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Laboratory Evaluation of Sustainable Asphalt Mix Using Bottom Ash and Styrene Butadiene Styrene

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Abstract: The increasing demand for sustainable road construction materials has prompted researchers to explore alternative methods for modifying bitumen to improve pavement performance while enhancing environmental sustainability. This research aims to evaluate the effect of using Bottom Ash (BA) as a bitumen modifier along with Styrene Butadiene Styrene (SBS) to enhance the mechanical properties and durability of hot mix asphalt (HMA). The effect on Marshall Stability, Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), and rutting resistance was evaluated using a Wheel Tracking Test (WTT). The results showed that using 5% BA and 4% SBS improved the performance of the asphalt. The Marshall Stability value increased by 33.65% compared to the unmodified mixture, indicating a significant improvement in load resistance. While the unconditional value of the (ITS) test increase by 32.46% compared to the unmodified mixture, the conditional value (after water immersion) increased by 54.16% compared to the unmodified mixture, indicating an improvement in moisture resistance. The TSR test results confirmed that the modified mixture achieved a 16.39% increase compared to the unmodified mixture, indicating high resistance to moisture effects. In addition, the (WTT) results also showed a 53% reduction in wear depth compared to the unmodified mix, reflecting an improvement in the resistance to permanent deformations under repeated traffic loads.BA is recommended for use with SBS because it significantly improves the mechanical performance of the asphalt mix. It provides an economical and sustainable solution by using recycled industrial waste, reducing reliance on virgin raw materials, and enhancing the durability of asphalt pavement in the face of harsh environmental and traffic conditions.

Keywords: Bottom ash, Mechanical performance, Modified asphalt binder, Styrene butadiene styrene (SBS), Sustainable asphalt

Introduction

There has been much advancement made in Hot Mix Asphalt (HMA) concrete products for decades as a result of technological developments and more knowledge of the performance characteristics affecting pavement quality and the capacity of roads to cope with load and climatic changes. Nevertheless, this also, in turn, led to the production of modified HMAs, which is specifically designed to reduce cracking, rutting, moisture damage, and deformation caused by constant heavy loads and severe climate conditions (Taghipoor et al., 2023). One of the significant factors in this process is the need to reduce cracking due to thermal and moisture-induced stress, ensure the fulfillment of performance requirements for asphalt mixtures, enhance sustainability, and reduce dependence on raw materials (Jin et al., 2024). The impact of environmental factors, oxidation, loss of volatile components, and repeated loading on the properties of asphalt mixes and leads to deterioration of physical properties, resulting in cracking and loss of durability. (Bocci et al., 2020; Huang et al.; Pan et al., 2021). These environmental conditions, in addition to the continuous movement of vehicles, lead to the deterioration and erosion of the upper layers of asphalt mixtures, resulting in numerous mechanical and engineering problems (Singh et al., 2013). In light of these challenges, there has been increasing interest in enhancing the physical and mechanical performance of asphalt mixtures by incorporating polymeric additives and recycled materials. Polymers such as SBS and various types of industrial waste have shown positive effects in minimizing deformation and improving crack resistance and thermoplastic behavior (Alhaji et al., 2022; Caputo et al., 2020; Liu et al., 2022; Zhang et al., 2022). One of the most promising materials in this field is bottom ash, which is produced from the combustion of fossil fuels in power plants. This ash is produced in large quantities, especially when using diesel and crude oil, and poses an environmental threat due to its heavy metal content, such as Cu, Pb, Cd, Hg, Zn, Ni, and others (Jaber et al., 2022; Jamshidi & White, 2019). Using ash in secondary applications as an additive or filler for asphalt mixtures is of great importance and an environmentally sound choice, as it improves the properties of asphalt mixtures, since accumulated ash poses an environmental threat to groundwater and soil (Buritatum et al., 2022; Jaber et al., 2022)(Ahmed et al., 2021; Akhira et al., 2023; Buritatum et al., 2022). In addition, studies have demonstrated the effectiveness of using SBS in improving asphalt flexibility by forming polymer chains within bitumen molecules, thus improving its viscoelastic properties and reducing bitumen's sensitivity to heat (see Figure 1) (Al-Nawasir & Al-Humeidawi, 2023a; Sengoz & Isikyakar, 2008; Stelescu et al., 2022). Studies have shown that the use of industrial waste and recycled materials (RAP) plays an effective role in improving physical, mechanical and thermal properties of asphalt mixtures, as well as being a sustainable material aimed at sustainability in road construction and maintenance (Hussein et al., 2021)(Hussein & Salih, 2019).

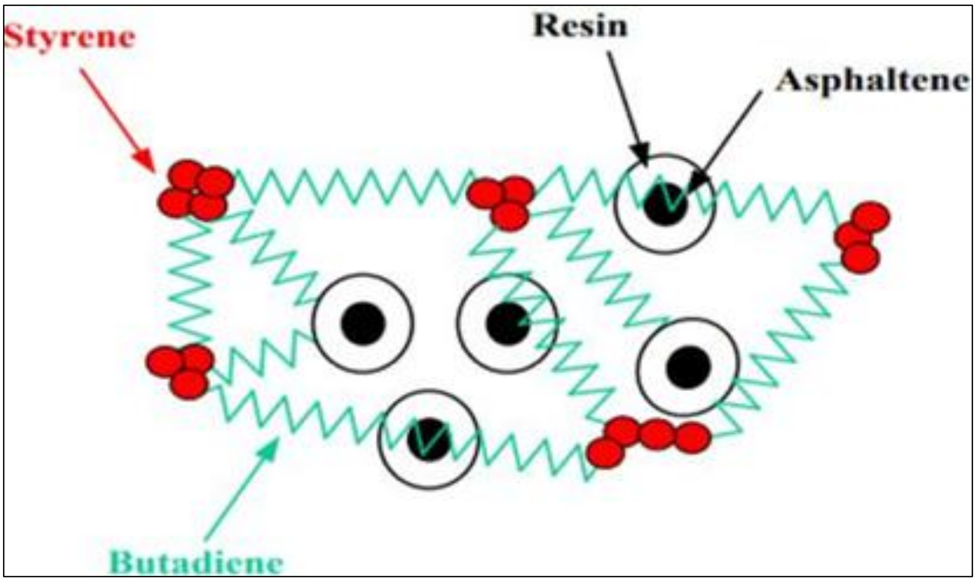

Figure 1.Bringing the SBS polymer and asphalt cement together (Kim, 2010)

Although much research has been conducted using polymers and industrial waste on bitumen, studying its properties and effects, few studies have investigated combined effect of these polymers and industrial waste to utilize each material to improve certain properties of asphalt, resulting in hot asphalt mixtures with enhanced mechanical and physical characteristics. This work aims to fill this gap by studying effect of bottom ash obtained from the combustion of oil, crude oil, and diesel in power plants, and bitumen modified with SBS, to improve mechanical properties of asphalt mixtures. This was accomplished by conducting indirect tensile strength (ITS), tensile strength ratio (TSR), Marshall Stability and deformation test, and wheel tracking test to assess the impact of mechanical and physical properties of mixture. These tests examined characteristics related to moisture susceptibility, rutting resistance, hardness and performance of the mixture.

Materials and Methods

Asphalt Binder

In this study, neat asphalt with a 40-50 penetration grade was used sourced from the Nasiriya refinery in southeastern Iraq. Asphalt testing for the conventional asphalt was tested according to ASTM standards to determine its properties, including Penetration (measuring the hardness of asphalt) softening point, ductility and flash point (the temperature at which asphalt ignites) the results in Table 1, which presents physical properties of asphalt used (see Fig. 2).

Table 1.Physical properties and test of asphalt cement

Property	Standard (ASTM)	Results	Requirement
Penetration (0.1 mm),25°C	D5 (ASTM, 2013b)	46	40-50
Softening point ()	D36 (ASTM, 2014)	48	-
Flash point (°C)	D92 (ASTM, 2002)	287	>232
Ductility (cm)	D113 (ASTM, 2007)	>100	>100
Specific gravity at 25°C	D70 (ASTM, 2009a)	1.036	------
Viscosity at 135 °C (C.P) at 165 °C (C.P)	D4402 (ASTM, 2015)	642.5 166	

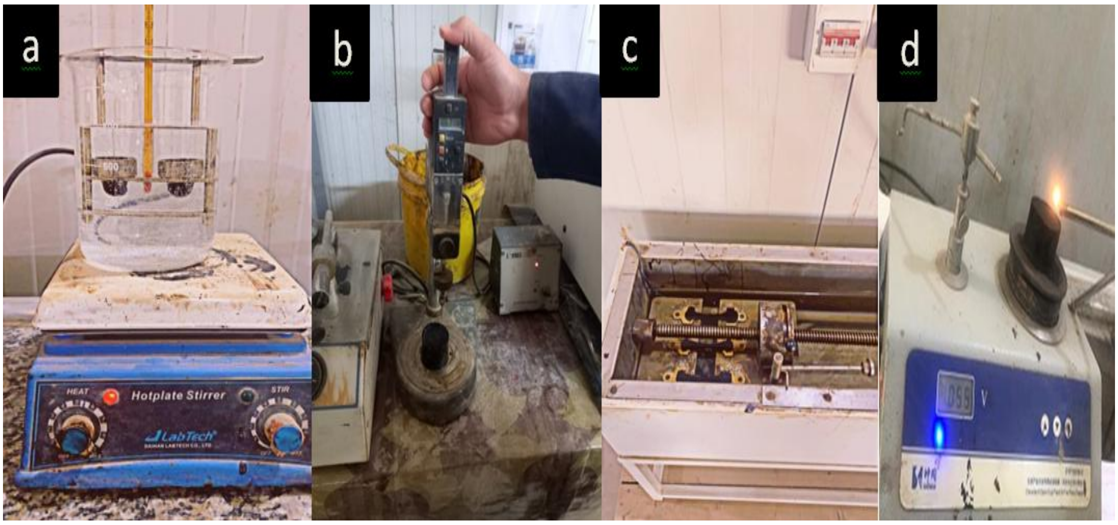

Figure 2. Asphalt test: (a) Softening point, (b) Penetration, (c) Ductility, (d) Flashpoint

Coarse and Fine Aggregate

Local sources were used to obtain coarse and fine aggregates from the Badura quarries in western Iraq with NMAS 12.5 mm. The gradient of aggregates used to design the mixture is mid to the Iraqi standard (see Table 2). Table 4 shows the physical traits of limestone dust. Crushed aggregates with a sharp angle and rough surfaces were used; crushed sand was also used. The tests were carried out for the course and fine aggregates followed ASTM standards to ensure physical properties of aggregate described in Table 3. All tests were performed in laboratories of the University of Al-Qadisiyah (see Fig.3).

Table 2. Gradation of aggregate for wearing course (SCRB, 2003)

Sieve size	mm	Specification limits SCRB (%)	Passing for selected Gradation (%)
3/4	19	100	100
1/2	12.5	90-100	95
3/8	9.5	76-90	83
NO.4	4.75	44-74	59
NO.8	2.36	28-58	43
NO.50	0.3	5-21	13
NO.200	0.075	4-10	7

Table 3. Physical properties of coarse and fine aggregates

Property	ASTM Designation	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity	C127, 128 (ASTM, 2015b)	2.57	2.6
Apparent specific gravity	C127, 128 (ASTM, 2015b)	2.68	2.81
SSD Specific Gravity	C127, 128(ASTM, 2015b)	2.61	2.64
Absorption %	C127, 128 (ASTM, 2015b)	1.67	1.94
Los Angeles Abrasion %	C131 (ASTM, 2014b)	20.4	-

Figure 3. Gradation of virgin aggregate for the surface layer

Table 4. Physical properties of limestone dust

Physical properties	Result
Specific gravity (g/cm^3)	2.6
Specific surface area, m^2/kg	389
%Passing sieve No.200	95

Styrene-Butadiene-Styrene (SBS)

A triblock polymer was purchased obtained from commercial polymer suppliers in Iraq. It comes in the form of small white particles and was used in this study a bitumen modifier. Because of their elastic qualities, SBS polymers are utilized to improve viscosity, complex modulus, and elastic responsiveness when mixing asphalt cement with SBS. Bitumen that contains a high level of aromatic compounds tends to form a more elastic SBS polymer network because of the improved compatibility and interaction between the polymers and the bitumen matrix (Davidson et al., 2014).

Bottom Ash (BA)

Low ash used in this study obtained from steam thermal power plants in Nasiriyah, Iraq. Crude oil and suppliers are burned to heat water and generate steam, which then drives turbines to produce electricity (see Fig. 4). This process produces lower ash as a by-product. During combustion at high temperatures within the ovens, the non-combustible ingredients turn into volatile ash, which remains suspended in the resulting gases, and lower ash, which settles at the bottom of the oven due to its heavy weight. Table 5 shows chemical and physical of BA.

Table 5. Chemical and physical properties of BA

Property	Properties
SiO2	48.15
Al2O3	24.43
Fe2O3	9.15
CaO	3.7
MgO	2
Na2O, K2O	2.3
SO3	1.66
Moisture content %	2
Bulk density g/cm3	1.6
Specific gravity	1.81
Water absorption %	14.8
Porosity %	11.6

Figure 4. Bottom ash production in a thermal power plant

Mixing Process

These paragraphs describe the steps for mixing conventional asphalt with additives to produce modified bitumen. The mixing process is carried out according to the following steps:

1- To mix cement asphalt with (SBS), first, the asphalt is preheated in a furnace at 160°C for 60 minutes. Second, using a high-shear mixer, SBS was gradually added to avoid agglomeration according to the specified proportions (1, 2, 3, 4, and 5) % of the pure asphalt weight. The bitumen sample is coated (covered) to achieve the required temperature and prevent bitumen from oxygen oxidation. Third, it is blended with a high-shear mixer at 2500 rpm and 180 °C for one hour. Finally, the blend is returned to the oven at 160 °C for two hours to achieve the curing process, complete the homogeneity and prevent phase separation to ensure the mixture remains uniform and does not separate; it is then transferred back to a blender and blended thoroughly for one hour at 180 degrees (see Fig .5) (Al-Nawasir & Al-Humeidawi, 2023a).

2- Lower bottom ash was used as a modifier after grinding and sieving from Sieve NO.200 (75 µm) and mixed in proportions of (1, 3, 5, and 7) %. The mixing processes of asphalt cement with lower ash; the asphalt was first heated in the oven at 160 ° C for 1 hour. Secondly, it is placed in a high-shear mixer, and the bottom ash is gradually added to avoid clumping according to the recommended specific ratios of (1, 3, 5, and 7) % of the pure asphalt weight. It is coated to achieve the required temperature and prevent bitumen from oxidation. Finally, the product is mixed with a high shear mixer at 2500 rpm and a temperature of 160° C for an hour.

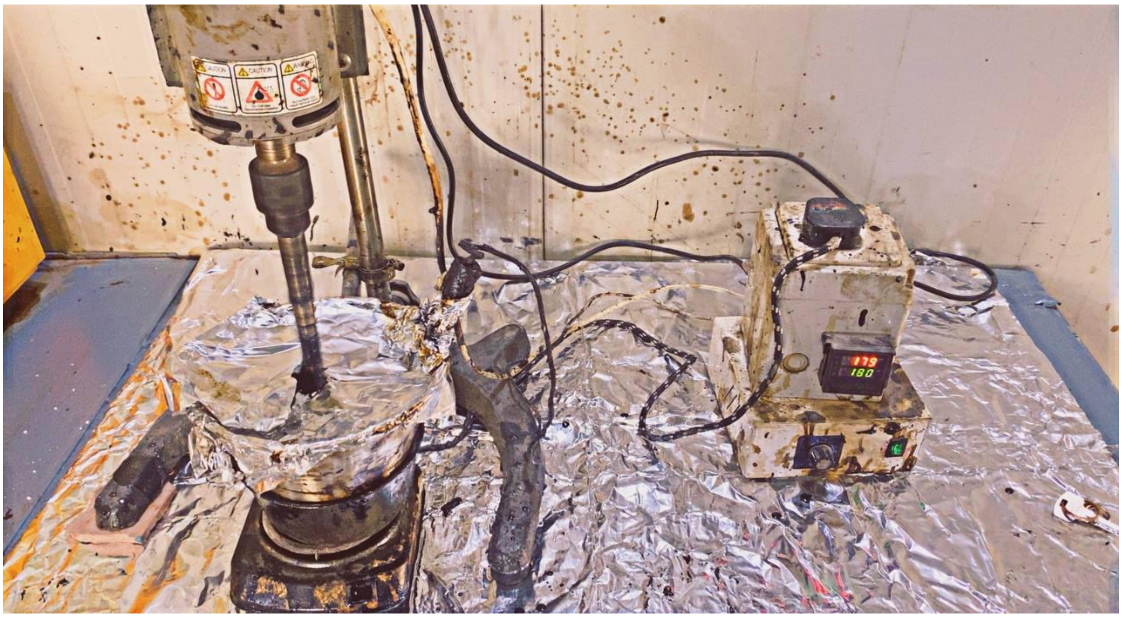

Figure 5. Preparation of polymer blend to enhance bitumen properties

3- To mix cement asphalt with SBS and bottom ash, the asphalt is first heated in the oven at 150 ° C for two hours. Second, it was placed in a high-shear blender, and SBS was gradually added to avoid lumpiness. Studies have shown that a 4% SBS ratio enhances stability, resistance to moisture damage, and adhesion strength between aggregate and bitumen, and has demonstrated superiority in terms of elasticity retention and workability of modified bitumen (Abbas & Abed, 2023; Zhang et al., 2019). 4% SBS of the weight of the pure asphalt at the temperature of 180 ° C was added with continuous mixing using a high-shear blender at a speed of 2500 rpm for an hour until the SBS fully dissolved and formed a homogeneous mixture thereafter adding a bottom ash passing from sieve 200 (1, 3, 5) % of asphalt weight and continues to mix for 30 minutes. Finally, it is placed in an oven at 160 ° C and mixed for one hour at 180° C (see Fig.5) (Al-Nawasir & Al-Humeidawi, 2023a).

Fourier Transforms Infrared Spectroscopy (FTIR)

FTIR is a practical method for analyzing bitumen samples using infrared radiation. The infrared absorption of the samples used is determined by providing chemical information about the molecular bonds of the chemical compound. Spectral data are collected from wavelengths in a wide range (Yao et al., 2015). The working principle is directing a beam of infrared rays at the sample. This sample absorbs certain frequencies that correspond to the vibrations of chemical bonds. The number of absorbed rays is measured at each frequency. Then the raw data is converted into a visible spectrum using a mathematical algorithm (Fourier transform) to represent absorption versus wavelength. The (FTIR) data showed that new polar groups appear when SBS is added to bitumen, improving material's flexibility even when exposed to high temperatures (tur Rasool et al., 2017; Zeng et al., 2023).

Mechanical Tests

Marshall Stability and Flow Test

The HMA mixture was tested using the Marshall test (ASTM-D6927, 2015). The specimen complied with ASTM D6926; strength is expressed in terms of the Marshall stability of the mixture, which is determined by the compressed specimen under the highest load it can endure a standard test temperature of 60°C. The Marshall design process created asphalt mixtures by blending coarse and fine aggregates according to a specified gradation curve (see Figure 6). The aggregates were oven-dried and heated to a mixing temperature of 160°C, and bitumen was heated separately to ensure proper coating of the aggregates. The heated aggregates were mixed with bitumen at five different asphalt binder contents (4, 4.5, 5, 5.5, and 6), and the mixtures were compacted with 75 Marshall blows on each side of the cylindrical specimens. Three samples were manufactured for each binder content. Based on the test results, (OAC) of 5.1% was determined, and this ratio was adopted in all modified mixes containing the improvers, as shown in Figures 7 and 8.

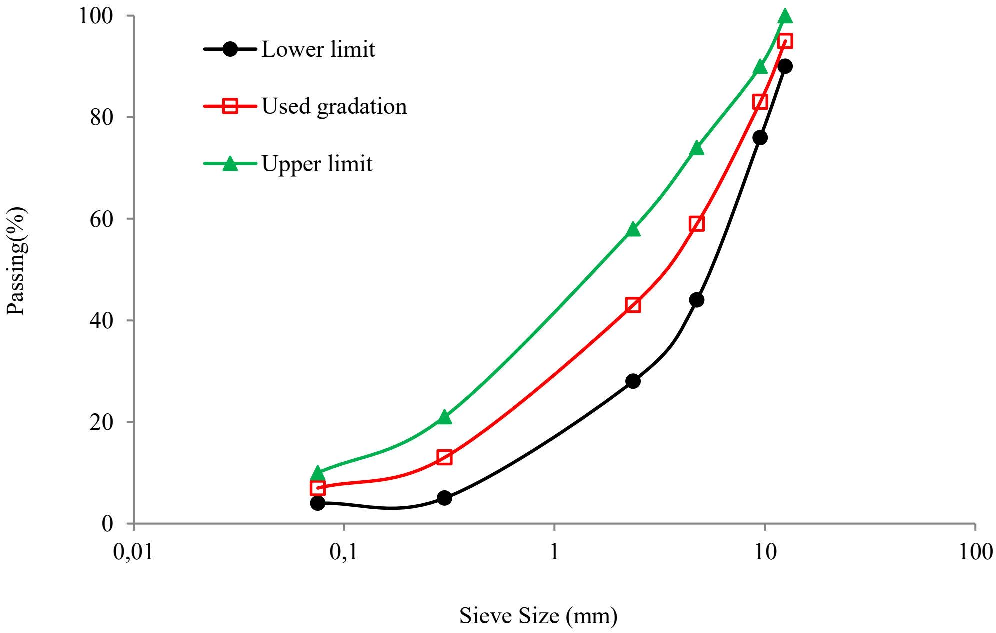

Figure 6. Gradation of coarse and fine raw aggregate used

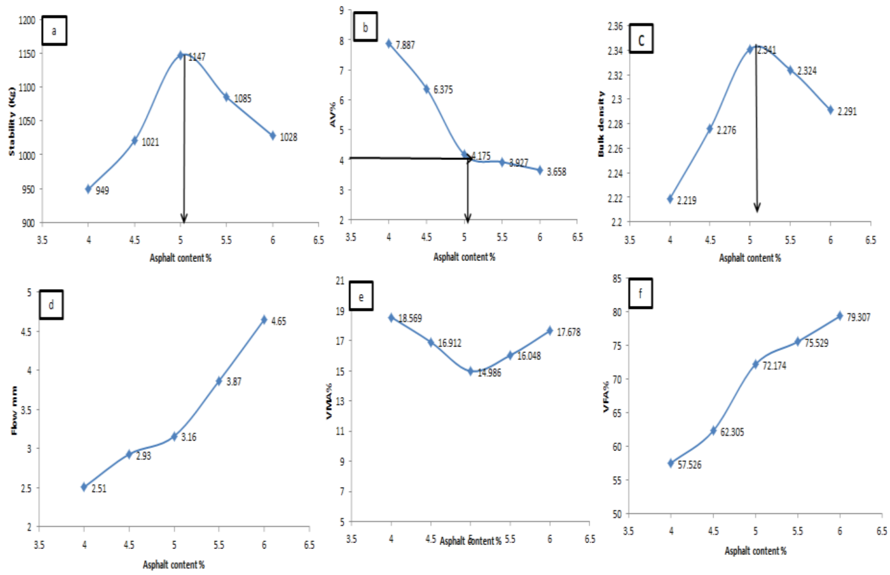

Figure 7. The relationship between asphalt content and mix properties: (a) Stability, (b) Air voids (AV), (c) Bulk density, (d) Flow, (e) Voids in mineral aggregate (VMA), and (f) Voids filled with asphalt (VFA)

Figure 8. Laboratory tests of Marshall in the highway lab at the University of - Al- Qadisiyah

Indirect Tensile Strength (ITS) Test

This test determines the potential of an asphalt mixture to resist tensile cracking at an intermediate pavement temperature. A line load, which refers to a uniformly distributed compressive load applied along diameter of the cylindrical specimen, is applied to perform the ITS test. The sample's tensile strength is calculated by measuring maximum load at the point of failure. A standard reference for this procedure is (ASTM-D4867). Equation (1) is used to compute ITS.

$$ITS = \frac{2000 * P}{\pi * t * d} \quad (1)$$

ITS =Indirect Tensile Strength (KPa)
P = Max load (N)
t = the height of the specimen (mm)
d =the diameter of the sample (mm)

Level of compaction preferred. The number of blows was varied in three separate efforts to find the optimal number of Marshall Hammers: 35, 55, and 75. Three samples were taken for every attempt, and the air voids were determined. After that, a chart was made to choose the air void percentage about 7% (see Fig.9). This graph suggests that 47 blows would be ideal. Six samples were created for each additive type and ratio (see Fig. 10).

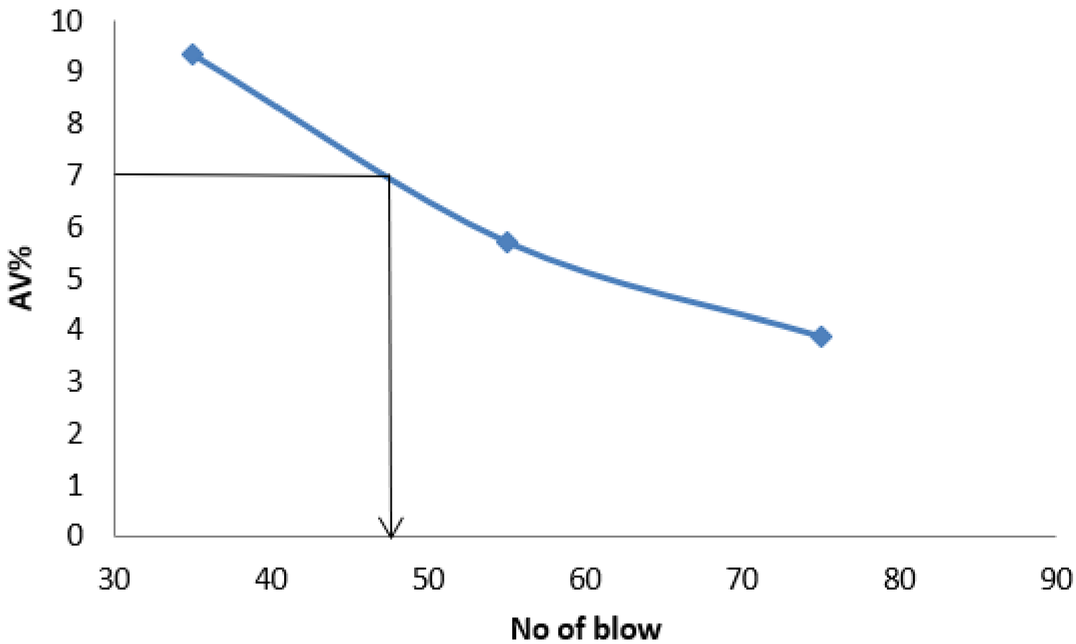

Figure 9. The Relationship between Number of Blows and Air Voids

Figure 10. Laboratory tests of ITS devices and specimens.

Tensile Strength Ratio (TSR)

Wetness damage is a typical issue with asphalt mixes. To test for this, we compare unconditioned and conditioned specimens; higher results indicate better resistance to water damage. Pavement distress, including cracking and rutting, may occur when water penetrates the pavement structure and weakens the link between asphalt binder and aggregate particles. Two sets of specimens were tested. Included three that had been conditioned in immersion bath at 60 °C for 1 day; conversely the other set included three that had not been conditioned. After conditioning, the specimens are subjected to tensile strength tests, and the TSR value is determined. Asphalt mixes are acceptable when their TSR values are 80% or greater (ASTM, 2009). If the value is if below 80%, the combination may be prone to moisture damage and might require adjustments to improve its performance. Moisture susceptibility is calculated to evaluate the quality of the materials used to make HMA, the pavement's design, and the surrounding environment. Equation (2) computes the Tensile Strength Ratio (TSR).

$$\text{TSR (\%)} = \frac{\text{Swet}}{\text{Sdry}} \times 100 \quad (2)$$

Below determines the compacted samples' moisture susceptibility.
Where:
TSR = is the tensile strength ratio.
Swet = is the average tensile strength of the moisture-conditioned specimens.
S dry = is the average tensile strength of the control unconditioned specimens

Wheel Tracking Test (WTT) for Rutting Performance

The (WTT) is a famous and widely used simulation that measures resistance of a mixture to rutting, which is the permanent deformation of a material and moisture damage. The WTT shows both the permanent deformation rate and the mixture's hardening. The test requires controlled wheel loading of a compacted asphalt sample many times. An asphalt sample is usually tested in a wheel track test by having a loaded wheel assembly roll over it repeatedly at a consistent speed and load. The pavement design's anticipated traffic and axle load dictate number of passes and the load applied. Preparing HMA specimens involves making rectangular slab specimens with the following dimensions: 340 x 180 x 50 mm. These readings may be used to calculate several performance measures, including rut depth and permanent deformations. One way to use the wheel track test results is to compare various asphalt mixes and see which ones work best for specific locations, weather condition, type of traffic, wheel load, layer of pavement and other factors. Fig11 illustrates the (WTT) equipment at the University of Al-Qadisiyah's Highway Lab. Specimens were compressed under the machine's compressive load, and three different levels of loads (700, 800, and 900, 1000KN) were tested to determine the optimal compact load that would result in about 7% air spaces. It was determined that specimens would be adequately compacted and have sufficient air space by applying a load of 870KN. The test provides results about the permanent deformation rate due to a moving wheel load. The wheel exerted 700 N (157 lb) of load on the slab during 10,000 cycles (EN 12697 22: 2003). Due to their viscoelastic properties, asphalt binders may easily distort when subjected to traffic stresses. Although a small fraction of the deformations will remain after releasing the load, the majority will be restored (Tahami et al., 2018).

Figure 11. Conducting the (WTT) to evaluate the performance of modified asphalt mixtures

Results and Discussion

Physical Properties of Modified Bitumen

Physical tests were conducted in road laboratories at the College of Engineering, where penetration, softening point, and ductility tests were measured using ASTM procedures. Based on the results obtained (see Table 6), we observe a decrease in penetration value, increasing SBS content. This indicates that the modified bitumen has become more resistant to high temperatures and exhibits improved hardness. Adding BA also improves physical properties, though less so compared to SBS alone. This improvement is attributed to BA's solid chemical composition, which enhances the structural cohesion of asphalt. Combining SBS with BA results in an improved softening point, as this mixture achieves a balance between stiffness and flexibility. This blend also demonstrates higher resistance to thermal deformation (Wang et al., 2021)(READ et al., 2015).

Table 6. Physical properties of the modified asphalt binder

	Asphalt (40-50)	SBS%				BA%				BA+SBS		
		2%	3%	4%	5%	1%	3%	5%	7%	1+4%	3+4%	5+4%
Penetration	46	41	37.5	32.5	27	41.5	37	32	29	31	27	24
Softening point	48	52.5	55	61	65	49.5	53	56	57.5	62	65	68
Ductility	>100	74	70	67	64.5	>100	94	87	85	62	59	55
Flash point	289			>300				>300			>300	

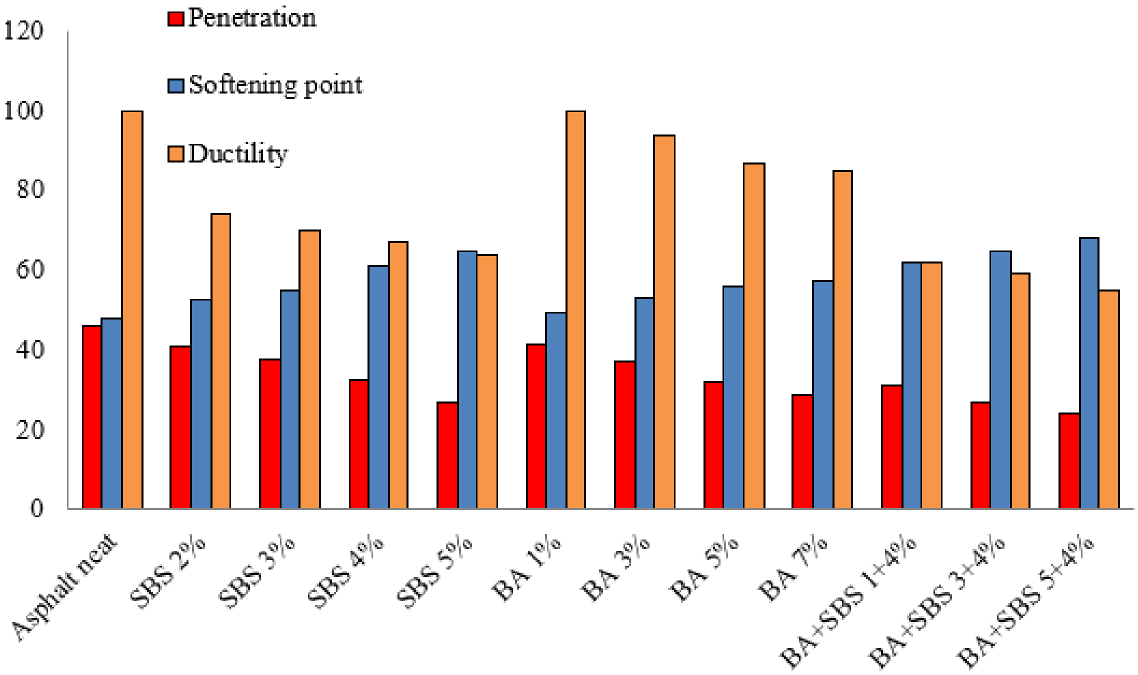

Figure 12. Effect of bottom ash and SBS modifiers the physical properties of asphalt binder

Chemical Tests

To understand the chemical interactions that occur during asphalt modification, Fourier Transform Infrared Spectroscopy (FTIR) was employed to analyze the characteristic functional groups in plain asphalt, bottom ash, and asphalt modified with Styrene-Butadiene-Styrene (SBS). The FTIR results for plain asphalt revealed peaks at 1200 cm^{-1} corresponding to C–O bonds of alkyl aryl ether type, and a peak at 800 cm^{-1} associated with out-of-plane bending vibrations of substituted C–H groups in aromatic compounds. Additionally, a peak appeared at 1600 cm^{-1} reflecting the stretching vibrations of C=C bonds in conjugated alkenes, along with a prominent peak around 3400 cm^{-1} attributed to the stretching of O–H, indicating the presence of hydroxyl groups within the bitumen structure .For bottom ash, the FTIR spectrum showed a broad peak around 3400 cm^{-1}, indicating the presence of hydroxyl (O–H) groups, which suggests the existence of free hydroxyl compounds within the ash components. A peak at 1680 cm^{-1} was also observed, likely due to the stretching of C=O bonds, along with a weak peak at 3000 cm^{-1} attributed to the stretching of O–H in alcohol groups.

Additionally, a significant peak was recorded at 1600 cm^{-1}, which could correspond to C=C bonds or to the bending vibrations of absorbed water, resulting from chemical reactions during combustion processes in power plants. When asphalt was modified with SBS, additional peaks appeared in the FTIR spectrum, confirming the occurrence of chemical interactions and the formation of new chemical structures. Among these, a peak was recorded at 900 cm^{-1} indicating trisubstituted alkenes, and another at 1500 cm^{-1} likely associated with the stretching of C=C bonds in aromatic rings (styrene units). A broad peak also appeared around 3400 cm^{-1} due to O–H stretching, along with a peak at 2900 cm^{-1} attributed to the C–H stretching in alkanes (see Fig13.). These results confirm that chemical interactions occur between the asphalt components and SBS, resulting in the formation of new functional groups that directly affect the mechanical and rheological properties of the modified asphalt binder (Hasan et al., 2017; Nandiyanto et al., 2019).

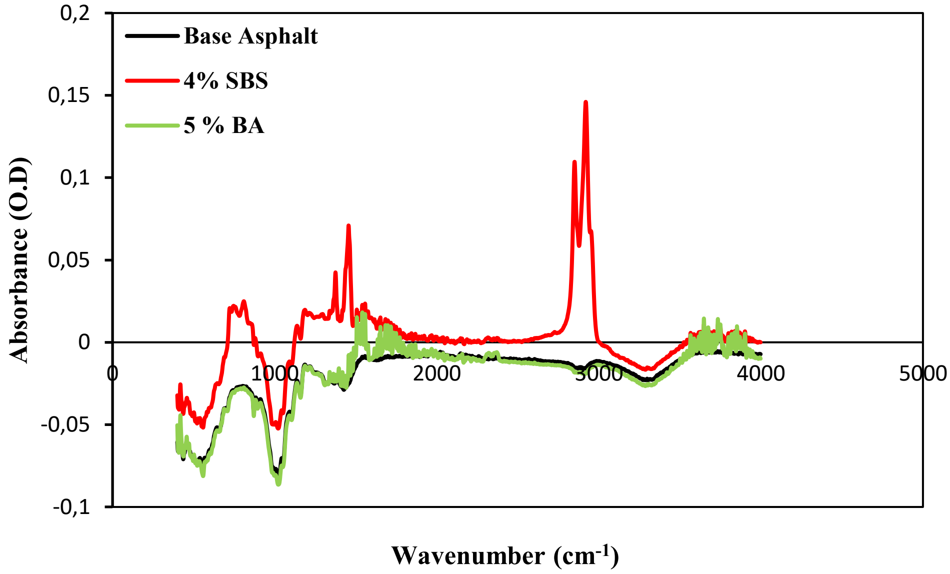

Figure 13. Comparative FTIR spectroscopic analysis of base asphalt and bitumen modified with SBS and bottom ash (BA)

HMA Volumetric Mechanical Characteristics

It is determined using the Marshall Test method (ASTM D6927) and found to be 5.1% when the air void content is 4%. Additionally, the values of VMA and VFA are computed for all mixes. Table 7 presents the Marshall characteristics for the HMA mixes produced at the optimal binder concentration.

Table 7. Volumetric properties of (HMA) and Mechanical characterizes of the mix at optimum binder 5.1%

Property	Test method	Result of the test	Standard
Mechanical Properties	Marshall Stability	1180kg	>1000kg(SCRB ,2003)
	Marshall Flow	3.2mm	2 – 4 (SCRB,2003)
	Air void%	4	3 – 5 (SCRB,2003)
Volumetric	V.M.A %	15.1	>14 (SCRB 2003)
	VFA %	73	70-85% MS2(Institute,2014)

Marshall Stability Test

The results of are Marshall Stability are as can be seen Figure 14, which shows effect of adding BA to pure asphalt. The results showed that when adding 5% of Bottom Ash, the highest Marshall stability value was achieved, reaching 1319 kg. The reason for this is that BA increases the material's viscosity and mechanical stability, which improves its resistance to deformation under traffic loads. When using a percentage of 7%, we notice a gradual decrease in Marshall Stability due to its effect on the chemical structure of bitumen, which negatively affects the performance of the asphalt mixture. When the percentage exceeds 5%, bitumen becomes harder due to the increase in solid materials within the asphalt material. This hardness makes the asphalt material less flexible (READ et al., 2015).

When 4% of SBS is mixed with varying proportions of BA (see Figure 14), we observe an improvement in the Marshall stability value with increasing BA content, recording a maximum reading of 1576 kg. This is attributed to the elasticity of SBS, which reduces its brittleness and resistance to thermal cracking, as well as its homogeneity when mixed with BA, thus enhancing the overall performance of the mixture (Luo et al., 2022; Zhou et al., 2024).

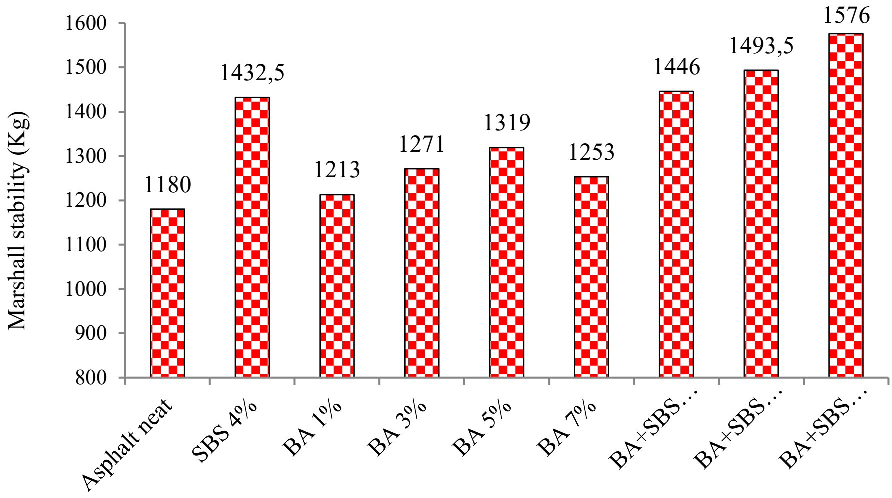

Figure 14. Effect of bottom ash content and SBS on Marshall stability

Marshall Flow

The flow results showed that BA improved stability and reduced flow when added at a rate of 5%, and that a decrease occurred when the BA percentage increased, with the flow increasing from 2.94 to 3.1. This is due to the increase in solid particles, leading to a reduction in the bonding between asphalt particles, which make the mixture more susceptible to gradual collapse. Therefore, the flow value increases, when SBS is added to the BA, the flow becomes more stable. SBS enhances the asphalt's ability to expand without losing cohesion, compensating for the negative effect of excessive hardness and enhancing flexibility, making the mixture more resistant to loading and harsh environments (see Fig. 15).

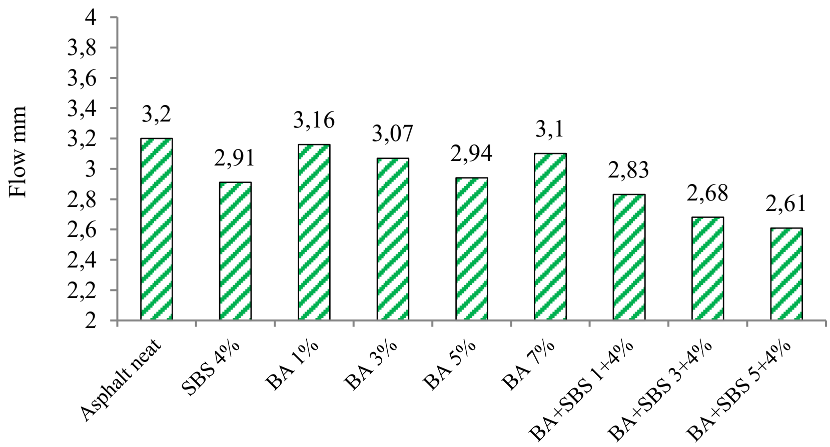

Figure 15. Results of the Marshall flow test for HMA with bottom ash and SBS.

Indirect Tensile Strength tests (ITS) and Tensile Strength Ratio (TSR)

The test was conducted on samples containing 5% bottom ash (this percentage was adopted based on the highest value obtained from the stability test) and on samples consisting of a mixture of 4% SBS and 5% BA, samples containing 4% SBS were used. The results showed that the samples containing a mixture of 4% SBS and 5% bottom ash gave the highest indirect tensile strength, reaching 1607kPa for unconditional and 1472kPa for condition (see Fig. 16). This is explained by the fact that BA increases cohesion and increases the asphalt's ability to distribute loads. When combined with SBS, a 91.6% increase in the TSR value is observed (see Figure 17). This indicates that the mixture has become more moisture-resistant, thanks to the presence of metal oxides (BA). These oxides enhance the interaction of bitumen with the aggregate (Kim et al., 2024; Su et al., 2024). When adding SBS To bottom ash, we notice an increase in the TSR due to the increased flexibility of the bitumen, which makes it more ability to resist volumetric changes that occur due to water absorption and reduces the fragility of bitumen, which maintains the cohesion of the mixture better when exposed moisture The study also showed that adding SBS contributed to enhancing the asphalt's resistance to moisture and increasing its flexibility, which enhances the cohesion of the mixture when exposed to water (Taki et al., 2019).

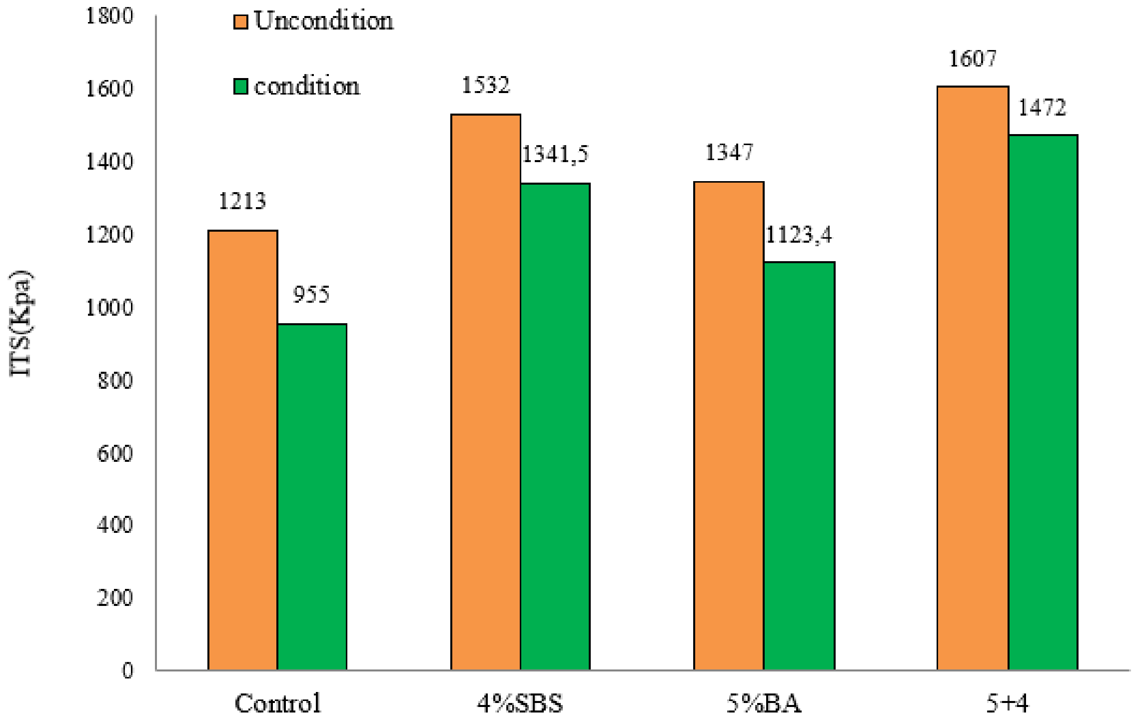

Figure 16. Effect of asphalt modification on indirect tensile strength (ITS)

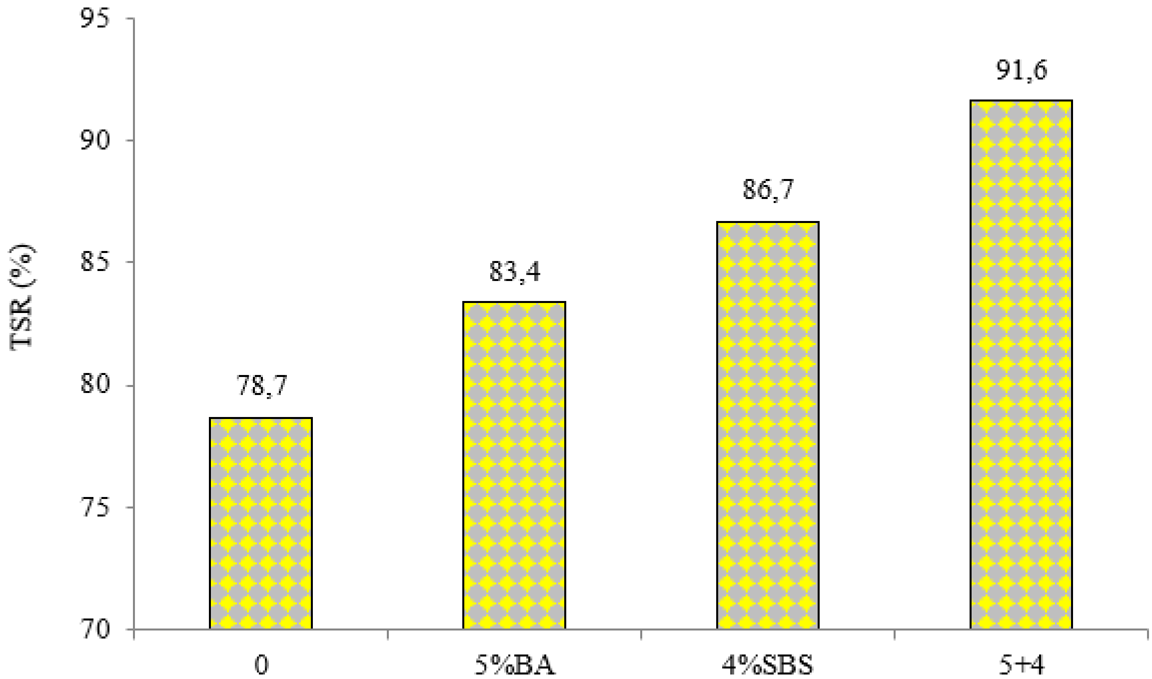

Figure 17. Impact of bottom ash and SBS modification on tensile strength ratio (TSR)

Wheel Track Test

It is a laboratory test to evaluate the permanent deformation (Rutting) under heavy vehicle loads of hot asphalt mixtures. This deformation leads to a decrease in the quality of the pavement and an increase in traffic and safety risks. This failure occurs especially in areas or main roads with high loads resulting from trucks. Figure 18 presents the WTT results highlighting the Rutting depth against a cycle number of 10,000 according to (EN 12697-22: 2003) with a weight of 700N (157 pounds). The results of the wheel tracking test using 5% BA showed a decrease in rut depth. This is because BA contains mineral oxides that enhance the bitumen's resistance to flow under repeated loads (Kim et al., 2024). However, the results showed its effect was limited compared to SBS, thanks to its flexibility, which helps the bitumen regain its shape after the load is removed. When 4% SBS was combined with 5% BA, this mixture achieved a balance between stiffness and flexibility, and the rut depth decreased to 7.6 mm (see Figure 19).

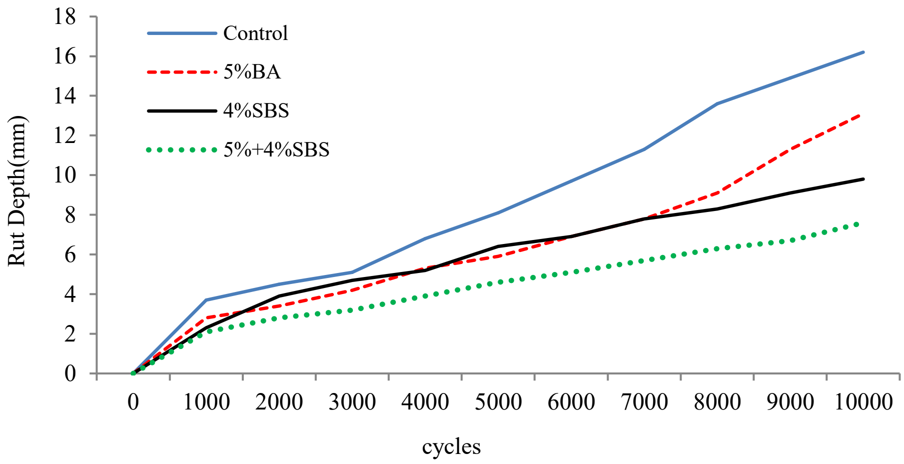

Figure 18. Effect of asphalt modification on rut depth under wheel tracking test.

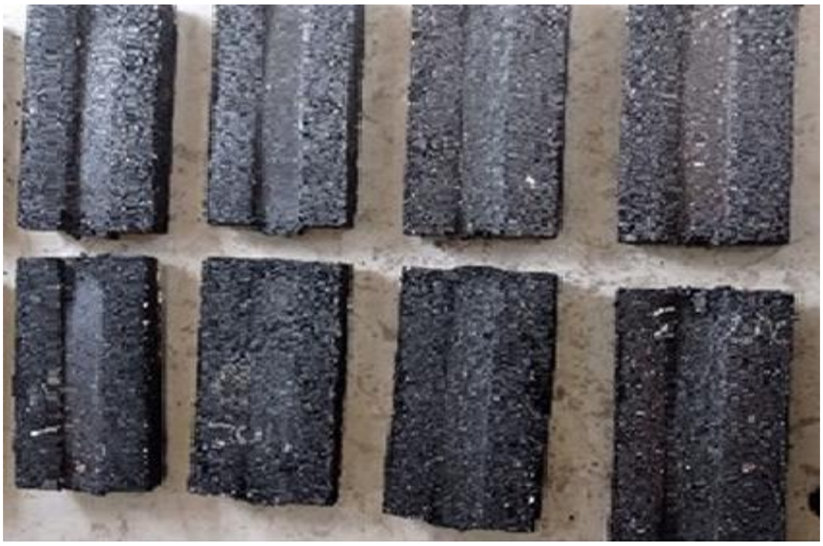

Figure 19. Effect of rut depth under wheel tracking test on asphalt samples

Conclusions

This study analyzed the possibility of producing sustainable asphalt mixtures by incorporating bottom ash (BA) as a bitumen modifier and adding SBS to improve the mechanical properties (HMA). BA is a by-product resulting from fuel combustion in thermal power plants for electricity generation, where large quantities are produced. The research focused on evaluating hot mix asphalt concretes using sustainable materials combined with SBS to improve bitumen's to permanent deformation, moisture resistance. The results lead to the following conclusions:

1- Adding BA as a modifier to bitumen increased its viscosity and softening point and decreased its penetration value. This enhanced bitumen's resistance to thermal changes and permanent deformations.

2- The Marshall Test results showed a significant improvement in the mix's load-bearing capacity when adding 5% bottom ash and 4% SBS, with the result being 33.65 %. The (WTT) results also confirmed a significant decrease in the rutting depth, as the modified bitumen showed the highest resistance to permanent deformations under repeated loads, in addition to the (ITS) results. It was shown that the consolidation led to a significant increase in tensile strength of treated and untreated samples, which indicates an improvement in internal cohesion,

increased durability, and reduced susceptibility to cracking under the influence of tensile force.
3- Moisture resistance tests represented by the (TSR) showed improved adhesion properties between bitumen and aggregate. Chemical analyses using infrared spectroscopy (FTIR) confirmed the occurrence of chemical reactions that led to the formation of stable molecular bonds, which enhanced mixture's resistance to moisture loss and stripping.
4- BA, as a partial alternative to bitumen, is environmentally and economically sustainable. It reduces reliance on virgin raw materials and promotes the recycling of industrial waste, making it an environmentally effective solution without affecting mechanical performance of asphalt mix.
Research shows that combining bottom ash and SBS as a bitumen modifier serves as apromising solution to improve performance of asphalt in modern infrastructure. Laboratory experiments have proven that sustainable asphalt mixtures can achieve higher rutting resistance, improved moisture durability, and good mechanical performance, making them a practical and sustainable option for developing road networks.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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Conflict of Interest

* The authors declare that they have no conflict of interest.

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