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Evaluating the Mechanical Performance of Hot and Warm Asphalt Mixtures Utilizing Sulfur Waste as an Alternative Filler

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ABSTRACT

In This research delved into the feasibility of substituting sulfur waste (SW) for traditional filler ($CaCO_3$), in both hot and warm asphalt mixtures. Warm mix asphalt samples were produced using a synthetic zeolite binder modifier. Various mechanical parameters, including Marshall stability, Marshall quotient, and indirect tensile strength at 25°C and 60°C, as well as tensile strength ratio, were assessed. Test results showed that incorporating SW as a substitute for $CaCO_3$ filler resulted in an increase in Marshall stability values in both hot and warm mixtures by 11.89% and 5.16%, respectively. while the increase in the value of the Marshall quotient for these mixtures was 12.9% and 23.48%, respectively. Furthermore, it is worth noting that the Marshall properties of all mixtures met the ASTM D6927-15 standards. The SW-blended mixtures exhibited significant moisture resistance improvement, particularly in warm mixtures. Notably, the TSR value increased by 50.84%, rising from 0.568 for WMA to 0.856 for WMASW. Furthermore, the incorporation of SW in asphalt mixtures offers the potential for economic and environmental benefits.

Keywords:

Sulfur waste; Synthetic zeolite; Warm mix asphalt; Tensile stiffness modulus; Mineral filler.

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1. INTRODUCTION

In the context of mounting global challenges, which include the exacerbation of climate change, elevating global temperatures, and escalating requirements for pollution control, there has been an unprecedented impetus towards the utilization of sustainable materials in the construction industry[1]. Specifically, Hot Mix Asphalt (HMA) is exceedingly prevalent and is implemented in over 95% of road pavement structures, owing to its considerable economic efficiencies, structural resilience, and functional advantages[2]. However, as environmental sustainability becomes a primary concern in both academia and industry, there is an increasing consensus that the exclusive dependence on traditional construction materials is no longer tenable for mitigating contemporary environmental challenges.

A Warm Mix Asphalt (WMA) is another innovation that has emerged as an environmentally favorable alternative to HMA. Produced at comparatively lower temperatures, WMA results in decreased energy consumption and CO2 emissions during its manufacturing process, and further reductions in emissions during the construction phase[3]. The technology behind WMA, incorporating distinct environmental and engineering advantages, is experiencing rising adoption rates[4]. An intriguing avenue of research has also indicated that incorporating synthetic Zeolite into WMA can bring about noteworthy enhancements in terms of resistance to moisture damage and deformation performance[5].

The adoption of waste materials as substitutions for conventional fillers in road construction is gaining traction for its potential to significantly bolster environmental sustainability[6]. For instance, waste glass, when utilized as a mineral filler in asphalt mixtures, not only serves to alleviate issues related to waste management but also delivers economic advantages. A specific study demonstrated that substituting waste glass powder as a filler at an 8% rate by the weight of aggregate resulted in asphalt mixtures characterized by superior Marshall stability, reduced flow, and fewer voids when compared to traditional fillers such as Calcium Carbonate ($CaCO_3$) and Portland cement[7].

In the Iraqi landscape, there is a ceaseless accretion of sulfur waste (SW), amplifying apprehensions related to environmental pollutant emissions and the concomitant economic implications of waste management [8]. Extant data suggests that Iraq generates an annual volume of sulfur waste ranging from 7,000 to 20,000 tons, incurring a landfill cost of 95 US dollars per ton [9]. Since the majority of sulfur waste cannot be recycled directly and must be disposed of, it becomes imperative to explore alternative waste management methods. This is particularly important due to the substantial expenses linked with landfill disposal and the non-biodegradable nature of the material[10]. The most efficacious strategy for mitigating these challenges appears to be the reutilization of this substantial waste volume, as it not only alleviates the environmental risks associated with greenhouse gas emissions but also offers a more sustainable avenue for waste management [11]. Pioneering approaches that employ sulfur waste as a partial substitute for traditional asphalt binders in mixtures have yielded promising outcomes. Specifically, substitutions ranging from 10% to 30% have been shown to augment the mechanical resilience and durability of the asphalt mixtures[12]. An additional groundbreaking opportunity lies in the prospect of utilizing sulfur waste as an alternative to conventional fillers in asphalt concrete mixtures, offering benefits in sustainability, cost-effectiveness, and conservation of landfill space[13].

Utilizing waste materials that would otherwise present environmental hazards accomplishes dual objectives in the drive toward sustainability: first, it contributes to environmental remediation by serving as a waste disposal mechanism; second, it offsets the costs of traditional materials that are being replaced, thereby offering economic efficiencies[14]. The predominance of Hot Mix Asphalt (HMA) in road construction activities can be attributed to its compelling blend of cost efficiency and performance attributes [15], In asphalt mixture formulations, substances such as stone dust, hydrated lime, and cement are frequently utilized as fillers due to their ability to confer satisfactory performance characteristics on the mixture [16], although effective, are increasingly being scrutinized for their environmental impact. Indeed, there is growing academic recognition that alternative fillers, either natural or synthetic, are viable replacements for these traditional materials[17]. As such, enhancing the sustainability of pavement construction through the incorporation of waste materials as alternative fillers has become a pressing research priority[18]. Numerous studies have already begun to evaluate the efficacy of diverse waste materials as potential substitutes for traditional fillers in asphalt mixtures.

Against this backdrop, the present research aims to elucidate the implications of utilizing sulfur waste as an alternative filler material in lieu of conventional filler for both hot and warm mix asphalt formulations.

2. METHODOLOGY AND RESEARCH OBJECTIVES

The significant abundance of sulfur waste at the Al-Mishraq sulfur plant, situated in northern Iraq (Nineveh), has prompted researchers to explore the utilization of this waste as a filler in Hot and Warm Mix Asphalt or as an eco-friendly paving material. The primary objective of this research encompassed two main aspects: (1) To assess the feasibility of employing sulfur waste as a sustainable filler in both hot and warm asphalt mixtures. This assessment involved conducting mechanical and durability experiments, which included testing for Marshall stability, Marshall quotient, indirect tensile strength at 25°C and 60°C, as well as tensile stiffness modulus at 25°C and 60°C. (2) To compare the performance of hot and warm asphalt mixtures that incorporate sulfur waste as a filler with those utilizing conventional filler ($CaCO_3$). A schematic outline of the experimental research approach is depicted in Figure 1.

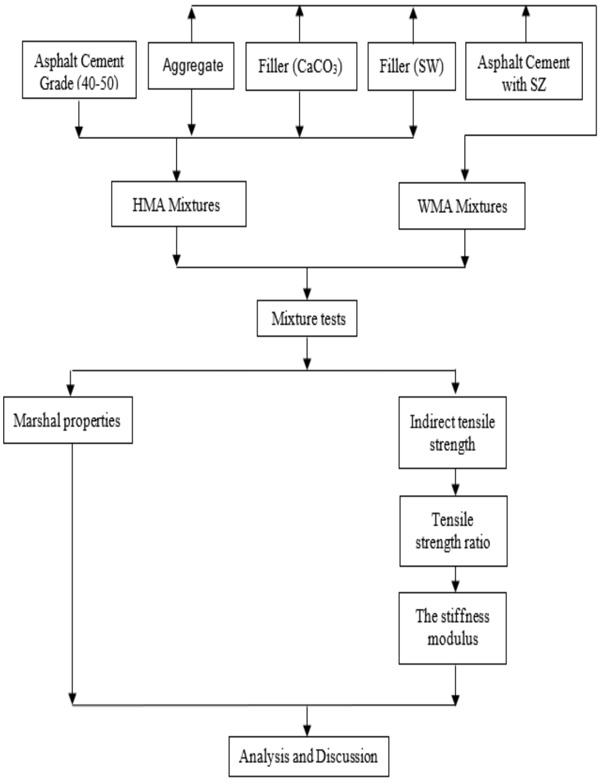

Fig. 1 Flow chart of the research experimental work

3. MATERIALS

3.1 Asphalt Cement

In the present investigation, asphalt cement of penetration grade 40–50 (P40-50) was employed. This specific grade is prevalently utilized in Iraqi road construction endeavors, and its fundamental attributes are delineated in Table 1. For the development of Warm Mix Asphalt (WMA), synthetic zeolite was amalgamated into the bituminous binder at a 5% weight concentration, in accordance with supplier-recommended guidelines for optimal performance. The physical properties of synthetic zeolite are detailed in Table 2. The blending of synthetic zeolite and bitumen was executed at a temperature of 130°C, utilizing a mixer operating at 1500 rpm for a duration of 15 minutes[19].

3.2 Aggregates

For the objectives of the current research, aggregates in the form of river sand and crushed gravel obtained from the Khazir quarry were utilized. Such aggregate types are conventionally used in the construction of highways in the northern regions of Iraq. The specific attributes of As provided from supplier (Arej Al-Furat company) these aggregates are comprehensively outlined in Table 3.

Table 1: Rheological properties of P40-50 asphalt cement.

Property	Asphalt Cement (P40-50)	ASTM (2015)	NCCL limits [20]
Penetration (25 deg. C,100gm,5 s,0.1mm)	40	D-5	40-50
Softening point (ºC)	57.5	D-36	51-62
Ductility (25 °C, 50 mm/min, cm)	>150	D-113	100+
Specific gravity (25 ºC/25 ºC)	1.036	D-70	--
Flash point (ºC)	300	D-92	230 min.
Fire point (ºC)	315	D-92	--
Loss on heat (5hrs, l63 deg. C, %)	0.218	D-1754	0.75 max.
Retained Penetration % of the original (25 deg. C,100gm,5 s,0.1mm)	63	D-5	55 min.
Retained Ductility (25 °C, 50 mm/min, cm)	57	D-113	25 min.
Rotational viscosity at 135°C, cP	571	D-4402	3000 max.
Asphaltenes (%)	27	D-4124	--

Table 2: Physicochemical properties of synthetic zeolite.

Properties	SZ*
Model name	y zeolite
Material	Aluminosilicate
Density (g/cc)	0.45-0.55
Purity	100 %
Color	White
PH	3-5

Table 3:Properties of Aggregate that used.

Property	Coarse Agg.	Fine Agg.	ASTM limits [21]
Toughness (%)	18.4	-	40 max.
Angularity (%)	99	47	55 min. (Coarse agg.) 40 min. (Fine agg.)
Soundness, Na2SO4 (%)	0.97	0.66	10 max.
Water absorption (%)	0.38	1.76	4.0 max.
Bulk sp.gr	2.63	2.59	-
Apparent sp.gr	2.67	2.58	-

3.3 Mineral Filler

In this scholarly investigation, calcium carbonate ($CaCO_3$), utilized as a mineral filler and possessing a specific gravity of 2.73, was procured from the Ashur Hot Mix Asphalt Factory situated in Mosul. The physicochemical characteristics of the filler material are elaborated in Table 4.

Table 4: Physicochemical properties of two fillers.

$CaCO_3$		Sulfur Waste	
Element	Weight %	Element	Weight % [22]
Silicon Dioxide (SiO2)	2.7	Total sulfur	92.3
Aluminum Oxide (Al2O3)	0.35	Combined sulfur with carbon	13.28
Ferric Oxide (Fe2O3)	0.93	Free sulfur	79.02
Calcium Oxide (CaO)	50.67	Total carbon	7.630
Magnesium Oxide (MgO)	0.64	Bitumen	0.029
Sodium Oxide (Na2O)	0.02	Ash as a pentonite	0.0693
Sulfur Trioxide (SO3)	0.75	Carbonized materials	20.980
Specific Gravity	2.731	Specific gravity	2.20
Gradation			
Sieve Opening (mm)	Passing %	NCCL limits [20]	
0.6	100	100	
0.3	100	100 – 95	
0.075	100	100 - 70	

3.4 Sulfur Waste (SW)

In the context of the present research, sulfur waste was employed as an alternative to the conventional mineral filler, calcium carbonate ($CaCO_3$). This waste sulfur was sourced from the Al-Mishraq Sulfur Plant situated in Nineveh, in the northern part of Iraq, where it is generated as a byproduct of sulfur manufacturing processes. The physicochemical properties of both sulfur waste and calcium carbonate fillers are elaborated in Table 4. Figure 2 offers visual representations of the waste sulfur and $CaCO_3$ utilized as filler materials.

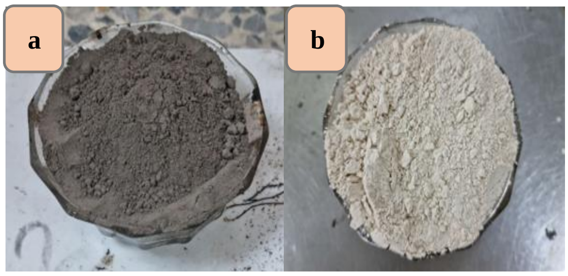

Fig. 2 The two types of fillers, a- $CaCO_3$ filler and b- Sulfur waste filler.

4. EXPERIMENTAL METHODS

4.1. Mixture Design

In the present research, a type D4 dense-graded asphalt mixture was utilized, in compliance with the norms outlined in ASTM D3515[23]. The aggregate gradation, which falls within the medium range of the stipulated specifications, is elaborated in Table 5.

For this scholarly investigation, asphalt mixtures were produced using the Marshall Methodology, strictly adhering to standards outlined in ASTM D6927-15 [24] and NCCL [20]. The optimal binder content (OBC) for each type of binder was determined through the preparation of asphalt specimens with five varying bitumen concentrations: 4%, 4.5%, 5%, 5.5%, and 6% by weight of the total mix. For each bitumen level, a trio of cylindrical samples were crafted using a standardized Marshall mold. Each of these specimens underwent 75 compaction blows on each face and was subsequently subjected to a 24-hour cooling period. Prior to any mechanical testing, these samples were immersed in a water bath stabilized at 60°C for a timeframe of 30–40 minutes. Mechanical stress, administered laterally, was applied at a rate of 50.8 mm/min until peak load was achieved, facilitated by an automated Marshall testing apparatus. A comprehensive evaluation, including flow (mm), air voids (%), stability (kN), and voids in mineral aggregates (%), was carried out on both hot-mix asphalt (HMA) and warm-mix asphalt (WMA) benchmark mixtures containing traditional calcium carbonate filler ($CaCO_3$).

The analytical strategy necessitated the calculation of three specific asphalt percentages: (1) the percentage resulting in maximum stability, (2) the percentage yielding peak density, and (3) the percentage coinciding with median air void specifications. The arithmetic mean of these determinations ascertained the OBCs, which stood at 5.05% and 5% (by total weight of the mixtures) for the virgin binder (P40-50) and WMA binder, respectively. Table 6 offers a detailed exposition of the Marshall properties of the binder layer, evaluated at the OBC for both warm and hot mixtures. These OBC values served as the benchmark for maintaining uniformity across all asphalt mixtures scrutinized in the study. The observed characteristics were subsequently cross-verified with the minimum ASTM (2015) norms to ascertain their compliance with established specification parameters.

In the scope of this academic investigation, four distinct asphalt mixture categories were examined, namely HMA, HMASW, WMA, and WMASW. The terms HMA and HMASW denote hot mix asphalt formulations incorporating virgin bitumen and two specific types of fillers: calcium carbonate ($CaCO_3$) and sulfur waste, respectively. While WMA and WMASW signify warm mix asphalt configurations that utilize a binder modified by the inclusion of zeolite, paired with either calcium carbonate ($CaCO_3$) or sulfur waste as fillers, respectively.

Table 5: Gradation of the mixtures evaluated in this study.

Sieve size (mm)	Gradation for each mix type (% passing)		Gradation specifications ASTM D3515-D4 Mixture [25]
	HMA and HMASW	WMA and WMASW	
25	100	100	100
19	95	95	90-100
9.5	68	68	56-80
4.75	50	50	35-65
2.36	36	36	23-49
0.3	12	12	5-19
0.075	5	5	2-8
OBC %	5.05	5	4-6

Figure 3 graphically presents the gradation boundaries specific to the Binder Course Type D-4 asphalt mixture, in alignment with the standards outlined in ASTM D-3515.

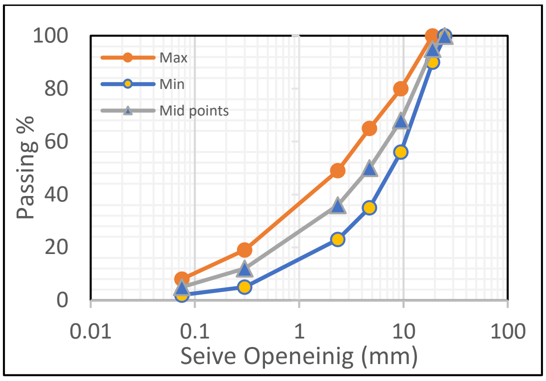

Fig. 3 The Gradation of the Mixtures

Table 6: Marshall properties at the optimum percentage of asphalt for Warm and Hot mixtures

Property	WMA	HMA	NCCL limits [20]
Asphalt Content %	5	5.05	4 - 6
Air Void (Va) %	4.61	4.08	3 - 5
Voids in Mineral Aggregate (VMA) %	14.4	15.9	Min. 13
Voids filled with Asphalt (VFA) %	68	73.3	------
Unit weight (kg/m3)	2386	2379	------
Stability (kN)	13.75	10.68	Min. 7
Flow (mm)	3.98	3.84	2 - 4

4.2. Tests for Marshall Stability and Flow

The Marshall test serves as an extensively employed empirical lab methodology, devised to evaluate resistance to deformative forces [26]. For both hot-mix asphalt (HMA) and warm-mix asphalt (WMA) specimens, encompassing those with traditional fillers as well as sulfur waste, Marshall testing was executed post-immersion in a water bath stabilized at 60°C for a duration of 30–40 minutes, in compliance with ASTM D6927-15 guidelines. Following surface drying, these specimens were subjected to mechanical loading within a Marshall testing apparatus at a rate of 50.8 mm/min until the point of failure was reached. The peak load value (in kN), which precipitates sample failure, is denoted as Marshall Stability. The cumulative deformation observed at this maximum load is termed as the Marshall flow (in mm). Additionally, the Marshall quotient, calculated by dividing Marshall Stability (in kN) by Marshall Flow (in mm), was also ascertained to gauge the stiffness attributes of the mixtures.

4.3. Tensile characteristics and moisture susceptibility tests

Moisture damage in asphalt compositions manifests as a diminution in structural integrity, resilience, and stiffness, arising from moisture infiltration that ultimately results in adhesive failure [27]. Numerous studies have predominantly adopted the Tensile Strength Ratio (TSR) as a quantitative measure to evaluate the vulnerability of asphalt mixtures to moisture, owing to the test's procedural simplicity and efficiency [28]. Concurrently, the Indirect Tensile Strength (ITS) test serves as a robust, performance-oriented evaluation technique for assessing rutting resistance in hot mix asphalt formulations [29].

In the present investigation, the ITS test was utilized to examine the tensile properties of both Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) mixtures, specifically focusing on the influence of moisture and thermal conditions. ITS testing was conducted in compliance with ASTM D6931 standards [30]. Two distinct sample categories were fabricated: unconditioned and conditioned. Unconditioned samples were preserved at ambient temperature devoid of moisture exposure, while conditioned samples underwent submersion for a 24-hour period at a thermal setting of 60°C. Both categories were subsequently acclimatized for an additional two-hour span at 25°C prior to undergoing testing. Loading was applied to the samples via a Marshall testing apparatus at a consistent rate of 50.8 mm/min until the point of failure was observed.

The ITS (in MPa) was ascertained through Equation (1):

$$\mathbf{ITS= ITS = 2P/ \pi dt} \qquad \ldots(1)$$

Where *P* represents the peak load in Newtons (N), *d* is the diameter of the specimen in millimeters (mm), and *t* is its thickness in millimeters (mm).

The Tensile Strength Ratio (TSR) was determined by the following equation:

$$\mathbf{TSR\ (\%) = ITS_C / ITS_U \times 100} \qquad \ldots(2)$$

The stiffness modulus, an essential performance metric for road base and base course strata, governs both tensile stresses generated by vehicular load at the foundational level contributing to fatigue cracking as well as compressive strains inflicted upon the subgrade, which may culminate in permanent deformation. Under uniaxial loading conditions, the stiffness modulus, often designated as TSM [31], is formulated as:

$$\mathbf{TSM= [P\ (\mu+0.27)]/D.t} \qquad \ldots(3)$$

In this equation, TSM (in MPa) is the stiffness modulus, *P* signifies the maximal vertical load in Newtons (N), *t* represents the average thickness of the specimen in millimeters (mm), *D* is the average horizontal deflection in millimeters (mm), and μ is the Poisson's ratio, commonly approximated as 0.35.

5. TEST RESULTS AND DISCUSSION

5.1. Statistical Evaluation of Tests

A statistical analysis employing the Analysis of Variance (ANOVA) was conducted, setting the null hypothesis (H0=0) and a significance threshold of 0.05, to draw comparisons between WMA and HMA mixtures. The Least Significant Difference Value (LSDV) was determined. A difference between the means of two groups that meets or exceeds the LSDV is deemed statistically significant. Conversely, a difference less than the LSDV suggests no significant divergence between the groups. Table 7 represents mean differences using alphabetical notations. Means designated by identical alphabetical labels are not statistically distinct.

Table 7: Statistical analysis of Marshall properties and ITS of HMA and WMA mixtures

Property	HMA	HMA SW	WMA	WMA SW
Marshall stability at 60°C, KN	10.68± 0.88C	11.95± 0.24B	13.75± 0.24A	14.46± 0.93A
Marshall flow, mm	3.84±0. 1A	3.8±0.0 4A	3.98±0. 08A	3.41±0. 22B
Air voids, %	4.08±0. 07B	3.96±0. 22B	4.61±0. 09A	3.08±0. 15C
Marshall quotient, KN/mm	2.79±0. 31C	3.15±0. 09BC	3.45±0. 08B	4.26±0. 49A
ITS at 25°C, MPa	0.81±0. 03C	1.11±0. 03AB	1.18±0. 04A	1.07±0. 08B
ITS at 60°C, MPa	0.67±0. 01B	0.87±0. 03A	0.67±0. 12B	0.92±0. 02A
TSM at 25°C, MPa	297.0± 52.6B	455.08 ±16.21 A	208.60 ±9.25C	347.7± 19.4B
TSM at 60°C, MPa	191.36 ±15.81 C	332.1± 32.40A	156.96 ±43.20 C	264.47 ±11.82 B

N.B.: Means that are denoted with varying alphabetical characters in a vertical arrangement exhibit a significant difference at a p-value of less than 0.05

5.2. Marshall and Volumetric Properties

The The Marshall stability average values for both hot and warm mixtures are delineated in Figure 4-a and Table 6 for analytical comparison. It is evident from the results that the HMA-SW mix, which incorporates sulfur waste as a mineral filler, boasts a stability that is markedly superior to the HMA mix, registering an uptick of 11.89%. Although the stability of warm mixtures saw a modest increase upon the inclusion of sulfur waste, the stability of the WMA-SW blend rose by 5.16% relative to the standard WMA. Notably, warm mixes with a 5% synthetic zeolite composition (based on binder weight) exhibited enhanced stability values compared to their hot counterparts, echoing conclusions drawn from prior research [5]. Mixtures integrated with sulfur waste manifest reduced air void content relative to those amalgamated with conventional fillers. This phenomenon can be attributed to the inherent filling capacity of sulfur waste, which amplifies the density of the SW-mixtures [32]. At elevated temperatures, sulfur waste undergoes polymerization, evolving into a bi-radical chain structure, thereby amplifying air pockets. The asphalt either couples with these radicals, forming a carbon-sulfur linkage, or undergoes hydrogen absorption, triggering the dehydrogenization process [33]. A slight change occurred in the percentage of air voids for hot mixtures After including sulfur waste as a filler at a rate of 5%, and this was confirmed by a previous study[8]. For the warm concoctions, the decrement in the air voids of the WMA-SW variant was pronounced, touching a peak difference of 33.19% against the WMA formulation. While the introduction of sulfur waste as a filler in hot mixtures yielded negligible shifts in flow values, a pronounced drop was observed in warm mixes laden with sulfur waste. Specifically, the flow value in the WMA-SW blend (supplemented with 5% SW) plummeted by 14.32% relative to the WMA mix Which may be mainly due to the significant reduction in the air void content of these mixtures compared to WMA mixtures. After adding sulfur waste to hot mixtures, the Marshall quotient (MQ) values displayed in Fig. 4c did not change significantly, as the mixture HMASW had a 12.9% increase in MQ values when compared to the mixture HMA. Regarding warm mixtures, there was a notable surge in MQ values upon the integration of sulfur waste, marking an ascent of 23.48% for the WMASW blends relative to WMA formulations. Broadly speaking, the data revealed that warm mixtures possess MQ values that are substantially superior to those of hot mixtures, suggesting a heightened resistance against deformation and rutting in the former. It's worth noting that the MQ metric is a recognized gauge of a substance's resilience against shear forces, enduring distortion, and consequently, rutting [11]

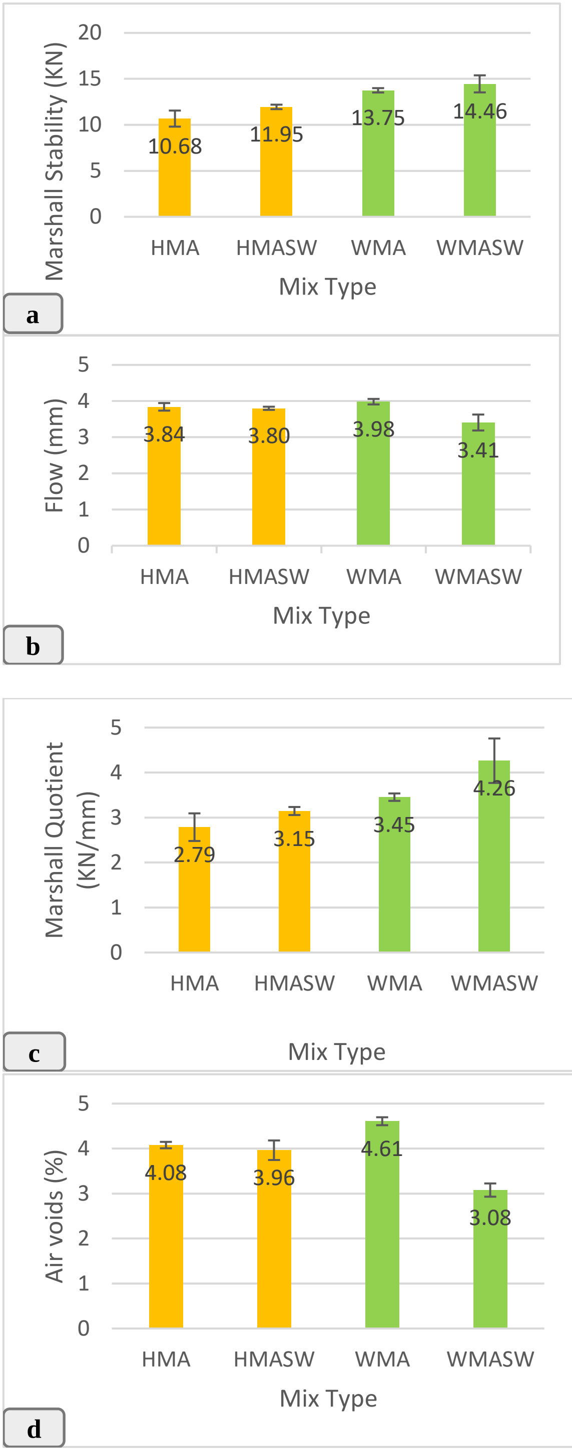

Fig. 4 Marshall properties of mixtures (a- Marshall stability, b- flow, c- Marshall quotient and d- Air voids)

5.3. Indirect tensile strength (ITS)

The indirect tensile strength (ITS) of hot and warm mixtures, both with and without SW, was evaluated under varying moisture and temperature conditions. Figure 5-a depicts the tensile strength results for both conditioned and unconditioned samples. For the unconditioned samples, the ITS for the HMA-SW mixture exhibited a significant enhancement, increasing by 37.04% compared to the HMA blend. In contrast, for warm mixtures, there was a notable reduction in ITS values when SW replaced the conventional filler, resulting in a 9.32% decrease for the WMA-SW mixture compared to the WMA. Of all the mixtures, the HMA showed the least ITS value. For conditioned samples, there was a 31.82% rise in ITS for the HMA-SW blend compared to the HMA. Similarly, the warm mixtures demonstrated enhanced ITS values with SW inclusion, recording a 37.31% increase for the WMA-SW blend in comparison to the WMA.

Figure 5-b illustrates the Tensile Strength Ratio (TSR) values, which were determined to gauge the moisture sensitivity of the mixtures. The introduction of sulfur as a mineral filler in hot mixtures had a marginal impact on the TSR, with the HMA-SW blend's TSR value decreasing by 3.85% relative to the HMA. Conversely, incorporating sulfur in warm mixtures led to a considerable surge in TSR values. This indicates a marked enhancement in the moisture damage resistance of the WMASW mixture, increasing by 50.84% compared to the WMA. Specifically, the TSR value rose from 56.79% for the WMA blend to 85.66% for the WMA-SW mixture. This marked improvement for sulfur-containing warm mixtures is crucial, especially given the prevalent concerns regarding moisture damage associated with WMA mixtures[34]. These results exhibited contrasting behavior compared to a prior study [32], which examined the combination of sulfur waste with asphalt mixtures incorporating a modified asphalt binder containing a styrene-butadiene-styrene (SBS) additive. In the earlier study, a decrease in both indirect tensile strength values and TSR values was observed in sulfur mixtures when compared to mixtures using traditional fillers ($CaCO_3$). Tensile Strength Ratio (TSR) threshold of 0.8 is typically established to identify mixtures that demonstrate adequate resistance to moisture damage[35]. Interestingly, the TSR values for WMASW mixtures exceed 0.8, indicating adequate resistance to moisture. While the TSR for HMASW is approximately 0.79, falling just below the 0.8 threshold, it's important to note that it decreased from 0.817 in HMA. Additionally, it's worth noting that the ITS values for HMASW mixtures are greater than the ITS values for HMA mixtures, both for unconditioned and conditioned samples, showing a respective increase of about 37% and 32%.

Collectively, these comparisons illustrate that SW mixtures provide higher ITS values than $CaCO_3$ mixtures. This observation underscores the substantial impact of SW on moisture damage, which positively influences the tensile properties of SW mixtures.

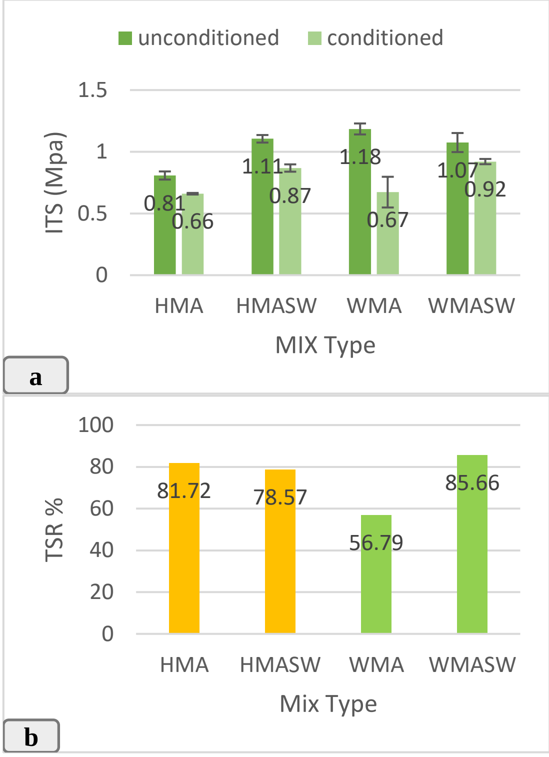

Fig. 5 Indirect tensile strength properties of mixtures (a- In direct tensile strength and b- Tensile strength ratio)

5.4. Tensile stiffness modulus (TSM)

The tensile stiffness modulus (TSM) values for hot and warm mixtures produced at 25 °C and 60 °C are shown in Figure 6 and Table 6. At 25 °C and 60 °C, the TSM values for hot and warm mixtures containing sulfur waste are significantly higher than those for mixtures without sulfur waste.

For the hot mixtures, the TSM values increased after the inclusion of sulfur waste instead of the traditional filler ($CaCO_3$) for both the unconditioned and conditioned samples by about 53% and 74%, respectively. As for the warm mixtures, the TSM values increased for the SW mixtures compared to the calcium carbonate mixtures for both the unconditioned and conditioned samples by about 67% and 68%, respectively. This behavior contrasts with the findings of a previous study [32] when sulfur waste was utilized as a filler in asphalt mixtures incorporating SBS-modified bitumen.

This implies that SW mixtures are stiffer than traditional filler ($CaCO_3$) mixtures for both warm and hot mixes because the strain values are lower and the tensile strength at failure is higher. In general, hot mixtures have higher TSM values compared to warm mixtures for both types of fillers, ($CaCO_3$) and SW.

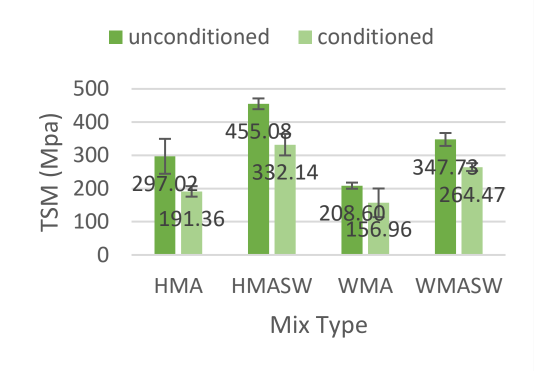

Fig. 6 Tensile Stiffness Modulus of mixtures

6. CONCLUSIONS

The research aimed to evaluate the influence of sulfur waste as a mineral filler in both hot and warm mixtures. Synthetic zeolite was employed in formulating the warm mixtures. Four distinct mixture categories were analyzed: HMA and WMA (with a standard filler of $CaCO_3$ at 5%) and HMASW and WMASW (each containing 5% sulfur waste). The study investigated the mechanical properties of the mixtures, such as Marshall stability, Marshall quotient, indirect tensile strength at 25°C and 60°C, and tensile strength ratio. Based on the test results, the subsequent conclusions and recommendations were formulated:

a. Marshall attributes of the sulfur waste-enhanced hot and warm mixtures conform to ASTM and NCCL standards. These blends displayed superior Marshall stability and quotient values while exhibiting decreased flow and air void measures compared to those incorporating conventional filler ($CaCO_3$)

b. Although the WMA-SW mixtures displayed a reduced indirect tensile strength at 25°C compared to the WMA, a substantial enhancement was observed at 60°C. This led to a significant increase in the TSR value, indicating that the moisture resistance of warm mixtures augmented notably upon the addition of sulfur waste. When sulfur waste was utilized in hot mixtures, its influence on TSR was modest. However, a notable improvement in the ITS at both temperatures was recorded for the HMASW mixture compared to the HMA blend. Additionally, both HMASW and WMASW mixtures demonstrated a significant rise in the Tensile Stiffness Modulus (TSM), suggesting they possess greater rigidity than their HMA and WMA counterparts, respectively.

c. The research affirms that sulfur waste can effectively serve as a mineral filler in hot and warm mixtures. This enhances the mixtures' resistance to moisture-induced deterioration, while still fulfilling the prerequisites of Marshall properties. Employing such wastes in asphalt mixture production could present economic and environmental advantages.

7. FUTURE STUDIES

Building on this study's outcomes, the subsequent research initiatives are proposed:

a. A comprehensive assessment is warranted to ascertain the impact of both short-term and long-term aging on the performance metrics of asphalt mixtures fortified with sulfur waste.

b. Delving deeper into the understanding of how varying loading rates and temperatures influence the fracture propensity of SW-mixtures is necessary.

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تقييم الأداء الميكانيكي لخلطات الأسفلت الساخنة والدافئة التي تحتوي على مخلفات الكبريت كمواد مالئة بديلة

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الملخص

بحثت هذه الدراسة في جدوى استخدام مخلفات الكبريت كمادة مالئة في المزجات الاسفلتية الساخنة والدافئة كبديل عن كربونات الكالسيوم ($CaCO_3$) شائعة الاستخدام. تم إنتاج العينات الأسفلتية الدافئة بإضافة الزيولايت الصناعي (SZ) بنسبة 5٪ (من وزن القير) كمعدل للمادة الرابطة. في هذه الدراسة تم انتاج المزجات الاسفلتية الدافئة والساخنة والتي تحتوي على نوعين من المادة المالئة احداها كربونات الكالسيوم والأخرى مخلفات الكبريت وبنسبة 5% من وزن الركام لكل منهما. تم تقييم معلمات ميكانيكية متعددة، بما في ذلك استقرار مارشال، نسبة مارشال، ومقاومة الشد غير المباشر عند 25 °C و60 °C، فضلاً عن نسبة قوة الشد. اظهرت النتائج أن دمج نفايات الكبريت كمادة مالئة معدنية في خلطات الأسفلت يعزز خصائصها الميكانيكية، مع تحسين ملحوظ في استقرار مارشال ومقاومة الرطوبة، مع تقديم فوائد اقتصادية وبيئية محتملة

الكلمات الداله :

مخلفات الكبريت، الزيوليت الصناعي، الأسفلت الدافئ، معامل المرونة، المواد المالئة المعدنية.