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Physical Properties and Marshall Stability of High-Density Polyethylene and Rubber Crumb Modified Bitumen for Road Application

Sunday Ojoajogwu IGOMU*, Tajudeen Kolawole BELLO, Muhammed Tijani ISA

Department of Chemical Engineering, Ahmadu Bello University, Zaria, Kaduna State, Nigeria

sunday2destiny@gmail.com, tkbello@abu.edu.ng, mtisa@abu.edu.ng

*Correspondence: sunday2destiny@gmail.com; Tel.: +2348036457170

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Abstract: *Standard bitumen used in road construction may not meet engineering requirements due to it becoming brittle in cold weather and softening in hot weather. This study investigates the mechanical and physical properties of bitumen modified with high-density polyethylene (HDPE) and rubber crumb for road applications. Bitumen sourced from Ilaje, Ondo State, Nigeria, underwent characterisation tests including penetration, softening point, ductility, and fire point. Waste HDPE and rubber crumb, collected from dumpsites in Zaria, Kaduna State, Nigeria, were sorted, washed, dried, and milled to a size of 600 microns. The waste plastic was then blended with the bitumen using an optimised mix design obtained from the design of experiment. Characterisation tests (Marshall stability, penetration, softening point, ductility, and fire point) were performed on the resulting waste plastic-modified bitumen. The test results showed that the stability of the road asphalt increases as the proportion of HDPE and rubber crumb used in the bitumen modification increases. The control group (100% bitumen) exhibited the lowest Marshall stability (19.81 kN, 13.12 kN, and 17.82 kN for samples A, B, and C, respectively). The stability of sample A increased by 62.2%, the stability of sample B increased by 75.6%, and that of sample C increased by 56.6%. Based on the research findings, modifying bitumen with waste materials offers several advantages for road construction, which are reducing material costs as waste plastics and tires are readily available, waste utilisation reduces environmental impact, and modified bitumen enhances road durability.*

Keywords: Marshall stability, high-density polyethylene, crumb rubber, bitumen, waste polymer.

1. INTRODUCTION

The term "plastic" encompasses a wide range of polymeric materials that play a crucial role in fulfilling the demands of an increasingly global economy [1]. Once plastic materials reach the end of their useful life and are discarded, they become plastic waste. Additionally, post-industrial waste, resulting from manufacturing processes, contributes to the overall plastic waste stream [2]. The global usage of plastic bottles is steadily rising. However, the production and recycling processes associated with plastic bottles have adverse environmental impacts. Plastics do not biodegrade naturally, necessitating the adoption of alternative approaches to recycle plastic materials [3]. Bitumen modification can enhance the performance of road surfaces, and there exists a variety of modifiers that can be employed for this purpose [4]. Waste plastics are among these modifiers, offering economic advantages and easy accessibility. By utilizing waste plastics as modifiers in road surfaces, it is possible to minimize material waste and simultaneously enhance the performance of the roads [5].

In accordance with the European standard (EN 12597), bitumen is described as an adhesive and waterproof material with minimal volatility [6]. This substance originates from either crude oil or naturally occurring asphalt and exhibits a significant solubility in toluene [7]. Bitumen exhibits high viscosity or solid-like properties at typical environmental temperatures [8]. It is widely acknowledged that the intrinsic properties of bitumen are significantly influenced by its processing and manufacturing methods, as well as the qualities of the crude oil from which it is derived. Generally, the yield of bitumen increases with the use of heavier crude oil [9]. From a functional perspective, bitumen needs to have sufficient fluidity at high temperatures (around 160 °C) to facilitate pumping and workability, ensuring a uniform coating of aggregates during mixing. Additionally, it should exhibit adequate stiffness at elevated temperatures (typically around 60 °C) to resist rutting based on local temperature conditions [7]. Lastly, it should maintain a soft and elastic nature, when the temperatures are low to withstand thermal cracking. Furthermore, due to the significant increase in traffic volume and speed, unplanned overloading has resulted in a considerable reduction in the lifespan of asphalt pavements, leading to higher maintenance costs and increased risks for road users. Consequently, to improve the performance characteristics of neat bitumen, various ingredient has been introduced and successfully employed in numerous applications. These additives and modifiers, such as hydrocarbons, oxidizers, antioxidants, polymers, chemical modifiers, extenders, and anti-stripping agents, have been utilized to improve the performance of bitumen [9]. The objectives of this research are to produce and characterize waste high-density polyethylene and rubber crumb-modified bitumen by doing property and Marshall stability tests on it; to know how suitable the waste plastic-modified bitumen will be for possible road application.

2. MATERIALS AND METHODS

The binder, that was used for the study is neat bitumen obtained from Ilaje, Ondo state, Nigeria. Before utilizing the bitumen, various tests and analyses were performed on it, including penetration, ductility, softening point, and fire point tests. Waste plastic mainly HDPE and Reclaimed Tire Tube Rubber was gotten from the roadside, garbage collectors, and dumpsites. Household plastics were also collected for the project in Zaria, Kaduna State. Collected plastics were sorted, washed, sundried, and heated in an air-tight container, then board milled to a size of 600 microns at the chemical engineering department, Ahmadu Bello University, Zaria, Kaduna state using the milling machine. The waste plastic composed of HDPE and Reclaimed Tire Tube Rubber was collected in weight percent of bitumen, HDPE, and rubber crumb gotten from Design Expert Version 13, using mixture method (simplex Lattice), which is, Bitumen (90% - 100%), HDPE (0% - 10%), Rubber Crumb (0% - 10%) displayed in Table 1. The waste plastic was heated to a temperature of 120 °C - 130 °C for melting to take place. The bitumen was heated to a temperature of 160 °C - 170 °C for melting to take place and they were mixed with a stirrer, using the percentage by mass formulated by the Design Expert as shown in Table 2, and the mixture was stirred manually for 30 minutes and the temperature was kept constant at 160 °C - 170 °C using a thermometer. A polymer bitumen mixture was prepared and used to carry out the Marshall stability, penetration, softening point, ductility and fire point test as shown in Table 3.

Table 1: Parameter for process formulation from design expert using mixture method (simplex lattice)

S/No	Material	Low (%)	High (%)
1	Bitumen	90	100
2	High Density Polyethylene	0	10
3	Rubber Crumb	0	10

Table 2: Percentage by mass of bitumen, HDPE and rubber crumb from design expert using mixture method (simplex lattice)

No of Runs	% Mass of Bitumen	% Mass of HDPE	% Mass of Rubber Crumb
1	90	5	5
2	96.67	1.67	1.67
3	91.67	1.67	6.67
4	95	5	0.00
5	95	0.00	5
6	100	0.00	0.00
7	93.33	3.33	3.33
8	90	10	0.00
9	91.67	6.67	1.67
10	95	5	0.00
11	100	0.00	0.00
12	90	0.00	10
13	90	0.00	10
14	90	10	0.00

Table 3: Physical properties of bitumen used in this study

S/No	Test	Standard	Result
1	Penetration (100 g, 5 s, 25 °C), 0.1 mm	ASTM D5	94
2	Ductility (25 °C, 5 cm/min), cm	ASTM D113	110+
3	Softening point (°C)	ASTM D36	45
4	Fire point (°C)	ASTM D92	295

3. RESULTS AND DISCUSSION

3.1 Marshall Stability and Flow Test

Tables 4 and 5 show the stability and flow result from run 1 to run 14 of different, ratio of bitumen, HDPE and rubber crumb with different bitumen weight of mix, of 5%, 5.5%, 6% been sample A, B and C.

Table 4: Marshall stability result of waste plastic modified bitumen

Runs	% Ratio of Bitumen, HDPE and Rubber Crumb	Marshall Stability Result in kN		
		A	B	C
1	90.00:5.00:5.00	41.302	42.521	29.904
2	96.67:1.67:1.67	33.670	33.530	23.209
3	91.67:1.67:6.67	52.432	26.467	31.461
4	95.00:5.00: 0.00	37.654	23.287	28.091
5	95.00:0.00:5.00	36.333	31.881	34.861
6	100:0.00:0.00	19.810	13.118	17.818
7	93.33:3.33:3.33	30.413	53.649	39.905
8	90.00:10.00:0.00	34.410	34.653	41.057
9	91.67:6.67:1.67	39.086	41.539	37.577
10	95.00:5.00:0.00	37.654	23.287	28.091
11	100:0.00:0.00	19.810	13.118	17.818
12	90.00:0.00:10.00	34.073	43.138	40.668
13	90.00:0.00:10.00	34.073	43.138	40.668
14	90.00:10.00:0.00	34.410	34.653	41.057

Marshall stability is a crucial parameter in road construction, especially when evaluating the quality and durability of asphalt mixtures used in pavement design. The Marshall stability test assesses the resistance of an asphalt

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specimen to deformation and cracking under specific conditions, simulating the stresses experienced by roads due to traffic loads and environmental factors [13]. Table 4 shows the table of measured stability versus the ratio of waste plastic modified bitumen for sample A, B and C, with run 3 (i.e. ratio 91.67:1.67:6.67) having the highest measured stability result of 52.432 kN for sample A, with run 6 and 11 (i.e. ratio 100:0.00:0.00) which is the control, that is bitumen without waste plastic, having the lowest measured stability result of 19.81 kN for sample A. For sample B, run 7 (i.e. ratio 93.33:3.33:3.33) is having the highest measured stability result of 53.649 kN with run 6 and 11 (i.e. ratio 100:0.00:0.00) having the lowest measured stability of 13.118 kN, while For sample C, run 8 and 14 (i.e. ratio 90:10.0:0.00) is having the highest measured stability of 41.057 kN, with run 6 and 11 (i.e. ratio 100:0.00:0.00) having the lowest measured stability of 17.818 kN for sample C.

The stability of sample A increased by 62.2%, the stability of sample B increased by 75.6% and that of sample C increased by 56.6%. The increase in stability can be attributed to improved adhesion between the aggregate, waste plastic and bitumen. It can be seen that the stability values for the mixtures met the Federal Government of Nigeria specification of not less than 3.5 kN [12]. From the result, there is an impact of high-density polyethylene and rubber crumb on the bitumen with the control (i.e. ratio 100:0.00:0.00) having the lowest measured stability, this is because it was not blended with high density polyethylene or rubber crumb.

Table 5: Flow result of waste plastic modified bitumen

Runs	% Ratio of Bitumen, HDPE and Rubber Crumb	Flow Result in mm		
		A	B	C
1	90.00:5.00:5.00	6.1	5.8	5.0
2	96.67:1.67:1.67	4.6	3.7	3.8
3	91.67:1.67:6.67	6.9	4.7	4.0
4	95.00:5.00: 0.00	5.0	6.2	5.5
5	95.00:0.00:5.00	4.0	5.0	5.8
6	100:0.00:0.00	4.8	4.5	5.0
7	93.33:3.33:3.33	4.1	8.0	5.6
8	90.00:10.00:0.00	4.4	5.85	5.15
9	91.67:6.67:1.67	5.0	5.0	5.0
10	95.00:5.00:0.00	5.0	6.2	5.5
11	100:0.00:0.00	4.8	4.5	5.0
12	90.00:0.00:10.00	5.3	5.5	6.3
13	90.00:0.00:10.00	5.3	5.5	6.3
14	90.00:10.00:0.00	4.4	5.85	5.15

Table 5 shows the table of flow versus the ratio of waste plastic modified bitumen for sample A, B, and C, with run 3 (i.e. ratio 91.67:1.67:6.67) having the highest flow result of 6.9 mm for sample A, with run 5 (i.e. ratio 95:0.00:5.00), having the lowest flow result of 4.0 mm for sample A. For sample B, run 7 (i.e. ratio 93.33:3.33:3.33) has the highest flow result of 8.0 mm with run 2 (i.e. ratio 96.67:1.67:1.67) having the lowest flow of 3.7 mm, while For sample C, run 12 and 13 (i.e. ratio 90:0.00:10.0) is having the highest flow of 6.3 mm, with run 2 (i.e. ratio 96.67:1.67:1.67) having the lowest flow result of 3.8 mm for sample C. The flow of sample A increased by 42%, the flow of sample B increased by 53.8% and that of sample C increased by 38.7%.

In the Marshall stability test, the flow value is a measurement of the deformation or "flow" experienced by an asphalt sample under a specified load and temperature. It represents the amount of horizontal deformation the sample undergoes at its maximum load [13]. The flow value obtained from the test is an essential parameter and has significant effects on road construction. Flow value is an indicator of the quality of the asphalt mix. A higher flow value might indicate that the asphalt mixture is susceptible to deformation under load, suggesting potential issues with rutting or permanent deformation on the road surface The flow value is inversely related to stability. Lower flow values typically correlate with higher stability. A lower flow value indicates that the asphalt mixture is less likely to deform under traffic loads, leading to a more stable road surface [12]. The result shows the impact of high-density polyethylene and rubber crumb on bitumen with the rate of deformation of the control (i.e. 100:0.00:0.00) been 4.8 mm for sample A, 4.5 mm for sample B and 5.0 mm for sample C.

Table 6: Property test result done on waste plastic modified bitumen

Runs	% Ratio of Bitumen, HDPE and Rubber Crumb	Penetration	Softening point, °C	Ductility, mm	Fire Point, °C
1	90.00:5.00:5.00	7.7	69.7	12.7	334
2	96.67:1.67:1.67	18.33	66.5	26.5	300
3	91.67:1.67:6.67	32.3	53	43	360
4	95.00:5.00: 0.00	21.7	68	78	300
5	95.00:0.00:5.00	27	46	65	310
6	100:0.00:0.00	94	45	110	295
7	93.33:3.33:3.33	18	64	24.3	300
8	90.00:10.00:0.00	30.3	66	8	310
9	91.67:6.67:1.67	10.3	73	15.03	310
10	95.00:5.00:0.00	21.7	68	78	300

Runs	% Ratio of Bitumen, HDPE and Rubber Crumb	Penetration	Softening point, °C	Ductility, mm	Fire Point, °C
11	100:0.00:0.00	94	45	110	295
12	90.00:0.00:10.00	56.3	60	40	320
13	90.00:0.00:10.00	56.3	60	40	320
14	90.00:10.00:0.00	30.3	66	8	310

3.2 Property Test Done on Waste Plastic Modified Bitumen

The results of the penetration test conducted on waste plastic modified bitumen are shown in Table 6. It indicates the hardness or softness of the bitumen modified from waste plastic. The bitumen is grade 80/100, according to Table 6, where run 1, ratio 90.00:5.00:5.00, has the lowest penetration of 7.7 and runs 6 and 11, ratio 100:0.00:0.00, which is the control, have the maximum penetration of 94. The results show that run 1, with a ratio of 90.00:5.00:5.00, is more difficult than runs 6 and 11, which have a ratio of 100:0.00:0.00. It demonstrates the effect of high-density polyethylene and rubber crumb on bitumen by demonstrating how the bitumen hardens when these materials are applied.

The results of the softening point test conducted on waste plastic modified bitumen are shown in Table 6. It indicates the temperature at which deformation and melting start to occur. According to the table, run 9 ratio 91:67: 6.67:1.67 has the maximum softening point of 73 °C, while run 6 and 11 ratio 100:0.00:0.00, which is the control, has the lowest softening point of 45 °C. The table's findings indicate that bitumen's softening point temperature rises with the addition of waste plastic. This illustrates how bitumen is affected by rubber crumb and high-density polyethylene.

The results of a ductility test conducted on waste plastic modified bitumen are shown in Table 6. In comparison to bitumen alone, it indicates the ductility of the waste plastic modified bitumen. According to the table, runs 6 and 11 with ratio 100:0.00:0.00, which is the control, have the maximum ductility of 110+ cm, whereas runs 8 and 14 with ratio 90.00:10.00:0.00 have the lowest ductility of 8 cm. The outcome demonstrates that the more plastic added, the less ductile the bitumen becomes, which explains why waste plastic modified bitumen becomes more ductile the less plastic is added. This illustrates how discarded plastic affects bitumen.

The results of a fire point test conducted on waste plastic modified bitumen are shown in Table 6. It indicates the temperature at which the material ignites and begins to burn. To determine the effect of waste plastic on bitumen, it analyses the temperature ratios of bitumen changed with waste plastic and bitumen alone, which serves as the control. Run 3 ratio 91.67:1.67:6.67 has the maximum fire point of 360 °C, whereas runs 6 and 11 of ratio 100:0.00:0.00 have the lowest fire point of 295 °C, according to the table. Based on the results, we can conclude that bitumen's fire point increases with the amount of plastic added, and decreases with the amount of plastic added. The table indicates that there is a high fire point for the ratio of high-density polyethylene to rubber crumb. This illustrates how discarded plastic affects bitumen.

4. CONCLUSION

The Marshall stability result indicated that the bitumen, high density polyethylene, and rubber crumb ratios used to modify bitumen increase road stability. The control bitumen had the lowest stability, measuring 19.81 kN for sample A, 13.118 kN for sample B, and 17.818 kN for sample C. The penetration test on waste plastic modified bitumen showed that the bitumen becomes harder when high-density polyethylene and rubber are added. The softening point test showed that the addition of waste plastic increases the softening point temperature, while the ductility test showed that the more plastic is added, the less ductile the bitumen becomes. The fire point test compared the temperature at which the substance ignites and starts burning between the waste plastic modified bitumen and the control bitumen.

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