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Investigation of the Properties of Waste Expanded Polystyrene (EPS) Modified Bitumen

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Abstract

The "white pollution'' caused by the indiscriminate disposal of waste-expanded polystyrene (EPS) packaging foams in Nigeria not only poses a serious environmental threat but also results in significant waste of resources. Again, the poor waste management practices adopted in most of the urban and rural areas in Nigeria also compounded this situation, coupled with the known fact that polymeric materials generally do not decompose (i.e., are non-biodegradable) easily, thereby making them serve as a threat to the surrounding environment. Given resolving this problem, these discarded EPS packaging foams were used in the modification of 60/70 bitumen in this study, as it has been reported that polymer modifiers are known as a possible solution for improving road life in the face of increasing and heavy traffic loading when suitably incorporated into the virgin bitumen. The binder physical tests were carried out on the virgin bitumen and the hot mix waste EPS-modified bitumen samples at modifier contents of 2.5, 5.0, 7.5, 10.0, 12.5, and 15.0%. The results from the tests showed that the best-improved properties were achieved at 5.0 % EPS modifier content with increased softening point (53°C), flash point (275°C), and decreased penetration (50 dmm), while its computed penetration index (-0.48) value indicated that this blend falls within the category of the most acceptable road bitumen. Waste EPS is a suitable bitumen modifier, which enhanced its performance and could equally solve the problem of "white pollution" in Nigeria.

Keywords: *Bitumen, Polymer Modified Bitumen, Waste Expanded Polystyrene (EPS), Test*

1. Introduction

Waste is simply anything thrown away once it is no longer needed. In some places, something that could be regarded as garbage could be a valuable resource. Waste management is inadequate and ineffective in many urban and rural areas of most developing countries. Waste generation and accumulation are inevitable, but they can be reduced by taking several actions, including recovering and recycling solid waste materials and reducing and reusing them [1]. Six of Africa's largest garbage yards are located in Nigeria, according to D-Waste's 2014 Waste Atlas report on the top 50 waste yards worldwide. The three largest cities in Nigeria—Ibadan, Lagos, and Port Harcourt—are home to these landfills. Managing public solid garbage is one of the most significant environmental issues faced by emerging nations [2].

Plastics have become a necessary commodity in modern life, and since 1950, the global production of plastics has been steadily increasing at a rate of 10 % per year [3]. According to estimates, the amount of plastic waste produced worldwide reached 390.7 million metric tons in 2021, growing by 4% annually [4]. Because it is a polymer, expanded polystyrene (EPS) is commonly referred to as Styrofoam. Because of its impact resistance, shapeability, and thermal insulating qualities, it is primarily used as a packaging material. These characteristics make it suitable for protecting thousands of different objects, such as electrical devices, freezers,

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refrigerators, cookers, machinery, and parts. The majority of families' increasing use of these in-demand products and resources would surely lead to significant production of EPS packing foams, which are usually thrown away carelessly. Polystyrene, which has the chemical formula $(C_8H_8)_n$, contains carbon and hydrogen atoms. Heat easily softens and molds polystyrene because the system is easily distorted above its glass transition temperature. Meanwhile, EPS is commonly used in cushions, insulation, and packaging and its negligent disposal causes "white pollution" that endangers human and aquatic life. Styrene monomer was categorized by [5] as "reasonably anticipated to be carcinogenic to humans" in its most current Report on Carcinogens (RoC); however, there was either insufficient evidence of a cause-and-effect relationship between styrene exposure and cancer in experimental animals or little evidence of cancer in humans.

However, the majority of highway construction industries' over-reliance on conventional, resource-intensive materials, such as bitumen binders, has sparked grave concerns and called for immediate action. Bitumen is a black or dark-colored, viscous liquid or solid with sticky properties that is mostly composed of hydrocarbons that are soluble in carbon disulphide (CS_2) and are obtained from petroleum or naturally occurring asphalt. Bitumen is mostly utilized in the construction of roads as an asphalt concrete binder or adhesive, and it is also used in the manufacture of roofing membranes, waterproofing compounds, and various sealants. Because bitumen is made from crude oil, which varies in composition depending on its source, it is challenging to pinpoint the exact breakdown of hydrocarbon groups. In general, bitumen is categorized into two groups: asphaltenes and maltenes, which are composed of saturates, aromatics, and resins [6].

As the world contends with the dual challenges of waste management and sustainable construction, innovative solutions have become increasingly vital. With the increasing accumulation of plastic waste, the construction sector is exploring opportunities for recycling EPS, as highlighted in recent studies that have identified hurdles and potential actions to enhance the use of recycled materials within the industry [7]. Thus, although the advantages of using waste EPS in modified bitumen are evident, there are still some obstacles to overcome. Meanwhile, conventional bitumen used in road construction frequently performs poorly because of early problems such as cracking and degradation before the design life span elapses, particularly in developing nations such as Nigeria. Premature failures on some of these roads have primarily been attributed to the poor performance of conventional bituminous mixes under higher traffic volumes and loads. This demonstrated underwhelming performance of bituminous mixtures lead to the development of polymer modified binder and its growing use, which is renowned for enhancing road life despite rising traffic and harsh climate. This study addresses the important question of whether waste EPS modification actually produces the desired property enhancements and effectively mitigates the waste EPS disposal problem or if it introduces new, unforeseen challenges.

This research aims to examine the prospect of utilizing waste EPS as a bitumen modifier, focusing on its effects on the physical properties of the resulting modified bitumen. Understanding how varying the EPS content influences the properties of the modified blend is crucial for developing sustainable construction materials that enhance performance, while providing a practical solution for EPS waste management. Through the development of reliable and long-lasting road construction materials that cover the anticipated design life span, this research will lead to a breakthrough in the nation's road and highway construction by saving government funds, lowering bitumen modification costs, and contributing to the goal of sustainable waste management for the "white pollution" problem caused by the careless disposal of waste EPS in the environment. The use of discarded EPS foam gathered from household trash cans, public landfills, and electronic retail stores is part of the project's scope. Waste EPS was used to partially replace 60/70 grade bitumen at 2.5, 5.0, 7.5, 10.0, 12.5, and 15.0% of the bitumen weight during the wet blending process. The softening point, flash point, viscosity, penetration, and sieve analysis of the ground EPS polymer were conducted according to the American and British Standards for testing. Following these tests, the results were compared and examined in accordance with the standard parameters to identify the best-performing modified blend that could be used to produce asphalt concrete for long-lasting road construction.

2. Literature Review

Currently, the asphalt paving industry uses the bulk of bitumen produced globally as a binder. Bitumen has paving grades of 30/40, 60/70, 80/100, and so on. In hotter regions, such as Nigeria, bitumen grade 60/70 is the most widely utilized, followed by grade 80/100. However, the current, constantly rising volume and loading of road traffic have made it necessary to develop and use modified polymers known to improve asphalt road performance owing to the poor performance of conventional bitumen. It has been shown that synthetic polymeric materials, such as polypropylene, polyethylene, and polystyrene, are efficient bitumen modifiers in a number of studies on asphalt modification. Meanwhile, growing concerns about waste management and environmental sustainability have brought much attention to the use of waste materials in bitumen modification in recent years. One such waste material that has been investigated as a potential modifier for bitumen is waste expanded polystyrene (EPS). EPS is a lightweight buoyant material commonly used in packaging and insulation, but it is also produced in large quantities as waste during the manufacturing process.

This literature review aimed to investigate the properties of waste EPS-modified bitumen and its potential applications in road construction. This study involves an analysis of related existing research articles. For example, Chindaprasirt et al. [8] examined the use of waste EPS in composite materials and found that fire resistance was increased by adding diammonium phosphate (DAP) as a flame retardant. This feature is particularly important for applications involving modified bitumen, where fire safety is a top priority. According to their research, the mechanical properties and thermal degradation of EPS composites are appropriate for use in construction, implying that comparable improvements in asphalt materials are anticipated. After evaluating the waste EPS-modified blend's thermal and chemical properties, including compatibility, a study by [9] proposed that waste EPS could be used as a bitumen modifier; however, other physical properties of the blends, such as penetration, softening and flash point tests, were not examined. Recent investigations have shown that hybrid biocomposites, such as those made from EPS and modified bitumen, exhibit improved thermal stability, which is crucial for materials subjected to temperature fluctuations [10]. Additionally, study by [11] concluded that because modified bitumen has a longer performance life, it may have a significant positive environmental impact. In their research, A. A. Murana et al. [12] found that 6.7% is the optimum EPS content based on the weight of the optimum bitumen component. Increases in the modifier percentage result in a reduction in penetration, specific gravity and ductility, but an improvement in the softening point. This implies that the rutting resistance will increase and the temperature susceptibility will decrease. Furthermore, according to M. Atakan et al. [13], the physical properties of asphalt were likewise shown to be unaffected by a 2% increase in the EPS ratio; instead, an inferential statistical analysis identified the optimum 4% EPS increment ratio when the modification of asphalt binder with waste expanded polystyrene was investigated using 50/70 grade bitumen with EPS foam at weight ratios of 2.0%, 4.0%, 6.0%, and 8.0%. Through experimental research, the possibility of utilizing EPS waste in 70/100 asphalt binder modification at percentages of 0.0%, 1.5%, 3.0%, and 4.5% by weight of bitumen were examined by [14] and the inference drawn from the study showed that while rutting resistance improves, there may be a trade-off with reduced fatigue and low-temperature cracking resistance. In addition, melted EPS in the slurry form was used for the modification of bitumen, ranging from 0.0 to 10.0%. A study by [15] found that, in terms of stability and stiffness, asphalt concrete mixes containing 5.0% waste EPS (in slurry form) mixed with bitumen are appropriate for asphalt road construction. Despite the progress made in understanding the properties of waste EPS-modified bitumen, several knowledge gaps persist and warrant further exploration. For instance, studies have highlighted the mechanical and thermal properties using modification with EPS composites or EPS alone in several (melted slurry or viscous) forms in the production of asphalt concrete mixes. However, there is insufficient literature on the investigation of the physical properties of waste EPS-modified bitumen when pulverized EPS (uniformly graded) modifiers in their pure solid state were blended with 60/70-grade bitumen, particularly at a higher percentage modification content of 0.0-15.0% (at an increment of 2.5%) exceeding the maximum 10.0% usually adopted by some previous studies. The potential for investigating the short- and long-term performances of the optimum modified blend in the assessment of blend durability will also provide an opportunity for future research.

3. Methodology

This section describes how all activities were conducted to ensure the actualization of the study. The details of these activities are presented in the following subsection.

3.1. Materials

This study used base bitumen of 60/70 penetration grade acquired from the Lagos State Public Works compound in Ojodu Berger, Lagos, Nigeria. The waste EPS polymer used for the modification was collected from residential dustbins, electronics appliance sales outlets, and public dump sites all within Lagos, Nigeria, employing the services of waste collection operators. The collected waste EPS was thoroughly cleaned and dried in an atmospheric environment to remove impurities. After the completion of the cleaning and drying processes, the pure EPS waste foams were subjected to size reduction using a milling machine to increase the surface area during the blending stage.

3.2. Sample preparation

By partly substituting the weight of bitumen with size-reduced EPS at 2.5, 5.0, 7.5, 10.0, 12.5 and 15.0 %, hot mix blends of discarded EPS and bitumen were produced. For each prepared blend, the required amount of bitumen was heated to a melted state for one to one and a half hours at temperatures between 160 and 180°C. Additionally, the expected amount of waste EPS polymer was gradually added and stirred at constant revolutions per minute (rpm) to prevent polymer aggregate formation. Following the preparation of the EPS-modified bitumen, the inscription percentage was appropriately labeled for each sample.

3.3. Laboratory testing

To determine the particle size distribution of the shredded EPS, properties, and class of the prepared waste EPS-modified bitumen, tests such as sieve analysis, softening point, penetration, viscosity, and flash point were conducted according to BS and ASTM standards, all in the Asphalt Lab of Julius Berger PLC, Lagos, Nigeria. In addition, these tests were conducted on the base bitumen to verify some of its properties before modification. The specifications of the base bitumen used prior to its modification with waste EPS are listed in Table 1.

Table 1. Specification of the Base Bitumen 60/70 (Unmodified).

Test Method	Specification
Specific Gravity @ 25 °C	1.01 – 1.06
Softening Point Ring & Ball (°C)	48 – 56
Penetration @ 25 °C---dmm	60 – 70
Ductility @ 25 °C---CM minimum	100
Loss on heating for 5 hours at 163 °C % by weight --- maximum	0.2
Solubility in CS_2, % by weight --- minimum	99
Drop in Penetration after heating % original --- maximum	20
Flash Point (Open cup) °C --- minimum	250
Ash % by weight --- maximum	0.5

3.3.1. Sieve analysis of shredded EPS

This is also referred to as mechanical analysis of aggregate in accordance with BS 410. Analyzing the size-reduced EPS particles to their appropriate aggregate sizes is the aim of this test. The sieve is set up on a sieve receiver, with the finest sieve at the bottom and the coarsest sieve at the top. After that, the sample is moved into the upper sieve and shaken for roughly five minutes. Each sieve's retained particles are moved into the crucibles and given labels. Each sieve's weight of size reduced EPS particles retained, i.e., percentage passing, is measured against the equivalent diameter. From the particle size distribution curve, the dust ratio (D_R) is derived. The coefficient of uniformity (C_U) and coefficient of curvature (C_C) are calculated using the grain size parameters D_{10}, D_{30}, and D_{60}, corresponding to 10, 30, and 60% passing based on the grading curve.

3.3.2. Penetration (ASTM D-5)

The most popular control test for penetration grade is penetration, which measures the bitumen's consistency or hardness. Both virgin bitumen and the modified bitumen underwent the standard 100 g, 25 °C, and 5-second penetration test, with the polymer concentration ranging from 2.5% to 15.0% by bitumen weight.

3.3.3. Softening Point (ASTM D-36)

The temperature at which bitumen reaches a specific level of softness, that is, when a typical 3/8-inch steel ball weighing 3.55 g falls and makes contact with the base plate, which is 2.5 mm distant, is known as the softening point. Moreover, bituminous materials lack a defined melting point, in contrast to certain substances such as water, which turns from solid to liquid at 0°C. Rather, these materials gradually get converted from brittle or extremely thick and slow-flowing solids to softer and less viscous liquids as the temperature rises.

3.3.4. Viscosity (ASTM D5)

A liquid's viscosity is the property that slows down flow; the slower the liquid moves when force is applied, the higher the viscosity; in this way, viscosity is a "pure" indicator of consistency. The viscosity of the binder is detected in seconds when a specified volume of the binder liquid (50 ml) passes through a standard orifice (10 mm) viscometer at a known test temperature and with an initial standard head. A typical tar viscometer was used for this viscosity test, and because the modified bitumen hardens at lower temperatures, all samples were tested at the same temperature of 100 °C.

3.3.5. Flash Point (ASTM D 92)

The lowest temperature at which the vapor released from the heated binder sample's surface burns with a brief flash of blue flame in the presence of air when a small flame is applied in a recommended way is known as the binder's flash point. The flash point is primarily a safety test that shows the temperature at which the binder sample can be heated without a fire hazard, although they may also be considered indirect reflections of the binder volatility. The test was carried out with the Cleveland Open Cup Method on the base bitumen and all the prepared modified samples.

3.3.6. Penetration Index Results

Penetration index (PI) helps in reflecting the temperature susceptibility of bitumen, but it is more useful in defining the rheological type of the bitumen tested, that is, in indicating how much it deviates from behaving like a Newtonian fluid. However, the higher the PI value, the harder the bitumen and vice versa. The PI values were computed by an expression established by Pfeiffer and Van Doormaal using the relationship between modified bitumen samples' softening point and penetration grade. This PI expression to be used in the computation is given below:

$$\frac{\log 800 - \log pen}{T_{R+B} - T} = \left(\frac{20 - PI}{10 + PI}\right)\frac{1}{50} \tag{1}$$

Log pen refers to the base-10 logarithm of the measured penetration, T represents the temperature at which the penetration test was performed, typically 25°C and T_{R+B} indicates the softening point in degrees Celsius. The asphalt's temperature susceptibility is indicated by the Penetration Index. Indicating low-temperature susceptibility is a high PI. Harder bitumen has a higher PI.

4. Results and Discussion

This section provides the laboratory results and discussion on both the modified and unmodified bitumen (control) samples. That is, the effect of the added modifier (EPS) on each test sample will also be discussed. Also, each of the percentage modified blends will be identified with the appropriate sample designated label as given in Table 2.

Table 2. Percentage Modified Blend Sample Designation.

Sample	Base Bitumen (%)	EPS Used (%)	Modified Bitumen
A	100.0	0.0	0.0%
B	97.5	2.5	2.5%
C	95.0	5.0	5.0%
D	92.5	7.5	7.5%
E	90.0	10.0	10.0%
F	87.5	12.5	12.5%
G	85.0	15.0	15.0%

4.1. Discussion on sieve analysis

According to BS 410, the results of the sieve analysis of 200 g of shredded EPS indicate that the percentage of materials that passed through sieve No. 3/4 (19 mm diameter) was 93%, which was the highest percentage passing, while the percentage passing through sieve No. 7 (2.36 mm) and No. 14 (1.18 mm) is 4% and 1.5%, respectively. See Table 3 for the sieve analysis result. The particle size distribution curve after sieve analysis is also shown in Figure 1. Additionally, the particle size distribution curve yielded the dust ratio (D_R), that is, D_{10}, D_{30} and D_{60}, which had respective values of 2.66 mm, 3.97 mm, and 7.00 mm as indicated on the curve by an arrow. Using the following equations, the C_U and C_C were also computed from these obtained values:

$$C_U = \frac{D_{60}}{D_{10}} \quad (2)$$

$$C_C = \frac{(D_{30})^2}{(D_{60} \times D_{10})} \quad (3)$$

(Note: C_C with values between 1 and 3 indicates a well-graded sample, whereas $C_U < 5$ indicates very uniform, $C_U = 5$ indicates medium uniform, and $C_U > 5$ indicates non-uniform). From the above values calculated for the C_U (2.63) and C_C (0.84), it is obvious that the sample is very uniform and is not well-graded.

Table 3. Sieve Analysis Result for the Shredded EPS.

Sieve Analysis of the Shredded EPS				
Sieve Size		Weight Retained (g)	% Retained	% Passing
BS	Mm			
1"	25.00	0.00	0.00	100.00
3/4"	19.00	15.00	7.50	92.50
1/2"	12.50	16.00	8.00	84.50
3/8"	9.50	16.00	8.00	76.50
No.4	4.75	75.00	37.50	39.00
No.7	2.36	70.00	35.00	4.00
No.14	1.18	5.00	2.50	1.50
No.25	0.60	3.00	1.50	0.00
No.52	0.30	0.00	0.00	0.00
No.100	0.15	0.00	0.00	0.00
No.200	0.075	0.00	0.00	0.00
PAN		200.00		

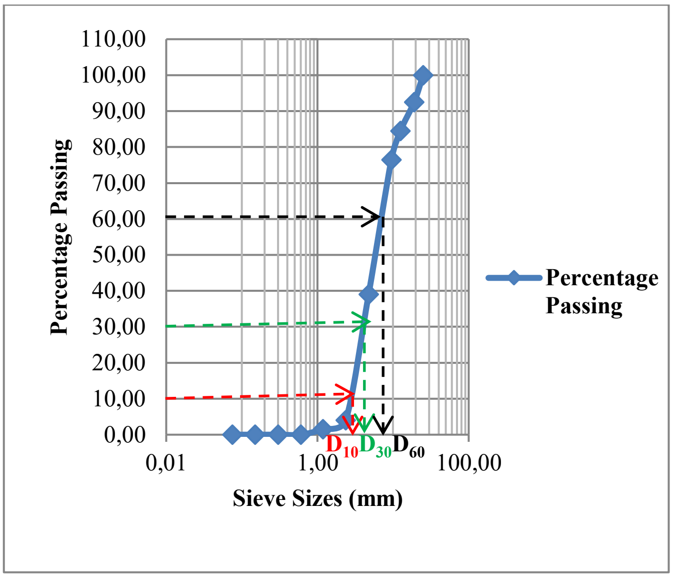

Figure 1. Particle Size Distribution Curve for the Shredded EPS used.

4.2. Discussion on penetration test results

This test was conducted to obtain the penetration grade of the samples prepared by the addition of the EPS polymer in different percentages to the conventional bitumen. Bitumen grading aids in determining its suitability for various construction types and climates. This test was repeated four times and the average was obtained to give the value of the penetration grade. From the below-shown Figure 2, it was clear that Sample A was 60/70 grade bitumen since it had a penetration value of 65 dmm. Sample B was 50/60 grade with a penetration value of 57 dmm, while Samples C (50 dmm) and D (46 dmm) were both grade 40/50. Sample E was grade 30/40 since it had a penetration value of 38 dmm. Sample F (23 dmm) was penetration grade 20/30 and Sample G (12 dmm) was penetration grade 10/20. Also, from the above-presented result, it was evident that there was a consistent decrease in the penetration grade as the EPS polymer was increasing in the bitumen and this implied an increase in the hardness of the modified samples. The unmodified Sample A (65 dmm) had the highest penetration grade, while Sample G (12 dmm) had the lowest penetration grade. However, the highest reduction in penetration value was obvious from Sample E to Sample F, while for Sample C to Sample D, the least reduction occurred. Sample F dropped in penetration value by 39.5% compared to the Sample E value, while Sample D had a reduction of 8% compared to the Sample C penetration value. In general, the modified bitumen became harder and more consistent due to the inclusion of EPS. This is beneficial in that it increases the mix's resistance to rutting, but it may also reduce the bitumen's flexibility by making it considerably stiffer, which could reduce its resistance to fatigue cracking. Therefore, caution needs to be taken to strike a balance against fatigue cracking.

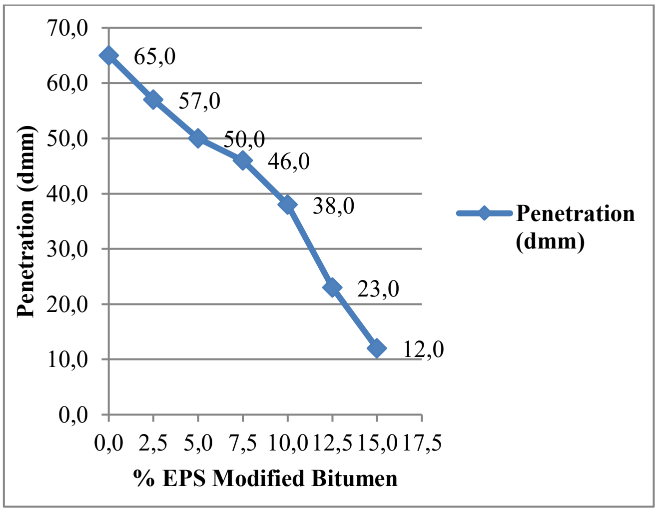

Figure 2. Graph of Penetration (dmm) against % EPS Modified Bitumen.

4.3. Discussion on softening point test results

From the below-shown results in Figure 3, the softening point of Sample A was 49 °C and that of the EPS-modified Samples B, C, D, E, F, and G were 51, 53, 55, 61, 65 and 71 °C, respectively. The softening point of the unmodified sample increases when modified by the addition of the EPS. There was a constant increase in the softening point of Samples A, B, C and D as the EPS modifier was increased, while Samples E, F and G had another differential increase in their softening point value, which in this case was not uniform, unlike the first set of samples listed above. Sample B had a 4% increase in softening point value than Sample A, while Sample C also had about a 4% increment in its value than Sample B, and also, Sample D had approximately a 4% increase in its softening point temperature than Sample C. For the second set of samples, Sample F had about 7% of its softening point value which was higher than that of Sample E, while Sample G had about a 9% increase in its softening point than Sample F, which had 65°C.

Further to the above, it was evident that there was a small increase in the softening points of Samples A, B, C and D, while Samples E, F and G had a moderate increment in their softening point temperatures. This implies that Samples E, F, and G would give a better reduction in temperature susceptibility when utilized. Overall, the test result demonstrated that adding EPS to bitumen raised the softening point temperature. This means the binder is more resistant to the effects of heat, which will prevent the binder from becoming soft in hot weather. Therefore, it can be concluded that bitumen with a higher softening point has better rutting resistance.

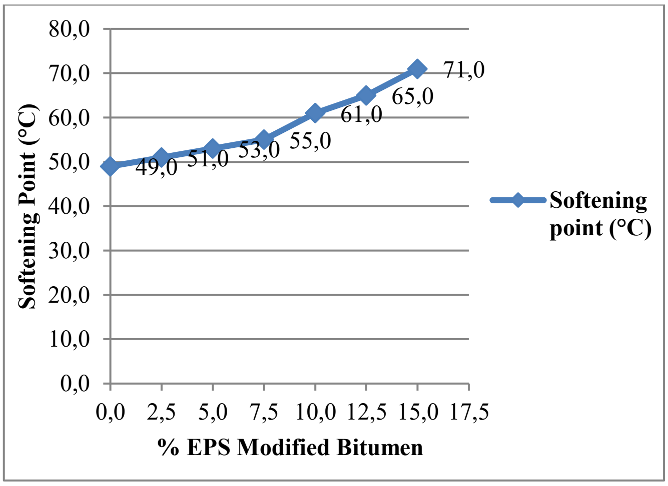

Figure 3. Graph of Softening Point (°C) against % EPS Modified Bitumen.

4.4. Discussion on viscosity test results

This test was conducted at a constant temperature of 100°C maintained by both the water bath and all the test samples. From the below results in Figure 4, it was clear that there was a sharp increase in time (seconds) required for the samples A (90 s), B (125 s) and C (152 s) to flow through, while there was strong resistance to flow by samples D, E, F and G. This increase experienced in the first 3 samples implies that there was a gradual increase in the resistance to flow (but not enough to completely resist flow) by the samples as the EPS modifier was increasing and this was due to an increasing cohesion force existing between the molecule of the bitumen and EPS. The further increment in the EPS content in the bitumen of Samples D, E, F and G resulted in a very strong attraction between the molecules, thereby making the samples completely resist flow. The comparatively higher fraction of swollen polymer (the polymer strands swelled after partially absorbing the base bitumen's low molecular weight oil portion) caused the polymer-rich phase to become the continuous phase. Samples D, E, F, and G resisted the flow because the swelled strands joined at nodes to produce a three-D network. Bitumen with excessive viscosity can lead to uneven and insufficient coating of aggregates. Conversely, when the viscosity is too low, the bitumen may bleed, resulting in inadequate coverage of the aggregates as well.

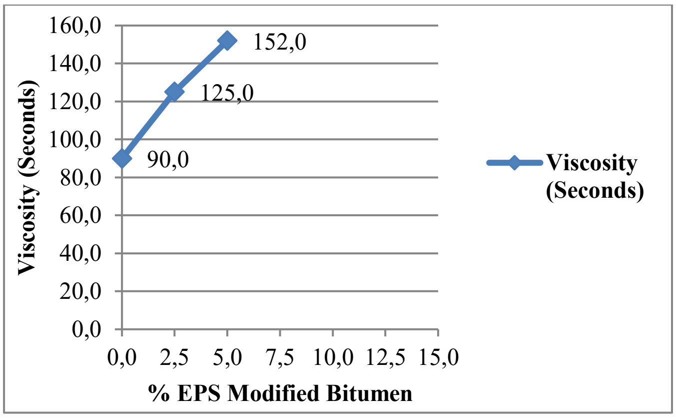

Figure 4. Graph of Viscosity (seconds) against % EPS Modified Bitumen.

4.5. Discussion on flash point test results

From the below graph in Figure 5, there was a progressive increase in the flash point of samples B (265°C) and C (275°C) by about 1.9% and 5.8%, respectively, to the unmodified sample. After this point, there was a steady fall in the flash point value till the last sample, Sample G (250°C), which had about a 3.9% reduction from the unmodified Sample A (260°C). From the above-shown results, Sample G (250°C) had the lowest flash point temperature, while Sample C (275°C) had the highest flash point. As a result of this, Sample G will ignite first at low temperature; thus, more cautions have to be taken when working with it compared to other samples.

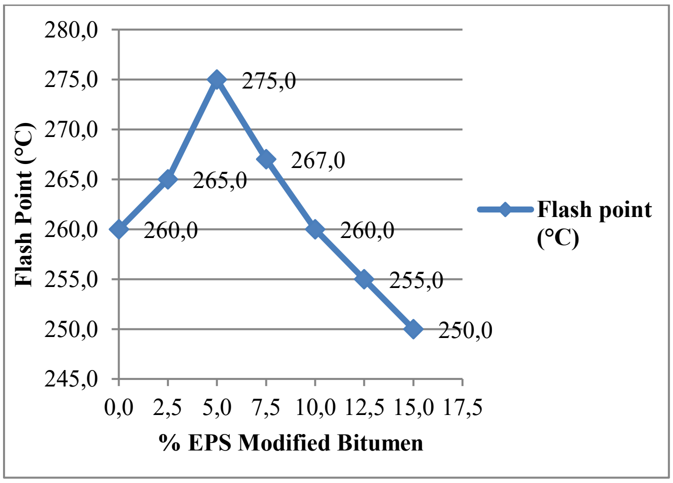

Figure 5. Graph of Flash Point (°C) against % EPS Modified Bitumen.

4.6. Discussion on penetration index results

From the below Table 4 computed PI values, the following facts can be deduced from the results: Samples E (0.5), F (0.25) and G (0.06) were the hardest groups, followed by Samples C (-0.48) and D (-0.22), while the least were Samples A (-0.83) and B (-0.64). Also, lower susceptibility to temperature changes will be offered by Samples E, F and G than Samples A, B, C and D. Although all the samples fall in the category of normal bitumen (-2 and +2), that shows some elasticity and a little thixotropy, Samples C, D, E and F had a very close range value to the most used bitumen for road purposes, having PI between +1 and -1 as specified by Whiteoak, 1990 [9]. Amongst all these above-listed categories of bitumen, Sample C is the most acceptable road bitumen grade since it had a PI value of -0.48, which is about -0.5 stated for the category of the most acceptable road bitumen grades. Given this, it can be said that the PI values indicated a decrease in temperature susceptibility of the modified binder as the addition of the EPS polymer was increased in the blend.

Table 4. Penetration Index Results.

Sample	%EPS	Penetration (dmm)	Softening Point (°C)	PI
A	0.0	65	49	-0.83
B	2.5	57	51	-0.64
C	5.0	50	53	-0.48
D	7.5	46	55	-0.22
E	10.0	38	61	0.50
F	12.5	23	65	0.25
G	15.0	12	71	0.06

4.7. Discussion on the relationship between penetration and softening point

The summarized findings from all tests conducted, as shown in Table 5, clearly demonstrated an inverse relationship between the penetration grade and softening point of all samples. As the amount of EPS polymer in the bitumen increased, the penetration grade decreased, while the softening point (°C) rose. This observed reduction in penetration and elevation in softening point among the test samples indicated an increase in the hardness and stiffness of the modified binder. Also, from the below Table 5 of the summarized results, the relationship existing between the penetration grades and the flash point of the samples was not a consistent one, as there was a stable rise in the flash point from Sample A (260°C) to C (275°C), while beyond this point the flash point began to decrease to the very low value of 250°C for Sample G. And as for the penetration, there was a progressive decrease from Sample A down to the last Sample G, which pattern was not proportional to that of the flash point results.

Considering all the test results, it could be conveniently said that Sample C had an optimum improvement in its physical properties coupled with its computed PI (-0.5), which made it fall within the category of the most acceptable road bitumen grades.

Table 5. Summary of all Results Obtained on the Unmodified and EPS Modified Bitumen Samples.

Sample	Softening point (°C)	Flash point (°C)	Viscosity (seconds)	Penetration (dmm)	PI
A	49.0	260.0	90.0	65.0	-0.83
B	51.0	265.0	125.0	57.0	-0.64
C	53.0	275.0	152.0	50.0	-0.48
D	55.0	267.0	Resist flow	46.0	-0.22
E	61.0	260.0	Resist flow	38.0	0.50
F	65.0	255.0	Resist flow	23.0	0.25
G	71.0	250.0	Resist flow	12.0	0.06

5. Conclusion and Recommendations

The investigation of the use of waste-expanded polystyrene (EPS) in the modification of bitumen shows that this innovation has the potential to significantly improve material properties and promote sustainability in the construction industry. Incorporating EPS as a sustainable substitute not only enhances bitumen's physical properties but also addresses the environmental issue of "white pollution," which is brought on by the careless disposal of waste EPS. The physical properties of practically all prepared modified samples tend to be improved by the bitumen's EPS modification. Although the softening point rises, the penetration grades fall as the amount of EPS added increases. The viscosity of the modified samples increased as the EPS modifier increased, resulting in a stronger cohesive force in the blend. Also, the EPS addition resulted in a decrease in the volatility of some of the modified blends, thereby making them safer to work with in terms of fire hazards. However, in more specific terms, the low penetration grade value of Samples C, D, E, and F makes them suitable for regions with hot climatic conditions since they can resist softening under high temperatures, which implies their high resistance to rutting. The volatility of Samples B, C, and D was reduced due to their high flash points, making them safer against fire hazards. With all of these, waste EPS polymer can be said to be a suitable bitumen modifier for improving the physical properties of bitumen for road construction. Finally, after carrying out a thorough analysis of all the modified blend sample results, Sample C (5% EPS) emerged as the most improved modified blend and will be suitable for asphalt concrete pavement construction. Therefore, the implications of these findings imply that EPS adoption in road construction projects can result in financial and environmental savings, ultimately fostering a more sustainable future for the sector as a whole. Addressing the urgent problems of resource depletion and climate change requires adopting such innovative techniques. Also, it is recommended that future studies should concentrate on the durability assessment of this improved modified blend to ascertain its performance.

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Conflicts Interest Statement

The authors affirm that no known conflicting financial interests or personal ties might have influenced any of the work reported in this study.

Data Availability Statement

This article contains all of the data generated or analyzed during this study.

Author Contributions Statement

Both authors (Ganiyu Lawal and Bamidele Dahunsi) generally contributed in equal measure to this study in terms of conceptualization, writing, supervision, editing, analysis and reviews. After reading, both authors gave their approval to the published version of the manuscript.

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