

Effect of sisal fiber length and content on the Marshall properties and moisture susceptibility of Sasobit-modified warm mix asphalt

Haneen Salih Khwayyir ^{*,a}, Alzerjawi Ahlam K. R. ^b

Department of Civil Engineering, University of Kufa, Najaf, Iraq

Article Info

Article History:

Received 22 July 2026

Accepted 24 Aug 2026

Keywords:

Warm mix asphalt (WMA);
Sasobit;
Marshall mix design;
Sisal fiber;
Sustainability;
Moisture susceptibility;
Environmental and emission reduction

Abstract

The present research examined effects of sisal-fiber length and content on Marshall, volumetric, and moisture-susceptibility properties of Sasobit-based WMA for a Type IIIA surface course. A total of nine fiber configurations, encompassing three lengths and three contents, were evaluated at the design asphalt content of the fiber-free WMA-Sasobit mixture. The configuration that satisfied all SCRB (2003) requirements while providing the highest Marshall stability was subjected to a separate Marshall mix design. Its properties were subsequently related with those of conventional hot-mix asphalt (HMA) and fiber-free WMA-Sasobit, while moisture susceptibility was evaluated according to AASHTO T283. The screening process identified a configuration of 0.3% sisal fiber measuring 9 mm in length as the optimal configuration, with an OAC of 4.7%. At this design condition, the mixture achieved a Marshall stability of 17.90 kN, which is numerically higher than those of WMA-Sasobit and HMA by 3.5% and 9.9%, respectively. The flow and volumetric properties of the substance in question satisfied all applicable SCRB limits. The mixture also exhibited a TSR of 84.4%, which is approximately three percentage points greater than those of both reference mixtures and above the specified minimum. The findings indicate that the laboratory-scale technical feasibility of the selected sisal-fiber configuration in Sasobit-based WMA at reduced production temperatures is demonstrated.

© 2026 MIM Research Group. All rights reserved.

1. Introduction

Roads and asphalt pavements are key components of the infrastructure of any developed society and are subjected to multiple stresses from heavy traffic use and harsh climatic conditions over many years. Thanks to their excellent engineering properties, such as skid resistance, low noise, and easy maintenance, asphalt mixtures account for over 90% of pavement applications in Europe and in many countries around the world [1-3]. Nonetheless, conventional hot-mix asphalt (HMA) is commonly produced and compacted at temperatures of approximately 150–180 °C, resulting in substantial fuel consumption and emissions during construction [4,5]. These demands are particularly relevant in regions such as Iraq, where asphalt pavements must also withstand high service temperatures and heavy axle loading [6,7].

Warm-mix asphalt (WMA) offers a minor-temperature alternative by reducing mixing and compaction temperatures, commonly by 20–40 °C, through foaming processes or chemical and organic additives [8]. Many studies have already been recorded, which show that WMA technologies can lead to a decrease in energy depletion and CO₂ emissions of up to 30%, and also reduce harmful fumes and dust in construction sites [9]. Sasobit is one of the most striking additives used in this context: It is a synthetic paraffin wax produced in the gas-to-liquid conversion process

*Corresponding author: haneens.khwayyir@student.uokufa.edu.iq

^aorcid.org/0009-0005-1458-5921; ^borcid.org/0000-0002-3559-4780

DOI: <http://dx.doi.org/10.17515/resm2026-2021ic0722rs>

Res. Eng. Struct. Mat. Vol. x Iss. x (xxxx) xx-xx

by employing Fischer-Tropsch technology. Sasobit is effective in reducing the dynamic viscosity of bitumen by about 20°C lower than the temperature used for conventional HMA, which aids in mixing and compaction processes[4,10].

While these environmental and operational advantages exist, moisture susceptibility is still a critical design consideration for WMA. The lower manufacturing temperatures can result in moisture remaining in aggregate that has not been dried, and can also cause a decrease in the short-term oxidative aging of the binder. These effects can change the stiffness of the binder, the adhesion of the binder to the aggregates, and thus the tensile strength after moisture conditioning [11,12], [13]. In this context, fiber reinforcement has been investigated as a complementary strategy to improve mixture integrity and potentially mitigate moisture-related deterioration[14,15]. If fibers are uniformly dispersed, they can help stabilize the asphalt mastic, help to redistribute localized stresses, and help to delay crack initiation and propagation [15-17]. However, reinforcement efficiency depends strongly on fiber type, length, content, surface characteristics, dispersion, and fiber-asphalt interfacial bonding, excessive fiber length or dosage may promote agglomeration or nonuniform distribution and adversely affect the mechanical and volumetric response of the mixture [15,17]. Fibers used in asphalt mixtures can be divided into two main groups: natural and synthetic. Normal plant fibers have attracted growing interest from researchers in recent years due to their renewable properties, low production costs, biodegradability, and low energy consumption [18,19].

Sisal fibers are in a special class of natural plant fibers. They are taken from the leaves of the *Agave sisalana* plant, which has a relatively low density, a chemical composition high in cellulose (47–78%), lignin (7–11%), and hemicellulose (10–24%), and endows good tensile strength and moderate cost[20]. On the applied level, Ramalingam et al. investigated the effect of varying fiber lengths (5–20 mm) and proportions (0.05–0.3%) of sisal fibers on the performance of HMA mixes, concluding that an optimal length of 15 mm at a proportion of 0.05% yields the best performance, while increasing fiber content diminishes Marshall stability[21]. Mahmood and Ahmed [22] evaluated coconut, corn, palm, and sisal fibers in Iraqi HMA wearing-course mixtures and identified 0.2% fiber content and a length of 15 mm as the most effective overall configuration.

Recent studies have extended fiber reinforcement to different WMA systems. Farkhondeh and Arabani [19] evaluated wheat-fiber contents of 0.1%, 0.3%, and 0.5% in WMA and SMA mixtures and found that 0.3% provided the most favorable moisture-resistance and fracture responses. Chahata et al. investigated Alfa fibers in WMA containing construction and demolition waste and reported improved rutting and thermal performance for a selected formulation containing 1% Alfa fiber and 20% recycled aggregate[21]. However, the simultaneous incorporation of the two materials prevented the isolated assessment of the fiber contribution.

In an Iraqi study, Dakhil and Al-Busaltan (2026) reported that 0.3% polypropylene fiber in Sasobit-based WMA increased ITS by 27.6% and TSR from 80% to 85%. Although 0.4% fiber produced the highest TSR (87%), 0.3% was selected as optimum because of its superior tensile and volumetric performance[23]. More recently, Li et al. incorporated micronized basalt fiber powder into Sasobit-based WMA and reported improvements in high-temperature deformation resistance, low-temperature flexural response, and residual Marshall stability, demonstrating the importance of fiber morphology and dispersion[24]. Collectively, these studies confirm the feasibility of fiber-reinforced WMA but also demonstrate that the resulting response is strongly dependent on fiber characteristics and the adopted WMA technology.

Despite growing interest in fiber-reinforced asphalt mixtures, the performance of Sasobit-modified WMA containing different combinations of sisal-fiber length and content remains insufficiently documented. Further research is therefore needed to clarify this interaction and establish a systematic basis for selecting appropriate fiber parameters. The present study addresses this gap to support the development of balanced and specification-compliant fiber-reinforced WMA mixtures.

2. Research Objectives

This research aims to present a thorough investigation using natural Sisal fibers as a reinforcement material in (WMA) mixes. This overall objective is achieved by the following specific objectives:

- Evaluation of Volumetric Properties: To study the influence of the use of sisal fibers at changed
- length (6 mm, 9 mm and 12 mm) and different ratios (0.3%, 0.5% and 0.7% in total mixture weight) on volumetric characteristics of Sasobit Modified Warm Mix Asphalt (WMA+Sisal), which include Air Voids content (AV), VMA, and VFA.
- Mechanical Performance Assessment: To assess effect of the added fibers on Marshall mechanical characteristics of WMA mixes, which include Marshall Stability, Flow Value, and MQ.
- Determining the Optimum mix design includes finding the optimum fiber length and optimum fiber proportion, and Optimum Asphalt Content (OAC) that would give optimum volumetric and mechanical properties of surface asphalt course (Type IIIA, NMAS = 12.5 mm), according to Iraqi Standard Specifications for Roads and Bridges (SCRB 2003).
- Comparative Analysis: To carry out a systematic and comprehensive comparative analysis on the performance efficiency of three types of mixture:
 - As a control reference group, conventional HMA was used.
 - WMA (no fibers).
 - Warm Mix Asphalt with optimum design of sisal fiber (WMA +Sisal)
- To assess moisture susceptibility and stripping resistance of proposed Sisal fiber-reinforced WMA mixtures systematically by means of ITS and TSR parameters.

3. Research Significance

Research Significance The relevance of this study can be summarized through following complementary dimensions:

- Scientific and Academic Contribution: This study contributes to the pavement engineering literature by systematically examining a hybrid mixture combining Sasobit-modified WMA with natural sisal fibers of varying lengths and contents. It addresses the limited evidence concerning the interaction of these components within a single asphalt-mixture system.
- Sustainability Relevance: The study combines lower-temperature asphalt production with natural sisal-fiber reinforcement, providing a materials framework relevant to sustainability-oriented pavement research.
- Applied and Engineering Relevance: The study provides locally relevant laboratory evidence based on Marshall, volumetric, and moisture-susceptibility testing conducted under SCRIB (2003) and AASHTO requirements. The comparison among conventional HMA, fiber-free WMA–Sasobit, and sisal-reinforced WMA supports the technical evaluation of these mixtures for surface-course applications.
- Moisture-Resistance Evaluation: The study evaluates the potential of sisal-fiber reinforcement to improve the retained tensile strength and moisture resistance of Sasobit-modified WMA through ITS and TSR testing.
- Future Research: The findings provide a basis for further investigations addressing long-term durability, field performance, advanced mechanical properties, life-cycle environmental impacts, and economic feasibility.

4. Materials and Methods

4.1 Asphalt Cement

The Al-Daurah refinery's asphalt cement, with a penetration grade of 40-50, was utilized as the base binder in this study. The physical characteristics of asphalt cement and whether they meet the corresponding ASTM specifications are recorded in Table 1.

Table 1. Physical features of asphalt binder and its limits

Tests	Standard	Tests value	Standards Limitations as per SCRB / R9, 2003
Penetration, 25°C, (0.1 mm)	ASTM. D 5	48	40-50
Ductility, 25°C, 5cm./ min.	ASTM. D 113	+100	>100
Softening Point. (°C)	ASTM. D 36	50	----
Specific gravity, 25°C	ASTM. D 70	1.041	-----
Flashpoint, °C	ASTM. D 92	324°C	> 232 °C
Viscosity a (centistokes)	ASTM. D4402	340 @ 135°C 151 @ 165°C	-
Solubility in (%) CHCL ₃	ASTM. D2042	99.9	99

4.2 Aggregates and Mineral Filler

The use of aggregates and mineral filler. In this study, crushed aggregates extracted from Al-Nibaie quarries were used, which are used in road construction projects in all parts of Iraq. The fundamental physical tests were conducted on both coarse and fine aggregate in agreement with ASTM standards and physical features of both aggregates are known in Table 2.

Table 2. The physical features of aggregates and mineral filler

Material	Test in the laboratory	ASTM standard	Findings	Specification
Coarse aggregate	Bulk Specific Gravity	ASTM 127	2.56	-----
	Absorption	ASTM C127	0.89%	-----
	Soundness by Sodium Sulfate %	ASTM C88	4.21%	Max. 12%
	Los Angeles abrasion, %	C131	23.5	Max. 30 %
	Clay lumps, %	ASTM C142-10	0.37%	3%
Fine aggregate	Bulk Specific Gravity	C128	2.61	-----
	Soundness by Sodium Sulfate %	C88	6.97%	Max. 15%
	Clay lumps, %	ASTM C142	0.26%	3%
	Sand equivalent, %	D2419	85%	Min.45%
Mineral filler	Specific Gravity	ASTM D854-23	2.87	-----
Hydrate lime	Specific gravity	ASTM C110	2.45	-----

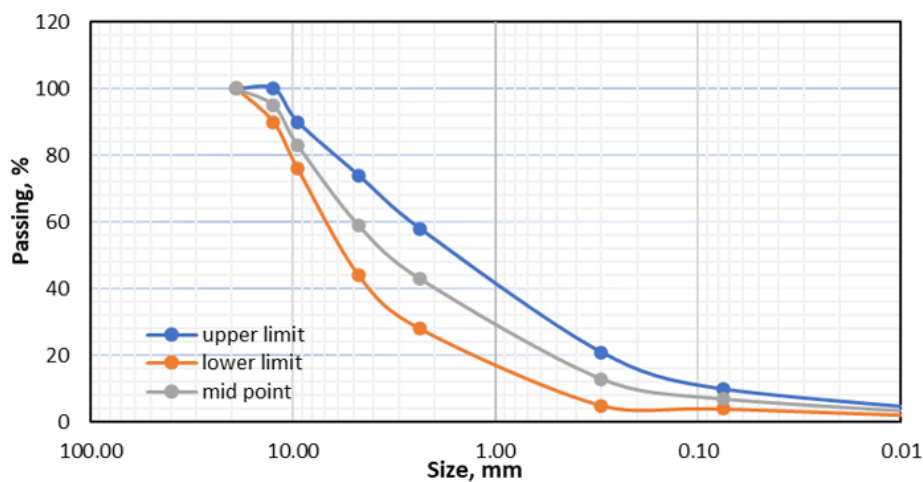


Fig. 1. Gradation for the selected aggregate

The mix was prepared for the wearing course, according to the Iraqi SCRB specification, which specifies the NMAS of 12.5 mm. The recommended gradation for Type IIIA wearing course is shown in Figure 1. The stone dust from the aggregate crushing was used as the mineral filler. A partial

replacement of mineral filler was made with hydrated lime at a rate of 1.5% of the total weight of dry aggregate[25]. This dosage was chosen based on the Iraqi specifications (SCR/R9) and the recommendations of previous studies and international organizations, such as the National Lime Association (NLA) and the European Lime Association (EuLA), which all agree that optimum quantity of hydrated lime in the asphalt mixture is 1.0–1.5% to advance durability of pavement and the resistance to moisture damage in asphalt mix without causing it to become brittle[26], [27].

4.3 Warm Mix Asphalt Additive

The modified asphalt binder was prepared by the addition sasobit at 2% of total amount of asphalt binder (40-50). This ratio has been set in accordance with the guidelines of the industry and accepted scientific advice. A typical addition rate is 0.8 to 3% to get the desired performance as recommended by the manufacturer (Sasol Wax). This range has been verified and used in other worldwide benchmarking studies, such as the report from National Center for Asphalt Technology[28].

To ensure that right sasobit content was used in the local asphalt binder, a preliminary trial in the laboratory was carried out by addition sasobit in 3% by weight of asphalt binder. The findings showed considerable degradation of physical and rheological characteristics of the modified binder, such as excessive stiffening, marked decrease in ductility, and unacceptable brittleness. These properties made the mixture potentially unsuitable for use in the field under the current climatic conditions. The observations are in agreement with those stated in literature, that will show that contents of sasobit near or above the recommended concentration will adversely affect the binder performance, especially at low and intermediate temperatures [28]. Furthermore, the 2% dosage was well supported by a local Iraqi study (Joni & Alkhafaji, 2021) that used the same type of 40-50 penetration grade binder produced by Iraqi refineries. They found that a 2% addition is the optimal content needed to get an optimum performance balance. Consequently, based on the outcomes of this preliminary assessment and the recommendations of Joni & Alkhafaji (2021), a sasobit content of 2% by weight of binder was adopted for all subsequent mixture preparations in this research[29]. The physical and rheological characteristics of sasobit used are summarized in Table 3.

Table 3. The physical and rheological characteristics of sasobit [10].

Characteristics	Test technique	Units	Specification	Typical values
Congealing point	ASTM D 938	°C	100 - 110	101
Penetration at 25°C	ASTM D 1321	0.1 mm	0 - 2	<1
Penetration at 65°C	ASTM D 1321	0.1 mm	0 - 13	11
Brookfield viscosity at 135°C	Sasol 1010	cP	10 - 15	12

4.4 Sisal Fibers

The fiber geometry and content of fiber in WMA-sasobit mix were systematically investigated in this study by using sisal fibers of three fiber lengths (6, 9, and 12 mm) and three dose levels (0.3%, 0.5%, and 0.7% by total weight of the mix). The fibers were dried to remove the moisture content that can affect the fiber-binder adhesion before use. The physical characteristics of fibers of Sisal are presented in Table 4. The sisal fiber utilized is shown in Figure 2.



Fig. 2. Natural sisal fibers prepared for use in (WMA-sasobit) mixtures

Table 4. Sisal fiber properties

Material Property	Result
Tensile strength (Mpa)	385 to 728
Elongation of break (%)	2.75
Diameter (μm)	5 μm
Density (g/cm ³)	1.58
Young modulus (Gpa)	9.22
	6.55
Moisture	67-72% Cellulose
Chemical composition	12-14% Hemicellulose
	8-11% Lignin
	2% Wax and fats

4.5 Mix Design and Specimen Preparation

In this research, the Marshall mix design technique was used as per the specifications of the Iraqi SCRB 2003 for surface course Type III A (NMAS = 12.5 mm). The experimental program was carried out in three sequential stages as described below. Calculation of OAC for HMA and WMA-Sasobit.

4.5.1 Stage 1: Determination of OAC for HMA and WMA

For both conventional HMA (control mix) and the WMA-Sasobit mix (without fibers), the OAC was calculated independently following the same process. Five asphalt content levels were investigated for each mix, with three cylindrical Marshall samples set at every level, yielding 15 specimens per mix. The OAC was then identified based on the average of the four Marshall criteria in accordance with SCRB 2003 requirements. An additional 3 specimens were prepared at the OAC for each mix to confirm compliance with the specification limits. Accordingly, a total of 18 samples were carried out for every of the two mixes (HMA and WMA-sasobit), giving a combined total of 36 specimens for Stage 1. Figure 3 presents the prepared samples of HMA and WMA.

4.5.2 Stage 2: Determination of Optimum Sisal Fiber Length and Content

Sisal fibers were incorporated into the WMA-Sasobit mix at the previously determined OAC of the WMA-Sasobit mixture. Three fiber lengths (6, 9, and 12 mm) and three dose levels (0.3%, 0.5%, and 0.7% by total weight of the mix) were investigated, with 3 specimens prepared for each combination. This yielded a total of 27 specimens (3 lengths $\times$ 3 dosages $\times$ 3 specimens) for this stage. The optimum fiber length and content were selected based on the best volumetric and mechanical Marshall performance.

4.5.3 Stage 3: Determination of OAC for WMA+Sisal at Optimum Fiber Parameters

Following identification of optimum fiber length and content, OAC for the WMA-Sasobit+Sisal mixture was determined using five asphalt content levels with 3 specimens at each level, yielding 15 specimens. An additional 3 specimens were then prepared at the final OAC to verify compliance with SCRB 2003 specification limits, bringing the total for this stage to 18 specimens. Figure 4 shows the final cast products of WMA-sasobit with sisal. The overall experimental program comprised a grand total of 81 Marshall specimens, distributed as follows: 18 specimens for HMA, 18 specimens for WMA-Sasobit, and 45 specimens for WMA+Sisal (27 specimens for fiber optimization + 15 specimens for OAC determination + 3 specimens for OAC verification). Figure 4 shows the final cast products of WMA-sasobit with sisal.

All specimens were prepared with a mass of 1200 g and compacted utilizing a Marshall hammer applying 75 blows per face to simulate heavy traffic loading situations. The sisal fibers were introduced using dry technique, whereby fibers were mixed with aggregates prior to the adding of asphalt binder, ensuring uniform fiber distribution throughout the mixture. The mixing temperatures adopted were 165°C for HMA and 145°C for WMA-sasobit mixes, while compaction was performed at 155°C and 130°C for HMA and WMA-sasobit mixtures, respectively. Before Marshall stability and flow testing, all samples were absorbed in a water bath at 60°C for 30–40 minutes in accordance with ASTM D6927.

It is interesting to note that there are no specific requirements in the Iraqi SCRB 2003 for Warm Mix Asphalt (WMA-sasobit) in terms of volume or mechanical properties. The WMA-sasobit and WMA-SASOBIT +Sisal mixes studied in this research were therefore compared to the same specification limits used for conventional HMA and a conventional HMA mix was utilized as the main reference benchmark for comparison. This method is similar to the one utilized in the previous studies carried out in the region and Iraq on WMA-sasobit.

4.6 Moisture Susceptibility Testing (ITS and TSR)

The moisture susceptibility for the three mixture types investigated was determined by the ITS test and the TSR per AASHTO T283. Six cylindrical Marshall samples were made for every mixture type using the optimum asphalt content to attain an air void content of $7.0 \pm 0.5\%$, with 3 specimens being unconditioned and 3 specimens being conditioned. The conditioned material was then located in a vacuum saturation to 55% - 80% saturation, exposed to one freeze-thaw cycle, and submerged in a water bath for 24 hours before testing.



Fig. 3. Laboratory-prepared marshall specimens: (a) Conventional HMA, (b) Warm mix asphalt (WMA-sasobit)



Fig. 4. Laboratory-prepared marshall specimens for warm mix asphalt (wma-sasobit) with sisal

The tests were carried out at 25°C and with a deformation ratio of 50 mm/min in a diametral loading configuration. The TSR was computed by the following procedure:

$$ITS = 2P / \pi Dt \quad (1)$$

$$TSR = ITS_{con} / ITS_{uncon} \quad (2)$$

Where; ITS: indirect tensile strength ,P: applied load, t: thickness of samples, D: diameter of sample, TSR: tensile strength ratio, ITS_{con}: indirect tensile strength for conditioned (kPa), ITS_{uncon}: indirect tensile strength for unconditioned (kPa). The minimum TSR value was selected as 80% based on AASHTO M 323 requirements. Figure 5 demonstrates a typical assembly and specimen alignment in the laboratory mechanical testing machine



Fig. 5. Experimental setup of the ITS test on a fiber-reinforced WMA specimen

5. Results and Discussion

5.1 Marshall and Volumetric Characteristics of Conventional HMA at Optimum Asphalt Content

The Marshall mix design was carried out for the conventional HMA control mixture in accordance with the requirements of the Iraqi SCRB 2003 for surface course Type IIIA (NMAS = 12.5 mm). The OAC was found to be 4.7%, where all Marshall and volumetric criteria were met, as shown in Table (5). Marshall Stability was 16.28 kN (Min. 8 kN), Flow 3.49 mm (2–4 mm), and MQ 4.66 kN/mm. Volumetric properties were: AV 4.68% (3–5%), VMA 17.26% (Min. 14%), VFA 72.88% (65–85%), and Gmb 2.279 g/cm³. The results show that the HMA mixture met all the SCRB 2003 requirements, making it a reliable reference for future comparisons.

5.2 Marshall and Volumetric Properties of WMA-Sasobit at Optimum Asphalt Content

The WMA-Sasobit mixture was produced at reduced mixing and compaction temperatures of 145°C and 130°C, respectively, representing a 20°C reduction compared to HMA. The OAC was 4.6%, marginally lower than HMA (4.7%). This small difference may be associated with the viscosity-reducing effect of Sasobit, which facilitates mixture workability and compaction at a slightly lower binder content.[30], [31] Marshall Stability was 17.3 kN, representing a 6.3% increase over HMA (16.28 kN), attributable to the crystalline network formed by Sasobit within binder at service temperatures. Flow was 3.4 mm, MQ 5.08 kN/mm, AV 4.5%, VMA 18.0%, VFA 75.0%, and Gmb 2.251 g/cm³, all within SCRB 2003 limits. These results demonstrate that WMA-Sasobit achieves performance comparable to or exceeding HMA while enabling meaningful temperature reductions, consistent with Jamshidi et al. [4] and Joni and Alkhafaji[29]. The results obtained at OAC are summarized in Table (5)

Table 5. Summary of Marshall and volumetric characteristics for HMA and WMA mixes at their respective (OAC) compared to SCRB specification limits

Property (Unit)	Conventional HMA (OAC = 4.7%)	Modified WMA (OAC = 4.6%)	SCRB Specification Limits (Wearing course)
Marshall Stability [kN]	16.28	17.3	Min. 8
Flow [mm]	3.49	3.4	4-2
Marshall Quotient [kN/mm]	4.66	5.08	-
Bulk Specific Gravity [g/cm ³]	2.279	2.251	-
Air Voids AV(%)	4.68	4.5	5-3
VMA(%)	17.26	18.0	Min. 14
VFA(%)	72.88	75.0	85-65

5.3 Effects of Sisal Fiber Length and Content on Marshall and Volumetric Characteristics of WMA-Sasobit+Sisal Mixtures

Sisal fibers were incorporated into WMA-Sasobit at OAC = 4.6%, across three lengths (6, 9, 12 mm) and three dosage levels (0.3%, 0.5%, 0.7% by total mixture weight), yielding nine combinations whose results are presented in Table (6).

Table 6. Marshall and volumetric characteristics of WMA-sasobit mixes with varying sisal fiber parameters

Property	0.3% (6 mm)	0.3% (9 mm)	0.3% (12 mm)	0.5% (6 mm)	0.5% (9 mm)	0.5% (12 mm)	0.7% (6 mm)	0.7% (9 mm)	0.7% (12 mm)
Stability (kN) > 8	11.6	18.30	12.00	9.92	20.20	10.06	8.90	10.90	10.56
Flow (mm)	3.85	3.80	3.91	4.00	5.33	5.12	4.50	5.20	5.26
Gmb	2.224	2.288	2.240	2.187	2.158	2.139	2.163	2.101	2.110
Gmm	2.335	2.397	2.349	2.346	2.307	2.201	2.341	2.201	2.160
AV % (3-5)	4.75	4.5	4.60	6.70	6.40	2.81	7.60	4.54	2.3
VMA % > 14	19.15	17.1	18.7	20.66	20.66	22.4	21.5	23.7	23.46
VFA % (65-85)	75.19	73.6	75.40	67.50	69.02	87.40	64.50	80.84	90.10

5.3.1 Effect on Marshall Stability

Marshall stability values were 11.60, 18.30 and 12.00 kN at fiber lengths of 6, 9 and 12 mm, respectively, at 0.3% fiber content. At a fiber content of 0.5%, the corresponding values were 9.92, 20.20, and 10.06 kN, whereas values of 8.90, 10.90, and 10.56 kN were obtained at 0.7%. All the mixtures evaluated were found to have a Marshall stability value higher than the minimum value of 8 kN recommended by the Society of Construction Allies (SCRB) in 2003. The 9-mm fibers showed the highest numerical stability at each fiber content, but this effect was less pronounced at 0.7%, where the difference between the 9- and 12-mm fibers was only 0.34 kN. The 0.5%–9 mm configuration was determined to be the most stable configuration with 20.20 kN. This configuration was, however, found to be sub-optimal because it could not satisfy the required flow and air-void requirements. The decrease in stability at fiber lengths greater than 9 mm and the degradation at high fiber levels could be related to fiber agglomeration, nonuniform dispersion, and loss of aggregate-to-aggregate contact

5.3.2 Effect on Flow Value

For 0.3% fiber content, the flow values were very similar, ranging from 3.80 to 3.91 mm, and all fiber lengths were within the SCRB (2003) specification of 2–4 mm. At 0.5%, only the 6-mm fiber length was within the specification, with a flow of 4.00 mm at the upper limit, while the 9- and 12-mm fiber lengths were 5.33 and 5.12 mm, respectively. All configurations had values above the upper limit, ranging from 4.50 to 5.26 mm, and overall, the higher the fiber content, the higher the

deformation at peak load, which may be due to a lack of homogeneity of the mixture at high fiber content. Thus, although the most stable configuration was obtained, the 0.5% – 9 mm configuration was not suitable as the flow was too high, which meant that the Marshall load – deformation response was not balanced.

5.3.3 Effect on Air Voids (AV%)

All mixtures containing 0.3% fiber satisfied the specified AV range of 3–5%. At 0.5%, the 6- and 9-mm mixtures exceeded the upper limit, whereas the 12-mm mixture fell below the lower limit. At 0.7%, only the 9-mm mixture complied. This non-monotonic response suggests that AV was influenced by fiber length, content, and distribution. Although Sasobit can enhance mixture densification and workability, fiber addition may either reduce AV through void filling or increase it through binder absorption, while unsuitable fiber dimensions or distribution may promote clumping and nonhomogeneous mixing[32], [33]

5.3.4 Effect on Voids in Mineral Aggregate (VMA%)

All nine combinations satisfied the minimum VMA of 14%, with values ranging from 17.1% to 23.7%. VMA increased generally with fiber content and length, attributable to physical displacement of aggregates by fibers creating additional inter-particle voids.[22], [32].

5.3.5 Effect on Voids Filled with Asphalt (VFA%)

The VFA values of all mixtures were within the required range of 65–85% at 0.3% fiber content. The 6 and 9mm mixtures were both within the established limits at 0.5%, while the 12 mm mixture was found to be above the maximum limit at 87.40% VFA. The 6 mm mixture exhibited a percentage of 64.50%, which was marginally below the minimum threshold, while the 12 mm mixture registered a percentage of 90.10%, thus exceeding the upper limit. These trends exhibited a high degree of similarity to the AV values, as VFA is directly related to the AV/VMA ratio. The mixture of 0.3%–9 mm yielded a VFA of 73.60%, which falls within the acceptable range.

5.3.6 Visual Observation of Fiber Agglomeration

Localized fiber agglomeration was visually observed during the preparation of mixtures containing 0.5% and 0.7% sisal fiber.



Fig. 6. Visual comparison of sisal-fiber agglomeration at: (a) 0.5% fiber content and (b) 0.7% fiber content, showing more pronounced fiber balling at the higher content

As shown in Figure (6), the agglomeration became more pronounced at 0.7%, indicating increasing difficulty in achieving uniform fiber dispersion as the fiber content increased. This visual observation was consistent with the excessive flow values and irregular volumetric characteristics recorded for several mixtures at these fiber contents.

5.3.7 Identification of Optimum Fiber Parameters

Of the mixtures tested, only those containing 0.3% fiber satisfied all SCRB (2003) requirements (Table 7). The 0.3%–9 mm mixture was selected from these because it achieved the highest

compliant Marshall stability, at 18.30 kN. This was higher than the ≤ 12.00 kN achieved by the other two mixtures. The 0.5%–9 mm mixture produced a higher stability of 20.20 kN; however, it was excluded because its flow and AV values exceeded the specified limits. The reported 18.30 kN represents preliminary screening at a fixed asphalt content of 4.6%. The properties at the subsequently determined optimal asphalt content (OAC) are presented in Section 5.4.

Table 7. Compliance of the optimum WMA-Sasobit+Sisal mixture parameters with SCRB 2003 specifications

Property	Value	SCRB 2003 Limit
Marshall Stability (kN)	18.30	Min. 8
Flow (mm)	3.80	2–4
Gmb	2.288	
AV%	4.50	3–5
VMA%	17.1	Min. 14
VFA%	73.6	65–85

5.4 Marshall and Volumetric Properties of WMA-Sasobit +Sisal at Optimum Asphalt Content

In accordance with the selection of 0.3% sisal fiber and a 9 mm fiber length in Section 5.3.6, a discrete Marshall mix design was executed for the WMA–Sasobit–sisal mixture. The resulting OAC was 4.7%, equivalent to that of HMA and 0.1 percentage point higher than that of fiber-free WMA–Sasobit (see Table 8). At OAC, the mixture achieved a Marshall stability of 17.90 kN, compared with 18.30 kN during preliminary screening at a fixed asphalt content of 4.6%. The OAC-based stability demonstrated in this study exceeded those of WMA–Sasobit (17.30 kN) and HMA (16.28 kN) and remained well above the SCRB (2003) minimum of 8 kN. The flow value of 3.70 mm satisfied specified range of 2–4 mm, while corresponding MQ of 4.84 kN/mm provided a comparative stability-to-flow index rather than a direct measure of rutting resistance.

Table 8. Summary of Marshall and volumetric properties of WMA-sasobit with sisal mixture at OAC compared to SCRB 2003 limits

Property	WMA-sasobit +Sisal (OAC = 4.7%)	SCRB 2003 Limit
Marshall Stability (kN)	17.9	Min. 8
Flow (mm)	3.70	2–4
Marshall Quotient (kN/mm)	4.84	—
Gmb (g/cm ³)	2.298	—
AV%	4.08	3–5
VMA%	16.7	Min. 14
VFA%	75.56	65–85
Pba%	0.738	

The mixture had a Gmb of 2.298 and an AV content of 4.08%, which is within the specified range. The mixture's VMA of 16.70% exceeded the minimum requirement of 14%, although it was lower than those of the reference mixtures. Meanwhile, its VFA of 75.56% satisfied the specified range of 65–85%. Accordingly, the selected mixture satisfied the applicable SCRB (2003) Marshall and volumetric requirements for Type IIIA surface-course mixtures and was retained for subsequent performance evaluation.

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

The unconditioned ITS values followed the order WMA–Sasobit–sisal (1338.2 kPa) > WMA–Sasobit (1120 kPa) > HMA (990 kPa), corresponding to increases of 19.5% relative to WMA–Sasobit and 35.2% relative to HMA after sisal-fiber incorporation. The same ranking was maintained after moisture conditioning, with conditioned ITS values of 1129.1, 910, and 810 kPa, respectively. The higher ITS of WMA–Sasobit may be associated with the temperature-dependent rheological stiffening produced by the crystalline network of Sasobit-modified binders[34]. The additional

strength and moisture resistance of the sisal-reinforced mixture are consistent with previous studies reporting improved TSR and higher unconditioned and conditioned ITS after sisal-fiber incorporation[35], [36]. Fiber–binder interfacial adhesion may also facilitate stress transfer and inhibit crack propagation within the mixture [24], although these mechanisms were not directly examined in the present study[37].

The TSR values were 81.8%, 81.3%, and 84.4% for HMA, WMA–Sasobit, and WMA–Sasobit–sisal, respectively, and all exceeded the adopted minimum criterion of 80%. HMA and WMA-Sasobit exhibited comparable strength retention, differing by only 0.5 percentage point. The fiber-reinforced mix demonstrated maximum TSR and lowest moisture-induced strength loss of 15.6%, in comparison to 18.2% for HMA and 18.8% for WMA–Sasobit. In accordance with the provisions stipulated within the parameters of AASHTO T283, outcomes of this research propose that incorporation of sisal fibers has probable to enhance retention of tensile strength following the process of moisture conditioning. The results of this study are summarized in Table 9.

Table 9. Offerings the ITS and TSR outcomes for the three investigated mixture types, evaluated in accordance with AASHTO T283

Mixture	ITS unconditioned (kPa)	ITS conditioned (kPa)	TSR	Min. requirement
HMA	990	810	81.8%	≥ 80%
WMA- sasobit	1120	910	81.3%	≥ 80%
WMA-sasobit +SISAL	1338.2	1129.1	84.4%	≥80%

5.6 Comparative Analysis of HMA, WMA-Sasobit, and WMA+Sisal Mixtures

The Marshall and volumetric characteristics of three mixtures at their optimum asphalt content (OAC) are summarized in Table 10 and related to limits set by SCRB R/9 (2003). The mixing and compaction temperatures were lowered by 20°C and 25°C, respectively, when replacing conventional HMA with Sasobit-modified WMA-sasobit. These lower temperatures were sustained after the addition of the sisal fibers, and Marshall stability was enhanced compared to conventional HMA and fiber-free WMA–Sasobit. All three mixtures met all the SCRB (2003) criteria for stability, flow, air voids, VMA, VFA, and retained tensile strength.

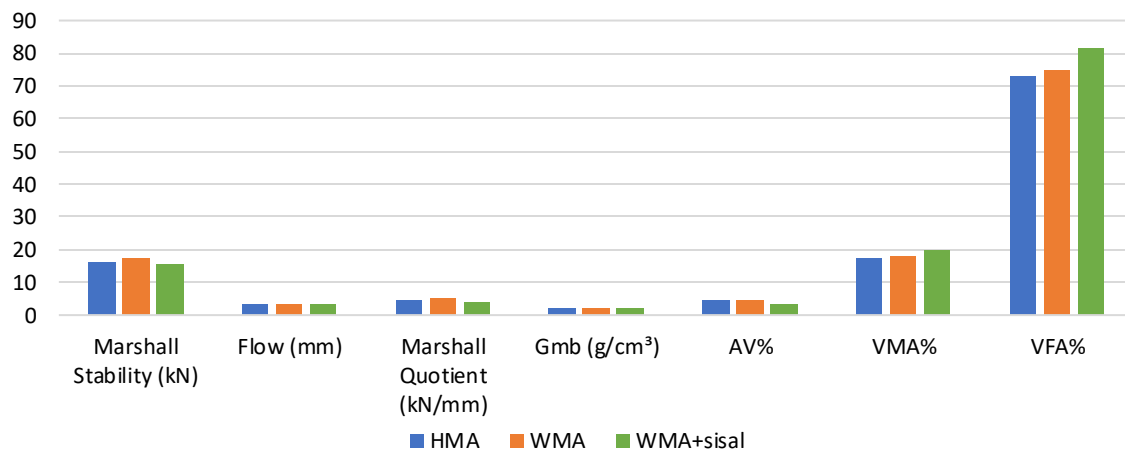


Fig. 7. Comparison of marshall mix design properties for HMA, WMA, and WMA+Sisal fiber mixes

The order of Marshall stability was the same (Figure. 7), with the fiber-reinforced WMA having the highest value, followed by the fiber-free WMA-Sasobit, and then the conventional HMA. All mixtures were within specification for flow. The fiber-reinforced mixture had the densest structure, the lowest air-void content, the highest bulk specific gravity, and a VMA greater than the minimum specified. Most importantly, it had the highest retained tensile strength ratio (84.4%) (Figure. 8) with the largest margin above the moisture-damage threshold of 80%. The results as a whole show that the use of sisal fiber in Sasobit-modified WMA -sasobit can compensate for the

moisture susceptibility that is usually experienced when the production temperature is lowered. The resulting mixture is as strong and durable as and durable as conventional HMA.

Table 10. Shows a detailed comparison of the Marshall properties of the three types of mixtures investigated at their optimum asphalt content and the corresponding limits specified in SCRB 2003

Property	HMA (OAC=4.7%)	WMA-Sasobit (OAC=4.6%)	WMA+Sisal (OAC=4.7%)	SCRB 2003 Limit
Mixing Temperature (°C)	165	145	145	—
Compaction Temperature (°C)	155	130	130	—
Marshall Stability (kN)	16.28	17.3	17.9	Min. 8
Flow (mm)	3.49	3.4	3.70	2–4
Marshall Quotient (kN/mm)	4.66	5.09	4.84	—
Gmb	2.279	2.251	2.298	—
AV%	4.68	4.50	4.08	3–5
VMA%	17.261	18.0	16.7	Min. 14
VFA%	72.8	75.0	75.56	65–85
TSR %	81.8	81.3	84.4	≥ 80%

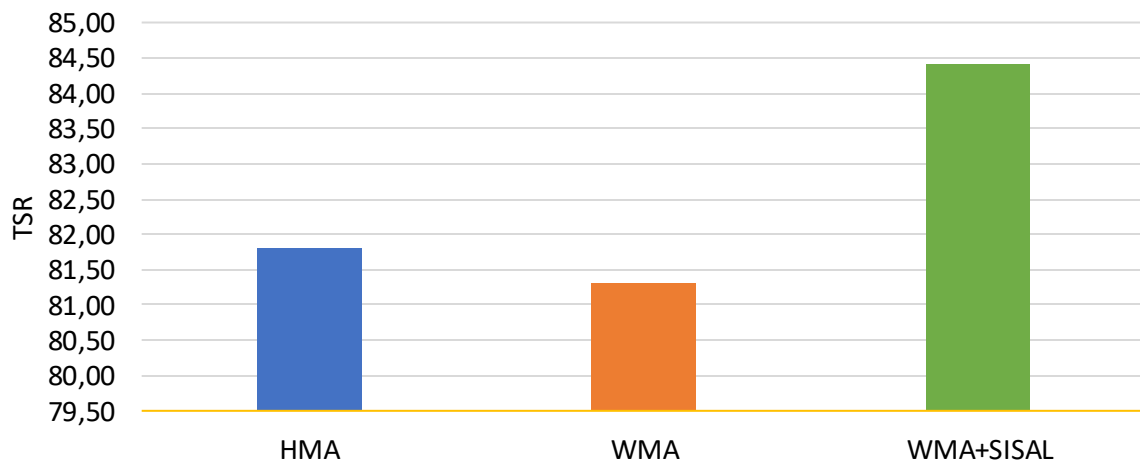


Fig. 8. Comparison of TSR for HMA, WMA-Sasobit, and WMA-Sasobit–Sisal

6. Conclusions

Based on laboratory assessment of volumetric, Marshall, and moisture-susceptibility features of conventional HMA, WMA–Sasobit, and WMA–Sasobit–Sisal mixes, the following conclusions were drawn:

- Effect of Sasobit: The WMA–Sasobit mixture achieved an OAC of 4.6%, compared with 4.7% for conventional HMA. Incorporating Sasobit decreased mixing and compaction temperatures by 20 and 25°C, respectively, while increasing Marshall stability from 16.28 to 17.3 kN. This demonstrates that the production-temperature reductions were achieved without compromising Marshall performance.
- Optimum Fiber Configuration: During the preliminary fiber-screening stage at a fixed asphalt content of 4.6%, the mixtures containing 0.3% sisal fiber at lengths of 6, 9, and 12 mm satisfied all the evaluated SCRB (2003) requirements. Among these compliant mixtures, the combination comprising 0.3% fiber with a length of 9 mm was selected because it achieved the highest compliant Marshall stability of 18.3 kN.

- Effect of Higher Fiber Contents: Visual inspection during mixture preparation revealed localized fiber agglomeration at contents of 0.5% and 0.7%, with more pronounced fiber balling at 0.7%. This behavior coincided with excessive flow values and irregular volumetric characteristics in several mixtures at these contents, indicating that excessive fiber incorporation reduced fiber dispersibility, mixture homogeneity, and workability.
- Performance at the Re-optimized OAC: Following the re-optimization of the selected fiber configuration, the WMA–Sasobit–Sisal mixture achieved an OAC of 4.7% and a Marshall stability of 17.9 kN. This stability was approximately 3.5% greater than that of WMA–Sasobit and 10.0% greater than that of HMA. Its flow and volumetric characteristics also satisfied the SCRB (2003) requirements.
- Volumetric Characteristics: The WMA–Sasobit–Sisal mixture exhibited the highest bulk specific gravity ($G_{mb} = 2.298$), the lowest air-void content (4.08%), and the lowest VMA (16.7%) among the three mixtures, while maintaining all volumetric properties within the specified limits. These results indicate a denser compacted mixture structure. Nevertheless, the volumetric results alone are insufficient to establish improvements in long-term durability.
- Moisture Resistance: All three mixture types satisfied the adopted minimum moisture-resistance requirement of $TSR \geq 80\%$. The WMA–Sasobit–Sisal mixture achieved the highest TSR of 84.4%, compared with 81.8% for HMA and 81.3% for WMA–Sasobit. Its unconditioned and conditioned ITS values were also 35.2% and 39.4% higher, respectively, than those of HMA. These results indicate better tensile-strength retention after moisture conditioning under the laboratory conditions adopted in this study.
- Technical and Environmental Implications: At the laboratory scale, incorporating 0.3% sisal fiber at a length of 9 mm into WMA–Sasobit produced a mixture that satisfied the evaluated SCRB (2003) requirements and the adopted TSR criterion, while reducing mixing and compaction temperatures by 20°C and 25°C, respectively, relative to HMA. This reduction in thermal demand, when combined with bio-based sisal reinforcement, provides a clear rationale for sustainability, as it has potential to decrease fuel consumption and production-related emissions[9]. Nonetheless, the net environmental and economic benefits must be substantiated through plant- and field-scale measurements, cost analysis, and life-cycle assessment.
- Recommendations for Future Research: Further studies should evaluate the rutting resistance, fatigue performance, long-term aging behavior, repeated moisture conditioning, and field performance of the selected WMA–Sasobit–Sisal mixture. Statistical analysis with adequate replicate specimens should also be conducted to calculate whether observed variances among the mixtures are statistically important.

Acknowledgement

The authors gratefully acknowledge the Faculty of Engineering, University of Kufa, and the National Center for Construction Laboratories for providing the laboratory facilities, equipment, and technical support essential to conduct the experimental work.

References

- [1] Dadaei MM, Hajikarimi P, Nejad FM. Sustainable prospective proposals for utilizing modifiers in bitumen industry to address global warming. *Sci Rep.* 2025;15(1):1065. <https://doi.org/10.1038/s41598-025-01065-4>
- [2] Kowalski KJ, Bańkowski W, Król JB, Gazda A. Eco-friendly materials for a new concept of asphalt pavement. *Transp Res Procedia.* 2016;14:3582-3591. <https://doi.org/10.1016/j.trpro.2016.05.426>
- [3] Lokesh Y, Parate HR, Swamy HM. Quantitative and comparative review of multifunctional performance of porous asphalt concrete. *Discover Civ Eng.* 2026;3(1):172. <https://doi.org/10.1007/s44290-026-00214-3>
- [4] Jamshidi A, Hamzah MO, You Z. Performance of Warm Mix Asphalt containing Sasobit®: State-of-the-art. *Constr Build Mater.* 2013;38:530-553. <https://doi.org/10.1016/j.conbuildmat.2012.08.015>
- [5] Rubio MC, Martínez G, Baena L, Moreno F. Warm Mix Asphalt: An overview. *J Clean Prod.* 2012;24:76-84. <https://doi.org/10.1016/j.jclepro.2011.11.053>

- [6] Joni HH, Alkhafaji AYM. Laboratory assessment of performance of WMA containing Sasobit. IOP Conf Ser Mater Sci Eng. 2021;1058(1):012036. <https://doi.org/10.1088/1757-899x/1058/1/012036>
- [7] Abtahi SM, Sheikhzadeh M, Hejazi SM. Fiber-reinforced asphalt-concrete - A review. Constr Build Mater. 2010;24(6):871-877. <https://doi.org/10.1016/j.conbuildmat.2009.11.009>
- [8] Capitão SD, Picado-Santos LG, Martinho F. Pavement engineering materials: Review on the use of warm-mix asphalt. Constr Build Mater. 2012;36:1016-1024. <https://doi.org/10.1016/j.conbuildmat.2012.06.038>
- [9] Calabi-Floody AT, Valdés-Vidal GA, Sanchez-Alonso E, Mardones-Parra LA. Evaluation of gas emissions, energy consumption and production costs of Warm Mix Asphalt (WMA) involving natural zeolite and Reclaimed Asphalt Pavement (RAP). Sustainability. 2020;12(16):6410. <https://doi.org/10.3390/su12166410>
- [10] Sasol Chemicals. Sasobit Data Sheet. Johannesburg: Sasol Chemicals; 2018. <https://doi.org/10.3390/su12166410>
- [11] Hurley GC, Prowell BD. Evaluation of Evotherm for use in warm mix asphalt. NCAT Report 06-02. Auburn: National Center for Asphalt Technology; 2006.
- [12] Bhargava N, Das BP, Siddagangaiah AK. Synergistic influence of aging and moisture on performance of warm mix asphalt. Int J Pavement Res Technol. 2018;11(6):629-638. <https://doi.org/10.1016/j.ijprt.2018.02.001>
- [13] Epps Martin A, Arambula E, Cucalon LG, Chow E, Lytton RL, Estakhri C, et al. Evaluation of the moisture susceptibility of WMA technologies. NCHRP Report 763. Washington, D.C.: Transportation Research Board; 2014. <https://doi.org/10.17226/22370>
- [14] Guo F, Li R, Lu S, Bi Y, He H. Evaluation of the effect of fiber type, length, and content on asphalt properties and asphalt mixture performance. Materials. 2020;13(7):1556. <https://doi.org/10.3390/ma13071556>
- [15] Singh S, Ransinchung RN, Lodhi BS, Kumar P, Debbarma S, Ravindranath M. Preference index of sustainable natural fibers in stone matrix asphalt mixture using waste marble. Materials. 2022;15(8):2729. <https://doi.org/10.3390/ma15082729>
- [16] Wu B, Pei Z, Xiao P, Lou K, Wu X. Influence of fiber-asphalt interface property on crack resistance of asphalt mixture. Case Stud Constr Mater. 2022;17:e01703. <https://doi.org/10.1016/j.cscm.2022.e01703>
- [17] Cheng P, Yi J, Guo S, Pei Z, Feng D. Influence of fiber dispersion and distribution on flexural tensile properties of asphalt mixture Based on finite element simulation. Constr Build Mater. 2022;352:128939. <https://doi.org/10.1016/j.conbuildmat.2022.128939>
- [18] Phan TM, Nguyen SN, Seo CB, Park DW. Effect of treated fibers on performance of asphalt mixture. Constr Build Mater. 2021;274:122051. <https://doi.org/10.1016/j.conbuildmat.2020.122051>
- [19] Aliha MRM, Razmi A, Mansourian A. The influence of natural and synthetic fibers on low temperature mixed mode I + II fracture behavior of warm mix asphalt (WMA) materials. Eng Fract Mech. 2017;182:322-336. <https://doi.org/10.1016/j.engfracmech.2017.06.003>
- [20] Qu W, Niu B, Lv C, Liu J. A review of sisal fiber-reinforced geopolymers: Preparation, microstructure, and mechanical properties. Molecules. 2024;29(10):2401. <https://doi.org/10.3390/molecules29102401>
- [21] Chehata H, Jendoubi A, Boudenne A, Neji J. Effect of the integration of alfa natural fibers and demolition waste on the mechanical and thermal properties of warm mix asphalt. Buildings. 2025;15(16):2845. <https://doi.org/10.3390/buildings15162845>
- [22] Mahmood OT, Ahmed SA. Influence of natural fibers on the performance of hot mix asphalt for the wearing course of pavement. ARO Sci J Koya Univ. 2020;8(2):57-63. <https://doi.org/10.14500/aro.10710>
- [23] Dakhil AF, Al-Busaltan S. Influence of polypropylene fiber on tensile strength and moisture resistance of warm mix asphalt. IOP Conf Ser Earth Environ Sci. 2026;1432(1):012074. <https://doi.org/10.1088/1755-1315/1432/1/012074>
- [24] Li C, Zhang Y, Wang L, Tian Z, Zhao M, Li Z. Effects of basalt fiber morphology on the crack resistance and damage behavior of warm-mix recycled asphalt mixtures. Constr Build Mater. 2026;506:144782. <https://doi.org/10.1016/j.conbuildmat.2026.144782>
- [25] State Organization for Roads and Bridges (SORB). General Specification for Roads and Bridges. Baghdad: Ministry of Housing and Construction; 2007.
- [26] National Lime Association. How to Add Hydrated Lime to Asphalt: An Overview of Current Methods. Arlington: National Lime Association; 2003.
- [27] Lesueur D, Petit J, Ritter HJ. The mechanisms of hydrated lime modification of asphalt mixtures: A state-of-the-art review. Road Mater Pavement Des. 2013;14(1):1-16. <https://doi.org/10.1080/14680629.2012.743669>
- [28] Hurley GC, Prowell BD. Evaluation of Sasobit® for use in warm mix asphalt. NCAT Report 05-06. Auburn: National Center for Asphalt Technology; 2005.
- [29] Joni HH, Alkhafaji AYM. Laboratory assessment of performance of WMA containing Sasobit. IOP Conf Ser Mater Sci Eng. 2021;1058(1):012036. <https://doi.org/10.1088/1757-899x/1058/1/012036>

- [30] Roja KL, Padmarekha A, Krishnan JM. Rheological investigations on warm mix asphalt binders at high and intermediate temperature ranges. *J Mater Civ Eng*. 2018;30(4):04018038. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002206](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002206)
- [31] Rezazad Gohari A, Lamothe S, Bilodeau JP, Mansourian A, Carter A. Laboratory study on the effect of kraft lignin and sasobit on construction temperatures, compactability and physical properties of hot and warm mix asphalt. *Infrastructures*. 2025;10(12):327. <https://doi.org/10.3390/infrastructures10120327>
- [32] Guo Y, Tataranni P, Sangiorgi C. The use of fibres in asphalt mixtures: A state of the art review. *Constr Build Mater*. 2023;393:131754. <https://doi.org/10.1016/j.conbuildmat.2023.131754>
- [33] Jamshidi A, White G, Mohd Hasan MR. New methodology to characterize the workability of asphaltic concrete mixtures based on kinematic compaction energy. *Sustainability*. 2022;14(11):6550. <https://doi.org/10.3390/su14116550>
- [34] Qin Q, Farrar MJ, Pauli AT, Adams JJ. Morphology, thermal analysis and rheology of Sasobit modified warm mix asphalt binders. *Fuel*. 2014;115:416-425. <https://doi.org/10.1016/j.fuel.2013.07.033>
- [35] Ramalingam S, Murugasan R, Nagabhushana MN. Laboratory performance evaluation of environmentally sustainable sisal fibre reinforced bituminous mixes. *Constr Build Mater*. 2017;148:22-29. <https://doi.org/10.1016/j.conbuildmat.2017.05.006>
- [36] Kar D, Giri JP, Panda M. Performance evaluation of bituminous paving mixes containing sisal fiber as an additive. *Transp Infrastruct Geotechnol*. 2019;6(3):189-206. <https://doi.org/10.1007/s40515-019-00079-6>
- [37] Wu B, Pei Z, Xiao P, Lou K, Wu X. Influence of fiber-asphalt interface property on crack resistance of asphalt mixture. *Case Stud Constr Mater*. 2022;17:e01703. <https://doi.org/10.1016/j.cscm.2022.e01703>