull applied at a speed of 50 mm per minute. The cross-section of the mould had a minimum width of 10 mm by 10 mm. The bitumen sample was heated until it became fluid, then poured into the briquette assembly and set on a brass plate. All of the equipment, including the brass plate and bitumen briquette, was left to cool in the air.

In addition to leveling the surface, a hot knife was used to chop away any extra bitumen.For 85 minutes, the entire assembly was immersed in a bath that was held at 27°C. After removing the mould's side and hooking the clips onto the machine, the pointer was set to zero. The clips are currently being dragged apart horizontally at a rate of 50 mm per minute, and the distance till a thread break was recorded. The bitumen's ductility rating is indicated by this distance in centimetres.

iv. Softening Point: The softening point of a bituminous material refers to the temperature at which it reaches a defined level of softness under specific test conditions. It serves as a substitute for the penetration test to assess the consistency of bitumen. After assembling the device and positioning the thermometer, ball centering guides, and rings, the beaker was filled with water up to 105 mm deep. To avoid air bubbles on the specimen during the test, the water used was distilled and allowed to cool in a stoppered flask. The starting water temperature should be 5 ± 1°C and maintained for 15 minutes by keeping the beaker in an ice-water bath.After the 15 minutes, the steel balls were placed with forceps, and a gas burner was used to heat the beaker.For the sample used in the first three minutes, the temperature rise at a rate of 48.8°C per minute, falling within the permitted range of ±5°C, which is the temperature at which bitumen must soften.

2.4 Asphaltic Concrete

Table 1 shows the mix proportion of the mix design. The asphalt was produced by keeping the percentage of Sasobit constant at 3.5% of the bitumen (Salami *et al.*, 2023). The percentage modification of crumb rubber tyre and waste plastic bottles in asphaltic concrete production range from 0% to 20% by weight of bitumen, at 2% intervals, the CRT and WPB was added using ratio 1:1. The weight of the aggregate and bitumen used maintain the same value for all mixes. The procedures in ASTM D6927-05 test method were used for Marshall Stability and flow of the asphaltic concrete. Samples of grade 60/70 asphalt cement (bitumen) was used in the production of the asphaltic concrete.

Table 1: Mix design of Asphalt

%	BITUMEN (g)	CA (g)	FA (g)	Filler (g)	Sasobit (g)	CRT (g)	WPB (g)
0	72	804	72	252	2.52	0	0
2	72	804	72		2.52	0.66	0.66
4	72	804	72	252	2.52	1.32	1.32
6	72	804	72	252	2.52	1.98	1.98
8	72	804	72	252	2.52	2.64	2.64
10	72	804	72	252	2.52	3.3	3.3
12	72	804	72	252	2.52	3.96	3.96
14	72	804	72	252	2.52	4.62	4.62
16	72	804	72	252	2.52	5.28	5.28
18	72	804	72	252	2.52	5.94	5.94
20	72	804	72	252	2.52	6.6	6.6

CA is the Coarse Aggregate, FA is the Fine Aggregate, CRT is the Crumb Rubber Tyre, WPB is the Waste Plastic Bottle

The laboratory test conducted on asphaltic concrete include:

i. Marshall stability Test: The stability of the mixture is determined by the greatest load sustained by a compacted specimen at a standardized test temperature of 60°C. The flow was quantified as the deformation in increments of 0.25 mm between no load and maximum load applied to the specimen during the stability test (the flow value could alternatively be calculated in increments of 0.1 mm). The test help to draw a Marshall Stability vs. % bitumen curve and performed in compliance with BS EN 12697-34:2007.In the Marshall Test technique of mix design, three compacted specimens were prepared for each binder component. The coarse and fine aggregates were proportioned to comply with the applicable specifications. The necessary amount of the mixture was obtained to create compacted bituminous mix specimens with an approximate thickness of 69.34 mm. 1200 grammes ofaggregates and filler were utilized to achieve the specified thickness. The aggregates underwent a temperature range of 175°C to 190°C, while the compaction mould assembly and rammer were cleaned and maintained at a pre-heated temperature of 100°C to 145°C.The bitumen was heated to 121°C to 138°C, before adding the heated aggregate and thoroughly mixed. The samples were transferred into the moulds after filter papers were placed at both ends. At a temperature of 130 to 145°C, 1200 g of the mixture was put in a heated mould and compacted with 70 blows each side. The specimen was submerged in a water bath at 60°C for 30 minutes. The specimen was thereafter positioned in the Marshall Stability testing apparatus (plate 3.10) and subjected to a constant deformation rate of 5 mm per minute until failure occurred. The total maximum load in kN, which induces specimen failure, was documented as Marshall Stability. The cumulative deformation measured in increments of 0.25 mm at maximum load was documented as Flow Value.

ii. Marshall quotient:This is the ratio of stability to flow in an asphaltic concrete mixture. It is also referred to as the toughness of asphaltic concrete mixture and Marshall stiffness. The modification with the highest Marshall quotients demonstrates optimal performance. Therefore, this change represents the optimal combined waste polymer or optimal sasobit content, as applicable.

III RESULT AND DISCUSSION

3.1 Properties of aggregate

The results of the physical properties (particle size distribution, specific gravity, bulk density, aggregate crushing and impact values) of aggregates determined in this study are presented and discussed in this section.Fig. 1 shows the particle size distributioncurve for quarry dust and crushed aggregate. According to the analysis, 91% of the quarry dust particles passed through the 2 mm sieve size. Additionally, there is 9% of the material retained on the 4.75 mm sieve size, suggesting that the quarry dust is majorly of medium size (ASTM D2487, 2011). From the curve, the particle diameter which 60%, 30% and 10% of the quarry dust particles is finer denoted as D_{60}, D_{30} and D_{10} are 0.9, 0.4 and 0.15, respectively. From these values, the coefficient of uniformity (C_u) and coefficient of curvature (C_c) obtained are 6.0 and 1.2 for quarry dust. Since, the values of C_u equals 6 and the C_c fall within 1 and 3, the sharp sand used in this study is well graded as specified ASTM D 2487 (2011). The particle size distributioncurve for crushed granite is as well shown in Fig. 4.1. About 92% of the crush granite passed through the 26.5 mm sieve size, while less than 5.1% of the material retained on 4.75 mm sieve size indicate that the crushed granite is predominantly of medium size. From the curve, the particle diameter D_{60}, D_{30} and D_{10} are 20.2, 10.8 and 10.4, respectively. From these values, the C_u and C_c obtained are 1.9 and 1.4. Since the values of C_u is lower than 4 and C_c falls between the range of 1 and 3, the crushed granite used in this study is poorly graded as specified ASTM D 2487 (2011).

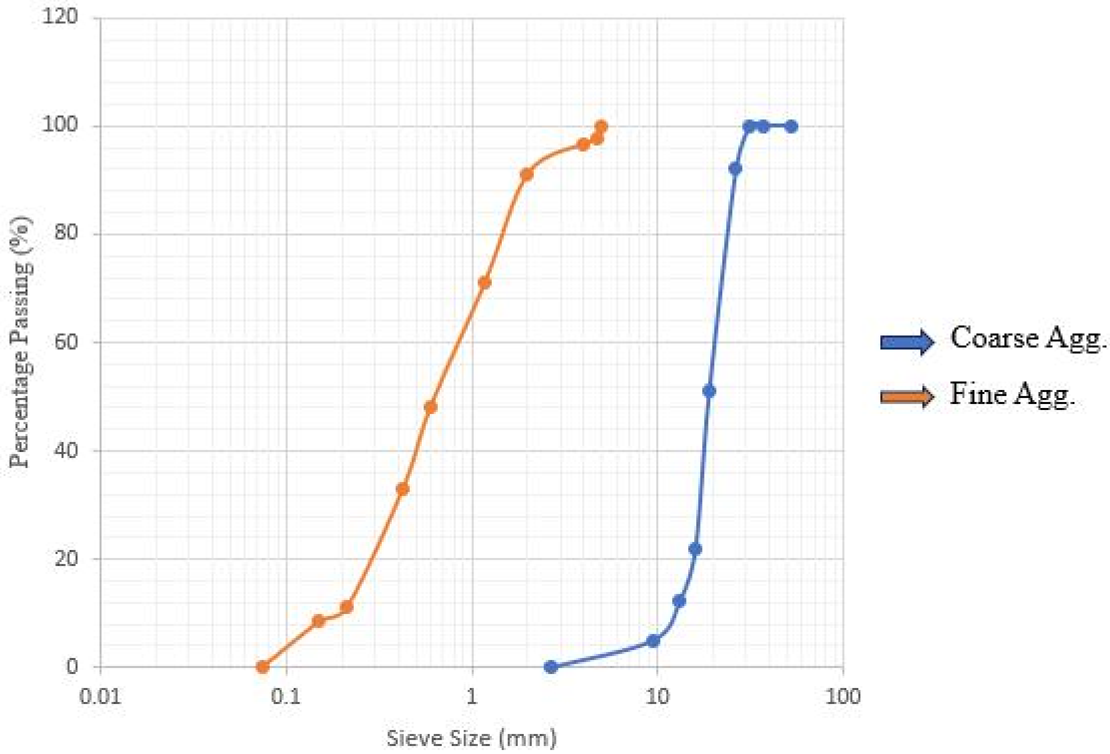

Fig. 1: Particle size distribution of quarry dust and crushed granite

Table 2 presents the properties of the aggregates used in this research work. These properties include aggregate impact value (AIV), aggregate crushing value (ACV), bulk density, specific gravity, and water absorption. The water absorption values for the filler, quarry dust, and crushed granite were 1.19%, 1.25%, and 0.38% respectively. These values represent the percentage of water the materials can absorb relative to their dry weight when fully saturated. All values fall within the typical range of 1–10% specified for normal weight aggregates, as noted by Neville (2021).In terms of specific gravity, the coarse aggregate recorded a value of 2.7, indicating a dense material that contributes positively to the strength and stability of asphaltic concrete. The specific gravity of the quarry dust was 2.6, also within acceptable limits. The filler, however, had a specific gravity of 1.9, which is relatively lower due to its finer particle size. Nonetheless, all values align with the standard range specified by BS 882 (1992), confirming the suitability of the materials for asphaltic concrete production.

The bulk densities of the materials were also evaluated. The filler had a bulk density of 1,450 kg/m³, quarry dust was 1,445 kg/m³, and crushed granite was 1,375 kg/m³. These differences are attributed to variations in particle shape and size, which affect how tightly the particles can pack together. All values fall within the ASTM C128 (2015) standard range of 1,200–1,750 kg/m³ for normal weight aggregates.

The Aggregate Crushing Value (ACV) of the crushed granite was found to be 27.07%, which is within the acceptable limit specified in IS 2386 (Part IV): 1963. This indicates a relatively high resistance to crushing under load, reflecting good material quality.

Finally, the Aggregate Impact Value (AIV) of the crushed granite was determined to be 18.75%. This value is well below the maximum permissible limit of 45% for road construction materials, as recommended by Alexander and Mindess (2020). Thus, the granite used is considered suitable for construction projects requiring aggregates with good strength and durability under moderate impact conditions.

Table 2: Properties of the aggregates

Properties	Filler	Sharp sand	Crushed granite
Water absorption (%)	1.19	1.25	0.38
Specific gravity	1.9	2.6	2.7
Bulk density (kg/m³)	1450	1455	1375
Aggregate impact value (%)	-	-	19.25
Aggregate crushing value (%)	-	-	27.07

3.2 Properties of bitumen

Table 3 presents the properties of the bitumen used in the asphaltic concrete mixture. The evaluated properties include penetration, softening point, ductility, viscosity, flash point, fire point, and specific gravity. These results are compared against standards set by various organizations such as the Federal Ministry of Works (FMW), American Society for Testing and Materials (ASTM), Bureau of Indian Standards (BIS), and the Asphalt Institute (AI).The penetration value obtained for the bitumen is 62.66 mm at a standard temperature of 25°C, as shown in Table 4.2. Penetration indicates the hardness of bitumen;higher values suggest a softer material. Thus, a penetration of 62.66 mm implies that the bitumen is relatively soft and more susceptible to deformation under load.

The softening point of the bitumen is 54.21°C, which defines the temperature at which the bitumen becomes soft and starts to deform. A softening point of this magnitude indicates that the bitumen has good thermal resistance, offering enhanced durability and improved resistance to rutting at higher service temperatures.

The ductility of the bitumen is measured at 99 cm, which reflects its ability to stretch without breaking. This value exceeds the minimum requirement of 75 cm specified by BIS, indicating good flexibility and elongation capacity.The viscosity of the bitumen was recorded at 76 seconds, falling within the FMW standard of ≤100 seconds. This indicates favourable flow characteristics and workability during mixing and compaction.The flash point and fire point of the bitumen were found to be 246.5°C and 288.5°C, respectively. These values exceed the minimum requirements specified by ASTM standards, signifying that the bitumen is safe to handle at typical production temperatures and has a low risk of ignition.Lastly, the specific gravity of the bitumen is 0.98, which means it is slightly less dense than water. Although this falls slightly below the FMW recommended range of 1.01–1.06, it is still considered acceptable for use in asphaltic concrete mixtures.

Table 3: Properties of Bitumen

Standard	Penetration (mm)	Softening (°C)	Ductility (cm)	Flash Point (°C)	Fire point (°C)	Specific Gravity
Results Obtained	68	55	99	246	288.5	0.98
FMW	60-70	48-56	≤100	Min.250	Min.250	1.01-1.06
ASTM	60-70	47-58	-	Min. 230	Min. 230	0.97-1.06
BIS	-	-	≥75	-	-	-
AI	-	>50	5-100	-	-	-

N.B.: *FMW is Federal Ministry of Works (2007); ASTM is American Society of Testing and Materials, D5-97 for penetration, D36-95 for softening, and D2041 for specific gravity; BIS is Bureau of Indian Standards (1986); and AI is Asphalt Institute (1991).*

3.3 Marshall Properties of Crumb rubber and Waste plastic bottle Modified Warm Mix Asphaltic Concrete

To investigate the effect of Crumb Rubber Tyre (CRT) combined with Waste Plastic Bottle (WPB) as modifier on performance of the Warm asphalt mix, eleven percentages by weight of bitumen (0, 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20%) were considered. Three Marshall specimens were tested for each percentage of CRT/WPB. Table 4 shows the result obtain to evaluate the effect of adding CRT/WPB as a modifier to Warm asphalt mixture as well determine the optimum proportion of Crumb Rubber Tyre (CRT) combined with Waste PlasticBottle (WPB) ranging from 0to 20%. Table 4 presents properties of asphaltic concrete.

Table 4: Properties of Asphaltic concrete

SAMPLE NO	% CRT/ WPB	MASS IN AIR	MASS IN H2O	GT	GM	VOLUME OF VOID (Vv)	% VOLUME OF BITUMEN(Vb)	VMA (%)	VFB	STABILITY (KN)	FLOW (mm)	Marshall Quotient (KN/mm)
1	0	1168	635	2.300	2.191	4.712	12.299	17.011	72.298	14	2.8	5.0
2	2	1198	645	2.300	2.166	5.800	12.158	17.958	67.704	14.7	3.0	4.9
3	4	1178	635	2.300	2.169	5.666	12.175	17.842	68.241	15.5	4.0	3.8
4	6	1090	590	2.300	2.180	5.207	12.235	17.441	70.147	16	4.5	3.5
5	8	1188	645	2.300	2.188	4.866	12.279	17.144	71.620	16.4	4.5	3.6
6	10	1190	655	2.300	2.224	3.280	15.802	19.082	82.809	17.6	6.0	2.9
7	12	1192	640	2.300	2.159	6.102	12.119	18.221	66.513	16.3	5.5	2.9
8	14	1166	625	2.300	2.155	6.282	12.096	18.378	65.817	16	5.0	3.2
9	16	1192	635	2.300	2.140	6.944	12.010	18.955	63.363	15.5	4.5	3.4

10	18	1148	625	2.300	2.195	4.553	12.319	16.872	73.013	15.2	4.5	3.3
11	20	1182	640	2.300	2.181	5.171	12.239	17.411	70.297	13.4	4.5	2.9

i. Bulk Specific Gravity: Bulk Specific Gravity (GM) is a key parameter in evaluating asphalt mix density. It reflects the overall compactness of the mix, including both aggregates and bitumen, and is essential for determining the volumetric properties of the asphalt concrete. GM shows slight fluctuations across the CRT/WPB percentages. It started at 2.191 for 0 % CRT/WPB and peaked at 2.224 at 10 % addition, suggesting better compaction and reduced air voids at this level. Beyond 10 %, the GM values slightly declined, which may indicate reduced compatibility or mix uniformity at higher modifier content.

ii. Volume of Voids: Volume of Voids (Vv) reflects the air spaces in the compacted mix. The lowest void volume was 3.280 at 10%, showing the densest mix with improved interlocking and reduced permeability. At higher additions (16 % with 6.944, and 20 % with 5.171), Vv increased again, possibly due to poor dispersion or stiffness caused by excessive CRT/WPB.

iii. Volume of Bitumen:Volume of Bitumen (Vb) reflects the proportion of the total volume of the compacted asphalt mixture that is occupied by bitumen. From the result obtained the Volume of Bitumen increased significantly at 10% CRT/WPB (15.802), suggesting higher binder absorption bitumen coating. Lower Vb at 0% (12.299) and 2% (12.158) indicates less interaction between bitumen and aggregates. Values at higher CRT/WPB percentages were relatively steady (~12.0–12.3), except for the spike at 10%.

iv. Voids in Mineral Aggregate: The amount of intergranular void space between the aggregate particles in a compacted asphalt mix is known as the Voids in Mineral Aggregate (VMA). VMA represents the amount of space available to hold bitumen and the voids required in the mixture. (VMA) is a crucial factor in the design of hot mix asphalt (HMA) mixes (John *et al.,* 2021). VMA's main goal is to guarantee a comparatively high

v. bitumen concentration to cover the mix's aggregate particles. From the result obtained (VMA) increased from 17.011 % (0 %) to a peak of 19.082 % at 10 %, then slightly declined again. This parameter reflects space available for bitumen and air; a higher VMA at 10% suggests improved bitumen film thickness and durability.

vi. Voids Filled with Bitumen: Voids Filled with Bitumen (VFB) is the percentage of the Voids in Mineral Aggregate (VMA) that is filled with bitumen, rather than left as air voids. It's essentially a measure of how effectively the available void space is filled by binder, which impacts durability and moisture resistance (Akinleye *et al.,* 2023; Vuthipalli*et al.,* 2023). In this study the Voids Filled with Bitumen reached its maximum value at 10 % (82.809), confirming optimal binder content and improved coating of aggregates. Lower VFB at 2 % (67.704) and 12–16 % (~63–66) shows less efficient binder usage at these levels.

vii. Stability: The Marshall stability principle refers to the resistance to plastic deformation of cylindrical specimens of a bituminous mixture subjected to lateral loading. The stability values obtained from the standard specification for Marshall compacted specimens at a test temperature of 60˚C indicate the mixture's strength. From the data obtained, Fig. 2 present a graphical chart on how the addition of CRT/WPB enhance the marshal stability from 14.000 kN (0%) to the highest at 17.600 kN (10%), showing that CRT/WPB enhanced the mix strength, the improvement performance of the CRT/WPBModified asphalt mixtures may arise from effective adhesion between the bitumen binder and waste plastic bottles, which enhances the stability and durability of the asphalt mix while also improving resistance to moisture-induced damage, similarly case observed by (Li *et al.,* 2021). A slight decrease was observed beyond 10%, suggesting that excessive addition of CRT or WPB may lead to embrittlement or incompatibility. This could be due to the increased presence of CRT/WPB particles filling the voids within the mixture, resulting in a more compact and less flexible structure.Fig. 2 reveals theMarshall stability.

viii. Flow: Flow values are quantified as vertical deformation of specimens in hundredths of inches, from the initiation of loading to the maximum load achieved by the compacted specimen during testing at 60˚C. Flow measurements are acquired concurrently with the execution of the Marshall stability test. Elevated flow values signify a plastic mixture that is more susceptible to persistent deformation. In this study the Marshall Flow value increased with CRT/WPB addition, peaking at 6.0 mm at 10%, then slightly reduced as shown in Fig. 3. This shows improved flexibility and resistance to cracking at optimal CRT/WPB levels. The elevated flow values within the acceptable range suggest that the amended asphalt mixture has increased flexibility, hence improving the hot mix asphalt pavement's capacity to deform without cracking (John *et al.,* 2021; Akinleye *et al.,* 2025; Salami *et al.,* 2025a; 2025b). Excessive flow (above 4 mm) is observed from 10% and above, which may affect structural stability if not managed properly. Marshall Flow is shown in Fig. 3.

ix. Marshall quotient: The Marshall Quotient (MQ) is defined as the ratio of Marshall Stability to Flow. It gives a single value that reflects the stiffness of the asphalt mix. From Fig. 4.4, the highest MQ (5.0) occurs at 0 % replacement, meaning the control mix is very stiff. As replacement increases, MQ gradually decreases, reaching the lowest point (2.93) at 10 %, where stability peaks (17.6 kN).An asphalt mixture with a high MQ value is inflexible, indicating that it possesses adequate density and stability. A low MQ signifies that the asphalt mixture is brittle and inadequately stable, increasing the likelihood of surface cracking and horizontal displacement in the direction of travel. A high Marshall Quotient asphalt mixture is therefore less prone to crack as a result of persistent deformation (Rangan *et al.,* 2023, Akinleye *et al.,* 2025; Salami *et al.,* 2025a; 2025b). From 10 – 14 %, MQ stays within a well-balanced range (3.0–3.2) indicating a mix that resists both rutting and cracking. MQ begins to rise again slightly after 14 %, suggesting the mix may be stiffening back up. The Marshall Quotient trends suggest that the mix becomes optimally balanced at 10–12 % replacement, with excellent strength and flexibility. Marshall Quotient is shown in Fig. 4.

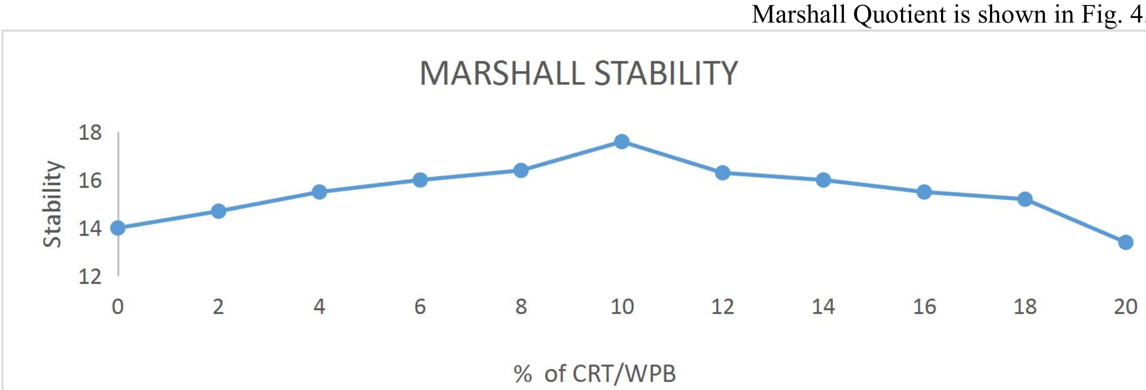

Fig.2: Marshall Stability

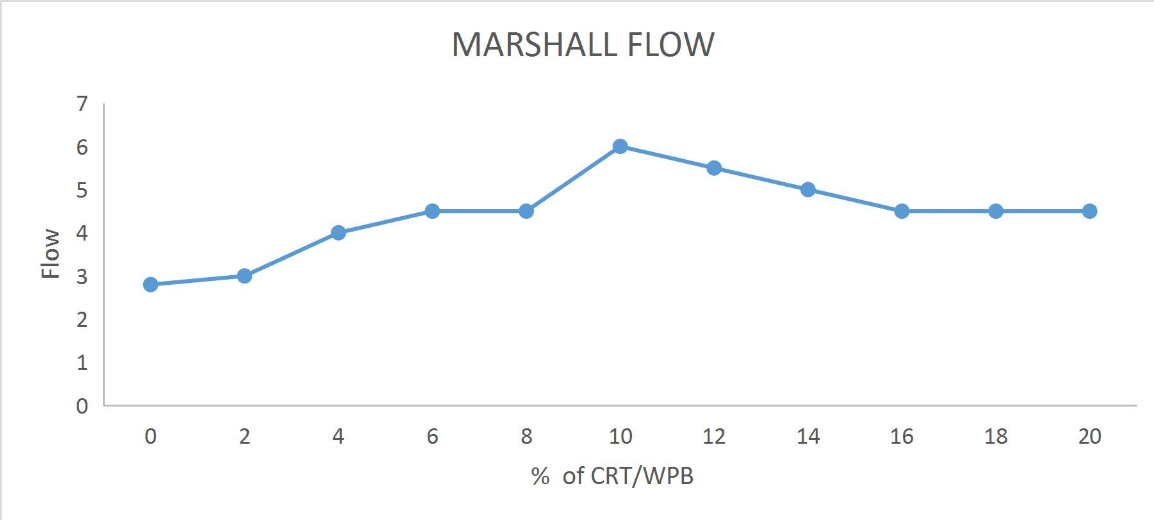

Fig. 3: Marshall Flow

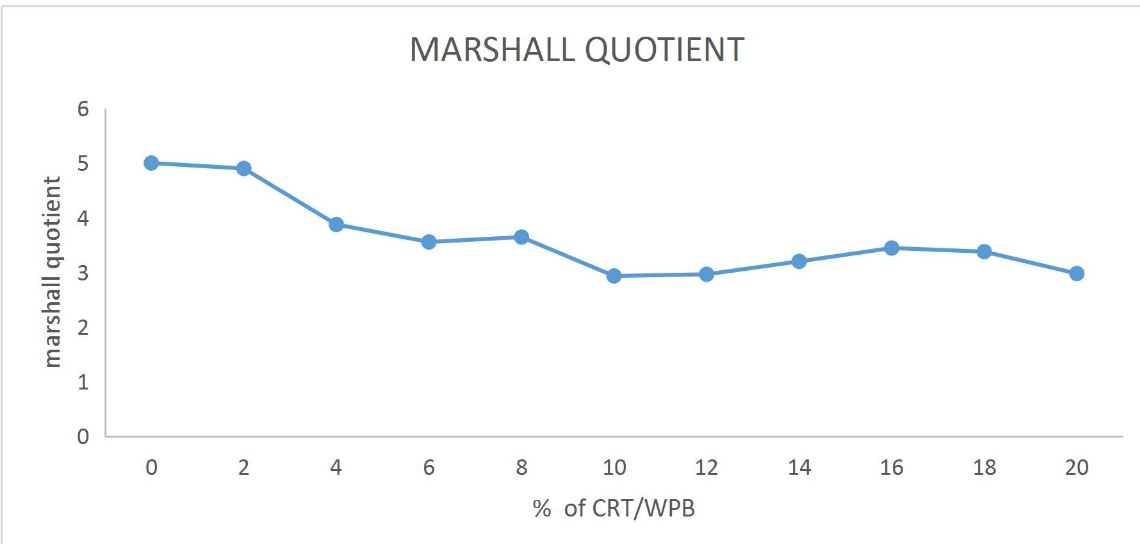

Fig. 4: Marshall Quotient

IV. CONCLUSION

This study evaluated the performance of warm mix asphaltic concrete modified with crumb rubber and waste plastic bottles in a 1:1 ratio, added in increments of 2% up to 20% by weight of bitumen. Laboratory tests on aggregate and bitumen properties, as well as Marshall stability and flow, confirmed the materials' suitability for asphalt production based on standard specifications. The modified mix showed improved Marshall properties, with the optimal performance achieved at 10% modification, yielding a stability of 17.6 kN, a flow of 6.0 mm, and a Marshall quotient of 4.6 kN/mm, all within the acceptable limits set by the Federal Ministry of Works (2016). Based on these findings, the study recommends adopting 10% crumb rubber and plastic modification for asphalt production in Nigeria to enhance pavement performance and reduce environmental waste. It also calls for further research into other mechanical properties like rutting resistance and ITS, and suggests government-backed test roads to validate long-term field performance. This research contributes to knowledge by confirming the suitability of crumb rubber and PET bottles as modifiers in asphalt concrete, demonstrating their ability to enhance pavement quality while offering a sustainable method for managing non-biodegradable waste in the construction industry.

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