ABUAD Journal of Engineering Research and Development (AJERD)
ISSN (online): 2645-2685; ISSN (print): 2756-6811

Volume 8, Issue 1, 61-70

Exploring the Expediency of Waste Materials as Modifiers for Bitumen Mixes

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Date Submitted: 12/10/2024
Date Accepted: 28/01/2025
Date Published: 02/02/2025

***Abstract**: This research explores industrial waste materials (waste plastic bottle and waste sachet water) as potentially modifiers for Hot Bitumen Mix (HBM) and Warm Bitumen Mix (WBM). This research becomes necessary because of the poor performance of HBM and WBM. Review of literature revealed that independent use of Waste Plastic Bottle (WPB) and Waste Sachet Water (WSW) significantly enhanced the performance of HBM and WBM. However, literature is scanty on blended use of WPB and WSW. The HBM samples were produced using 60/70 penetration grade of bitumen. Additive (sasobit) was added to the bitumen at 3.5 wt. % of the bitumen for the production of WBM. The HBM and WBM were modified by incorporating blended WPB and WSW thereby forming a composite mixture. The composite was varied at a proportion of 0 – 18 wt. % at 2% interval by 1:1 of the bitumen. The index properties of the HBM and WBM were analyzed. The modified HBM and WBM samples were characterized for microstructure using the X-Ray Fluorescence (XRF). The softening point and penetration index increased with increasing composite mixtures. The penetration reduced with increasing content of the composites. However, the optimum performances were obtained at 10 and 14 wt. % of WPB and WSW for HBM and WBM replacement, respectively, with specific gravity, penetration index, ductility and viscosity of 96, 54, 92, and 75% for HBM and 91, 32, 88, and 89% for WBM, higher than the control mix, respectively. The XRF revealed an enhancement in the adhesion and interlocking in the mineral structure. Exploring WPB and WSW as a modifier for the bitumen mixtures is feasible due to the improved performance of the bitumen mixes. Furthermore, incorporation of the waste materials through their conversion into useful raw materials is an environmental way of waste disposal, and sustainability.*

Keywords: *Waste Materials, Hot Bitumen Mix, Warm Bitumen Mix, Sustainability, Modifier*

1. INTRODUCTION

Waste materials are pollutants that adversely affect our environs as a result of economic activity, utilization and increasing population [1,2]. Virtually everyone on earth's surface is generating waste. The growing rate of many sectors has resulted in the constant exploitation of natural resources and the vast generation of waste materials. Environmental wastes have a negative impact on the air, water, and land if not appropriately handled. According to [3], global solid waste generation in 2012 is 1.30 billion tonnes. However, it is expected to increase to 2.2 billion tonnes in 2025. In addition to environmental concerns, researchers and decision-makers are adopting waste as secondary materials instead of traditional construction materials due to rising costs of natural resources and a rapidly dwindling natural resource base. As a result, waste must be effectively managed when it is generated, including reuse, recycling, storage, treatment, and recuperation of energy [2]. According to [4], various form of waste generation can be categorized as; biodegradable and Non-biodegradable industrial waste, agricultural waste, sewage sludge, building and demolition debris, health-related waste, radioactive waste, agricultural and animal waste. The continuous generation of industrial wastes such as Waste Plastic Bottle (WPB) and Waste Sachet Water (WSW) causes environmental issues related to their disposal. In terms of disposal and management, the ongoing production of WPB and WSW poses environmental concerns. According to [5], global plastic production in 2015 increased from 2 million tonnes in 1950 to 380 million tonnes, for a total output of 7.8 trillion tonnes. According to [5], Nigeria was second in plastic imports from 1990 to 2017, with 19.9 million tonnes. According to [6], polymer can be found in practically every fissure in Nigeria. As a result, the aim of this research is to address the issue of environmental sustainability through the recycling of non-biodegradable WPB and WSW. According to [7, 8, 11 - 16], this accounts for a considerable share of municipal waste on a global scale. Polymer problem can be addressed by recycling, reduction, and reuse [10, 14-16].

Bitumen is the binder of asphaltic concrete, and the primary source is petroleum. It is a thick, viscous black liquid whose behaviour in asphaltic concrete is determined by the material's composition, loading, and ambient conditions. Hot bitumen mix (HBM) is produced at temperatures above 140°C, while Warm Bitumen Mix (WBM) is produced at temperatures ranging from 100 to 140°C [3-5]. As a result, HBM has a high production temperature, which causes harmful discharge of gaseous emissions. The HBM manufacturing process consumes an abnormally high amount of energy which results into release of hazardous gaseous discharges such as Sulphur dioxide (SO_2), carbon dioxide (CO_2), and volatile organic compounds (VOCs) thereby endangering worker safety, and causes environmental damage [6 - 8]. As a result of HBM's negative impacts, research into WBM manufacturing is necessary. To reach a maximum temperature reduction of 30°C, the bitumen production temperature must be lowered by adding a special additive called sasobit. Sasobit is a South African indigenous substance. The manufacturer of Sasobit recommended adding 3% of the additive to a solution with a maximum temperature reduction aim of 30°C. In contrast, the current investigation used the 3.5% sasobit content recommended by [7]. The rationale for its adoption is that [7] established the best mixture for Nigerian conditions by adjusting the percentage of organic component (sasobit) using locally accessible materials. It is critical to emphasize that research into WBM generation is necessary due to the negative effects of HBM. The WBM on the other hand, produces lower performance characteristics than conventional HBM [7, 8].

However, WBM reduces the bitumen's engineering characteristics. As a result, in contrast with conventional HBM, the current study investigated the performance issue of WBM. The continuous generation of industrial wastes such as Waste Plastic Bottle (WPB) and Waste Sachet Water (WSW) causes environmental issues relating to their disposal. In terms of disposal and management, the current production of WPB and WSW poses environmental concerns. According to [7, 8, 9, 10 11 - 16], current production of those wastes accounts for a considerable share of municipal waste globally. Recycling, reduction, and reuse are approaches for addressing the polymer problem [10, 14-16]. According to [17], recycled WSW is viscous in nature, which improves the engineering properties of asphaltic concrete and increases cohesiveness. The effect of WSW on modified HBM was investigated by [17-19] and it was observed that WSW material increased the bitumen's softening point, suggesting higher resistance to deformation, and decreased the penetration value, showing improved shear resistance. Furthermore, according to the findings of [13, 15, 16, 20], bitumen modified with WPB have a higher softening point and greater resistance to deformation. A review of prior studies [13, 15, 16, 20] revealed that WPB and WSW, when utilized independently, improved the engineering properties of HBM mixtures. Despite several studies on utilizing waste materials in asphaltic concrete manufacture, there has been little to no research on the binary blending of WPB and WSW as bitumen modifiers.

This research explored the expediency of WPB and WSW as bitumen modifiers. The HBM and WBM were modified by incorporating blended WPB and WSW thereby forming a composite mixture. The composite was varied at a proportion of 0 – 18 wt. % at 2% interval by 1:1 of the bitumen. The index properties of the modified HBM and WBM were examined. The microstructure of the modified HBM and WBM were analyzed using the X-Ray Fluorescence (XRF). Findings from this research would reduce environmental waste, thereby promoting environmental sustainability and improving the quality of flexible road pavement.

2. MATERIALS AND METHOD

The materials and method used during the research are spelt out in the subsequent sections.

2.1 Materials

Bitumen that was adopted for this study was obtained from Construction Products Nigeria Limited, based in Ilorin, Nigeria. The bitumen was classed as Viscosity Grade 30 (VG-30). The VG-30 grade bitumen is usually referred to as the 60/70 penetration grade. The specific gravity of bitumen is 1.01. Figure 1a shows a sample of bitumen. The WPB and WSW were collected from Adeleke University Ede's halls of residence and cafeteria. Figure 1b - f displays the water samples from a WPB and WSW. Figure 1g depicts the shredder used in shredding the WPB and WSW. The sasobit was supplied by Reynolds Construction Company Ltd. of Ibadan, Nigeria. Sasobit is the organic additive used in the production of WBM. The WBM was produced by incorporating a 3.5% sasobit into the bitumen. Figure 1h contains a sasobit sample.

2.2 Method

The WPB and WSW's fundamental physical parameters evaluated in the laboratory include specific gravity, melting point, density, and size. The WPB and WSW sizes were determined using a vernier calliper. The WPB and WSW were sun dried after purifying the WPB and WSW with distilled water. The WPB and WSW were crushed at a Crushing Workshop in Ilesa (Latitude: 70°18'67"N, Longitude: 35°6'57"E), Nigeria. However, the WPB corks were exempted from the crushing. This study adopted the dry procedure of modification, which entails blending the WPB and WSW to the bitumen in a dry form. Furthermore, equivalent weights of crushed blended WPB and WSW were blended in a 1:1 ratio to modify the bitumen. The bitumen was modified with of 0 – 18 wt. % at 2% interval by 1:1 crushed WPB and WSW. The bitumen was improved by mixing crushed blended WPB and WSW into HBM and WBM at temperatures over the blended WPB and WSW point of melting. A variety of experimental tests were performed on bitumen samples, including ductility, specific gravity, penetration, viscosity, softening point, loss on heating, penetration index, flash point, and fire point. The penetration index was obtained using Equation. 1. The experimental procedures were carried out in accordance with the standardized method of testing established by [22-29]. The data gathered for this investigation were analyzed utilizing sources such as [29]. The microstructural property of the unmodified and modified HBW and WBM were determined using the X-Ray Fluorescence analyzer.

$$PI = \frac{1952 - 500 \log pen - 20\, softening\ point}{50 \log pen - softening\ point - 120} \qquad 1$$

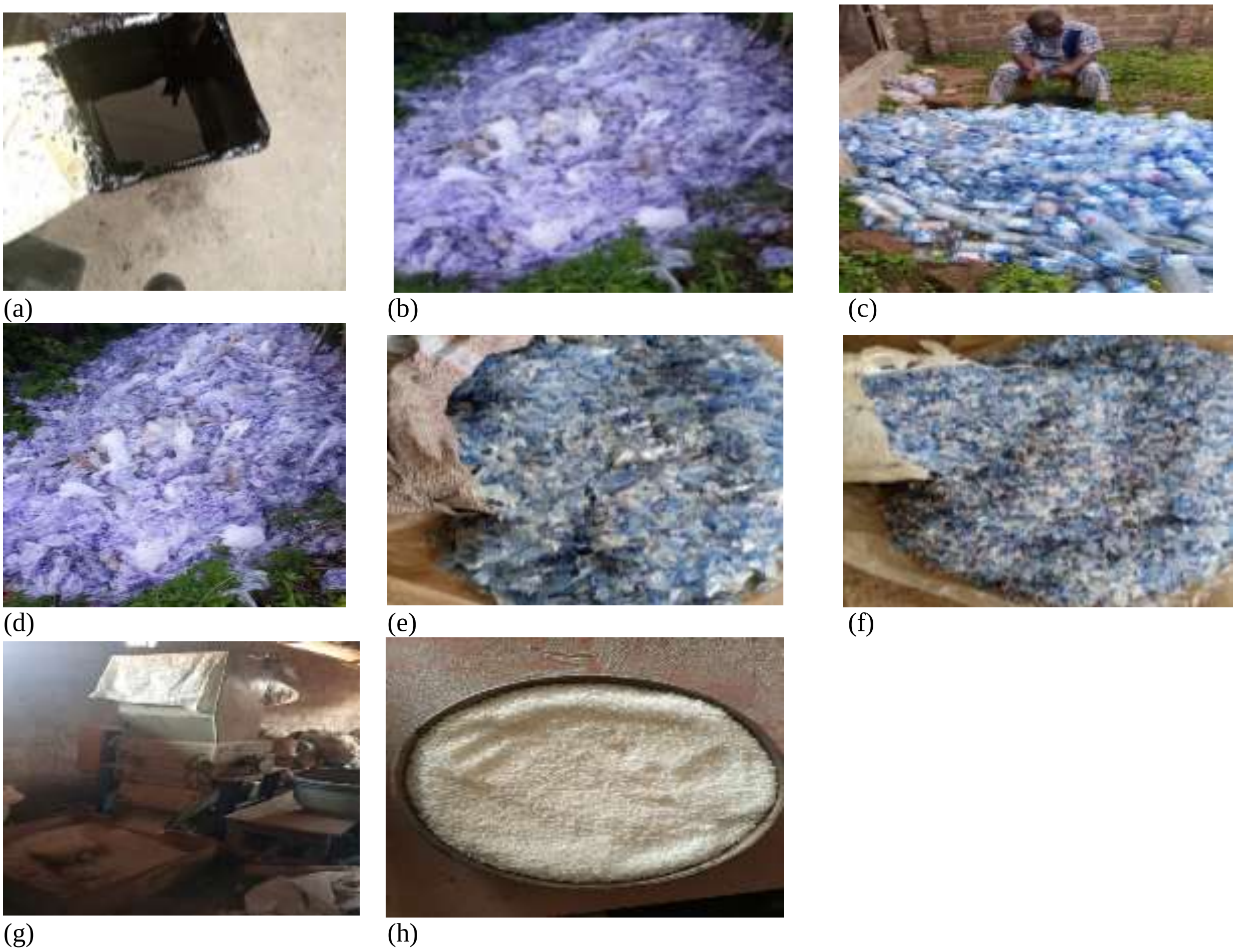
(a) (b) (c)
(d) (e) (f)
(g) (h)

Figure 1: Materials utilized during the research: (a) Sample of bitumen, (b) WWS in a landfill (c) WPB prior to shredding, (d) WWS prior to shredding, (e) WPB following shredding, (f) WWS following shredding, (g) Shredder, (h) Sample of sasobit

3. RESULTS AND DISCUSSION

3.1 Properties of Blended WPB and WSW Modified Hot and Warm Bitumen Mixes

3.1.1 Penetration

The HBM penetration with blended WPB and WSW is shown in Table 1. As modified blended WPB and WSW increases, penetration decreases. The maximum penetration value was 70 mm with 2% blended WPB and WSW, and the lowest was 33 mm with 18%. [30-33] showed comparable trends. Similar to [8, 11, 14, 16, 19], increasing WPB in bitumen mix decreased penetration. Thus, a decrease in penetration metrics reflects an increase in modified bitumen stiffness and WPB content [30-32]. The penetration ranged from 0% to 10%, meeting [29] requirement. However, the blended WPB and WSW of 12 to 18% modification does not fall within the required specification. Table 2 shows how blended WPB/WSW affects WBM penetration. According to the statistics, penetration diminishes when the blended WPB and WSW percent modification increases. Maximum penetration was 70 mm at 0% blended WPB and WSW. However, 18% blended WPB and WSW had a minimum penetration of 38 mm. As overall WPB and WSW content increased, modified bitumen penetration decreased (Table 2). Thus, enhanced bitumen's total WPB and WSW content indicates stiffness by decreasing penetration values [10, 31, 32]. Numerical penetration values of 0 – 8% satisfy [26, 29]. The criteria were not met for 12-18% blended WPB and WSW modification penetration. As blended WPB and WSW content increases in WBM, the WBM becomes hardened thereby reducing penetration and lowering penetration values. Thus, modifying bitumen with WPB and WSW increased WBM deformation resistance.

3.1.2 Softening point

The Blended Waste Polymer (BWP) effect on HBM softening is shown in Table 1. Only 0 and 2% of softening point values surpassed the [23] criterion, while all others fulfilled the [29] criteria. Increased BWP enhanced softening point measurements. Table 1 shows that the modified polymer's softening point values improve with an increment in BWP content. This is corroborated by [8, 11, 14, 16, 31-33], which used the WPB and WWS separately. Adding WPB and WWS to bitumen improves its heat resistance and reduces its tendency to soften in colder temperatures, thereby improving road life span [11, 16, 31]. Table 2 shows that BWP affects WBM softening point when WPB and WSW concentration increases. Data obtained from this study is corroborated by [11, 16-19], when the WPB and WSW were applied separately. Blending WPB and WSW to bitumen boosts its heat resistance and lessens its susceptibility to softening in warmer climates, thereby improving road performance over time [11, 14, 16, 31-33]. The WPB and WSW modification of WBM decreases bitumen's temperature sensitivity.

3.1.3 Penetration index

The rate at which BWP affects penetration index measurements for BWP-modified HBM and WBM is shown in Table 1. The HBM studies demonstrated that penetration index rates rise in parallel with BWP content. According to [34], bitumen with a high penetration index is more resistant to thermal degradation and has a higher resilience. As a result, the higher penetration index values for the bitumen mixture suggest that the modified bitumen has better flexibility and is less sensitive to temperature variations. The WBM results show that penetration index rates grow in parallel with the blended WPB and WSW content. According to [35], increasing the penetration index improves bitumen's elasticity and resistance to temperature variations. This implies a fair match between the BWP percentage ratio and the penetration index.

3.1.4 Ductility

The influence of BWP on ductility of HBM and WBM is revealed in Table 1. The HBM studies showed that bitumen treated with 0 – 10% BWP became more ductile. Increasing ductility from 0% to 10% BWP decreased ductility. The BWP enhanced bituminous mixture ductility. Researches by [11, 14–16, 34, 36–39], showed that bitumen treated with WPB and WSW separately without blending the waste polymer decreased in ductility. However, the blended WPB and WWS increased the ductility of modified bitumen, explaining the difference in ductility between this study and others. Thus, due to its increased ductility, modified bitumen can withstand significant deformation before rupture. For the WBM, ductility increased from 0 to 14% blended WPB and WSW. Thus, all WBM ductility values meet [22, 29]. Integrating WPB and WSW increased WBM ductility. As BWP substitution rises, sample ductility increases. However, prior studies [36-39] indicated that bitumen treated with WPB and WSW independently decreased ductility. Increased viscosity from WPB and WSW enhances the ductility of modified heated bitumen, which may explain the difference between this work and the literature. This investigation found that modified bitumen can endure large deformation before rupture due to its higher ductility values.

3.1.5 Viscosity

The influence of BWP on the viscosity of HBM and WBM is revealed in Table 1. According to the HBM data, viscosity values increased as the BWP content increased from 0 to 18% BWP modification. However, variations from the required standard specification account for only 18% of all BWP modifications. The results showed that viscosity values increased linearly as the amount of BWP increased from 0 to 18%. According to the data collected as revealed in Table 2, the viscosity values of the WBM increased as the blended waste polymer content increased, ranging from 0 to 18% modification. However, the cumulative variance between WPB and WSW changes and the needed standard specification is only 18%. The results show that viscosity values increased linearly as the proportion of BWP increased from 0 to 18%.

3.1.6 Flash and fire points

The influence of BWP on the flash and fire points of HBM is shown in Table 1. According to HBM data, flash point values rose with BWP content. The findings indicate that all BWP changes meet the 250℃ criterion as reported in [27]. The HBM could be heated to 263 - 285℃ without exploding. [8, 9, 11, 35, 44] found that flash and fire points values increased with the WPB and WSW, thereby corroborating this study's data. Table 1 shows that BWP concentration increases fire point values, indicating that BWP reduces heated bitumen mixture combustibility. The percentage of BWP modification increases the heated bitumen mixture's fire point linearly. This study is in tandem with those of [16, 20, 21]. Table 2 shows that WBM flash point values decreased as overall WPB and WSW content increased. The WPB, WSW, and sasobit make heated bitumen more flammable. Flash points from 0 to 6% satisfy the requirements of [24, 27]. However, incorporating all WPB and WSW modifications meets the minimum temperature requirement of 250℃ [29]. Thus, the WBM can be heated to 263–312°C without exploding. This notion is supported by [9, 17, 19], who found that values increased with the WPB and WSW content. Table 2 shows that adding sasobit to WPB and WSW increases the combustibility of the heated bitumen mix by decreasing fire point values as BWP concentration increases. The blended WPB and WSW alteration linearly improved the heated bitumen mixture's fire point. Temperature differences in the mixture may induce this [37, 42]. Results from this study correlate with those from [7, 14, 19].

Table 1: Properties of BWP modified HBM

% blended polymer modification	**Penetration (mm)**	**Softening Point (°C)**	**Penetration Index**	**Ductility (cm)**	**Viscosity (Pa.s)**	**Flash Point (°C)**	**Fire Point (°C)**	**Loss on Heating (WT %)**	**Specific Gravity**
0	70	55	0.94	112	2653	263	312	0.14	1.01
2	69	56	1.04	113	2807	265	317	0.14	1.02
4	67	59	1.66	116	3091	266	321	0.16	1.03
6	63	60	1.72	118	3122	270	323	0.17	1.04
8	61	61	1.73	121	3209	274	328	0.20	1.05
10	60	61	1.73	122	3539	276	335	0.20	1.05
12	48	65	1.89	115	3778	281	341	0.21	1.07
14	41	69	2.08	108	3851	283	344	0.21	1.08
16	35	71	2.13	102	3861	284	347	0.23	1.09
18	33	78	3.03	101	4091	285	353	0.23	1.11
FMW	60-70	48-56	-	100 Min.	-	250 Min.	-	0.2 Max.	1.01-1.06
ASTM	60-70	47 Min.	-	100 Min.	4000Max.	250 Min.	-	0.2 Max.	1.00-1.06

Table 2: Properties of BWP modified WBM

% blended polymer modification	**Penetration (mm)**	**Softening Point (°C)**	**Penetration Index**	**Ductility (cm)**	**Viscosity (Pa.s)**	**Flash Point (°C)**	**Fire Point (°C)**	**Loss on Heating (WT %)**	**Specific Gravity**
0	70	55	0.94	112	2653	263	312	0.14	1.01
2	68	58	1.37	114	2735	262	310	0.17	1.03
4	64	61	1.81	118	2793	256	306	0.18	1.03
6	63	62	2.02	120	2878	250	304	0.19	1.05
8	60	64	2.36	121	2880	241	299	0.22	1.07
10	58	67	2.79	125	2929	240	296	0.23	1.07
12	56	68	2.86	127	2947	238	293	0.23	1.09
14	54	72	2.93	128	2953	237	288	0.24	1.10
16	41	74	3.18	116	2967	232	282	0.25	1.11
18	38	77	3.38	108	2976	229	278	0.25	1.12
FMW	60-70	48-56	-	100 Min.	-	250 Min.	-	0.2 Max.	1.01-1.06
ASTM	60-70	47 Min.	-	100 Min.	4000Max.	250 Min.	-	0.2 Max.	1.00-1.06

3.1.7 Loss on heating

The loss on heating values for BWP-modified HBM and WBM are shown in Tables 1 and 2, respectively. Loss on heating values of 0-10% caused by BWP changes for the HBM satisfy the requirements given in the standards [25, 29]. However, data's that deviated from the standards by 12-18% BWP were unacceptable. The flash and fire point values rise in proportion to the loss on heating. This is because certain characteristics of WPB and WSW evaporate during the heating process, increasing the weight loss of the modified HBM. The bitumen mixture experienced a linear increase in loss of heating value when BWP changes increased from 0 to 18%. The findings of this research are congruent with those reported by [36, 37]. The blended WPB and WSW changes boosted the WBM's loss of heating value from 0 to 18%, resulting in a linear rise. According to the requirements of [25 and 29], the optimum amount was determined to be 6%. The findings obtained in this investigation are consistent with those published by [42 - 44]. The flash and fire point values rise in proportion to the loss on heating. This is because certain qualities of WPB and WSW evaporate during the heating process, increasing the weight loss of the modified WBM.

3.1.8 Specific gravity

The specific gravity data for BWP-modified HBM and WBM are shown Tables 1 and 2, respectively. Based on the data acquired for the HBM, the specific gravity values for BWP spanning from 0 to 10% range between 1.01 and 1.06, as specified by [27, 29]. The findings of [8, 10, 11, 14, 21] provide additional support for this claim. However, BWP changes vary by 12 - 18% stipulated by [27 and 29] requirements. The variation is due to the result obtained for heating loss with 10% as the optimal change to the BWP fraction. For the WBM, the specific gravity values for the WBM vary from 0 to 6% blended WPB and WSW, which falls within the range of 1.01 to 1.06 stipulated by the [27 and 29] requirements. The discrepancy can be traced to the result obtained for heating loss after a 6% change to the ideal proportion of blended WPB and WSW. This is consistent with the findings of [16, 19, 42]. Specific gravity values increased in a linear pattern with the amount of blended WPB and WSW, from 0 to 18%. The observed increase in quantity could be due to the fluidity of the bitumen mixtures as the temperature rises.

3.2 Microstructural property

The XRF analysis of blended WPB and WSW modified HBM and WBM samples and their control/unmodified samples are shown in Table 3. The blended WPB and WSW modified WBM has the greatest SiO_2 content of 53.71% compared to HBM control, WBM control, and blended WPB and WSW modified HBM. The SiO_2 is associated with strong mechanical strength, hardness, and mineral structure interlocking [46, 47]. Thus, blended WPB and WSW modified WBM samples have high mechanical strength, hardness, and mineral structure interlocking. In terms of Al_2O_3, BWP modified WBM has the greatest concentration at 13.47%. The Al_2O_3 improves bitumen adherence, making combinations more rut-resistant [46]. Pozzolanic oxides (SiO_2 and Al_2O_3) improve asphalt mixture internal and surface cohesiveness [48]. Oxides also improve bitumen moisture resistance [46]. High SiO_2 concentration can lead to poor moisture damage performance due to inadequate adhesion between asphalt components and the mineral [49]. The mixed WPB and WSW modified WBM sample had the highest CaO concentration of 5.36%. Research by [46, 48 - 50] discovered that alkaline CaO improves adhesion in asphaltic concrete, enhancing resistance to moisture damage and stripping. Thus, improved WBM samples may improve asphaltic concrete moisture damage and stripping resistance.

Table 3: XRF analyses of HBM and WBM samples

Element	Concentration (%)			
	HBM Control	WBM Control	HBM + Blended	WBM + Blended
Fe_2O_3	2.85	2.99	2.91	2.99
TiO_2	0.57	0.84	0.72	0.89
CaO	4.28	5.05	4.85	5.36
K_2O	-1.59	-2.86	-2.44	-3.32
SiO_2	50.09	50.65	53.56	53.71
Al_2O_3	9.61	11.39	10.60	13.47
MgO	0.48	0.47	0.48	0.47

4. CONCLUSION

The expediency of hot and warm bitumen mixes enhanced with industrial waste materials has been evaluated. The HBM and WBM with blended WPB and WSW at 0 - 18% decreased penetration while increasing softening point, penetration index, ductility, specific gravity, and viscosity. Thus, a decrease in penetration indicates an increase in shear resistance. Consequently, the blended WPB and WSW increased the shear resistance of the HBM and WBM. In higher temperatures, blended WPB and WSW modified HBM and WBM have a greater softening point, showing heat and deformation resistance. As a result, the blended WPB and WSW improved the heat and deformation resistance of the HBM and WBM. Consequently, the blending of WPB and WSW modified HBM and WBM improved bitumen engineering performance. The XRF revealed an enhancement in the adhesion and interlocking in the mineral structure. This finding is significant as it demonstrates that exploring waste materials at 10 and 14 wt. % optimal substitution improves HBM and WBM, respectively and promotes environmental sustainability. It is worth noting that this research study aligns with Sustainable Development Goals 12 and 13. The use of waste plastic bottle with its bottle neck is hereby recommended for further research. Moreover, further studies should conduct Dynamic Shear Rheometer (DSR) test, Multiple Stress Creep and Recovery (MSCR) test at high temperatures and Linear Amplitude Sweep (LAS) test at intermediate temperatures.

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