

Evaluating the Mechanical and Durability Performance of Carbon-Sulfur Mix Asphalt Modified with SBS and SZ Additives

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ABSTRACT

The rising quantities of the blowdown (carbon-sulfur) hydrocarbon waste generated in the production of sulfur posed challenges to the environment in Iraq. This research paper explored the application of blowdown as a sustainable filler in asphalt mix that had been modified with SBS polymer and synthetic zeolite (SZ) additives. Six asphalt mixtures were prepared with blowdown and traditional fillers of CaCO₃ and were tested concerning mechanical and durability performances, using Marshall stability, indirect tensile strength, and deformation strength tests. Findings indicated that the SBS-modified blowdown mixtures had better strength, cracking, and rutting resistance than any other mixtures. These results proved that blowdown waste can be a good filler to be used in sustainable pavements to provide improved performance and environmental advantages.

Keywords:

Blowdown waste; SBS polymer; Y zeolite; Mechanical properties; Rutting resistance; Moisture damage.

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1. INTRODUCTION

The amount of blowdown (carbon-sulfur) waste from sulfur production is increasing yearly in Iraq, while the disposal facilities are becoming less able to handle it. Improper disposal of blowdown causes significant environmental problems and wastes material. Moreover, like other solid wastes disposed of in landfills, blowdown cannot break down. But using blowdown can also save money and protect the environment, which is crucial considering Iraq's current issues with environmental contamination and waste management [1]. Blowdown (carbon-sulfur) waste from sulfur production units in Iraq is increasing annually, while disposal facilities struggle to manage the growing volume. This situation contributes to significant environmental challenges, including contamination and resource wastage, which threaten sustainable development policies and ecosystem health. The extensive use of natural resources interacts with environmental contamination, which is thought to be the primary cause of environmental and human health risks. Hazardous waste has no end, but it can be

summed up as deteriorating vegetation, contaminating groundwater aquifers, and upsetting the existing ecosystem [2]. Additionally, regular everyday garbage (home waste) generates millions of tons of solid waste. For practical, financial, and environmental reasons, the asphalt paving business uses solid waste from a variety of sources as filler material [3]. However, as this economic model grows increasingly unsustainable, management is being compelled to reevaluate and develop a plan that conserves resources and benefits the environment. Repurposing waste materials into more useful products is the goal of the growingly popular waste valorization technique.

A variety of modifiers, such as carbon fibers, polymers, and anti-stripping agents, are often used to enhance the mechanical and physical properties of asphalt binder. Understanding the properties of these modified mixtures and perhaps even learning how they function can also lead to new opportunities for implementations that could enhance civil engineering practices, which could eventually usher in a more sustainable and greener future for future generations [4],

[5]. Normal bitumen's viscoelastic nature prevents it from controlling rutting, deformation, and cracking under harsh weather and with high traffic loads because to its low temperature, weak elastic properties, and adhesive properties [6]. Using additives to change the properties of the asphalt binder can improve bitumen's performance. It seems that adding polymers to asphalt mixtures in different forms and doses has the best chance of producing flexible pavements [7]. The application of polymer-modified asphalt binders has demonstrated potential in lowering early pavement failures among these initiatives, especially in regions with large truck traffic volumes and notable seasonal climate variations [8], [9]. The performance of porous hot asphalt mixes was assessed by Ali & Khoshnaw [10] in relation to two types of asphalt modifiers: propylene modifier polypropylene (PP) and styrene butadiene styrene (SBS). According to the study, introducing modifiers lengthens the durability of porous asphalt by decreasing abrasion loss and boosting stability. The most successful binder for increasing the pavement mixture's stability was the one containing 4% SBS and 4% PP modifier. Moussa et al. [11] investigated the moisture sensitivity of asphalt mixes modified with high-density polyethylene (HDPE), paying particular attention to how HDPE concentrations affected the characteristics and performance of the asphalt binder. According to the findings, adding HDPE to asphalt mixtures may improve their resistance to moisture damage, improving pavement durability and service life while lowering repair costs.

The environmental benefits of Warm Mix Asphalt (WMA), which is made at comparatively lower temperatures than HMA, are drawing more attention. It is a better alternative for the environment since it uses less energy and produces less CO₂ emissions, and it produces fewer emissions when building pavement [12]. The asphalt business has advanced significantly with the introduction of Warm Mix Asphalt (WMA) technology, which is a collection of technologies that enable the production and application of asphalt mixtures at lower temperatures. With an emphasis on lowering greenhouse gas emissions during the production process, WMA was pioneered in Europe and mostly created in response to environmental concerns. Significantly lowering gas and vapor emissions from asphalt plants, lowering energy costs and consumption, improving mixability and workability, paving in colder climates, reducing thermal cracking because of lower mix and compaction temperatures, and improving asphalt mixture transportability over longer distances are just a few benefits of the technology [13], [14].

The study by Hasan et al. [15] evaluated the effects of Sasobit (organic) and zeolite (water-based) additives on warm-mix asphalt, testing their impact on rutting, cracking, and moisture susceptibility. Results showed that zeolite improved moisture resistance and cracking, while Sasobit enhanced rutting resistance but negatively affected moisture susceptibility. Optimal performance was achieved with 4-6% zeolite and 4% Sasobit, with 6% zeolite providing the best moisture resistance and 6% Sasobit the lowest. The study concluded that higher additive percentages generally improved mechanical performance.

The effects of water acidity and zeolite on moisture sensitivity in asphalt mixtures have been investigated by Arabani et al. [16], using mechanical and surface free energy (SFE) tests. Results showed that acidic runoff increased moisture damage, while zeolite modification improved resistance by enhancing cohesion, reducing debonding energy, and altering SFE components. Zeolite also mitigated the drop in tensile strength caused by pH changes. Overall, zeolite effectively reduced moisture damage potential in asphalt mixtures.

Although previous studies have examined the use of industrial by-products and asphalt modifiers such as SBS and synthetic zeolite, a significant research gap remains regarding the systematic evaluation of blowdown (carbon-sulfur) waste as filler in both hot mix asphalt (HMA) and warm mix asphalt (WMA) mixtures, especially in direct combination with SBS and SZ additives under local conditions. No prior work has comprehensively assessed the synergistic effects, durability, and mechanical performance of these specific composite mixtures, nor provided performance-optimized recommendations for field applications. Therefore, the present study distinctly contributes to the literature by investigating the comparative properties and field suitability of blowdown/CaCO₃-based HMA and WMA systems modified with SBS and SZ, explicitly addressing this critical gap in sustainable pavement technology.

2. RESEARCH OBJECTIVES

Using blowdown (carbon-sulfur) waste as a sustainable filler in both hot mix asphalt (HMA) and warm mix asphalt (WMA) and comparing it with commonly used filler, which is calcium carbonate (CaCO₃), is the objective of this study. The study specifically aims to (1) analyze the durability and performance characteristics of a blowdown (carbon-sulfur) waste asphalt concrete mixture that contains 4% styrene-butadiene-styrene (SBS) and contrast the outcomes with those of a mixture that contains 5% synthetic zeo-

lite. Besides comparing these mixtures with the control mixture that contains CaCO_3 with 40-50 asphalt cement (AC); (2) recycling blowdown waste reduces costs and pollution, making it an environmentally friendly option; and (3) design an optimization table to determine which of the following HMA or WMA should be used in any field applications.

3. PREPARATION OF MATERIALS

Commonly used local materials that are readily available in the asphalt paving industry in Iraq were employed over the course of this investigation. The materials used will be listed and detailed as follows:

3.1. Aggregates

The Al-Khazer quarry in Mosul City supplied the aggregate, crushed gravel, and river sand. Sedimentary rock with a high silica concentration makes up the gravel [17]. These aggregates were sorted and graded using the criteria guidelines specified in ASTM D3515-D5 [18] to make sure they met the requirements for appropriateness in the surface layer. As shown in Fig. 1, these procedures were used to accomplish the aims of this research.

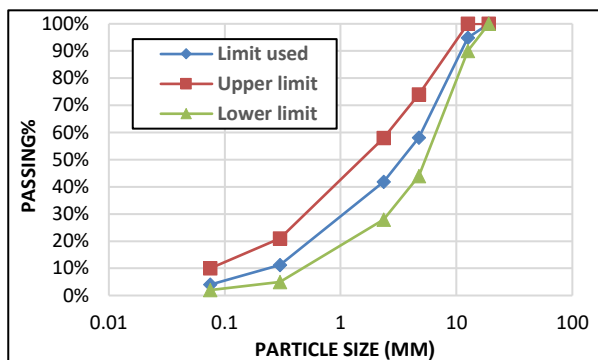


Fig. 1 ASTM D3515-D5 (surface layer) gradation limits for mixtures.

3.2. Mineral Fillers

In order to give specific qualities, finish the necessary skeleton of the mixture, and satisfy the requirements for aggregate gradation, filler has been added to construction materials. In this research, both fillers were passed through an ASTM 200 sieve before they were used in this investigation. The most common mineral filler for asphalt mixtures, calcium carbonate (CaCO_3), was employed as the reference filler in this study. It is readily available in Mosul City and has a specific gravity and plasticity index of 2.734 and 1.2, respectively. The choice of CaCO_3 as the reference filler is due to its local availability and common use in asphalt production in the study area. Focusing on CaCO_3 provides a clear baseline to assess the performance of blowdown filler without add-

ing complexity from multiple fillers. Future work can include other fillers like cement or fly ash for broader comparison. Carbon-sulfur alternative filler, specifically blowdown waste material, was utilized. After passing through an ASTM 200 sieve, blowdown, a solid, black, granular by-product material was utilized, as shown in Fig. 2. It was provided by Mishraq Sulfur State Company. According to Shareef et al. [1], blowdown filler's physical and chemical properties demonstrate that it is suitable for employing in asphalt mixtures. The presence of carbon-sulfur components (18.21%) and a high free sulfur content (81.04%) enhance its binding capabilities and ability to interact with asphalt binders. A comparatively pure and non-corrosive substance is indicated by the low acidity level (0.001%) and ash content (0.31%). For asphalt applications, the low moisture content (0.42%) guarantees appropriateness. The filler's capacity to raise the density, strength, and general performance of asphalt mixtures is further enhanced by its 2.20 specific gravity and fine particle size distribution (100% passing through a 0.075 mm sieve).



Fig. 2 Blowdown (Carbon-Sulfur) waste mineral filler.

3.3. Modified Asphalt Binder Preparation

The Dura refinery provided the asphalt cement (AC) used in this study, which was of penetration grade (40-50). The Gold Mass Company in Erbil City provided the SBS that appears in Fig. 3(a). Table 1 displays the properties of SBS. P40 asphalt binder was mixed with one percent (4% wt.) of SBS in pellet form. To achieve a homogeneous binder, a high-speed stirrer, as indicated in Fig. 3b, revolving at 1000 rpm, was used to blend the mixture at $180 \pm 5^\circ\text{C}$ for 120 ± 5 minutes [19]. The SBS-modified asphalt was poured into tiny cans, allowed to cool to lab temperatures, wrapped in aluminum foil, and then kept for use in future testing. Regarding SZ-modified asphalt preparation, firstly it should be mentioned that the physicochemical properties (as provided by the supplier Arej Al-Furat company) of the synthetic zeolite used, as shown in Fig. 3c, the model name, the material, density (gm/cm^3), purity, color, and pH were Y zeolite, aluminosili-

cate, 0.45-0.55, 100%, white, and 3-5, respectively. As shown in Fig. 3b, the bitumen is gradually heated to 150°C using the stirring bubble while being swirled at 200 rpm using high-shear mixers. After that, the stirrer speed is increased to 240 rpm as the binder is gradually mixed with the additives. To provide the mixtures the properties they need to mix at compaction temperatures, the asphalt binder and additives were mixed for 30 minutes [20], [21]. In contrast to their corresponding HMA control mixtures, which were mixed and compacted at approximately 150°C and 130°C, the WMA mixture was mixed and compacted at 137°C and 116°C, conforming to a viscosity of 0.17 ± 0.02 and 0.28 ± 0.03 Pascal-seconds, respectively, after synthetic zeolite was added at a rate of 5% based on binder weight.

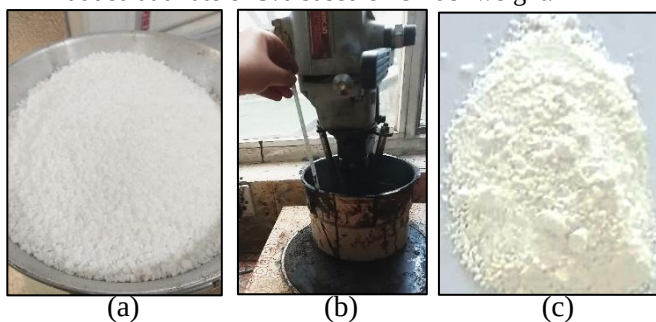


Fig. 3 Modified asphalt binder preparation (a-SBS pellets, b-Shear mixer, and c-SZ “aluminosilicate”).

Table 1: The rheological properties for P40 and SBS/SZ modified asphalt.

Property	Test method	P40	NCCL limits [22]	SBSMA	NCCL limits [22]	SZMA
Penetration at 25°C (0.1mm)	ASTM D5 [23]	40	40-50	33	-	43
Softening point (°C)	ASTM D36 [24]	52	51-62	67	-	48
Ductility at 25°C (cm)	ASTM D113 [25]	140	>100	40	-	143
Rotational viscosity at 135°C, cP	ASTM D4402 [26]	580	-	2130	3000 max.	465

4. EXPERIMENTAL METHODS

An explanation of the procedures required to prepare the raw materials for the asphalt mixture and its design may be found in the flowchart in Fig. 4. Additionally, by performing laboratory tests such as Marshall stability and flow at 60°C, Kim at 60°C, and indirect tensile

strength at 25 and 60°C, it validates the effects of SBS and SZ on asphalt mixes that incorporate blowdown as mineral filler.

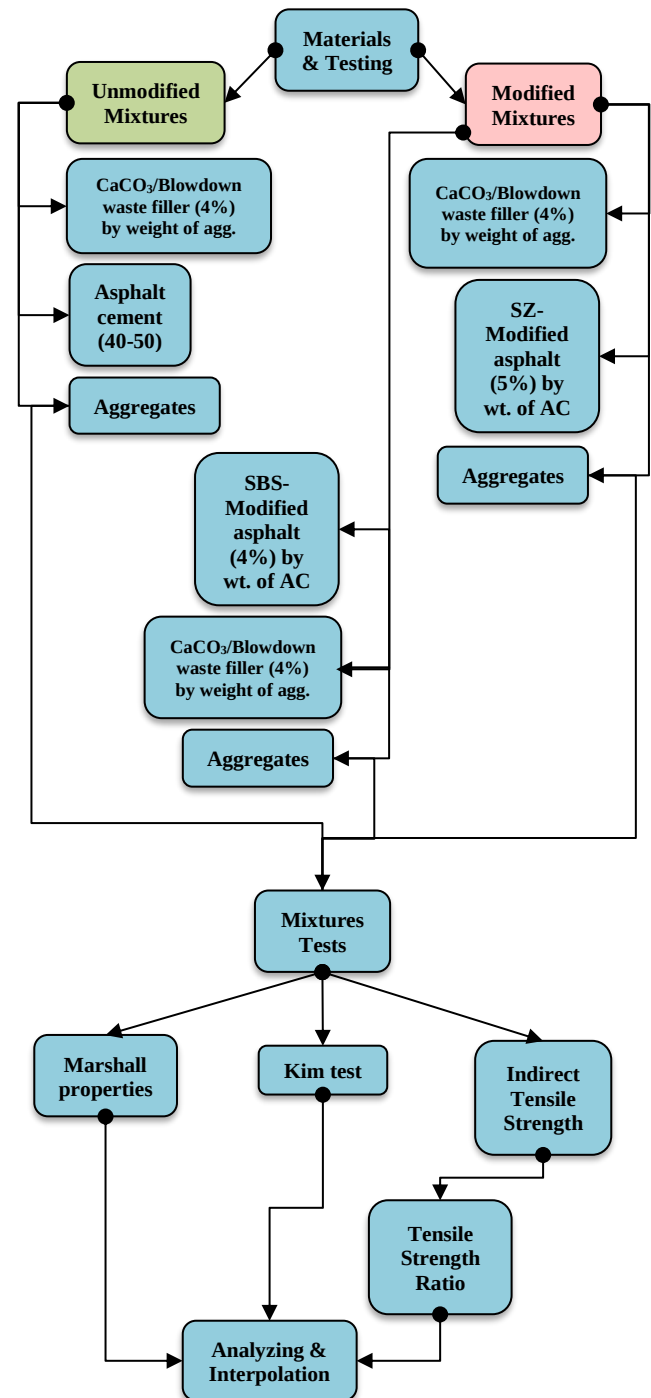


Fig. 4 Flowchart of the study.

4.1. Asphalt Concrete Mixture Design

According to Section 3.1, the gradation limitations for dense grading employed in mixture design were based on ASTM D 3515-D5 [18]. The Marshall mix design ASTM D 6927 [27] approach is a commonly used procedure for optimizing asphalt concrete mixtures. When develop-

ing asphalt concrete mixtures, the Marshall method of mix design is frequently used to guarantee that there are enough voids. Five asphalt percentages (4.0, 4.5%, 5.0%, 5.5%, and 6.0%) were used. Table 2 shows the optimal asphalt content as well as the other Marshall properties; optimum asphalt content for all the mixtures is within the NCCL [22] tolerance of $\pm 0.3\%$. Therefore, the actual asphalt content for the control mixture was used in all other mixes (i.e., 5.0%) to ensure uniformity throughout the study. Using a high shear mixer, the SBS-modified and SZ-modified samples are mixed for two minutes at this asphalt ratio and the advised mixing temperatures of 180 and 137°C, respectively. A Marshall mechanical compactor was utilized to compact the samples. Then, at a tire pressure of 1379 kPa with 75 Marshall blows per face, the specimens were compacted for heavy-duty usage. After being taken out of the mold, the specimens were allowed to air-cure for a full day [8]. The specimens were sorted into groups called the following:

- FAC: mixes contain 4% CaCO₃ filler;
- BDAC: mixes contain 4% blowdown filler;
- FSBS: mixes contain 4% CaCO₃ filler and 4% SBS polymer;
- BDSBS: mixes contain 4% blowdown filler and 4% SBS polymer;
- FSZ: mixes contain 4% CaCO₃ filler and 5% synthetic zeolite, and BDSZ: mixes contain 4% blowdown filler and 5% synthetic zeolite.

Table 2: Marshall properties of the mixes.

Property	FAC	BDAC	FSBS	BDSBS	FSZ	BDSZ	NCCL Limits [22]
Optimum Asphalt Content %	5.05	5.05	5.25	5.25	5.00	5.00	4-6
Air Voids (V _a) %	4.21	4.08	4.40	4.20	4.41	4.07	3-5
Voids in Mineral Aggregate (VMA) %	15.6	15.7	15.0	15.2	14.2	14.3	13 min.
Voids Filled with Asphalt (VFA) %	73.12	73.44	70.23	70.45	67.87	68.12	-
Unit Weight (Kg/m ³)	2368	2379	2367	2389	2365	2386	-
Stability (kN)	9.78	10.68	15.85	18.24	11.16	12.16	8 min.
Flow (mm)	3.90	3.84	3.63	3.33	3.28	3.15	2-4

4.2. Marshall Test

The Marshall test is a frequently used empirical laboratory approach for determining deformation resistance [28]. Marshall tests were conducted on samples of HMA and WMA mixtures after submerging them in a water bath at 60°C for 30-40 minutes, in accordance with ASTM D6927 [27]. The samples were subsequently put into a Marshall test machine (after

being dried) at a rate of 50.8 mm per minute until failure occurred. Marshall stability refers to the highest load (kN) that produces sample failure. Marshall flow (mm) refers to the entire amount of deformation measured at maximum load. The stiffness of the mixes was also determined using the Marshall quotient, which is obtained by dividing the Marshall stability (kN) by the Marshall flow (mm).

4.3. Indirect Tensile Strength and Moisture Susceptibility Tests

The loss of stiffness, resistance, and durability in asphalt mixtures caused by moisture causes adhesive failure. This is known as moisture damage [29]. Considering the test protocol is relatively simple and easy to conduct, the Tensile Strength Ratio (TSR) result has been used in most studies as a metric for evaluating the moisture susceptibility of asphalt mixes [30]. The tensile strength of both hot mix asphalt (HMA) and warm mix asphalt (WMA) mixtures was evaluated in this study using the indirect tensile strength (ITS) test, with a focus on the effects of temperature and moisture. ASTM D6931 [31] was followed for conducting the ITS tests. The Marshall method's procedure was the same as the one used to prepare specimens for the ITS test. The specimens were produced with a diameter of 101.6 mm and an air void content of $7.0 \pm 1\%$. For the ITS test, the specimens were divided into three groups after the compaction stage: FAC, BDAC, FSBS, BDSBS, FSZ, and BDSZ mixtures, which were then recombined. The conditioned samples (C) were immersed in a water bath at 60°C for 24 hours and then in a water bath at 25°C for 2 hours, whereas the unconditioned samples (U) were immersed in a water bath at 25°C for 2 hours. The samples were then tested at a rate of 51 mm/min on the automatic multi-tester equipment until they failed. ITS has been computed using Eq. (1) based on the specimen's failure load maximum:

$$ITS = \frac{2000P}{\pi dt} \quad (1)$$

Where ITS = indirect tensile strength (kPa); P = ultimate load (N); t = specimen thickness (mm); and d = specimen diameter (mm).

Moisture susceptibility is shown by the tensile strength ratio (TSR). The ASTM D4867/D4867M [32] standard can be used to compute the tensile strength ratio (TSR) from ITS conditioned (ITS_C) and ITS unconditioned (ITS_U), and Eq. (2) can be used to get the final percentage.

$$TSR (\%) = \frac{ITS_C}{ITS_U} \times 100 \quad (2)$$

4.4. Deformation Strength in the Kim Test

The rutting resistance of asphalt mixtures at high temperatures was estimated in this study using the Kim test. A quick test called the Kim was created to provide a technique for estimating rutting strength and deformation using static loads [33]. The determination of material resistance to high temperature deformation and the fabrication of a load-induced spot deformation to simulate static wheel effects were made possible by applying stress in the compaction and wheel load directions. The loading head simulated a stationary wheel, which first generated consolidation and thereafter progressively depressed the material, causing shear movement. As a failure signal, cracking started at peak load due to the loading head's wedge effect and propagated tangentially [34]. The resistance to deformation, or S_D , is closely related to the rut characteristics of asphalt mixtures. When evaluating asphalt mixtures' resilience to rutting and high temperatures, S_D is helpful. The Marshall specimens are tested by immersing them in a water bath set at 60°C for 30 minutes. After that, the specimens' surfaces are dried and put within a loading mold. The specimen is continuously loaded perpendicularly by a loading head, which compacts it at a rate of 50.8 mm/min. The device comprises a loading head with a fat bottom, a rounded edge, a 30 mm radius, and a 7.5 mm radius of curvature. Results of force and sample displacement are obtained using this test procedure. The specimen's surface is not flat but rather has a dimple created by the impact of a loading head with a rounded edge. Furthermore, the cracks propagate straight from this depression. Given that the deformation strength is a function of both compressive and shear stress, this impact shape nearly replicates the contact area between the tire and the road surface [35]. A calculation of the deformation strength (S_D) was completed by using Eq. (2):

$$S_D = \frac{4P}{\pi [D - 2(r - \sqrt{2ry - y^2})]^2} \quad (3)$$

Where S_D = deformation strength (MPa); P = peak load (N); D = the loading head's diameter (mm); r = the loading head's bottom curvature radius (mm); and y = deformation (mm).

5. DISCUSSIONS OF THE TEST RESULTS

5.1. Physical Properties of SBSMA and SZMA

The physical properties of asphalt cement have been altered when styrene-butadiene-styrene (SBS) polymer is added. These changes include an increase in softening point and possible viscosity values, as well as a decrease in penetration and ductility values. The following factors are responsible for these changes [36], [37]:

- Increased Viscosity: Long-chain molecules called SBS polymers form a network inside

the asphalt binder. The asphalt becomes more viscous as a result of this network, increasing its flow resistance. Because the asphalt is less susceptible to penetration by a conventional needle, the increased viscosity results in a decrease in penetration.

- Enhanced Thermal Stability: By strengthening asphalt cement's resistance to temperature-related changes, SBS polymers increase its thermal stability. Because the asphalt needs a greater temperature to soften, this enhanced thermal stability leads to a higher softening point.
- Reduced Ductility: SBS polymers' greater viscosity and cross-linking may result in less ductility. The asphalt's capacity to flex under tensile stress is gauged by its ductility. Asphalt that has a stronger network structure and is more viscous is less ductile.

Y-zeolite, as tabulated in Table 1, in fact, has altered the physical properties of asphalt cement by increasing its ductility and penetration values while decreasing its softening point and possible viscosity values. It's crucial to remember that the precise mechanisms and effects can change based on a number of variables, including the kind and quantity of zeolite, the characteristics of the base asphalt, and the processing circumstances [16]:

- Increased Ductility and Penetration: During the mixing and compaction procedures, zeolites can function as tiny reservoirs, absorbing and releasing water vapor. This may cause the asphalt binder's viscosity to decrease, increasing its fluidity and deformability. Zeolites' porous structure may give them more surface area to interact with the asphalt binder, which could result in better plasticity and more ductility.
- Reduced rotational viscosity and softening point: In comparison to asphalt, zeolites have a comparatively high heat conductivity. A lower softening point may result from this more effective heat dissipation. The asphalt binder's viscosity may decrease as a result of the zeolite particles' interaction with it, which may also cause the intermolecular forces to be disrupted.

5.2. Aspects of Statistics

Using Minitab software version 21.1 [38], the study applied statistical analysis of variance (ANOVA) to obtain a look at BDAC, BDSBS, and BDSZ mixes. A significance level of 0.05 was used to test the null hypothesis ($H_0 = 0$). To ascertain whether there was a significant difference between two averages, the least significant difference value (LSDV) was utilized. Two averages may be considered significantly different

if their differences are at least as large as the least significant difference value (LSDV). On the other hand, they are not regarded as significantly different if the difference is less than the LSDV. In Table 3, the average variances are shown as letters. There is no statistically significant difference between two averages when they have the same letter [39]. 'A' stands for the highest test score, while subsequent letters denote a gradual decrease in these scores. Additionally, Table 3 summarizes the key performance indicators (Table 3: Marshall stability, MQ, ITS, TSR, and SD) into an ANOVA-based optimization/comparison table to select the field: BDSBS is the top performer for general use, particularly favored for heavy-traffic, high-temperature, rut-resistant surface layers. In contrast, BDSZ offers better moisture resistance and should be prioritized when moisture performance and cost-effectiveness are critical. Meanwhile, FAC and the FS series serve as baseline benchmarks.

Table 3: Comparison of the mixtures.

Property	Mixture type					
	FAC	BDAC	FSBS	BDSBS	FSZ	BDSZ
	Mean ± Standard Deviation (Grouping)					
Marshall stability (kN)	9.78 ± 0.457 (E)	10.68 ± 0.875 (DE)	15.85 ± 0.26 (B)	18.24 ± 0.840 (A)	11.16 ± 1.060 (CD)	12.16 ± 0.816 (C)
Marshall flow (mm)	3.90 ± 0.1000 (A)	3.84 ± 0.1044 (A)	3.63 ± 0.0321 (AB)	3.33 ± 0.336 (BC)	3.28 ± 0.189 (C)	3.15 ± 0.15 (C)
Marshall quotient (kN/mm)	2.51 ± 0.0726 (D)	2.71 ± 0.307 (D)	4.37 ± 0.1105 (B)	5.51 ± 0.350 (A)	3.41 ± 0.379 (C)	3.86 ± 0.294 (C)
Air voids (%)	4.21 ± 0.0389 (A)	4.08 ± 0.840 (A)	4.40 ± 0.400 (A)	4.20 ± 0.529 (A)	4.41 ± 0.1102 (A)	4.07 ± 0.344 (A)
ITS at 25°C (kPa)	814.3 ± 27.8 (D)	1059.2 ± 76.1 (C)	1571.3 ± 28.3 (B)	1777.9 ± 27.6 (A)	993.66 ± 7.84 (C)	1023.0 ± 29.4 (C)
ITS at 60°C (kPa)	503.3 ± 40.4 (E)	689.9 ± 17.8 (D)	1409.6 ± 47.1 (B)	1653.0 ± 31.6 (A)	706.09 ± 6.69 (D)	795.6 ± 59.7 (C)
TSR (%)	61.93 ± 6.51 (D)	65.38 ± 5.52 (CD)	89.71 ± 2.77 (A)	92.98 ± 1.063 (A)	71.06 ± 0.676 (BC)	77.79 ± 5.81 (B)
Deformation strength (MPa)	3.70 ± 0.1657 (C)	5.79 ± 0.0564 (B)	6.60 ± 0.681 (B)	8.55 ± 1.300 (A)	3.75 ± 0.0977 (C)	4.09 ± 0.276 (C)

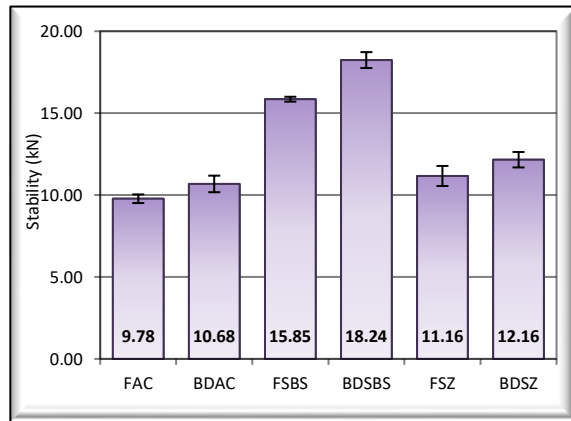
N.B.: (1) Means with different letters vertically have a significant difference at $p < 0.05$ using the Fisher LSD Method, and (2) "A" refers to the best performance attribute, with subsequent letters indicating inferior performance.

5.3. Parameters of Marshall Test

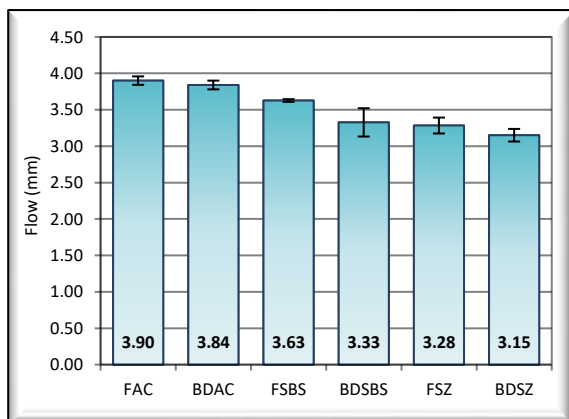
The Marshall stability test findings (Fig. 5a) show significant variations between the several asphalt mixtures evaluated using the LSD test, as shown in Table 3. The maximum load that can be applied to hot mix asphalt (HMA) is indicated by Marshall stability (MS). All asphalt mixes in this study had test results that were higher than the permitted limit, which is equal to 8 kN for the surface course [22]. It is evident that the stability is increased by 9.20% when blowdown was added instead of CaCO_3 filler. Regarding the modified mixtures, when SBS polymer was added to the asphalt mixture, CaCO_3 filler (FSBS) mix, FSBS stability was 15.85 kN, indicating a considerable 15.08% increase in MS due to the usage of the blowdown filler with SBS polymer. Because the inclusion of polymers can alter asphalt and enhance its viscosity and stiffness, the BDSZ mixture increased MS by 8.42% when compared to the FSZ mixture. In the meantime, the filler's primary function is to raise binder viscosity and fill in voids between aggregate particles, which increases adhesion and, ultimately, improves MS. Flow is the vertical deformation of the specimen upon failure. High flow numbers typically imply the possibility of long-term deformation in a plastic mix. Lower flow rates could indicate lower air voids, which could lead to early cracking. It is evident from Fig. 5b that adding blowdown for both unmodified (BDAC) and modified (BDSBS and BDSZ) mixtures decreased flow by 1.54%, 8.26%, and 3.96%, respectively, compared to FAC, FSBS, and FSZ. Additionally, it should be stated that all of the mixes met the designated limitations of 2-4 mm flow [22], as seen in the same figure.

The stiffness is evaluated by dividing MS by the flow-resulting MQ. It is well known that a higher MQ value indicates greater stiffness, which translates into greater resistance to permanent deformation. As illustrated in Fig. 5c, BDSBS had a 97.49% greater MQ than BDAC. In contrast to BDAC, BDSZ demonstrated a 38.35% improvement. Increased density (fewer air spaces) and increased viscosity may be the main causes of the mixtures' higher MQ values. Improved material toughness (toughness is equal to stress times strain) is the result of higher stability values. Both low-temperature cracking and thermal fatigue can affect asphalt mixtures. Increased hardness may help stop cracking and its spread. According to Table 3's data entry, the LSD AVOVA analysis reveals that the averages for each mix do not differ significantly; all of the mixes in Fig. 5d met the 3-5% limits. As Al-Hadidy [17] found in his investigation, a mixture of SBS polymer can greatly improve all Marshall parameters of as-

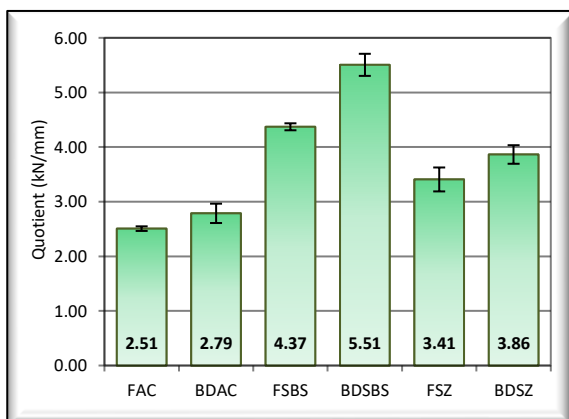
phalt mixtures. As RASHED and Al-Hadidy [40] concluded in their study, zeolite is very good at improving asphalt mixtures performance, but zeolite can also offer further advantages, including increased durability and less environmental impact.



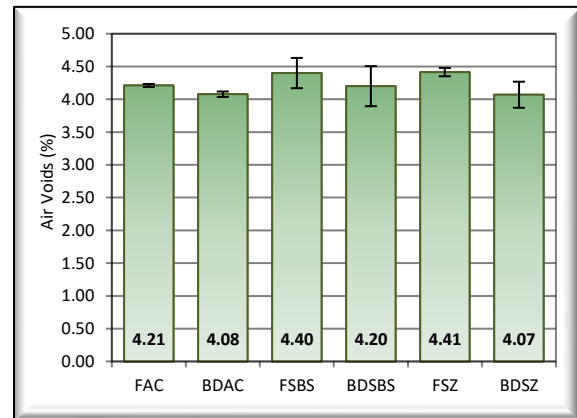
(a)



(b)



(c)



(d)

Fig. 5. Parameters of the Marshall test for the mixtures (a-Marshall stability, b-Marshall flow, c-Marshall quotient, and d-Air voids).

5.4. Effect of Temperature and Moisture on Tensile Strength

To find out how temperature and moisture affected tensile strength, indirect tensile strength (ITS) was used. In comparison to FAC, FSBS, and FSZ, the BDAC, BDSBS, and BDSZ mixtures demonstrated a significant increase in ITS values for both unconditioned and conditioned specimens, as indicated by the ITS test results for unconditional and conditional specimens in Fig. 6 and the statistical significance of the change in ITS value as determined by the LSD test in Table 3. This indicates that the BDSZ mix is somewhat less resistant to cracking than the BDSBS mix. Moreover, from the results in Fig. 6 and Table 3, besides the addition of polymers, it should be mentioned that the fatigue performance has been increased and also showed a predominant impact on high- and low-temperature after replacing CaCO_3 filler with blowdown, and this performance was clear in BDAC, BDSBS, and BDSZ mixtures [41], [42]. Additionally, tensile strength ratio (TSR) calculations for both the conditioned and unconditioned groups were used to evaluate moisture susceptibility. Mixtures with adequate moisture susceptibility are often identified by a minimum TSR value of 0.85, which is appropriate for use in Iraq [43]. Higher resistance to moisture damage is indicated by the slightly increased TSR values of BDAC of 42.20% and 19.26%, respectively, for the BDSBS and BDSZ mixtures in Fig. 6. It can be inferred from the preceding section that the conditioning process weakens BDAC. The Asphalt Institute thought that TSR values of 0.8 or higher were acceptable [44], whereas other agencies thought that 0.7 or higher was acceptable. Nevertheless, the TSR results for all of the adjusted mixtures in this study are sufficient. The ITS test findings show

that zeolite and SBS polymer can both improve asphalt mixtures' tensile strength. SBS polymer works especially well for enhancing initial strength and offering some aging resistance. According to the results of a study by [17], zeolite can also increase strength, particularly in terms of resistance to moisture.

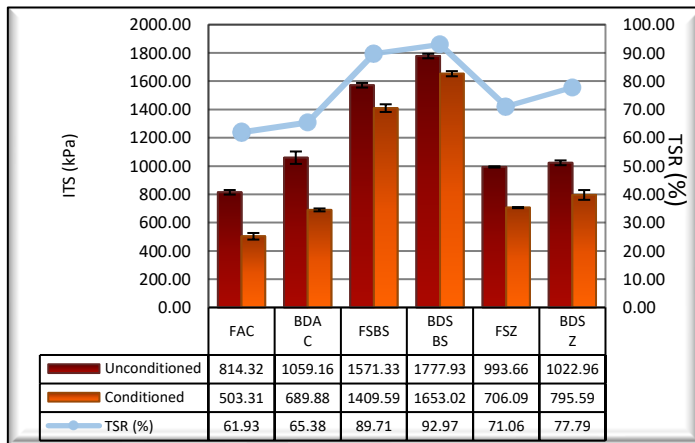


Fig. 6. Indirect tensile strength and tensile stiffness ratio of the mixtures.

5.5. Deformation Strength via Kim Test

According to the requirements set forth by the Korean Ministry of Land, the deformation strength (S_D) value must be at least 3.20 MPa [45]. In addition to blowdown filler, which contains 81.04% weight of free sulfur [1], the LSD test results and Fig. 7 show that adding SBS polymer in the BDSBS mixture has raised the S_D by 47.67% in the BDAC mixture; besides, it was clear in all the mixtures with blowdown filler that increased S_D due to asphalt containing 80% weight of carbon and 10% weight of hydrogen [46]. As a result, this sulfur begins to react with the asphalt's hydrocarbon, causing oxidation, when the mixture's temperature reaches 150°C or above. Instead of oxygen entering, oxidation in this context refers to the dehydrogenation, which increases aromatic systems and entangles sulfur with asphalt [47]. Furthermore, the main ways that SBS polymer interacts with asphalt are through cross-linking and physical intermingling. According to the results of a study by Al-Hadidy [17], these interactions result in a number of advantages that directly enhance deformation strength. The BDSZ mix has demonstrated a 29.36% decrease in comparison to the BDAC mixture. Because of its acidic nature (pH = 3-5), zeolite may absorb some of the asphalt binder, lowering its amount in the mixture and limiting its capacity to deform; also, Table 2's characteristics show that adding SZ reduced the softening point

from 52 to 48, indicating less resistance to temperature-related changes.

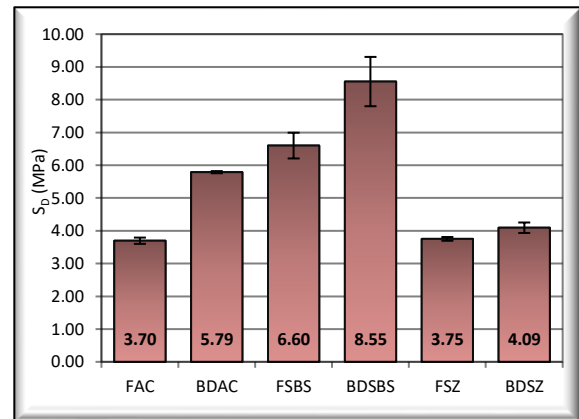


Fig. 7. Kim test results of the mixtures.

5.6. Comparison Between the Blowdown and CaCO_3 Filler

From the results obtained in this study, the following can be observed:

- The addition of 4% blowdown as an alternative filler in the unmodified mixtures enhanced the Marshall stability, MQ, TSR, and S_D compared to the control mixture containing CaCO_3 filler by 9.20%, 11.16%, 5.57%, and 56.49%, respectively.
- The addition of 4% blowdown as an alternative filler in the SBS-modified mixtures enhanced the Marshall stability, MQ, TSR, and S_D compared to the control mixture containing CaCO_3 filler by 15.08%, 26.09%, 3.63%, and 29.55%, respectively.
- The addition of 4% blowdown as an alternative filler in the SZ-modified mixtures enhanced the Marshall stability, MQ, TSR, and S_D compared to the control mixture containing CaCO_3 filler by 8.96%, 13.20%, 9.47%, and 9.07%, respectively.

5.7. Novelty and Significance of the Current Study

This study stands apart from previous local and international works by systematically evaluating the synergistic impacts of blowdown carbon-sulfur waste, SBS polymer, and synthetic zeolite in both hot and warm mix asphalt under Iraq's specific conditions. Recent studies such as Al-Mohammed & Al-Hadidy [48], showed significant improvements in Marshall stability using blowdown waste as a filler but did not comprehensively address the combined effects of SBS and zeolite or their optimization in WMA/HMA compared to the locally preferred CaCO_3 fillers. Globally, research in sustainability by Dimulescu & Burlacu [49] confirmed the broad feasibility of industrial wastes in sustainable asphalt, yet it

lacked regionally tailored performance analysis like the present study. The enhanced mechanical properties and moisture resistance found here, especially for the BDSBS mixes, clearly surpass conventional local benchmarks, suggesting practical field advantages and a direct response to Iraq's environmental and infrastructural needs.

6. CONCLUSIONS

Dense-graded asphalt mixes that contained CaCO_3 and blowdown as a surface layer filler were treated with SBS polymer and Y zeolite as additives. Based on the asphalt cement's weight, 4% and 5% of SBS and zeolite, respectively, were added to the resulting mixture. The impact of the SBS polymer on cracking resistance, and rutting resistance was investigated. The following general conclusions were drawn from the investigation:

- Asphalt was stiffened with SBS polymer, which increased viscosity and decreased penetration. In addition to softening because of more efficient heat dissipation, SZ caused the viscosity of the asphalt binder to drop.
- BDSBS mixes have more significant Marshall stability and quotients than BDAC and BDSZ mixes.
- Compared to the BDAC and BDSZ mixes, the BDSBS mix exhibits greater tensile strength and tensile strength ratios. Additionally, compared to BDAC mix, BDSZ mix exhibits a better tensile strength ratio and tensile strength conditioned state.
- The deformation strength (Kim test) results demonstrate that the BDSBS mix has greater rutting resistance; however, the BDSZ mix shows no improvement when compared to the unmodified mix BDAC but still meets the minimum requirement of 3.20 MPa.

7. RECOMMENDATIONS

Given the results of this study, it is imperative that future research look at the following domains:

- Investigate the impact of both short-term and long-term aging, freeze-thaw cycles, fatigue resistance on blowdown waste asphalt mixes' performance, both with and without SBS/SZ.
- The flexural beam test, which provides information on how asphalt responds to repeated loading instances, gauges the material's capacity to sustain bending stresses.
- It is necessary to measure the creep compliance, fatigue endurance limit, flow number, and dynamic modulus in order to ascertain the possibility of deformation under loading.

- When considering asphalt binder, the following tests must be taken into account: dynamic shear, bending beam rheometer, rolling thin-film oven, pressure aging vessel, and direct tension.
- Wheel tracking test to simulate the impact of wheel loads and provide information on surface stability in order to assess asphalt mixes' resistance to rutting.

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