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Styrene Butadiene Rubber and Plastic Bottle Wastes as Sustainable Materials in Hot Mix Asphalt

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Abstract**—** Environmental concerns associated with waste tires and plastic bottles have driven the adoption of recycling-based modifiers to enhance pavement performance. This study investigates the feasibility of utilizing Styrene–Butadiene Rubber (SBR) and Plastic Bottle Waste (PBW) as sustainable modifiers in Hot Mix Asphalt (HMA). Modified asphalt mixtures were prepared with PBW and SBR contents ranging from 2% to 10% by weight of the Optimum Binder Content (OBC). The performance of conventional and modified mixtures was evaluated using Marshall Stability, rutting resistance, Indirect Tensile Strength (ITS), and microstructural and chemical characterization through Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD). Results indicate that a 6% modifier content provides optimum performance enhancement, leading to significant improvements in stability, tensile strength, rut resistance, thermal stability, and stiffness. Microstructural analyses confirmed improved binder–modifier interactions and enhanced material compatibility. Comparatively, SBR demonstrated superior performance improvements over PBW, indicating its higher effectiveness as an asphalt modifier. In addition to mechanical benefits, the incorporation of SBR and PBW offers substantial environmental advantages by reducing landfill disposal and incineration, thereby lowering the associated carbon footprint. Overall, the findings support the use of recycled SBR and PBW as cost-effective, durable, and environmentally sustainable alternatives for producing high-performance asphalt mixtures, contributing to extended pavement service life and sustainable infrastructure development.

Keyword**—** Hot mix asphalt, Plastic bottle waste, Rut resistance, XRD, FTIR, XRF.

I. INTRODUCTION

A country requires an interconnected system of highways to connect different regions. As the population grows, traffic flows increase, which leads to a demand for applications that manage road pavements and are more efficient. Historically, traditional pavement materials would not be able to sustain the increased flow of traffic and weights. In order to enhance asphalt, researchers have blended asphalt with natural and synthetic polymers to create polymer-modified asphalt (PMA). Research teams in Canada, the United States, China, and Europe have developed a great deal of research and science to modify asphalt with an assortment of polymers [1]. While there are numerous pavement modifiers available, there are just a few natural modifiers available [2]. The use of low-grade waste material as a modifier is an economic and environmentally friendly method for to produce high quality pavements and an approach to combat waste disposal [3]. Plastic waste is becoming a global phenomenon both caused by commodity, but also as a general society issue. For example, plastic resins have developed consistently over the last 50 years, and in 2013, over 298 million tons of plastics were produced, an increase of 3.92% from 2012. Between years in 1952 and 2012, the rate of increase to the total volume of annual production was about 8.80% and have accounted for about 350 million metric tons. Regardless, plastics that provide a beneficial use, are known to have a negative effect on the environment [4-9]. Polyethylene terephthalate (PET) provides strength and water resistance for PET bottles [10]. Polypropylene fibers are utilized as a substrate, reusing them for road construction can decrease waste and improve road performance [11-15]. In recent years, considerable efforts have been made regarding conceptualizing sustainability and looking at systematic means of achieving sustainability [16]. When determining a pavement's lifespan, a full life cycle must be analyzed, including extraction, fabrication, compaction, operation, maintenance, and end-of-life.

Green pavements incorporate waste materials into asphalt mixtures, with these asphalt mixtures being designed to be flexible to increase the lifespan and save money on pavements. This study analyzes the Marshall quality and tensile durability asphalt of a mixture made with three different waste materials (plastic bottle, SBR tire rubber) and moisture damage. The inclusion of tire rubber makes a positive difference to the rheological properties of asphalt mixtures, especially in hot climates, improves temperature resistance, and rutting resistance [17-18]. Around 1.7 billion tires are produced each year, a significant proportion of which will ultimately be considered end-of-life tires (ELTs). In 2010 and 2011, about 3.4 million tons of used tires were recycled into an environmentally sound manner. The approximate volume of estimated waste ELTs is 3.75 million tons [19]. As a precaution, car tires are recycled into granulate and asphalt pavement is delivered as recycled material. Excessive waste stored in landfills presents complexity in the waste management process and contamination of water sources [20]. There are 20-30 years of experience with crushed tire rubber as an asphalt modifier. It was initially used in Arizona as a chip seal binder on roads [21]. Wet processes are done as a side process using rubber with SBR asphalt mixtures [22-23]. These methods use rubber particles and binders to blend into a combination of asphalt cement and aggregates [24].

Products that can fall under definitions of waste or surplus such as PET or Polyethylene Terephthalate can serve as new ingredient sources into pavements when repurposed [25]. Repurposing materials intended for waste to be used in pavements serve a dual purpose: it removes waste and contamination to the environment [26]. Contrarily, increased heavy-axled truck traffic can adversly accelerate deterioration of flexible pavements, requiring thicker, more expensive pavements [27]. Using a repurposed material might be more acceptable than advancing pavement degradation. Plastic waste products can be introduced into asphalt in two ways: as part of a wet process modifying an asphalt emulsion mixed with aggregate, or a dry method directly modifying the mixture itself [28]. PET waste products in plastic bottles have a relatively high polymer count relative to asphalt mix [29]. Bottles like PET can be blended into asphalt through a wet process [30]. HDPE is generally considered to have a higher level of polymer interaction than LDPE to improve stability in asphalt concrete mixtures [31]. Introduction of HDPE or polymeric particulate can also reduce the temperature at which modified asphalt is susceptible to damage [32-33]. The addition of HDPE to hot mix asphalt increases stability to reduce degradation while also increasing the Marshall's stability and minimum flow values [34-36].

Modified asphalt mixtures, notably rubberized asphalt concrete featuring crumb rubber from recycled waste tires, enhance performance and prolong service life while benefiting the environment by repurposing waste. Rubber reduces slipperiness and increases shear strength against traffic loading in the flexible pavement asphalt layers in which rubber is included [35]. The findings above indicate an important trend and benefit of crumb rubber. Rubber improves many important qualities of asphalt mixtures, including; better resistance to temperature changes and rutting, higher stability, 10% lower values of flow, and better stripping resistance [36]. SBR-modified asphalt mixtures modified using a wet option outperform both control and PBW modified mixtures with respect to crack prevention [37-38]. Performance of SBR modified mixtures using the wet-process is affected by VA and VMA [39]. However, wet-technique, SBR modified concrete is less rigid and more susceptible to moisture damage compared to PBW mixtures [40]. Recently, laboratory studies measures have focused on improving plain asphalt, such as adding chemicals, to enhance quality. As more and more concerns are raised about the impacts of disposing tires as waste, awareness is being raised on the benefits of using SBR in paving-asphalt as an ecological alternative to waste tire incineration.

The objective of the study is to assess the application of PBW and styrene-butadiene rubber (SBR) in hot mix asphalt (HMA) and their impacts on aspects such as pavement durability, flexibility, and performance. Furthermore, the study will investigate the use of reclaimed materials (e.g., plastic bottles and SBR) as a sustainable alternative to minimize carbon footprint and contribute to environmental sustainability.

A. Research Objectives

The core goals of the investigation are;

i. To investigate the feasibility of using plastic bottles and styrene butadiene rubber wastes as sustainable materials in hot mix asphalt.

ii. To investigate the physical and mechanical characteristics of hot mix asphalt modified with plastic bottles and styrene butadiene rubber wastes.

iii. To study the mode of action of bitumen, waste plastic bottles and styrene-butadiene rubber using FTIR and XRD tests.

II. MATERIALS AND METHODS

A. Bitumen

In this study, Penetration Grade Bitumen (60/70) was selected as the asphalt binder. This particular grade of bitumen was sourced from Attock Refinery, located in Attock, Pakistan. Bitumen of this grade is typically employed in road construction, and its properties are outlined in Table 1, which provides the specific characteristics of the 60/70 grade binder used in this research.

Table 1. Binder physical properties

1. Properties	2. Value	3. Reference
4. Penetration (25°C, 1/10th of mm) [33]	5. 65	6. ASTM D5
7. Softening point, (°C)[34]	8. 48.5	9. ASTM D36
10. Ductility, (cm) [34]	11. 101	12. ASTM D1,13
13. Flash and fire point, (°C) [35]	14. 268, 285	15. ASTM D 3143
16. Viscosity (135 °C), (Pa.s) [36]	17. 0.612	18. ASTM D4402
19. Viscosity (165 °C), (Pa.s) [36]	20. 0.192	21. ASTM D4402

B. Aggregates

Aggregates for this study was obtained from Margalla hills and the Physical properties of aggregates were described below in table 2.

Table 2. Physical Characteristics of aggregates

Name of Test	Experiment Code	Findings (%)	Specifications
Los Angeles abrasion	ASTM C131	21.5	<30%
Soundness (Coarse)	ASTM C88	7	<8%
Soundness (Fine)	ASTM C88	4.6	<8%
Absorbing Water	ASTM C127	0.39	<2%
Flakiness	ASTM D4791	4.1	<10%
Elongation	ASTM D4791	4.7	<10%
Fractured particles	ASTM D5821	99.6	>90%
Uncompacted voids	ASTM C1252	47.3	>45%
Sand equivalent value	ASTM D2419	72	>50%

C. Plastic Bottle

PBW refers to the process of emptying plastic containers, typically made from PET, that are used to package liquids such as water, soft drinks, dairy beverages, fruit juices, and other liquid products. It was obtained from local waste collection factories in Peshawar. Table 3 shows the complete physical characterization of PBW.

Figure 1. Plastic bottle waste

Table 3. Physical Characteristics of PBW

Property	Result	Property	Result
Polymer Type	PET	Specific Gravity	1.38
Size of particles used	5mm	Water Absorption	< 0.01%
Density	1.38 g/cm³	Elastic Modulus	2.1 - 3.1 GPa
Melting Point	250 - 265 °C	Tensile Strength	50 - 80 MPa
Glass Transition (Tg)	70 - 78 °C	Clarity	High
Ignition Point	324 °C		

Table 4. Physical Characteristics of PBW

Property	**Result**	**Property**	**Result**
Polymer Type	Synthetic Elastomer	Specific Gravity	0.94 - 1.20
Size	4mm	Water Absorption	Low
Glass Transition (Tg)	-50 to -60 °C	Tensile Strength	15 - 25 MPa
Density	1.20 g/cm³	Elongation at Break	400 - 600%
Service Temperature	-40 to 70 °C	Abrasion Resistance	Excellent
Ignition Point	349°C		

D. Styrene Butadiene Rubber’s Wastes

SBR is a synthetic rubber made from a polymer chain of butadiene monomers with styrene monomers bonded to it. Due to its excellent mechanical properties, resistance to wear, and cost-effectiveness, it is widely used in various engineering applications.

Figure 2. Crumb rubber from SBR

Table 4 shows the complete physical characterization of SBR.

III. RESEARCH METHODOLOGY

The testing was conducted at the highway engineering laboratory of Sarhad University located in Peshawar, Pakistan, and utilized 60/70 Penetration grade bitumen from Attock Refinery Limited (ARL) and aggregates obtained from the Margalla quarry. The specific method employed for the tests are demonstrated in Figure 3.

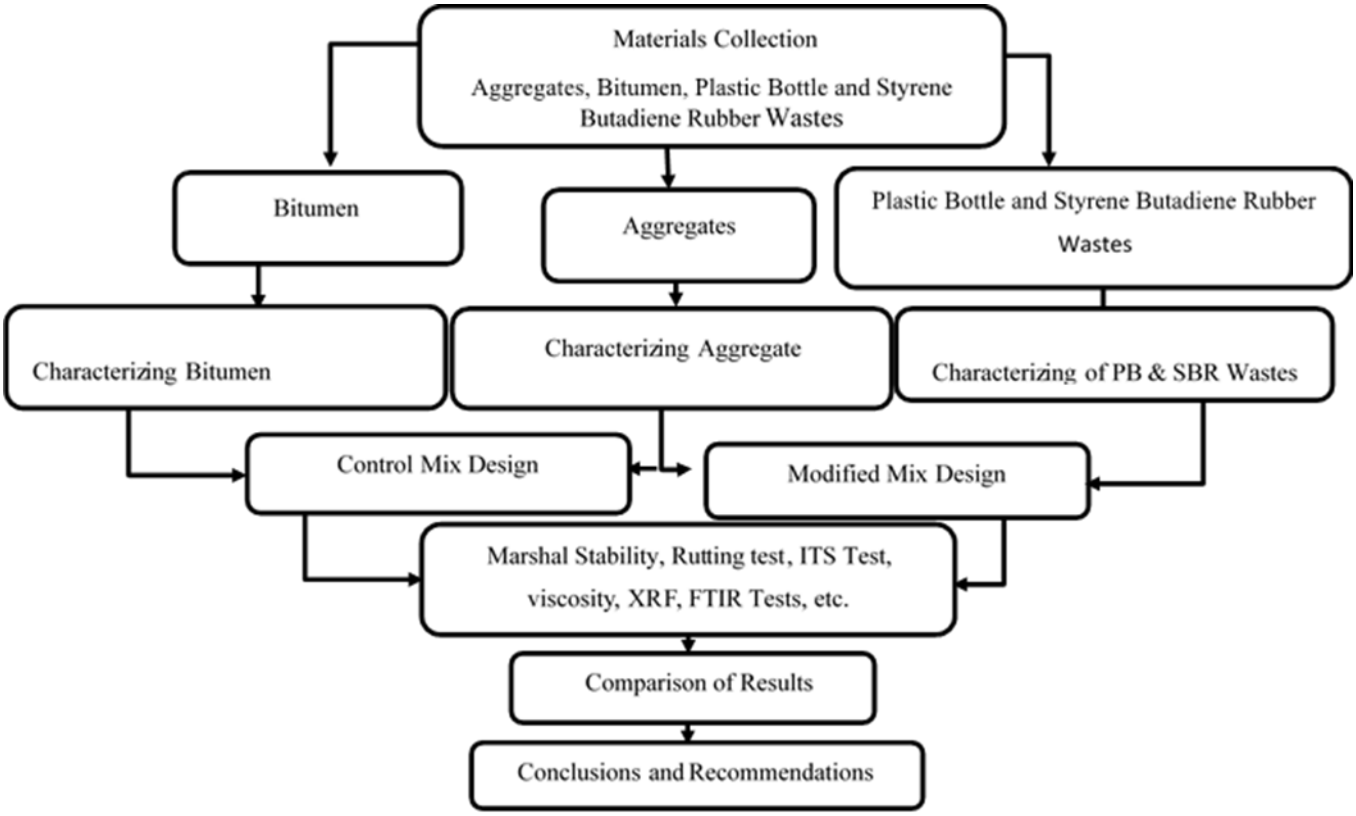


Figure 3. Detailed Methodology

A total of 146 samples were made for the tests that were performed. Eleven samples were made for the rutting resistance, twenty-two samples were made for the indirect tensile strength (both conditioned and unconditioned), eleven samples were made for the dynamic modulus testing, eleven samples were made for the XRD analyses and again eleven samples were made for the FTIR analyses. Three samples were made for XRF at 6% and eleven samples were made for the tests, including penetration, ductility, softening point, flash and fire point tests and viscosity. Eleven Marshall samples were also made for the modified asphalt with varying PBW and SBR percentages alongside additional samples for the unmodified asphalt. The Optimum Binder Content (OBC) for the conventional asphalt was determined via the Marshall mix design method following ASTM D1559. The process observations can be found in Table 5 in the results and discussion section. Modified asphalt mixtures with SBR and PBW were formulated based on two percent (2%), four percent (4%), six percent (6%), eight percent (8%), and ten percent (10%) of the Optimum Binder Content (OBC) obtained from the wet method for the standard asphalt grades designations. Figure 4 shows the aggregate blend using Asphalt Institute grading and contained to be heated to one hundred eighty degrees Celsius (180°C) for three hours. Regular and modified asphalt mixes were fabricated by the recommended aggregate gradation pattern filled into the convention four-inch (4") diameter and two and one half (2.5") thick Marshall mold. The samples were place in a Marshall Compact and compacted to seventy-five (75) blows.

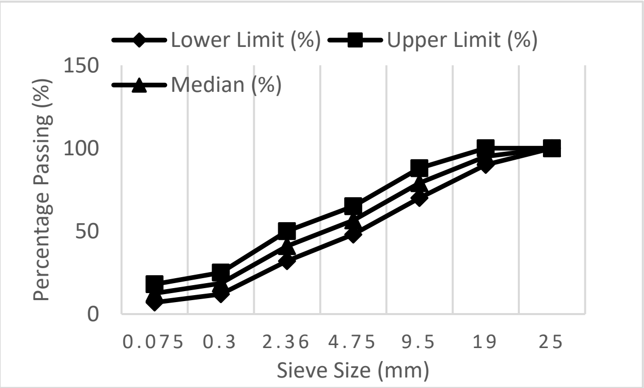


Figure 4. Gradation Curve

Then, after twenty-four hours (24 hrs.), the mixture was removed from the mold and soaked in in a water bath at sixty degrees Celsius (60°C) for one hour (1 hr.) and tested with the Marshall Tester to obtain the OBC. For example, the modified was made by combining zero percent (0%) - ten percent (10%) of the OBC with seesal and unsaturated polyester and heated; the ensuing modified binder was then mixed with the binder and combined aggregate. The amalgamated mixture was then compacted using a Marshall Compactor and allowed to cool overnight.

A. Physical Tests

The tests include penetration, softening point, ductility, flash and fire point and viscosity tests were conducted for finding physical properties of standard and modified binder samples with SBR and PBW according to ASTM standards for each test and their effects on pavement in service.mm

B. Mechanical Analysis

C. Indirect Tensile Strength and TSR Test

The Indirect Tensile strength (ITS) testing of the bituminous mixtures was conducted using a load applied along the vertical diametrical plane to a 150 mm diameter cylindrical specimen at a rate of 50mm/minute, while maintaining a constant temperature of 25°C. The moisture susceptibility was tested by conditioning a specimen in water under pressure (13 – 67KPa) for a period of 5 – 10 min, freezing the specimen for a period of 14 hrs. and then placing it in a water bath with a temperature of 60°C. The ITS was determined based on:

$St=\pi tD2000P$ ------------------------------------(1)

Where tSt is the tensile strength (KPa), t is the thickness (mm), D is the diameter (mm), and P is the load (N). The Tensile Strength Ratio (TSR) was calculated as:

$TSR=Scond/ Suncond.$ ------------------------------(2)

Where Scond. is the tensile strength of conditioned samples, and Suncond.is the tensile strength of unconditioned samples.

D. Wheel Tracking Test

To assess rut resistance in the wheel tracker testing, each sample was 125 mm high and 150 mm dia, with mixing temperature set at 160oC. The testing of each sample occurred under tightly controlled conditions at 60°C with 10 thousand cycles of the standardize wheel, and recording depth of rutting when 10,000 cycles complete.

E. Dynamic Modulus Test

The Dynamic Modulus experiment is widely used for examination of stiffness and viscoelastic behavior of asphaltic materials, polymers, and other materials, especially in road and pavement construction applications. This test complies with ASTM D 3497 and is used to measure the mechanical behavior of asphalt materials and modified with SBR &PBW at different temperatures (-10 °C to 60 °C) and loading's frequencies (0.1 Hz to 25 Hz). In this case, a 4-inch diameter and 6-inch height sample is measured on a dynamic modulus machine to measure the strain response under repetitive weight, and the value the dynamic modulus (E*) is back-calculated from these stress and strain data to give the effect of traffic loads on pavement materials.

F. Micro-structural Analysis

G. XRD Test

XRD testing shows how additives can change the physical and chemical properties of the binder by changing the crystal structure. In the lab, this test reveals useful information about the crystallite structure and crystallite content in materials, including asphalt binders and mixes. The XRD test is used to show the presence of crystalline phases (observed for strength) or amorphous regions (which reflect the material's flexibility). (XRD) test of SBR & PBW-modified asphalt at 0%, 2%, 4%, 6%, 8% and 10% consists of determining the crystalline structure of the asphalt samples at several modification levels. The asphalt samples are ground into fine powder and are subsequently exposed to X-ray radiation in the presence of an XRD machine capable of recording the diffraction pattern to determine the crystalline phases present in the samples and understand how different modification levels of SBR & PBW interact with the structural attributes of black top at specific concentrations. The resulting data may elucidate the thermal stability, and the overall performance of the modified asphalt. The use of an XRD analysis assists in the determination of material property enhancement for varying levels of modification.

H. FTIR's Analysis

The FTIR's experiment is utilized to analyze the chemical composition and functional groups of the SBR & PBW modified asphalt involved obtaining SBR & PBW altered black top specimens at 0%, 2%, 4%, 6%, 8%, and 10% SBR and PBW concentrations. Subsequently, the samples that were prepared were placed inside the FTIR spectrometer, which emits infrared light passing through samples, while the software collected absorbance data, from which a spectrum is generated. Once plotted, the resulting spectrum allows for inspect of the absorbance peaks representing the various chemical bonds and functional groups. Once the samples with and without modifiers were compared, the FTIR test was utilized to inspect the modification and interactions taking place in the plastic binding material (asphalt) and SBR and PBW composite and a it can serve as an insight as the modifiers effect to the chemical behavior of the binding mixture.

I. XRF Test

The XRF (X-ray fluorescence) assessment for SBR- and PBW-modified asphalt at 6% entails investigating the elemental makeup of asphalt samples. In this method, samples are irradiated with X-ray energy. The X-rays incident on the samples cause the sample elements to emit secondary (also known as fluorescent) X-rays. The XRF machine measures these emitted X-rays, and the resulting spectrum quantifies which elements are in each sample and the quantity of the different types of elements that are present. This analysis helps provide information on the ultimate elemental changes in the asphalt with the incorporation of SBR and PBW, including heavy metals, sulfur, and/or other elements that may contribute to material properties. The assessment evaluates the chemical composition information and potentially whether the presence of either of these modifiers contributes to different impacts on the asphalt mixture.

IV. RESULTS AND DISCUSSION

In Table 5 are shown the physical properties of both blacktop and altered blacktop. When the amount of SBR and PBW in asphalt increased, the penetrability decreased, elasticity increased, and the softening point also increased and also showing good flash and fire point results compare to standard bitumen. The manual mixing of the asphalt influenced how the binders interacted, indicating the importance of proper mixing for uniform properties of the asphalt. These physical affects from modifiers may increase service of life of asphalt pavements.

Table 5. Standard testing results of asphalt

Kind of asphalt mixture	Amount of additives (%)	Penetration at 25 ºC (1/10th mm)	Softening Point (ºC)	Ductility at 25 ºC	Flash Point (ºC)	Fire Point (ºC)	Specific Gravity at (ºC)
Testing standards		ASTM D5	ASTM D36	ASTM D113	ASTM D92	ASTM D92	ASTM D70
Pure Bitumen results	0	65	48.5	+100	268	285	1.03
	2	63	50	88	274	288	1.028
PBW Amount (%)	4	61	53	85	287	298	1.025
	6	58	57	78	298	309	1.022
	8	53	65	70	308	317	1.020
	10	48	65	64	315	324	1.018
SBR Amount (%)	2	60	55	95	292	300	1.025
	4	56	59	91	297	315	1.021
	6	53	65	86	311	327	1.017
	8	49	71	79	321	337	1.014
	10	43	76	73	332	349	1.012
Specification		60-70	45-52	<100	>225	>250	1.01-1.05

The changing percentages of SBR and PBW modifiers have a direct effect on the characteristics of black top, as demonstrated in the figures 5, 6, 7, 8, 9, and correspond to performance of pavements. By increasing the quantity of the modifier, the reduction in penetration & rising in the softening point indicates that the modified asphalt will perform better under elevated temperature conditions compared to standard asphalt, which may soften and deform in hot climate conditions. The higher flash and fire points indicate improved thermal stability and decreases the risk for fire hazards or softening of the asphalt due to extreme highs on the pavement surface. Lastly, the decline in ductility related to increased modifier content implies less flexibility that may affect thermal cracking in colder climates. Overall, the features attained from SBR and PBW modified asphalt provide the necessary thermal stability and mechanical stability to extend pavement longevity and support load, especially in situations of heavy traffic or extreme temperature. Though it may not seem as ethnic, ultimately optimizing the percentage of modifier used for each event previous proposed quantity needs to balance between strength and flexibility to adequately predict even as an average environmental condition.

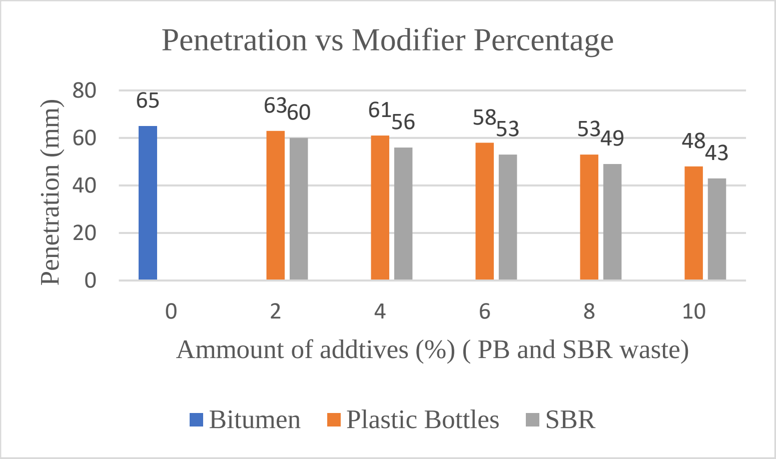


Figure 5. Findings of penetration for pure and PBW & SBR Modified Bitumen Sample

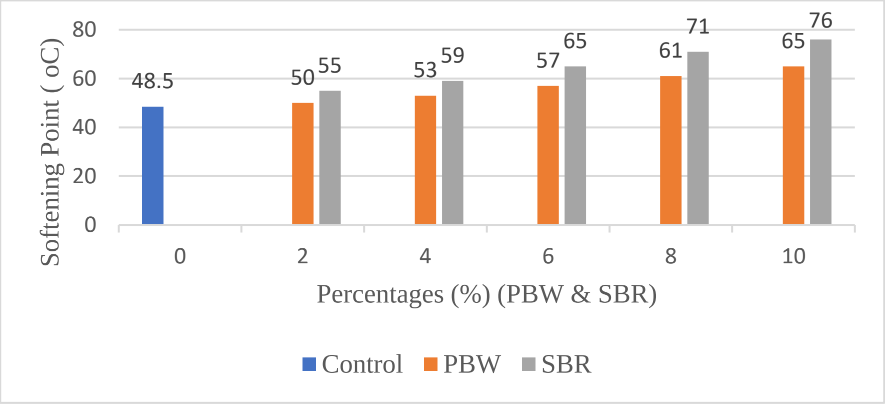


Figure 6. Softening Point Results of pure and PBW & SBR Modified Bitumen Sample

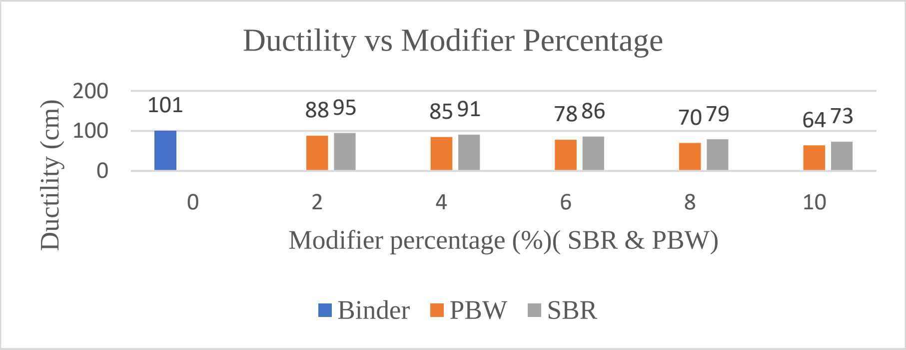


Figure 7. Ductility Results of pure and PBW & SBR Modified Bitumen Sample

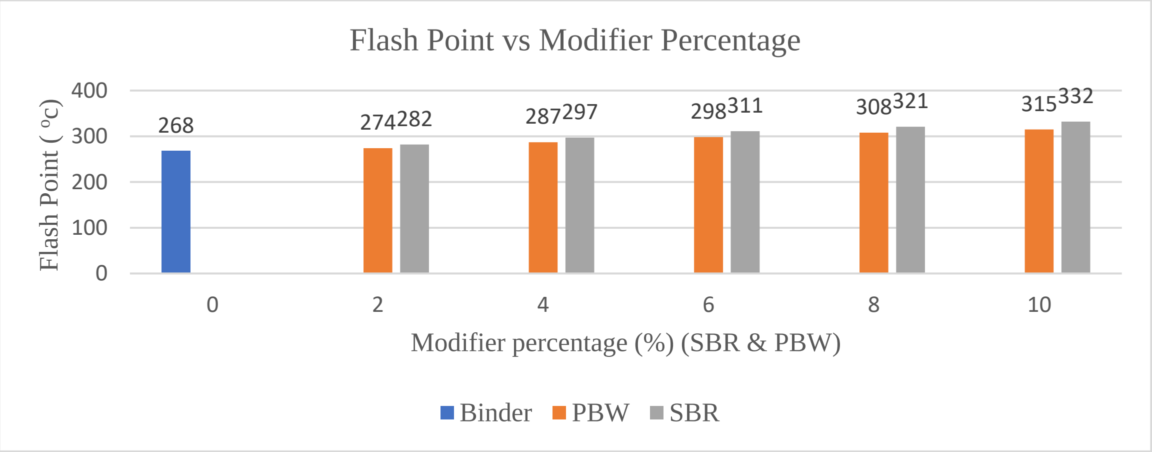


Figure 8. Flash Point Results of pure and PBW & SBR Modified Bitumen Sample

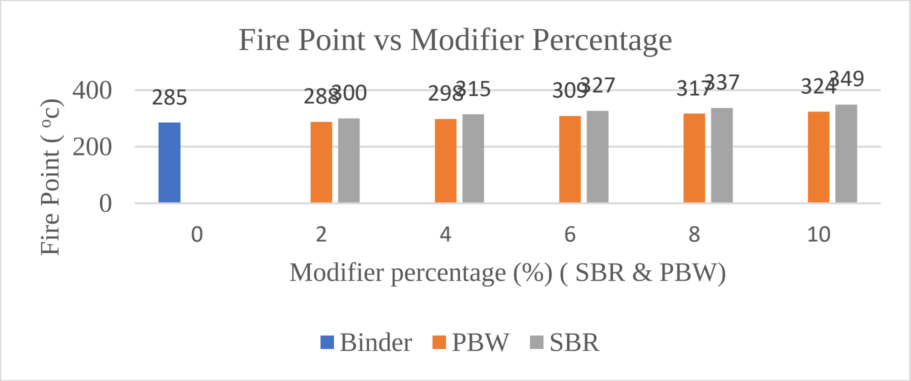


Figure 9. Fire Point Results of pure and PBW & SBR Modified Bitumen Sample

Marshall samples were made at 165°C with total binder contents of 4%, 4.5%, and 5%, based on the Marshall briquette weight. The optimum binder content (OBC) was determined to be 4.2%, according to the data shown in Table 6 and ASTM D1559 standards. The mix also met the minimum stability requirement of 5.88 KN and the flow requirement of 2-4mm. Volumetric properties (VMA, VFA, and AV) remained within the applicable thresholds of 14% (VMA), 65-75% (VFA), and 3-5% (AV). Modified asphalt mixes were then made with 2%, 4%, 6%, 8%, and 10% SBR & PBW using 4.2% OBC for conventional asphalt. Their test results are shared in Table 6.

Table 6. Volumetric Properties of Marshal Mix Design for Standard and Modified Samples

Names	Dosage of modifiers (%)	OBC (%)	Marshall stability (kN)	Flow (mm)	VMA (%)	VFB (%)	Va (%)
Control sample	0	4.2	6.3	2.7	16.80	74.34	4.30
	2		5.9	3.6	15.62	74.30	4.20
PBW	4	4.2	9.9	2.8	15.30	74.36	4.10
	6		10.2	2.3	15.00	74.50	4.00
	8		9.6	2.9	14.65	74.71	3.80
	10		8.5	3.3	14.3		

					5	74.81	3.65
SBR	2	4.2	7.9	2.6	15.20	74.37	4.00
	4		10.3	2.4	14.80	74.62	3.85
	6		12.4	2.0	14.50	74.75	3.70
	8		10	2.5	14.15	74.82	3.45
	10		9.4	3.0	13.95	74.94	3.20
Requirements			<5.88	<2-4	<13	65-75	3-5

The figures 10, 11, 12, 13, 14 show the effects of the two additives (PBW and SBR) on key performance measures for pavements. Marshal Stability has a steady increase with higher percentages of additives, particularly at 6% (10.2 KN for PBW modified asphalt and 12.4 KN for SBR modified asphalt sample, indicating capacity for carrying the wheel loads has improved as compared to standard sample of asphalt which was 6.3KN and at 8% & 10% the stability gets decrease may be due to over modification that results in negative. Flow values continued to decrease with more additives up to 6% for both PBW & SBR modified samples of 2.2 & 2mm, which implies workability has improved with additives and brittleness was substantially reduced, which is desirable in flexible pavements. VFB remained stable along with the increasing percentage of additives at 6%, thus ensuring in-place uniform distribution of aggregates. VA also continued to slightly decrease at 6%, which indicated that durability improved in pavement by decreasing percentage voids to reduce infiltration of water. In summary, the additives improved stability, flow, and durability, indicating capability for improving pavement performance, in particular cracking and deformation under traffic loads.

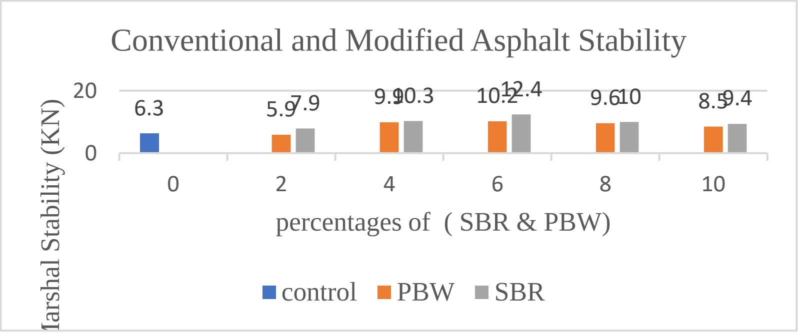


Figure 10. Marshal Stability for pure and PBW & SBR Modified Asphalt Specimens

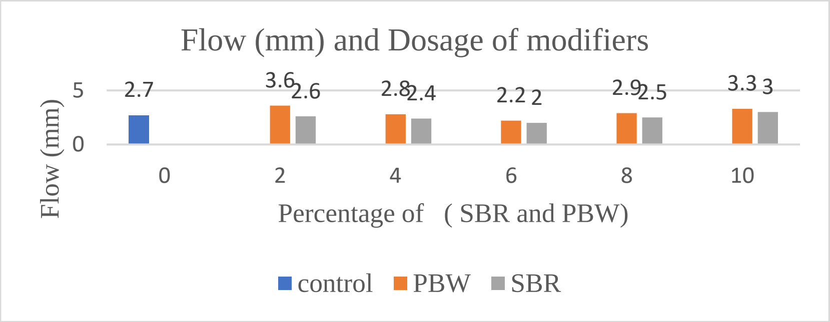


Figure 11. Flow Results of Pure and PBW & SBR Modified Asphalt Specimens

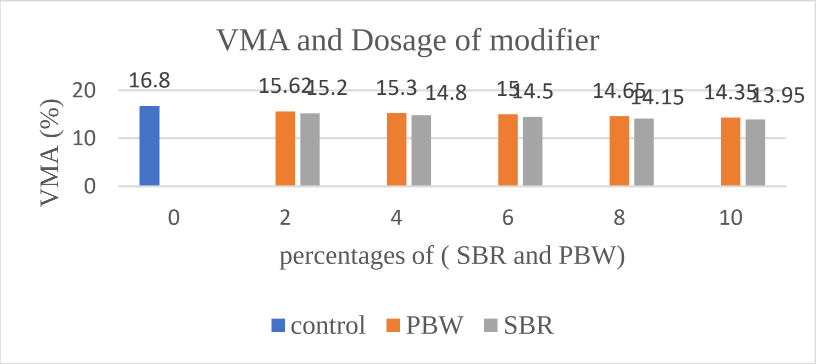


Figure 12. VMA Results of Pure and PBW & SBR Modified Asphalt specimen

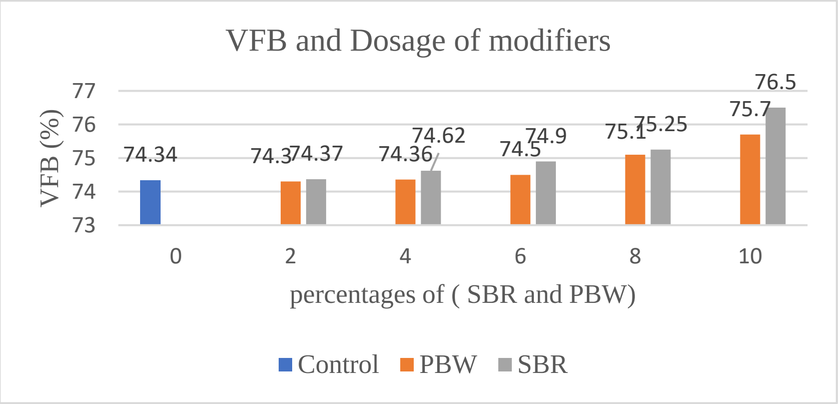


Figure 13. VFB Results of Pure and PBW & SBR Modified Asphalt specimens

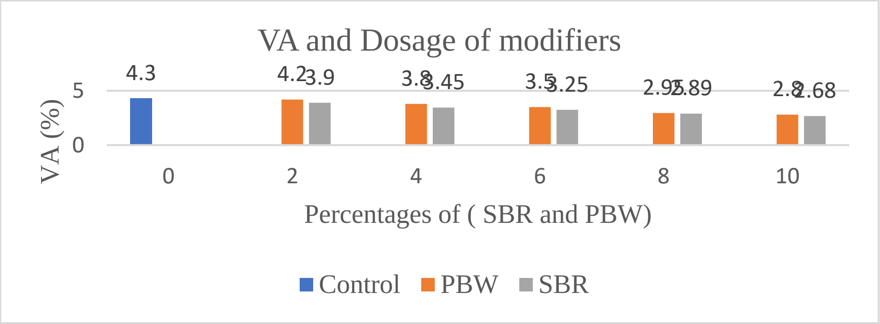


Figure 14. VA Results of Pure and PBW & SBR Modified Asphalt specimen

The figure 15 indicates the influence that PBW and SBR additives have on the viscosity of binders at varying temperatures of 135°C and 165°C. Increased viscosity is observed at both temperatures with the higher additive percentages, particularly with PBW and SBR, indicating greater stiffness of the binder. Viscosity is an important property that increases the potential for rutting resistance, where deformation can occur with heavy traffic volume. Therefore, the added viscosity that is created through the use of additives improved the overall durability and performance of the pavement, particularly at higher temperatures.

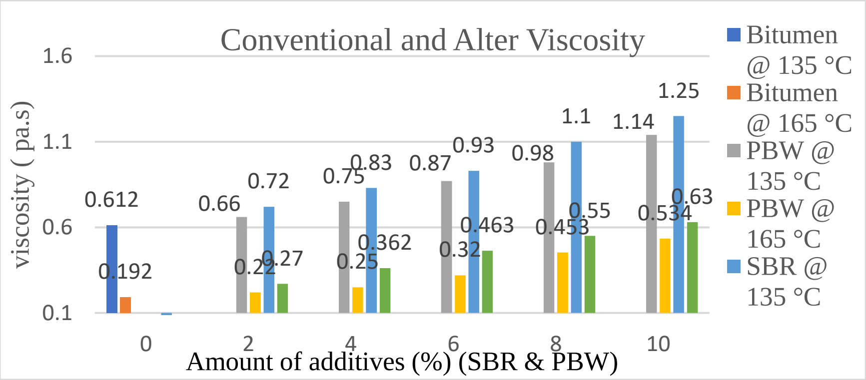


Figure 15. Viscosity Results of Pure and PBW & SBR Modified Asphalt Samples

The demonstration of increasing SBR & PBW content is shown in Figure 16 to exhibit on the indirect tensile strength for conditioning & un-conditioning states. In the moisture susceptibility testing that included freeze-thaw cycles, the capitalization of water damage was reduced to the testing conditions. As increasing SBR & PBW content to 6%, the TSR values improved indicating an increased resistance to moisture is shown in figure 17. However, at the 8% & 10% SBR & PBW content the TSR values dropped to low levels and indicated a reduced performance of the pavement. The PBW & SBR modified mix significantly outperformed the standard mix due to the limited mobility and coverage the SBR & PBW provides enhancing the cohesiveness of the asphalt modified mix. Nevertheless, 8% & 10% SBR & PBW content reduced the integrity of the asphalt mixture.

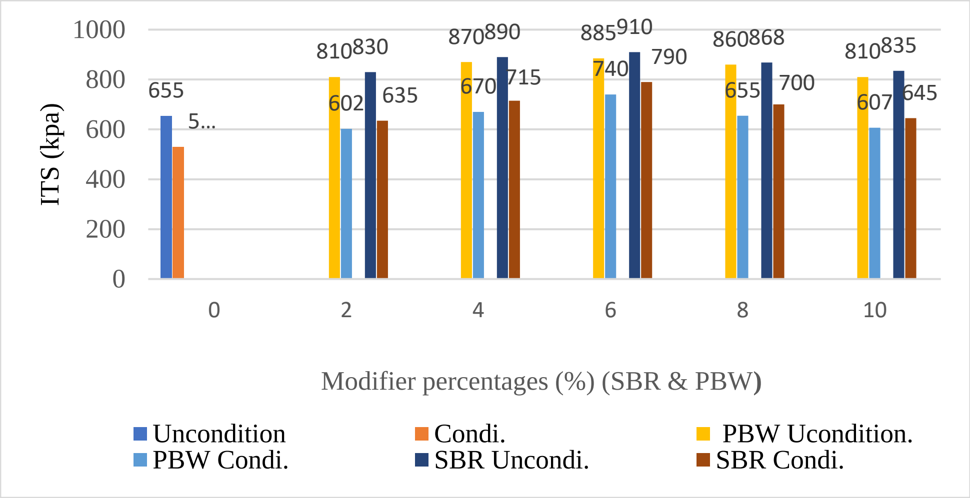


Figure 16. ITS Results of Pure and PBW & SBR Modified Asphalt Samples

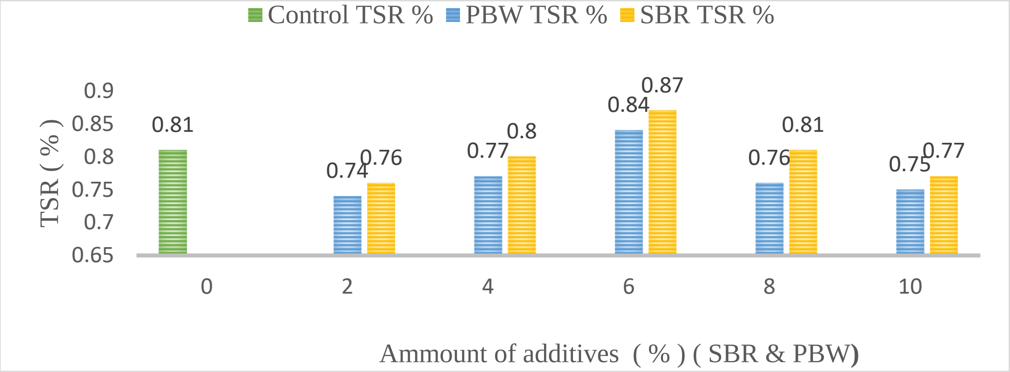


Figure 17. TSR Results of pure and PBW & SBR Modified Asphalt Samples

To evaluate the endurance of standard and modified asphalt mixtures against permanent deformation induced by wheel loading at 55°C, eleven specimens measuring 7 kg each were initially prepared with 2%, 4%, 6%, 8% and 10% PBW & SBR contents using a Marshall compactor. These specimens were subsequently exposed to a Wheel Tracking Test, recording rut depth after 10,000 machine passes. The Wheel Tracking Test results directly comparing each mixture under the same wheel loading after 10,000 passes can be seen in Figures 18 and 19. It was noted that all mixtures regardless of percent PBW & SBR content complied with the maximum rut depth criterion of 12.5 mm. The mixture using 6% PBW & SBR exhibited the minimum rut depth, suggesting it showed the greatest resistance against permanent deformation when compared to the standard mixture. As noted from the respective rut depth findings, mixtures with 8% PBW & SBR and 10% PBW & SBR also presented acceptable performances exhibiting rut depths of 1.6 mm and 2.1 mm, respectively, but did exhibit an upward trend in rut depth during the time period that was observed, most likely due to a loss of cohesion and integrity associated with a higher percent content of PBW & SBR facilitating permanent deformation which demonstrates the mixtures would not have been able to withstand additional wheel loading.

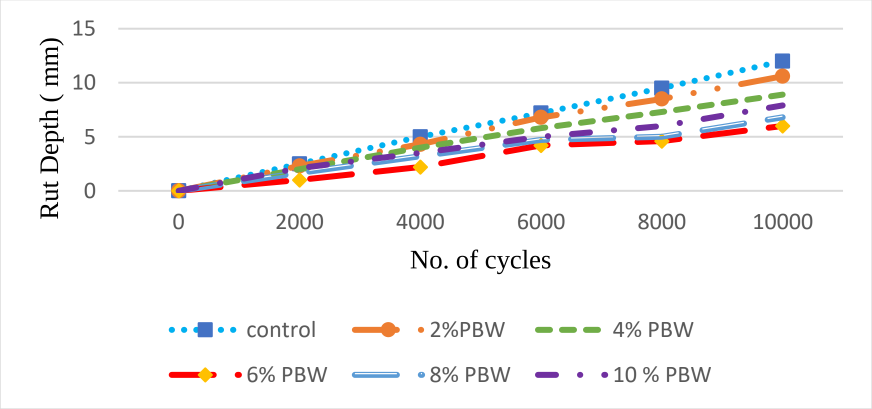


Figure 18. Rut resistance of pure and PBW Modified Asphalt Samples

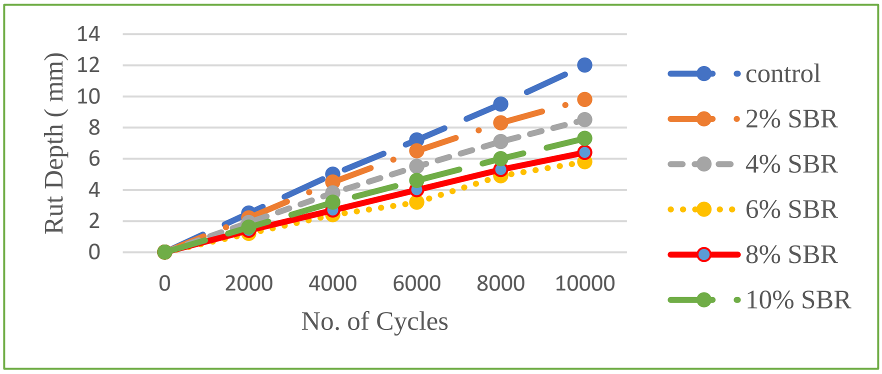


Figure 19. Rutting Results of Pure and SBR Modified Asphalt Samples

The figure 20 illustrates that PBW & SBR additive content has an impact on dynamic modulus at different frequencies, which represents pavement stiffness. The dynamic modulus increases as PBW & SBR increases from 0% - 6%, which shows an increase in stiffness and strength of the asphalt mixture, consequently allowing the mixture to resist traffic deformation. The dynamic modulus starts to decline at 8% and 10% PBW and SBR , implying that high amounts of PBW & SBR content may cause damages to the asphalt structure, which can ultimately lead to performance issues. This reduction in the dynamic modulus past the maximum point could be due to the excess PBW & SBR impacting the cohesion of the mixture, which ultimately reduces the overall stiffness of the mixture, thus potentially leading to longer-term performance issues. Therefore, it appears a PBW and SBR additive content of 6% is ideal for the asphalt mixture due to the dynamic modulus beginning to level off past this percentage.

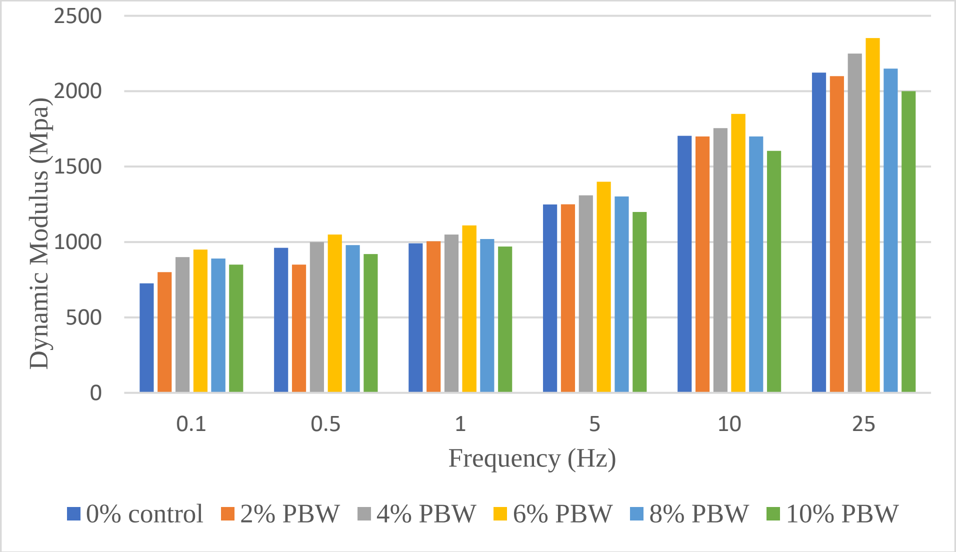


Figure 20. Dynamic modulus of pure and PBW modified asphalt specimen

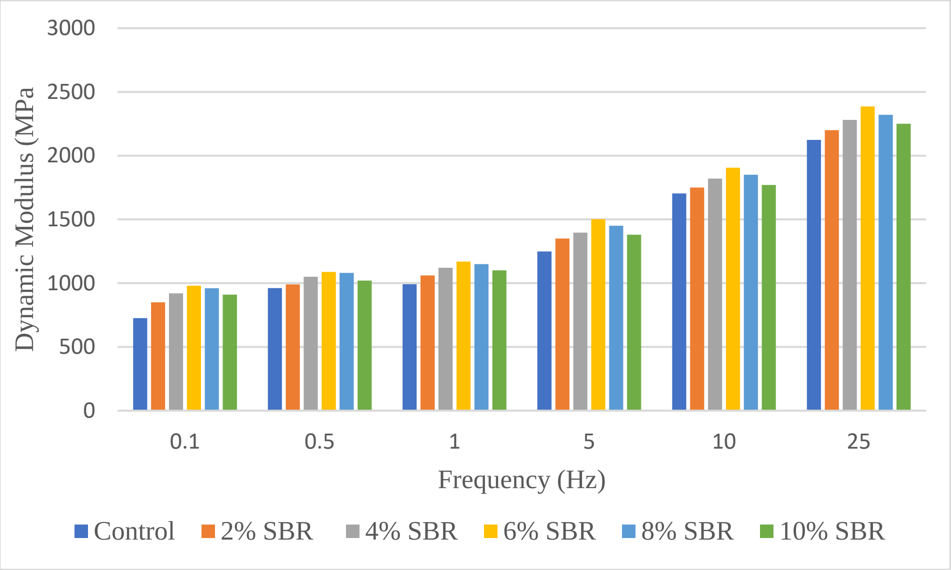


Figure 21. Dynamic modulus for pure & SBR modified asphalt specimens

The XRD (X-ray diffraction) patterns shown in pure bitumen, PBW-modified bitumen at 6%, and SBR-modified bitumen at 6%, as shown in figure 22, 23, and 24, reflect the crystallinity and the resulting structural change observed in the asphalt binder when modified with the aforementioned additives. The pure bitumen exhibited a less crystalline structure with low intensity peaks, implying it is a relatively softer modification. When modified with PBW and SBR, the intensity peaks increased notably, especially closer to the 20° and 30° angles, suggesting increased structural stability and improved cohesion. These changes have a significant meaning in terms of pavement life and durability, since they will improve the resistance to deformation, cracking, and aging of the binder. The increased crystallinity of both PBW and SBR modified binders at 6% demonstrates increased durability under traffic loading and environmental conditions, which is expected to extend the pavement life. While too much modification could risk producing a too-stiff binder at increments beyond 6%, increasing the risk of stiffness and subsequent cracking.

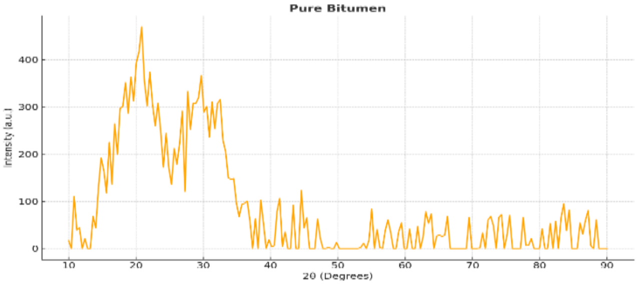


Figure 22. XRD Findings of Pure Bitumen specimen

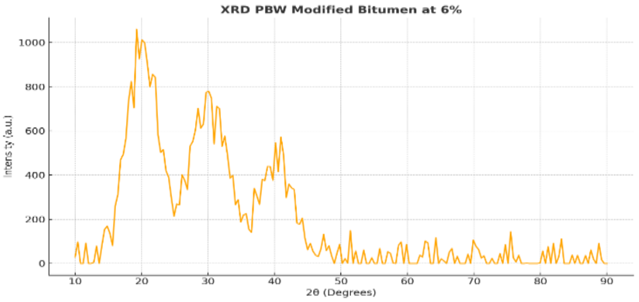


Figure 23. XRD Findings of 6% PBW Modified Bitumen

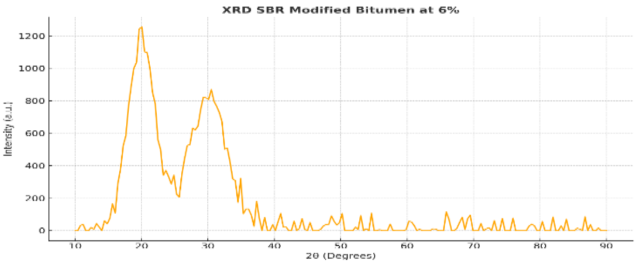


Figure 24. XRD Findings of 6% SBR Modified Bitumen Sam

The FTIR spectra for pure bitumen, bitumen modified with 6% PBW, and bitumen modified with 6% SBR, as shown in figure 25, 26, 27, show significant differences in their molecular chemistry, which affects long-term pavement performance. The spectra show that the pure bitumen has comparatively higher transmittance at the wavenumbers 3350 cm^{-1} and 2920 cm^{-1}, indicating a molecular structure that is relatively simple and prone to the impacts of the environment. Excluding transmittance, the spectra for the bitumen modified with 6% PBW show higher peaks (2925 cm^{-1}, 2859 cm^{-1} and 1726 cm^{-1}) which are indicators of the polymer and the bitumen interactions. Greater cohesion of the polymer and an enhanced resistance against oxidative aging, which can improve long-term durability of the binder, are possible explanations for the peak intensities resulting from the polymer-modified binder. The spectra for the bitumen modified with 6% SBR also showed similar indicators, pointing out the greater cohesion and potential improvements for flexibility and cracking resistance over time. It should be noted that both polymer-modified bitumen types were low transmittance wavenumbers, which indicate a more complex molecular structure, thereby possibly contributing to improvements in long-term performance, including the reduction of moisture-related failure, oxidative aging, and thermal cracking. Overall, modifications to the binder material through PBW and SBR show potential to improve durability and flexibility of the binder material for pavements subjected to extreme weather and traffic conditions.

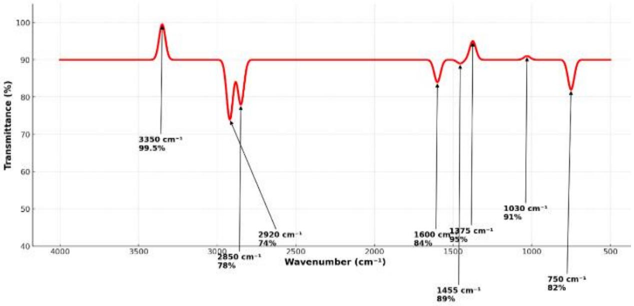


Figure 25. FTIR Results of Pure Bitumen Sample

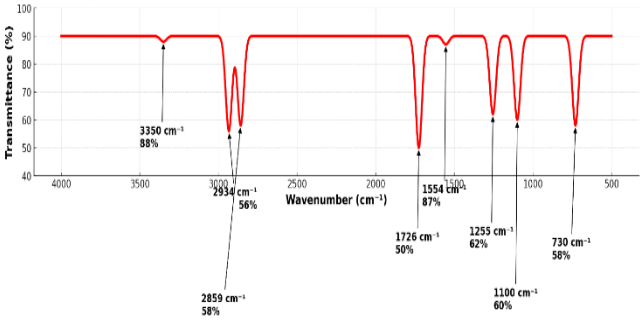


Figure 26. XRD Results of 6% PBW Modified Bitumen Sample

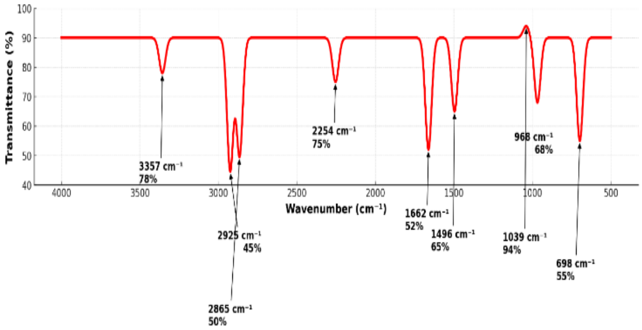
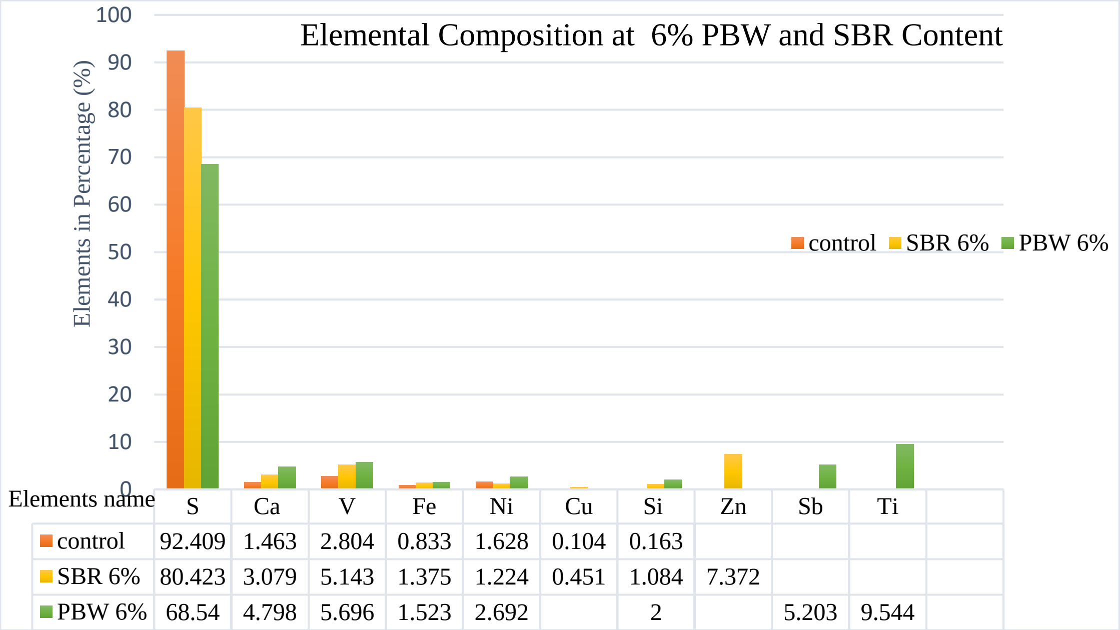


Figure 27. XRD Results of 6% SBR Modified Bitumen Sample

The elemental makeup shown in figure 28 of the control and modified bitumen (6% PBW and SBR) demonstrates distinct differences, particularly in sulfur (S) content. The control bitumen has a higher sulfur proportion, which may induce brittleness and a lack of resistance to oxidation. Both modified bitumen (PBW and SBR) displayed lower sulfur levels which will improve the durability of the bitumen and its resistance to aging. Moreover, the addition of elements such as calcium (Ca) and titanium (Ti) specifically contributes to the overall stability and resistance to environmental influences of the modified bitumen which will improve long-term pavement performance. These modifications contribute to improved strength, flexibility, and durability of the bitumen under varying conditions of traffic and weather.



Elements name	S	Ca	V	Fe	Ni	Cu	Si	Zn	Sb	Ti
control	92.409	1.463	2.804	0.833	1.628	0.104	0.163			
SBR 6%	80.423	3.079	5.143	1.375	1.224	0.451	1.084	7.372		
PBW 6%	68.54	4.798	5.696	1.523	2.692		2		5.203	9.544

Figure 28. XRF Results of Standard, 6% PBW and SBR Modified Bitumen Samples

The findings of the present study has approved the recent studies show that adding Styrene-Butadiene Rubber (SBR) to asphalt increases its Marshall stability, with a 9% SBR addition improving stability by approximately 18% [41]. Similarly, the incorporation of Polybutadiene (PBW) rise the stability & flow characteristics of black top mixes [42]. However, SBR tends to provide better performance in terms of stiffness and resistance to deformation compared to PBW. All the outcomes highlighting the usefulness of both alters in improving asphalt binder durability.

Recent research has shown that SBR can be added to asphalt mixtures to greatly impact the Tensile Strength Ratio (TSR) which indicates greater strength and moisture resistance at 7%.

The outcomes of the recent investigation relate the results of the investigation performed by Shaker et al. (2020) reported that SBR mixtures significantly increased the TSR compared to control mixtures [43]. Likewise, Farajollahi et al. (2022) noted that the mixture of SBR with PET at 6% produced an even higher TSR effect. These findings represent the same findings you have shown in your graph that increasing SBR and PBW percent achieves higher TSR, which is indicative of better durability of the asphalt [44].

The results of your study indicate that an increase in both SBR and PBW modifier percentages significantly decreases rut depth under cyclic loading, with the 6% modified samples exhibiting the best performance. These results are aligned with information from the existing literature. In terms of SBR, Ahmed et al. (2021) showed that by including an SBR modifier at up to 8%, the rutting resistance of the asphalt binder was notably improved as indicated by changes in G/sin δ and recovery from MSCR tests signifying lower permanent deformation under thermal and stress conditions [45]. Similarly, Al-Khateeb et al. (2021) [46] reveals that the SBR altered black top mixes performed significantly better with lower rut depths and exhibited improved viscoelastic characteristics compared with the unmodified mixture especially at higher levels of SBR inclusion.

With respect to PET or the plastic waste (similar to PBW), Ali et al. (2020) [47] noted that recycled PET yielded modifications in rutting resistance of the asphalt mixtures which appeared to be enhanced at 5–8% although high levels resulted in increased stiffness and decreased ductility. Mahrez and Karim (2010) [48] also find out that PET altered black top mix had the potential to perform better in the high-temperature deformation, but they cautioned about optimizing the content of modifier to assure a ductile material and not yield brittleness. The observations you made about PBW follow the similar trend-- moderate to high content (6–10%) increased rutting performance of the asphalt mixtures relative to SBR, but did not perform as effectively at low levels.

The addition of 6% of both SBR & PBW into hot mix asphalt (HMA) has demonstrated better performance than traditional HMA under traffic loading and exposure to environmental conditions. This modification improves pavement durability, thus making it a feasible implementation within the industry to produce cheap, sustainable and higher performance road surfaces as well as to protect our eco-system [48].

CONCLUSION

1. An OBC of 4.2% was conclude by weight of marshal sample for conventional and modified samples as per marshal stability and flow.
2. PBW and SBR of 6% is concluded as optimum in terms of Pavement in-service performance.
3. PBW decrease penetration up to 26% and SBR up to 34% making it stiffer. SBR improves the softening point up to 57% and PBW up to 34% making it more heat absorbent during serviceability.
4. The use of 6% PBW and SBR in asphalt increase the Marshal stability 10.2 kN and 12.4 kN from 6.3kN of conventional sample. The 6% content of both PBW and SBR keeps the flow value within an acceptable range of 2.0 – 4mm.
5. The use of 6% PBW and SBR in asphalt increases stiffness and modifying its chemical composition adequately as per FTIR analysis.
6. The 6% PBW and SBR concentration enhancing the crystalline structure of the binder which consequently improves the pavement performance as per XRD analysis.
7. The addition of 6% PBW and SBR results in a more stable mixture in terms of rutting, dynamic modulus and indirect tensile strength performance compared to unmodified mixture under the prevailing condition of traffic and environment.
8. SBR modified asphalt increases asphalt pavement life up to 50% and PBW modified asphalt up to 35% when subjected to traffic and environment.

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