https://doi.org/10.26682/sjuod.2022.25.1.18
Journal of University of Duhok, Vol. 25, No.1 (Pure and Eng. Sciences),Pp 164-173, 2022

TENSILE STRENGTH AND MOISTURE SENSITIVITY OF SULFUR WASTE IN ASPHALT MIXTURES AS AN ECO-FRIENDLY FILLER

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(Received: ,; Accepted for Publication: July)

ABSTRACT

Sulfur waste (SW) materials continue to accumulate in Iraq, posing an expensive disposal and gas emission problem. Utilizing SW as a mineral filler is a cost-effective way to reduce the amount of common filler (calcium carbonate; CaCO3) used and hazardous gas emissions. SW was used to gradually replace a component of the asphalt binder in hot asphalt mixes. The purpose of this research is to explore the use of SW as a mineral filler in the construction of sustainable pavements. Three sulfur waste asphalt concrete (SWAC) mixes with asphalt binder penetration grades of 40–50 were created and compared to the study's CaCO3-asphalt concrete (AC) reference mix. Different percentages of SW (4%, 5%, and 6%) by weight and one AC blend contained a CaCO3 content of 5% (by weight) were prepared. The Marshall stability, Marshall quotient, tensile strength ratio at 25 and 60°C, tensile strength modulus at 25 and 60°C, tensile strength ratio, and tensile stiffness modulus of AC and SWAC mixtures were all determined. Tensile strength, tensile stiffness modulus, tensile strength ratio, and resilience modulus are all decreased in SWAC mixtures. Despite the lower SWAC percentage, tensile strength ratios remain higher than the required minimum of 85 percent when 40-50 penetration grade asphalt is used. Additionally, SWAC combinations have higher flow values, indicating a greater strain capacity to rupture. As long as the proper binder content is maintained, all SWAC combinations meet the ASTM standards for 8kN stability, 2-4mm flow, 5% air voids, and 14% VMA. This study found that SW can be reused and used as a mineral filler in pavement applications at a rate of 4–5% by aggregate weight.

KEYWORDs: Sulfur waste; Mineral filler; Sustainable materials; Durability; Tensile strength; Tensile stiffness modulus.

1. INTRODUCTION

Industrial and home solid waste generation, management, and disposal have become important global concerns. Asphalt pavements have long been investigated and encouraged to use waste or by-product materials for functional, environmental, or economic reasons. Asphalt mixture components, comprised of recycled asphalt paving (RAP), recycled asphalt shingle (RAS), recycled waste tire (RWT), and recycled waste lime (RWL), are so widely employed that their inclusion is no longer a source of controversy (Thøgersen et al., 2013; Arabani et al., 2010; Yalcin E. 2021; González A., 2018; Do et al., 2008).

The most environmentally friendly solution to the challenge of disposing of bulk trash is to reuse them. Road pavement development and maintenance in Iraq is a potential goldmine for waste material reuse because of the enormous volume of composite materials required. As a result, due to the high volume of 'new' materials required in the road construction sector, such as mineral fillers, the environmental benefits are tied to the safe disposal of bulk trash and reducing environmental impacts arising from greenhouse gas (GHG) emissions.

Most energy and carbon savings can be accomplished by progressively reducing the amount of filler required. Asphalt mixtures can last longer by lowering or eliminating common fillers (such as calcium carbonate) and increasing the time between replacements.

The Federal Highway Administration's FHWA-HIF-16-012 (FHWA, 2016) outlined strategies for minimizing the environmental impact on the mixture of asphalt binders and aggregate. Reducing the material utilized, how it's made and constructed is one of these

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approaches. In some instances, novel materials like warm mix asphalt (WMA), polymers, rubber, and other modifiers may be employed. (FHWA, 2016). However, the study was silent on using sulfur waste (SW) as a mineral filler, as is the case with other waste products, ignoring SW results in material waste and environmental degradation. Utilizing SW can result in further cost savings and environmental stewardship benefits. Sulfur production plants' increased SW output creates waste disposal concerns and environmental degradation in Iraq (Al-Hadidy, 2001). The annual output of SW in Iraq is increasing continuously, while the capacity of existing disposal sites is dwindling. Like the majority of solid waste disposed of in landfills, SW does not decompose. SW does not disintegrate, like most solid waste disposed of in landfills. According to reports, Iraq manufactures and disposes of between 7,000 and 20,000 tons of SW per year. Costs associated with SW landfilling are expected to be $95 per ton. Thus, the landfilled area's annual cost ranges between 665 and 2000 thousand US dollars (Al-Hadidy, 2001). SW is projected to be the most often utilized mineral filler in asphalt mixtures to save money and the environment.

SW, like sulfur, is a great mineral filler for asphalt mixtures, significantly improving the performance of asphalt pavements. To begin, sulfur alone has an effect on the physicochemical properties of asphalt. Second, vast quantities of SW are readily available in powder form in Iraq at a low cost. Due to the SW's abundance and inexpensive cost, researchers in northern Iraq have begun incorporating it as a mineral filler into the asphalt mix to improve its properties. SW melts at 140 and 145 degrees Celsius, depending on the sulfur content. SW has a specific gravity ranging from around 2.03 to 2.215. The majority of used SWresults cannot be reused and must be discarded (Al-Hadidy, 2001).

These results demonstrate the vast remaining potential for sulfur waste recovery and encapsulation. Bituminous road surfacings present a fantastic opportunity to incorporate huge amounts of unique sulfur waste into a civil engineering structure, hence increasing the road layers' strength and longevity. The goal of this study is to provide light on the performance of asphalt mixtures, including SW, in order to assist long-term road infrastructure development.

For this purpose, sulfur waste was employed to replace a portion of the asphalt cement binder in asphalt mixtures at various replacement rates (Al-Hadidy, 2021; Ahmed et al., 1985). Al-Hadidy (2021) was discovered that replacing sulfur waste for asphalt cement improved the cement's rheological qualities while maintaining its tensile strength and stability at or above the ASTM minimum standards. While this is true, no research on the use of sulfur waste as a mineral filler in asphalt mixtures has been conducted.

The effect of SW as a mineral filler on the behavior of asphalt mixtures is crucial to understand. While Al-Hadidy (2021) conducted research on the use of SW as a partial replacement for asphalt binder and its effect on asphalt paving mixtures, additional research is required. The current research aims to: (1) determine the feasibility of using sulfur waste as a mineral filler in asphalt mixtures; (2) estimate the ideal sulfur waste content; and (3) study the sulfur waste's effects on asphalt mixtures performance. The purpose of this study is to gain insight into the performance of asphalt mixtures, incorporating SW as a mineral filler, with the goal of promoting the sustainable development of road infrastructure. Fig. 1 illustrates the tactics used to accomplish the study's objectives.

2. Materials and experimental methods

2.1. Materials used

Aggregate, river sand, and crushed gravel were extracted from one of Kashe's hot mix plants (located in Duhok city). This gravel is composed of sedimentary rock that is high in silica. This material is widely available and is regularly utilized in northern Iraqi highway construction projects. The aggregates' tested qualities, including angularity, toughness, soundness, water absorption, and specific gravities, are summarized in Table 1. Calcium carbonate (CaCO3) was used as a reference filler material. It was taken from the Kashe hot mix factor y in Iraq's Duhok-Kurdistan province. CaCO3 has a specific gravity of 2.734 after passing through a 200-mesh screen.

Table (1):- The aggregate's source and consensus properties

Property	ASTM No.	Coarse Agg	Fine Agg	ASTM limits (2015)
Toughness (%)	D-131	19.8	-	40 max.
Angularity (%)	D5821& C-1252	95.7	43.0	55 min. (Coarse agg.) 40 min. (Fine agg.)
Soundness, Na_2SO_4 (%)	C-88	0.91	0.68	10 max.
Water absorption (%)	D127 & D-128	0.987	1.40	4.0 max.
Bulk sp .gr.	D127 & D-128	2.666	2.646	-
Apparent sp .gr.	D127 & D-128	2.739	2.748	-

The asphalt cement used in this research came from the Kara oil refinery (located in the Erbil-Kurdistan region of Iraq). The asphalt cement had a penetration grade of 40–50 (P40). This asphalt grade is primarily used in the pavement construction of roadways around the United States. The rheological characteristics of P40 are summarized in Table 2.

Table (2):- Rheological properties of P40 binder

Property	Result	
	P40	NCCL limits (2018)
Penetration (25 deg. C,100gm,5 s,0.1mm)	44	40-50
Softening point (ºC)	51.3	51-62
Ductility (25 °C, 50 mm/min, cm)	>150	
Specific gravity (25 ºC/25 ºC)	1.03	-
Flash point (ºC)	305	-
Fire point (ºC)	317	230 min.
Loss on heat (5hrs, l63 deg. C, %)	0.12	0.75 max.
Retained Penetration % of original (25 deg. C,100gm,5 s,0.1mm)	61	55 min.
Residue Ductility (25 °C, 50 mm/min, cm)	55	25 min.
Rotational viscosity at 135°C, cP	575.6	3000 max.
Asphaltenes (%)	28	--

The SW is a sulfur-producing plant's leftover solid waste. SW is frequently accessible in the form of a dark green powder at the Al-Meshrak industrial complex (400 kilometers north of Baghdad). It was transported to the laboratory in vacuum-sealed bags. Table 3 summarizes the physicochemical and gradational properties of SW materials.

Table(3):- Sulfur waste's physicochemical properties

Element	Weight, % (Al-Hadidy, 2001)	
Total sulfur	92.3	
Combined sulfur with carbon	13.28	
Free sulfur	79.02	
Total carbon	7.630	
Bitumen	0.029	
Ash as a pentonite	0.0693	
Carbonized materials	20.980	
Specific gravity	2.20	
Gradation		
Sieve size (mm)	Passing (%)	NCCL (2018)
0.6	100	100
0.3	100	95-100
0.075	95	70-100

2.2. Mixture design

The study employed a dense asphalt mixture type D5 that adhered to ASTM D3515 requirements (ASTM, 2015). The aggregate was sieved into various sizes before being recombined with sulfur waste to meet the ASTM D3515 surface course gradation limits in the mid-range (ASTM, 2015). The combined aggregate with varying filler percentages is graded in Table 4. To generate the asphalt mixture, the Marshall Method was employed (ASTM, 2015). To comply with the NCCL (2018) and ASTM specifications (ASTM, 2015), an analysis of air voids (percent), flow (mm), stability (kN), and voids in mineral aggregates (percent) was conducted, resulting in an optimal binder content (OBC) of 5.0 percent of the aggregate weight for an asphalt concrete (AC) reference mixture containing 5% CaCO3 filler. This OBC was utilized to manufacture all asphalt mixtures investigated in this work to preserve consistency throughout the study. Three AC containing SW (i.e., SWAC4, SWAC5, and SWAC6) and AC including CaCO3 combinations were chosen after a mixture design procedure. The factors of sulfur waste contents and asphalt binder types were assessed. AC and SWAC combinations containing P40 had mixing and compaction temperatures of 155 and 135 degrees Celsius, respectively. These values were determined using the viscosity-temperature connection.

Table (4):- Gradation of tested mixtures

Sieve size (mm)	Gradation for each mix type (% passing)				Gradation specifications ASTM D3515-D5 Mixture (ASTM, 2015)
	AC	SWAC4	SWAC5	SWAC6	
19	100	100	100	100	100
12.5	95	94.89	94.94	95	90-100
4.75	59	58.163	58.58	59	44-74
2.36	43	41.83	42.42	43	28-58
0.3	13	11.22	12.12	13	5-21
0.075	6	4	5	6	2-10
OBC, %	5.0				4-6

2.3. Marshall stability and flow tests

Marshall stability and flow tests on compacted specimens containing varied percentages of sulfur waste were conducted in line with ASTM D6927 (2015) for both binder types. Marshall compression testing is an empirical procedure in which cylindrical compacted specimens with a diameter of 100 mm and a height of approximately 63.5 mm are immersed in water at 60 °C for 30–40 minutes before being compressed to failure along their diameter using curved steel loading plates at a constant rate of 51 mm/min. Marshall stability is a force unit expressed in (kN) that indicates the amount of pressure applied to an object during compression. The unit of flow is the millimeter. It is used to describe the amount of pressure created when something is compressed.

The Marshall quotient (MQ) (kN/mm) is the ratio of stability (kN) to flow (mm) and is used to determine the stiffness of a mixture. BSEN 12697-34 is a draft standard for hot mix bituminous mixtures testing methods: Marshall Test, the MQ has been restored. Asphalt-Part 34: BS 598-Part 107 will be superseded by the BS referred to previously (BS 598, 1990).

2.4. Tensile characteristics and moisture susceptibility tests

Bitumen stripping (detachment of bitumen from aggregate) is associated with moisture-sensitive mixtures. Stripping is highly improbable in dense asphalts or macadams with a low void content. Stripping occurs in water-permeable materials, even when they are relatively dense, resulting in a loss of internal cohesion and possibly collapse. The affinity of the aggregate with the bitumen, as well as the aggregate's resistance to water displacement, dictate the potential of stripping.

Immersion mechanical testing is performed to examine the mechanical properties of a compacted bituminous mixture following its immersion in water. As a result, the ratio of the after-immersion property to the initial property acts as an indirect indicator of stripping. The indirect tensile strength (ITS) is probably the most frequently used parameter; the tensile strength ratio (TSR) is the ratio of the ITS of bituminous specimens after wet conditioning to the ITS of identical specimens that were not subjected to the conditioning procedure and is typically expressed as a percentage.

According to ASTM D6931, we employed indirect tensile strength (ITS) to measure the tensile properties and moisture susceptibility of the AC and SWAC combinations (2015). Compression of the mixtures resulted in an average air void content of 7.0 percent. The AC and SWAC samples were separated into two subsets for the ITS test: unconditioned (U) and conditioned (C). For two hours, unconditioned samples were held at 25°C, whereas conditioned samples were kept at 60°C for 24 hours before being returned to 25°C for two hours. The samples were then tested at a 51 mm/min pace utilizing Marshall equipment until they failed. The maximum load on the specimen has been determined, and the ITS has been computed using Eq (1).

$$ITS = 2P/\pi dt \quad \text{……………………………………………………………….. (1)}$$

Where ITS is the indirect tensile strength (N/mm^2), P is the ultimate load (N), t is the thickness of the specimen (mm), and d is the diameter of the specimen (mm).

Tensile strength ratio (TSR) of conditional (C) to unconditional (U) group was calculated from ITS test at 25ºC as given in Eq. (2).

$$TSR\ (\%) = ITS_C / ITS_U \times 100 \quad \text{……………………………………….. (2)}$$

Where ITS_C and ITS_U are the indirect tensile strength (N/mm^2) of conditional and unconditional specimens, respectively.

The stiffness modulus of the road base and base course layers is a significant performance characteristic of these layers. It is a load-spreading capacity test for bituminous layers. It regulates the amount of traffic-induced tensile strains at the underside of the road foundation, which causes fatigue cracking, and compressive strains in the subgrade, which can result in permanent deformation. The stiffness modulus of a material subjected to uniaxial loading is defined as the ratio of maximum stress to maximum strain. At 25°C and 60°C, tensile stiffness modulud (TSM) values (N/mm^2) were calculated using the peak of the applied vertical load and the mean of the horizontal deformation (Eq (3)).

$$TSM= [P\ (\mu+0.27)]/Dt] \quad \text{………………………………………………(3)}$$

where P is the applied vertical load's peak value (N), D is the mean horizontal deformation (mm), t is the test specimen's mean thickness (mm), and is the Poisson's ratio (a value of 0.35 is normally used).

3. Test results and discussions

3.1. Statistical analysis

The analysis of variance (ANOVA) with the null hypothesis (H0 = 0) and 0.05 level of significance was used to compare AC and SWAC-mixes in this investigation (SPSS, 1999). To determine whether there is a significant difference between the two averages, the least significant difference value (LSDV) was provided. The difference between the two averages is significantly different if it is more than or equal to the LSDV and vice versa. Table 5 shows the average differences in alphabet letters. Averages with the same letters indicate that the difference between means was not significant.

Table(5):- Statistical analysis of Marshall properties and indirect tensile strength of AC and SWAC mixtures

\	AC	SWAC4	SWAC5	SWAC6
Marshall stability at 60°C, kN	20±1.62A	18.7±1.09AB	19.9±0.96A	17.34±1.1B
Marshall flow, mm	3.12±0.29A	3.49±0.315A	3.3±0.4A	3.65±0.36A
Air voids, %	3.8±0.22A	4.2±0.27A	4±0.31A	3±0.37B
VMA, %	14.95±1.88A	15±1.09A	14.8±1.77A	14±2.09A
ITS at 25°C, MPa	1.605±0.22A	1.482±0.27A	1.408±0.3A	1.378±0.28A
ITS at 60°C, MPa	1.43±0.2A	1.255±0.18A	1.21±0.14A	1.122±0.21A

NB: The Fisher LSD Method reveals that means with different letters vertically exhibit significant differences at p0.05.

3.2. Density characteristics of the mixture

As expected, the compacted densities of the sulfur waste mixtures were comparable to those of the control mix. As a result of the lower density, the sulfur waste contains an additional 6% of airspace (Fig. 2), . A 5% sulfur waste by weight of aggregate leads in a 5.3 percent reduction in air gaps in the compacted mix (Fig. 3). Sulfur waste polymerizes at higher temperatures and takes on the shape of a two-radical chain, resulting in a decrease in density and air space. When radicals come into contact with asphalt, they can form a carbon-sulfur bond or take up hydrogen, resulting in dehydrogenation.

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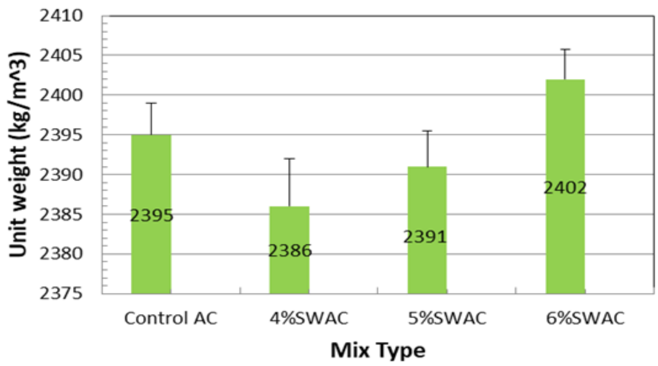


Fig. (2):- Unit weight of control AC and SWAC mixtures

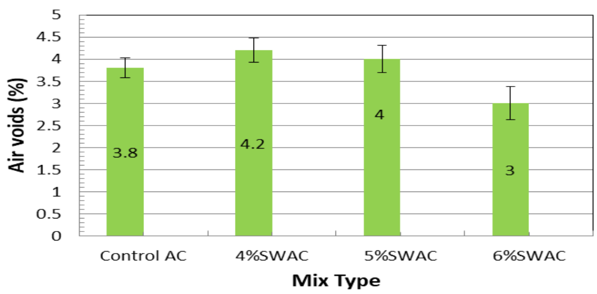


Fig.(3):- Air voids of control AC and SWAC mixtures

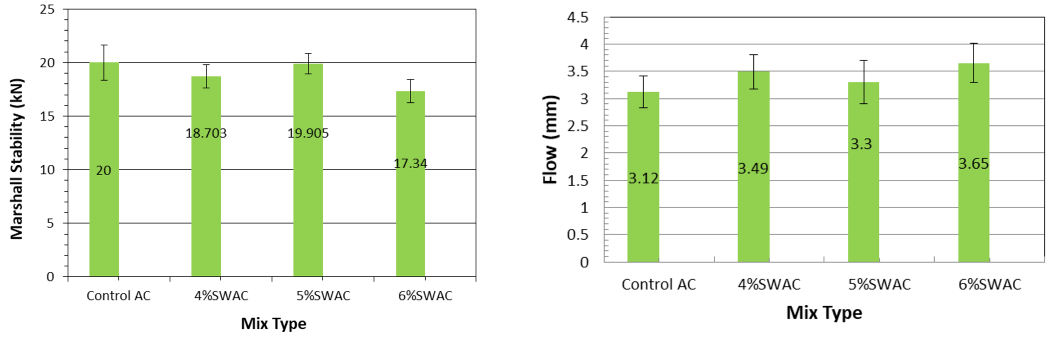
3.3. Marshall stability, flow, and Marshall quotient

Sulfur waste mixtures have slightly lower Marshall stability ratings as compared to the AC reference mix (Fig. 4a). Among SWAC combinations, SWAC5 has a nearly equal stability value to the AC control mix. This strength (stability) is possible because the sulfur waste is combined and crushed at precisely predetermined temperatures. ANOVA and LSDV (2.435) for Marshall stability indicate that there was no statistically significant difference between the averages of AC, SWAC4, and SWAC5 (i.e., AC, SWAC4, and SWAC5 all produce approximately the same Marshall stability); however, there was a statistically significant difference between AC and SWAC6.

The sulfur waste mixes had a more significant flow value (Fig. 4b) than the AC reference mixtures, indicating that the sulfur waste specimens are less brittle than the control mixes. As a result, the odds of premature cracking were reduced. At the same optimum binder concentration, all sulfur waste combinations meet the minimum ASTM (2015) and NCCL (2018) standards of 8kN stability, 2-4mm flow, 3-5 percent air voids, and 14 percent VMA (Fig. 4c).

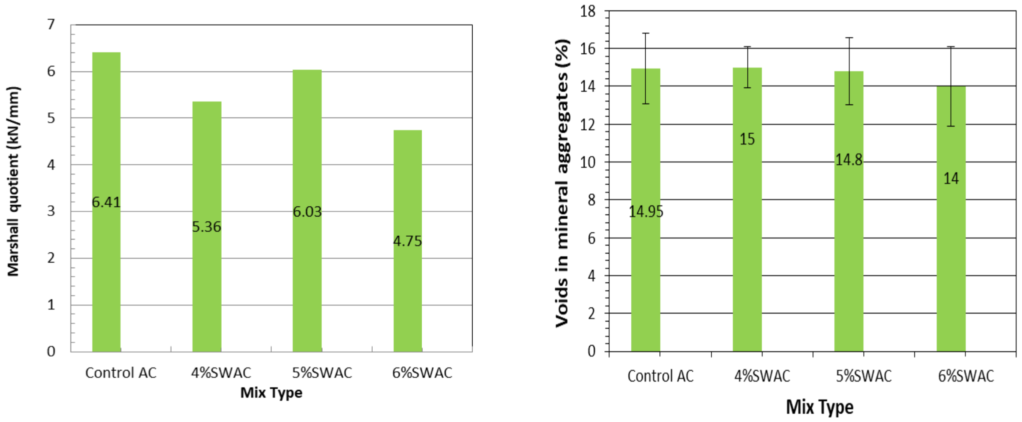
The presence of a high Marshall quotient (MQ) in typical dense-graded mixtures (Fig. 4d) indicates a stiffer mixture capable of dispersing applied load and resisting creep deformation. Due to their reduced tensile strain capacity to failure, high stiffness mixtures must be handled carefully because they are more prone to break when laid on inadequately supported foundations. While the Marshall stability of the sulfur waste mixtures is lower than that of the control mixtures, the flow values are also greater, indicating a greater capacity for strain-induced breakdown. The sulfur waste combinations have a lower MQ value than the control mixtures. MQ (pseudo stiffness) is a well-known parameter that indicates a material's resistance to shear stresses, persistent deformation, and thus rutting (Zoorob and Suparma, 2000).

Results obtained from SWAC4, SWAC5, and SWAC6 combinations demonstrate a drop in MQ values of roughly 16.4%, 6.0%, and 25.9%, respectively, compared to the AC mixture. The decrease in MQ is due to the SWAC



combinations' weaker stability and greater flow values.

(a) (b)



(c) (d)

Fig. (4):- Marshall parameters of control AC and SWAC mixtures
(a- stability**, b-** flow**, c-** voids in mineral aggregate, & **d-** Marshall quotient)

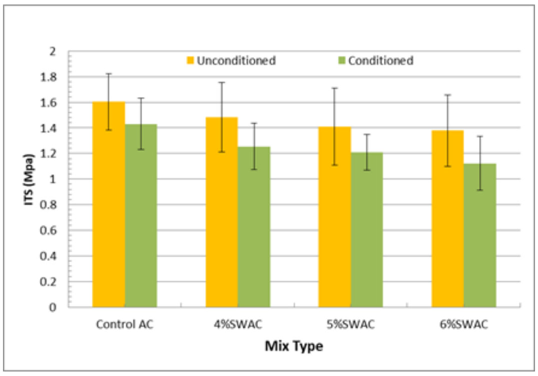
3.4. Indirect tensile strength (ITS)

The ITS test was performed to determine the effect of humidity and temperature on the tensile strength of sulfur waste mixtures. The unconditioned and conditioned tensile strengths of various combinations are seen in Figure 5a. As seen in the figure, the magnitudes of ITS are smaller for both conditioned and unconditioned sulfur waste specimens than for control AC mixtures. Unconditioned asphalt samples containing sulfur waste have a lower ITS value when used in asphalt mixtures.

Results obtained from SWAC4, SWAC5, and SWAC6 combinations demonstrate a decrease in the ITS values of unconditioned specimens by roughly 7.7%, 12.3%, and 14.2%, respectively, compared to the AC mixture. Similarly, the average ITS values of conditioned SWAC4, SWAC5, and SWAC6 combinations decrease by 12.3%, 15.4%, and 21.6 percent, respectively. The use of sulfur waste in asphalt mixtures causes a decrease in the ITS values of unconditioned and conditioned specimens. At intermediate temperatures, it's possible that using sulfur waste reduced the binder's ductility and elongation properties. Previous research has come up with similar results (Al-Hadidy, 2022). For unconditional and conditional ITS specimens, ANOVA and LSDVs (0.538 and 0.369, respectively) indicate no significant difference between the averages of AC, SWAC4, SWAC5, and SWAC6 (i.e., AC, SWAC4, and SWAC5 produce approximately the same unconditional and conditional ITS).

Additionally, as shown in Fig. 5b, the moisture susceptibility of AC and SWAC mixtures was determined by comparing the conditioned to the unconditioned group's tensile strength ratio (TSR). All SWAC mixtures have a lower TSR than the AC mixture, indicating that they are more susceptible to moisture damage. Other researches discovered that supplementing a mixture with sulfur/sulfur waste affects the tensile strength ratio (Timm et al., 2009; Al-Hadidy, 2022). TSR values in SWAC4, SWAC5, and SWAC6 combinations are lowered by 4.9 percent, 3.6 percent, and 8.5 percent, respectively, when compared to the AC mixture.

Using an appropriate tensile strength ratio of 85 percent (Van Hung and Van Phuc, 2019), the TSR values of SWAC4 and SWAC6 combinations are less than 0.85, indicating moisture vulnerable mixtures; however, the SWAC5 mixture exhibits adequate moisture resistance with a TSR value (0.86) more than 0.85. The explanation for the increase in the TSR of SWAC5 is that when sulfur waste is added, viscosity drops as well. However, when sulfur waste content reaches 5%, it increases and approaches the value of virgin asphalt. When sulfur waste content is increased further, viscosity decreases again. This type of behavior has also been documented in earlier research (Al-Hadidy, 2009).



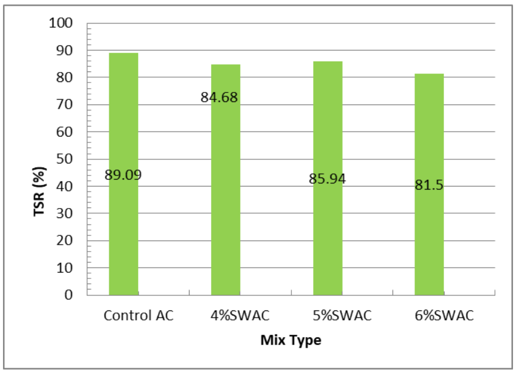


Fig.(5):- Indirect tensile strength properties of control AC and SWAC mixtures
(a- In direct tensile strength & **b-** tensile strength ratio)

3.5. Tensile stiffness modulus (TSM)

The tensile stiffness modulus (TSM) values obtained at 25 and 60 degrees Celsius are shown in Fig. 6. Three measurements are taken on average for each type of mixture. At both 25 °C and 60 °C, the sulfur waste mixes have lower TSM values than the control mixes. The graph indicates that the SWAC4, SWAC5, and SWAC6 combinations evaluated at 25°C have a TSM of 30%, 28%, and 46% less than the AC control mixture, respectively. Similarly, at 60 °C, the average TSM values of SWAC4, SWAC5, and SWAC6 mixed specimens decrease by 41%, 39%, and 45%, respectively. This test verifies the ITS test findings.

The TSM of the sulfur waste specimens, on the other hand, was lower than that of the reference mixes. This suggests that, while the sulfur waste mixtures are not as stiff as the control mixes, which would imply higher strain values, they have a lower tensile strength at failure ITS values. This would also mean that the sulfur waste mixtures can withstand more tensile strains before cracking.

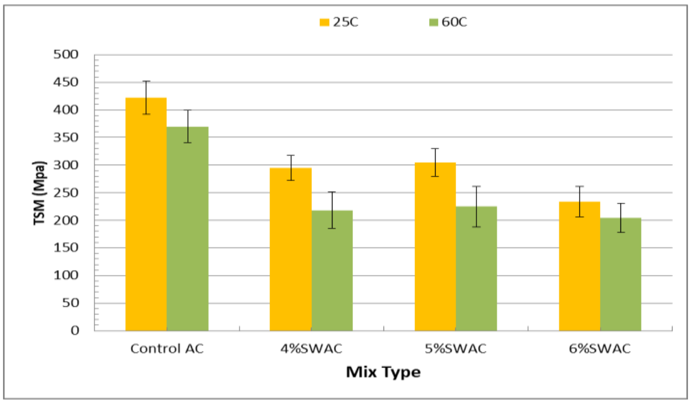


Fig. (6):-Indirect tensile stiffness modulus of control AC and SWAC mixtures

4. CONCLUSIONS

The goal of this study was to determine the efficacy of sulfur waste (SW) in dense-graded asphalt mixtures as a mineral filler. The laboratory investigated the effect of sulfur waste at three different concentrations (4 percent, 5 percent, and 6 percent by aggregate weight) on the mechanical and durability parameters of an AC mixture comprising a 40-50 penetration grade asphalt binder. We investigated the effect of SW on the mechanical and durability qualities of an AC mixture using indirect tensile strength, tensile stiffness modulus, and moisture damage tests. The following summarizes the findings and recommendations of the study:

1. When sulfur waste is used as a mineral filler, the Marshall characteristics meet ASTM and NCCL standards. Calcium carbonate (CaCO3), on the other hand, produces marginally better results. Additionally, the flow values of sulfur waste asphalt mixtures are larger than those of AC control mixtures, as determined by the tensile stiffness modulus. This would also mean that sulfur waste mixtures can withstand more tensile strains before breaking than AC mixtures can.

2. The implicit and explicit tensile strengths, as well as the tensile strength ratio, of sulfur waste asphalt mixtures are lower than those of AC reference mixtures. Tensile strength ratio testing demonstrated that AC mixtures containing 5% SW mineral filler and 40-50 penetration grade asphalt achieve the required minimum tensile strength ratio of 85 percent. This indicates that these mixtures are more resistant to moisture deterioration (and thus have a longer service life) than traditional sulfur waste asphalt mixtures.

3. In general, it is inferred that an AC mixture with an SW concentration of between 4% and 5% can exhibit nearly identical mechanical and durability properties.

5. FUTURE STUDIES

The following recommendations for further research are based on the findings of this study:

1. Additional research is necessary to determine the medium- and low-temperature resistance of sulfur waste asphalt mixtures.

2. Further research is required to determine the effect of short- and long-term aging on the performance of the sulfur waste asphalt mixtures investigated in this study.

3. Future research can also benefit from a life cycle cost analysis from an economic and sustainability standpoint.

4. Additional research is needed to establish the fracture potential of sulfur waste asphalt mixtures including P40 binder at varying loading rates and temperatures.

5. Additional research is necessary to investigate the influence of modified P40 including Styrene-Butadiene-Styrene on the performance of sulfur waste asphalt mixtures.

6. ACKNOWLEDGMENTS

The author wishes to express his gratitude to the National Center for Construction Laboratories (NCCL), Duhok-Kurdistan region of Iraq, for technical assistance, as well as to the Kashe hot mix plant (Duhok—Kurdistan region of Iraq), Kara oil refinery (Erbil—Kurdistan Region of Iraq), and Al-Mushrak industrial company for sulfur production for supplying the materials for this study.

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