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Durability and Rutting Resistance of SBS-Modified Asphalt Mixtures Containing Blowdown as a Sustainable Filler

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ABSTRACT

In the pursuit of a sustainable environment, and facing the threat of the continuous growth of solid waste in Iraq, this study investigated the impact of using blowdown, a carbon-sulfur byproduct material of sulfur purification, as a mineral filler on durability and rutting resistance in dense-graded asphalt mixtures using Styrene-Butadiene-Styrene (SBS)-modified asphalt. Three different blowdown rates (4%, 5%, and 6% by weight of aggregate) were used as potential calcium carbonate ($CaCO_3$) replacements. Laboratory tests and parameters, including Marshall stability, indirect tensile strength, tensile strength ratio (durability), and deformation strength, were conducted, and the results were analyzed statistically using Minitab software. The results showed that using 5% blowdown in SBS-modified asphalt mixtures increases the deformation strength, indirect tensile strength at 25 °C, Marshall stability, and Marshall quotient by 51.23%, 0.21%, 14.27%, and 31.44%, respectively, compared to the control mixture that contains $CaCO_3$ filler indicating that using of blowdown as a filler in asphalt mixtures may offer benefits such as enhancing the cracking and rutting resistance of asphalt mixtures while meeting Marshall properties and moisture susceptibility standards and the potential to provide financial advantages and reduce landfill use.

Keywords:

Blowdown; Sustainable materials; Durability; Deformation strength; Mineral filler.

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1. INTRODUCTION

Asphalt binder is the most commonly used material for various pavement types in construction projects. Asphalt mixtures consist of two main components: Aggregates and asphalt binder. As for hot mix asphalt (HMA), over 90 percent of the asphalt mixture is composed of aggregates (course, fine, and mineral filler), whereas the rest contains asphalt binder [1]. The rapid progress of road construction has accelerated the consumption of large quantities of commonly used mineral fillers. Thus, there is an urgent demand to explore alternative fillers that can effectively replace them [2]. In today's pavement construction materials, filler plays a key role, working together with aggregates and bitumen. Although it makes up a small part of the total weight, it notably affects the way bituminous pavement works and how much it costs. Using filler in the right way enhances the HMA mixtures, making them better and more effective [3, 4].

Iraq faces the challenge of increasing solid waste generation and decreasing disposal site capacity. Sulfur production byproduct such as blowdown is difficult to decompose and contributes to solid waste as shown in Fig. 1. The country generates and disposes of 7,000 to 20,000 tons of solid waste and blowdown annually, costing between $665,000 to $2 million per year. Incorporating blowdown into asphalt mixtures as filler material can reduce landfilling costs and promote sustainability in the construction industry by providing a valuable use for waste materials [5]. Research [6] found sulfur waste and byproduct materials cost $15 per ton in Iraq, making them economically viable.

In contrast, polymer materials have been widely employed in the enhancement of asphalt mixtures to improve their mechanical characteristics and overall performance [7]. Nevertheless, there is limited knowledge regarding the fundamental characteristics of polymer-modified asphalt (PMA) when sulfur-based compounds are present. The study [8] revealed that an increase in sulfur content leads to a reduction in the size of asphalt particles. This finding suggests that sulfur plays a role in facilitating a homogeneous distribution of Styrene-Butadiene-Styrene (SBS) within the asphalt matrix. Based on the aforementioned findings, it can be concluded that the incorporation of sulfur into asphalt-SBS blends results in enhanced stability and compatibility when compared to asphalt solely modified with SBS. The inclusion of sulfur enhances the stability of PMA.

However, there is currently a lack of research on the use of blowdown as a substitute filler in SBS-modified asphalt mixtures. As a result, this study is part of a series of investigations that aim to examine the feasibility of incorporating blowdown material in this particular role.

Fig. 1 Blowdown material in the Al-Mishraq plant.

2. STUDY OBJECTIVES

The study's primary objective is to investigate the viability of using blowdown as a filler in SBS-modified asphalt mixtures. This study also includes a performance comparison between asphalt mixtures made with blowdown filler and those made with $CaCO_3$ filler. This investigation is expected to provide a comprehensive understanding of the behavior of asphalt mixtures containing blowdown as a mineral filler, specifically in terms of moisture susceptibility and rutting resistance.

3. MATERIALS

3.1 Aggregates

The aggregates used in this study were sourced from the Al-Kazer quarry (Mosul-Iraq). Both coarse and fine aggregates were used to prepare the asphalt mixture specimens. To ensure that the aggregates met the necessary specifications for use in the binder layer, they were sieved, separated, and graded according to the ASTM D 3515 specification [9]. This study utilized the midpoint gradation between the upper and lower limits of the dense-graded gradation using the D-4 mix designation, as specified in ASTM D 3515 and illustrated in Fig. 2. Table 1 shows the basic properties of the coarse and fine aggregate.

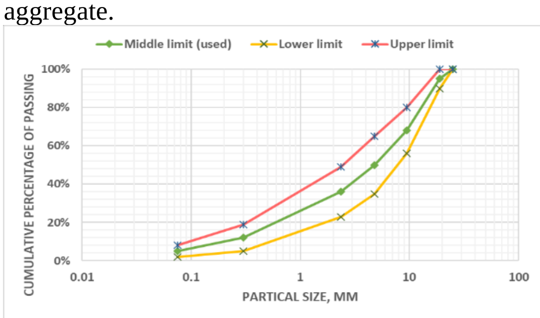


Fig. 2 Gradation limits for D-4 mix designation of ASTM D 3515, and the used gradation curves.

Table 1: Coarse and fine aggregate properties.

Property	Coarse aggregates	Fine aggregates	Specification
Toughness	19.6%	-	ASTM C131[10]
Angularity	96.2%	44.7%	ASTM D5821 [11] & C1252 [12]
Soundness Na_2SO_4	0.95%	0.72%	ASTM C88 [13]
Water absorption	0.981%	1.43%	ASTM C127 [14] & C128 [15]
Bulk specific gravity	2.731	2.652	ASTM C127 [14] & C128 [15]
Apparent specific gravity	2.769	2.715	ASTM C127 [14] & C128 [15]

3.2 Mineral fillers

For this research, two types of fillers were used. Firstly, calcium carbonate ($CaCO_3$) is one of the most common mineral fillers used for asphalt mixtures in Mosul City. $CaCO_3$ filler was obtained locally and used in this study as the reference, secondly, the blowdown as a sustainable filler was obtained from Al-Mishraq Sulfur State Company near Mosul, Iraq. Blowdown is a solid by-product material from the sulfur production unit available in black grainy form (Fig. 3). Table 2 presents the physical and chemical properties of both fillers.

(a) (b)

Fig. 3 Photos of blowdown material.
(a- Before crushing & b- After crushing)

Table 2: Physicochemical properties of calcium carbonate and blowdown fillers.

Calcium carbonate filler		**Blowdown filler**	
Chemical			
Component	Weight % [16]	Component	Weight % [17]
SiO_2	2.7	Free sulfur	81.04
Al_2O_3	0.35		
Fe_2O_3	0.93		
CaO	50.67	CarSul	18.21
MgO	0.64	Ash	0.31
Na_2O	0.02	Acidity	0.001
SO_3	0.75	Moisture	0.42
Physical			
Specific Gravity	2.731	Specific Gravity	2.20
Gradation of calcium carbonate and blowdown fillers			
Sieve Opening (mm)	% passing	Iraqi standard specification (SCRB) limits [18]	
0.6	100	100	
0.3	100	100-95	
0.075	100	100-70	

A recent study [19] discovered that the crystalline configuration of elemental sulfur present in blowdown exhibits an orthorhombic structure. Through the extraction of carbo-sulfite materials (CarSul) using carbon disulfide, it was revealed that these compounds predominantly comprise carbon and sulfur, characterized by distinct chemical bonds and nanostructures.

3.3 Asphalt Binder

SBS-modified asphalt (SBSMA) was made from Al-Dura Oil Refinery's asphalt with 40/50 penetration grade and SBS. 5% SBS (KRATONTM D1192) to modify the base binder. A high-shear laboratory mixer blended SBS pellets at 170 ± 5 °C. For 2 hours at 3000 rpm, to ensure consistency of the binder [20]. According to the test results, the SBS-modified asphalt used in this study was equivalent to the PG76-16 binder.

SBS and asphalt compatibility were tested using the storage stability (separation tendency) method according to ASTM D7173 [21]. Initially, the Asphalt modified with polymers was heated to 163±5°C, carefully stirred, and transferred into a vertically positioned aluminum foil tube with 32 mm diameter and 160 mm height, and sealed to prevent the entry of air. This tube was then placed in an oven calibrated at the same temperature for 48±1 hours, completing the conditioning phase. Afterward, the tube was relocated to a -10 ±10°C freezer for a minimum of 4 hours to solidify the sample, maintaining the tube's vertical position. Once removed from the freezer, the tube was positioned on a flat surface and the sample was divided into three equal parts. The middle asphalt section was discarded and the top and bottom sections were moved to separate containers. Lastly, the softening points of the top and bottom sections were determined. The difference in SBSMA's softening points between the top and the bottom was 2.0 ℃, which is less than 2.5 ℃, indicating good storage stability [22]. Table 3 shows the rheological parameters of SBS-modified asphalt utilized in the study.

Table 3**:** Properties of SBSMA.

Property	Test method	Results	
		SBSMA	NCCL limits [23]
Penetration at 25°C (0.1mm)	ASTM D5 [24]	34	-
Softening point (°C)	ASTM D36 [25]	67.5	-
Specific gravity at 25°C	ASTM D70 [26]	1.051	-
Flash point (°C)	ASTM D92 [27]	313	≥ 230
Fire point (°C)	ASTM D92 [27]	332	-
Rotational viscosity at 135°C (cP)	ASTM D4402 [28]	2149	≤ 3000
Elastic recovery at 25 °C (%)	ASTM D6084 [29]	78.5	-
Loss of heat for 85 min. at 163 °C (%)	ASTM D2872 [30]	0.286	≤ 1.0
DSR (G/sin δ), @ 10 rad/sec, (kPa): Original binder (G*/sin δ) RTFO (G*/sin δ) PAV (G*sin δ))	ASTM D7175 [31]	1.894 3.665 1542	≥ 1.0 ≥ 2.2 ≤ 5000
Creep stiffness, S, -6 °C, MPa m-value @ 60 sec, -6 °C	ASTM D6648 [32]	71.25 0.3208	≤ 300 ≥ 0.3

4. EXPERIMENTAL METHODS

4.1 Mixture Design and Preparation

The Marshall method (ASTM D6927) [33] was employed to establish the optimal binder content (OBC). Five bitumen percentages (4%, 4.5%, 5%, 5.5%, 6% by weight of mix), creating three cylindrical specimens for each using a standard mold. Specimens were compacted with

75 blows per face and cooled for 1 day before testing. Marshall test starts with submerging the specimens in a water bath set at 60°C for 30 to 40 minutes, then applying lateral compression at 2 inches/min until the maximum load was reached using an automatic Marshall testing machine (Fig. 4). The maximum load and flow values were recorded and The OBC was determined by calculating the average of the asphalt content values corresponding to the highest stability, highest unit weight, and median percentage of air voids contain. The tests showed the OAC for SBSMA mixtures was 5.16%, which satisfies the SCRB [18] specification (4-6 % by total weight). Four groups of specimens are listed below:

- **SN**: SBS-modified asphalt (SBSMA) with 5% normal filler ($CaCO_3$).
- **SB4**: SBS-modified asphalt (SBSMA) with 4% Blowdown filler.
- **SB5**: SBS-modified asphalt (SBSMA) with 5% Blowdown filler.
- **SB6**: SBS-modified asphalt (SBSMA) with 6% Blowdown filler.

Fig.4 Automatic Marshall testing machine.

4.2. Tensile and moisture damage characteristics

Indirect tensile strength (ITS) is a frequently employed property for describing asphalt mixtures' resistance to tensile stresses. Specimens for the indirect tensile strength (ITS) test were prepared according to the procedure outlined for the Marshall method. Specimens with a diameter of 101.6 mm and an air void content of 7.0 ± 1 percent were prepared. The ITS test was conducted according to ASTM D6931 [34]. After that, the specimens were submerged in a water bath at 25°C for 30 minutes and tested at a rate of 50.8 mm/min in a Marshall compression machine, The ITS values were calculated using the following equation :

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

In this equation, 'ITS' is measured in (kPa) 'P' is the failure load (N), 't' is the specimen thickness (mm), and 'd' refers to the specimen diameter (mm). All the specimen groups were gone through the ITS test to determine the ITS value for each specimen.

The tensile strength ratio (TSR) test evaluates the moisture damage of asphalt mixtures to assess their durability. The test follows the ASTM D4867/D4867M [35] standard, which requires an air void volume of 7 ± 1%. Three Marshall specimens are submerged in 60°C water for 24 hours to condition them for the ITS test. This comparison is achieved through the calculation of the indirect tensile strength (ITS) test at 25°C, providing the unconditional specimens (ITS_U), and at 60°C, providing the conditional specimens (ITS_C). The final TSR percentage is then determined using the following equation:

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

4.3 Kim test (deformation strength)

The Kim Test is used to evaluate the deformation strength (SD) of asphalt mixtures to establish their resistance to rutting. Following a specimen preparation procedure same to the Marshall method, the test was conducted 30 minutes after the specimen was immersed in 60°C water bath. A loading head with a diameter of 30 mm and a circular edge radius of 7.5 mm is positioned at the upper center of the specimen for the test. A static load is then imparted to it at a rate of 50,8 mm/min. The calculation for deformation strength was as follows [36]:

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

Here, ‘SD’ represents deformation strength in megapascal (MPa), ‘P’ is the peak load (N), ‘D’ is loading head diameter (mm), ‘r’ is the radius of curvature at the bottom of the loading head (mm), and ‘y’ is the deformation (mm).

It is noteworthy that the SD values correlate very well (R^2>0.9) with the commonly used rut-related tests, such as the wheel tracking test, and that it is relatively easy and quick to conduct. Thus, the Korean Ministry of Land, Transport, and Maritime Affairs made SD a standard asphalt mixture design criterion [37].

5. TEST RESULTS AND DISCUSSIONS

5.1 Statistical analysis method

Statistical analysis of variance (ANOVA) and Fisher's least significant difference (LSD) comparisons at a significance level of = 0.05 were conducted using Minitab statistical software. ANOVA was used to identify significant differences among sample means, and LSD was subsequently calculated to compare all sample means. Table 4 shows the LSD test group information. Groups with non-identical letters were considered significantly different. It is noteworthy that the letter 'A' stands for the highest test value. Each following letter denotes a progressively lower value in the sequence.

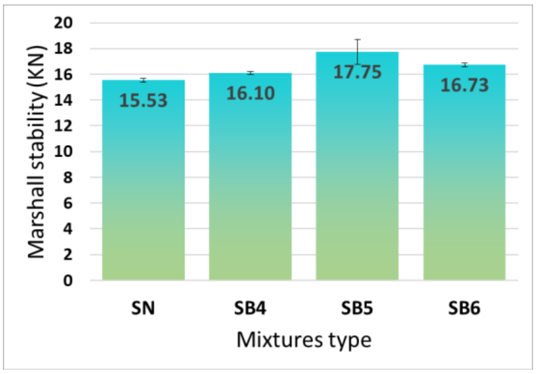
5.2 Marshall test characteristics

The results of the Marshall stability tests as shown in Fig. 5a, and based on the LSD test (Table 4) indicate notable differences among the various asphalt mixtures tested. When comparing SBSMA mixtures, the use of blowdown filler in SB4, SB5, and SB6 leads to enhanced stability, with SB5 reaching the highest stability of 17.75 KN, representing a significant increase of 14.27% over the control mixture that contains $CaCO_3$ filler, SN. Overall, incorporating Blowdown filler in SBSMA mixtures contributes to enhanced Marshall stability. Regarding Marshall flow values, the SBSMA mixtures with blowdown filler, SB4, SB5, and SB6, show reduced flow values relative to SN, and are significantly distinct from SN when statistically analyzed, with SB4 registering the lowest flow of 3.03 mm, a decrease of 19.06% (Fig. 5b). Overall, incorporating blowdown filler SBSMA mixtures led to reductions in Marshall flow.

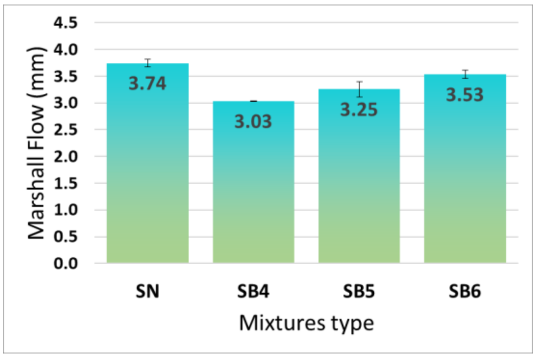
The Marshall quotient (MQ), derived by dividing stability by flow, was used to assess stiffness and the mixture's rutting tendency. Higher Marshall quotient values indicate stiffer mixtures, which resist rutting [38]. As shown in Fig. 5c, the SBSMA with blowdown filler mixtures (SB4, SB5, SB6) has significantly higher Marshall quotient values than the SN mixture, with SB5 having the highest value of 5.46 KN/mm, a 31.44% increase, suggesting improved performance and rutting resistance.

Furthermore, the air voids percentage for SBSMA mixtures with blowdown filler shows lower air void percentages for the SB6 mixture and a higher void percentage for SB4 and SB5 mixtures compared to SN as shown in (Fig. 5d).

In general, these findings comply with recent research [39] suggesting that the free sulfur (which is more than 80% in blowdown) could act as a filler in asphalt mixtures, increasing their stability, hardness, and rut resistance. Overall, The asphalt mixtures containing blowdown as a filler satisfy the SCRB [18] minimum requirements for 7 kN Marshall stability, 2 to 4 mm Marshall flow, and 3 to 5% air voids.



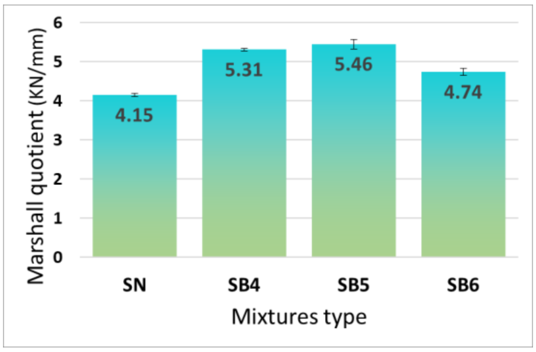
(a)



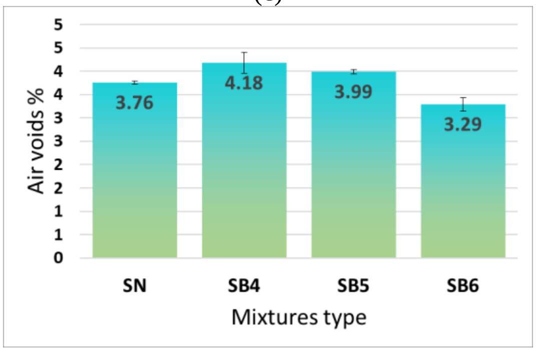
(b)

Table 4: Grouping Information using Fisher's least significant difference (LSD).

Test/Mixtures	SN	SB4	SB5	SB6
Marshall stability	C	BC	A	B
Marshall flow	A	D	C	B
Marshall quotient	C	A	A	B
Air voids	B	A	AB	C
Indirect tensile strength, 25 °C	AB	B	A	C
Tensile strength ratio	A	B	AB	B
Deformation strength	C	B	A	BC



(c)



(d)

Fig. 5 Marshall test results
(a- Marshall stability, b- Marshall flow, c- Marshall quotient & d- Air voids)

5.3 Tensile characteristics and moisture damage tests

The indirect tensile strength (ITS) test results for unconditional specimens, as shown in Fig. 6, and based on the LSD test (Table 4), show that SBSMA mixtures with blowdown filler SB4 and SB6 have insignificantly lower ITS values with a decrease of 2.13%, and 4.8% respectively, whereas the SB5 mixture improved, reaching a maximum value of 1316.21 kPa, a slight increase of 0.21% as compared to SN indicating greater resistance to tensile stresses and can help prevent cracking.

Alongside the ITS values, the tensile strength ratio (TSR) is used to evaluate durability by determining the moisture damage that affects conditional specimens. Here, it's found that the SN mixture shows the highest TSR at 93.18%, followed by SB5 with an insignificant decrease to 86.74%. Meanwhile, mixes SB4 and SB6 demonstrate signifying lower values compared to SN. However, there is no set value for TSR; some agencies have chosen to accept TSR values of 70% or more. The Asphalt Institute [40] considers a TSR value of 80% or greater to be acceptable. Based on this, all the TSR values of the tested mixtures met the minimum requirement, implying that these containing blowdown filler mixtures still maintain satisfactory resistance to moisture damage.

5.4 Rutting resistance

The Kim Test determined the deformation strength (SD) of specimens, thereby indicating resistance to rutting. Fig. 7 and the LSD test as shown in Table 4 reveal that the SBSMA mixtures containing blowdown filler, SB4, SB5, and SB6, exhibit higher SD values than the SN mixture, reaching up to 20.41%, 51.23 %, and 15.47% improvement, with SB5 registering the highest significant SD value of 10.99 MPa. Overall, the incorporation of Blowdown filler to SBSMA mixtures substantially improves deformation strength, indicating enhanced resistance to rutting and enhanced performance under load. As investigated in these studies [41, 42], the increase in deformation strength may result from the addition of sulfur-based material to bitumen mixtures, which stiffens the mixtures and improves their resistance to rutting. All SD values

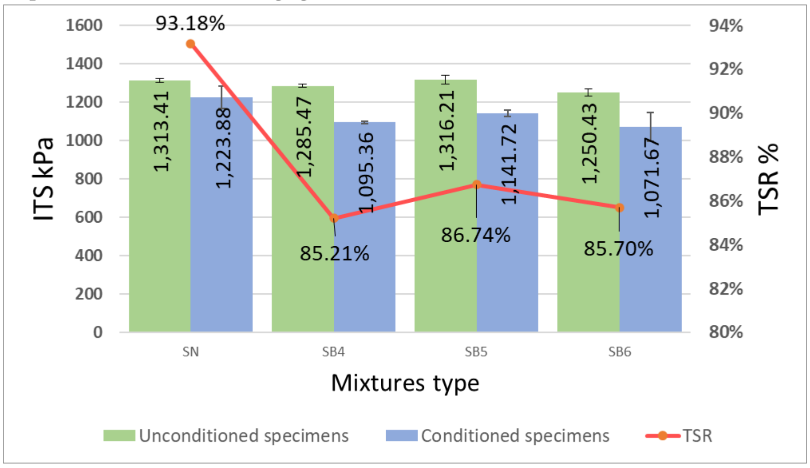


Fig. 6 Tensile and moisture damage characteristics results.

met the minimum requirements (>3.20 MPa) specified by the guidelines of the Korean Ministry of Land [43].

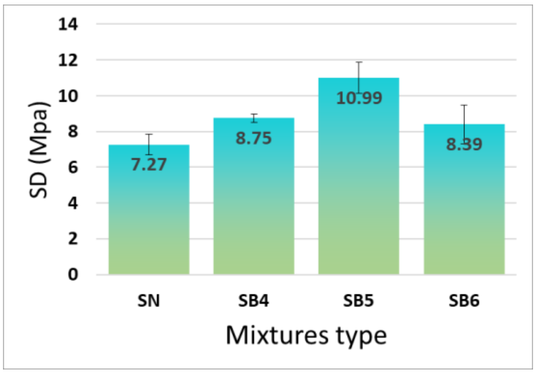


Fig. 7 Deformation strength results.

6. CONCLUSIONS

In this study, the potential of utilizing blowdown as a mineral filler in dense-graded asphalt mixtures was investigated using SBSMA when used in the binder layer. The laboratory analysis entailed testing blowdown at three distinct concentrations (4%, 5%, and 6% by total aggregate weight). Upon analyzing the results of multiple performance tests, several key conclusions are outlined below:

- Using blowdown as a filler with different rates (4%, 5%, and 6% total aggregate weight) led to variant results: 5% with the highest performance, 4% with the lowest, and 6% in between.
- Using 5% blowdown for SBSMA mixtures as a filler replacement led to improve Marshall stability (ultimate load), indirect tensile strength (cracking resistance), deformation strength (rutting resistance), Air voids, and Marshall quotient of the asphalt mixture specimens.
- There is an insignificant decrease in the tensile strength ratio (moisture damage resistance) of the SBSMA mixtures at 5% blowdown but still satisfies the TSR the requirements.
- The Marshall flow of the SBSMA mixtures decreased with the inclusion of blowdown filler, but, all values still meet the SCRB standards.

Based on these findings, it can be inferred that utilizing 5% of blowdown as a mineral filler alternative with SBS-modified mixtures can offer promising benefits, such as enhancing the cracking and rutting resistance of the mixture, while also fulfilling the required Marshall properties and durability performance standards. In comparison to commonly used industrial fillers, $CaCO_3$, employing blowdown as a mineral filler in asphalt mixtures can potentially lead to cost savings and conserve valuable landfill space.

7. RECOMMENDATIONS

Considering the findings of this study, this is the following recommendations and suggestions for future study:

- Additional research may be conducted to investigate the impact of short-term and long-term aging on the performance of blowdown asphalt mixtures examined in this study. This would provide a better understanding of the durability of these mixtures in real-world applications.
- A feasibility study analysis focusing on the economic and environmental aspects of utilizing blowdown as a mineral filler in asphalt mixtures.
- Further research may explore other potential applications for blowdown material in asphalt mixtures, such as an alternative asphalt modifier, providing more understanding of the capabilities and limitations of this material.

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ديمومة ومقاومة التخدد للمزجات الاسفلتية المطورة بمادة ستايرين-بيوتادين-ستايرين الحاوية على مادة البلوداون كمادة مالئة مستدامة

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الملخص

بحثت هذه الدراسة في إمكانية استخدام مادة البلوداون، وهو مادة ثانوية من الكربون-الكبريت لعملية تنقية الكبريت، المتواجدة بكثرة في معمل كبريت المشراق واستخدامها كمادة مالئة في المزجات الإسفلتية كثيفة التدرج المطورة بمادة ستايرين-بيوتادين-ستايرين. تم اختبار ثلاثة تراكيز مختلفة من مادة البلوداون (4٪، 5٪، 6٪ من الوزن الكلي للركام) في المختبر كبديل للمادة المالئة شائعة الاستخدام، كربونات الكالسيوم ($CaCo_3$). تم إجراء اختبارات أداء ومعايير مختلفة، بما في ذلك اختبار ثبات مارشال، اختبار مقاومة الشد غير المباشر، نسبة قوة الشد، ومقاومة التشوه على كل مجموعة من المزجات الاسفلتية. تم تحليل البيانات التي تم جمعها من جميع الاختبارات احصائيا باستخدام برنامج Minitab لتقييم آثار مادة البلوداون. أشارت النتائج إلى أن استخدام 5٪ من مادة البلوداون كمادة مالئة معدنية في مزجات الإسفلت المطورة بمادة ستايرين-بيوتادين-ستايرين يمكن أن يقدم فوائد واعدة، مثل زيادة مقاومة التشوه، قوة الشد غير المباشرة عند 25 درجة مئوية، ثبات مارشال، وحاصل مارشال بنسبة 51.23٪، 0.21٪، 14.27٪، و31.44٪ على التوالي، مع تلبية خصائص مارشال ومقاومة تأثير الرطوبة. يمكن أن يؤدي استخدام مادة البلوداون كمادة مالئة في المزجات الاسفلتية إلى توفير التكاليف وأيضًا توفير مساحة كبيرة لطمر النفايات مقارنةً بالمواد المالئة شائعة الاستخدام.

الكلمات الدالة:

بلوداون; مواد مستدامة; ديمومة; مقاومة التشوه; مادة مالئة.