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Mechanical and Durability Properties of HMA Containing PG76-16 and Sustainable Sulfur Waste as Filler

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ABSTRACT: In Iraq, sulfur waste (SW) accumulates, posing a costly disposal and gas emission problem. Using SW as a mineral filler is a cost-effective method for reducing the quantity of common filler (calcium carbonate; CaCO3) and hazardous gas emissions. SW was utilized to replace an asphalt binder component in hot asphalt mixes gradually. This study investigates the use of SW as a mineral filler in the construction of sustainable pavements. Three SWAC mixes with PG76-16 asphalt binder were created and compared to the CaCO3-asphalt concrete (AC) mix used as the study's reference. SWAC refers to 4 percent, 5 percent, and 6 percent sulfur-contaminated asphalt concrete, while one AC blend contained a 5 percent CaCO3 concentration (by weight). AC and SWAC mixtures had their Marshall stability, Marshall quotient, tensile strength at 25 and 60°C, tensile strength ratio, and tensile strength modulus at 25 and 60°C determined. SWAC mixtures have decreased tensile strength, tensile stiffness modulus, and tensile strength ratio. When the PG76-16 binder is used, tensile strength ratios remain above the required minimum of 85 percent despite the lower SWAC percentage. In addition, SWAC combinations have greater flow values, indicating a higher rupture strain capacity. All SWAC combinations meet the ASTM standards for 8kN stability, 2-4mm flow, 4 percent air voids, and 14 percent VMA, so long as the correct binder content is maintained. This study found that SW can be used as a mineral filler in pavement applications at a 4–5 percent rate by aggregate weight, similar to the applications studied.

Keywords: Sulfur waste; Mineral filler; Sustainable pavements; PG76-16; Durability; Tensile strength; Tensile stiffness modulus.

1. Introduction

Generation, management, and disposal of industrial and residential solid waste have become important global concerns. Utilizing waste or by-product materials in asphalt pavements has been studied and encouraged for decades for functional, environmental, and economic reasons. Recycled asphalt mixture components, including recycled asphalt paving (RAP), recycled asphalt shingle (RAS), recycled waste tire (RWT), and recycled waste lime (RWL), are so widely used that their inclusion is no longer controversial (Thgersen et al., 2013; Arabani et al., 2010; Yalcin E. 2021; González A., 2018; Do et al., 2008).

Reuse is the most environmentally friendly solution to the problem of disposing of large amounts of trash. Due to the vast quantity of composite materials required for road paving construction and maintenance in Iraq, recycling waste materials could be extremely lucrative. Due to the large quantity of "new" materials required in the road construction industry, such as mineral fillers, the environmental benefits are contingent on the safe disposal of bulk trash. and minimizing the environmental effects of greenhouse gas (GHG) emissions (Zoorob and Suparma, 2000). The majority of energy and carbon savings can be realized by gradually reducing the amount of filler required. Asphalt mixtures can last longer if common fillers (such as calcium carbonate) are reduced or eliminated, and the time between replacements is increased (Zoorob and Suparma, 2000).

FHWA-HIF-16-012 (FHWA, 2016) highlighted strategies for reducing the environmental impact of asphalt binder and aggregate mixtures. Reducing the amount of material used, as well as its manufacture and construction, is one of these strategies. Innovative materials like warm mix asphalt (WMA), polymers, rubber, and other modifiers may be used in certain situations. The case with other waste products, the publication was silent on using sulfur waste (SW) as a mineral filler. Ignoring SW resulted in material waste and environmental harm. Utilizing SW can lead to additional cost savings and environmental stewardship advantages. The increased SW output of Iraq's sulfur-producing facilities raises issues about waste management and environmental degradation (Al-Hadidy, 2001). The annual production of SW in Iraq is steadily increasing, but the capacity of existing disposal sites is diminishing. SW does not degrade, much like the bulk of solid waste disposed of in landfills. The annual production of SW in Iraq continues to increase while the capacity of existing disposal facilities continues to decrease. SW does not dissolve, like most solid waste disposed of in landfills. Reports indicate that Iraq produces and disposes of between 7,000 and 20,000 tons of SW annually. The cost per ton of SW landfilling is anticipated to be $95. Thus, the annual cost of the landfill is between 665 and 2000 dollars (Al-Hadidy, 2001). SW is anticipated to become the most often used mineral filler in asphalt mixtures to save money and the environment. SW, like sulfur, is an excellent mineral filler for asphalt mixtures, considerably enhancing asphalt pavement performance. Sulfur has an effect on the physicochemical properties of asphalt on its own. Second, massive quantities of SW are readily available and inexpensively priced in powder form in Iraq. Due to the SW's ubiquity and low cost, researchers in northern Iraq have begun adding it as a mineral filler to improve the characteristics of asphalt. SW melts at temperatures between 140 and 145 degrees Celsius, depending on its sulfur concentration. SW has a specific gravity of between 2.03 and 2.215. The majority of obsolete software must be discarded and cannot be reused (Al-Hadidy, 2001). These numbers illustrate the tremendous potential for sulfur waste recovery and encapsulation that remains. Bituminous road surfacings provide an excellent opportunity to incorporate vast quantities of unique sulfur waste into a civil engineering structure, thereby boosting the strength and durability of the road layers. This study aims to provide insight into the performance of asphalt mixtures, including SW, to aid in creating long-term road infrastructure. In asphalt mixtures, sulfur waste was used to replace a portion of the asphalt cement binder at varied replacement rates (Al-Hadidy, 2021; Ahmed et al., 1985). It was discovered by Al-Hadidy (2021) that replacing sulfur waste with asphalt cement increased the cement's rheological properties while maintaining its tensile strength and stability at or above the ASTM minimums. While this is true, no research has been undertaken on the use of sulfur waste as a mineral filler in asphalt mixtures. Nonetheless, the current research intends to: (1) determine the viability of employing sulfur waste as a mineral filler in asphalt mixtures, including PG76-16 asphalt binder; (2) estimate the appropriate sulfur waste content; and (3) compare the impacts of sulfur waste on asphalt mixtures. This research aims to understand the performance of asphalt mixtures containing SW as a mineral filler intoromote the sustainable development of road infrastructure.

2. Materials and test program

2.1 Materials

As aggregate, river sand, and crushed gravel were removed from one of Kashe's hot mix factories (located in Duhok city). This gravel is comprised of silica-rich sedimentary rock. This material is abundantly accessible and is frequently used in highway construction projects in northern Iraq. Table 1 summarizes the aggregates' tested properties, including toughness, soundness, water absorption, and specific gravities. As a standard filler material, calcium carbonate (CaCO3) was used. It was obtained from the Kashe hot mix factory in the Iraqi province of Duhok-Kurdistan. The specific gravity of CaCO3 after passing through a 200-mesh screen is 2.734.

The experiment employed 40-50 penetration grade polymer-modified asphalt with Styrene-Butaidene-Styrene (SBS) to generate PG76-16. For the modification of the base binder, 4 percent of SBS linear block copolymer (Europrene SOL T 6302 in pellet form was blended for 2 hours at 1805°C using a high shear laboratory mixer (Silverson machine, model L5 series) running at 3000 rpm to generate a homogenous binder (Al-Hadidy, 2020). Table 2 provides a summary of the rheological parameters of PG76-16 adhesive.

The sulfur waste (SW) is the remaining solid waste from a sulfur-producing factory. SW is frequently accessible at the Al-Meshrak industrial complex as a dark green powder (400 kilometers north of Baghdad). It was delivered in vacuum-sealed bags to the laboratory. The physicochemical and gradational features of SW materials are summarized in Table 3.

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, Na2SO4 (%)	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	4.0 max.
Apparent sp .gr.	D127 & D-128	2.739	2.748	4.0 max.

Table 2: Rheological properties of PG76-16 binder

Property	**PG76-16**	**NCCL limits (2018)**
Penetration (25 deg. C,100gm,5 s,0.1mm)	33	40-50
Softening point (oC)	67.1	51-62
R & B separation difference in softening point, °C	2.0	2.5 max.
Elastic recovery (25 °C, 50 mm/min, cm)	78.5	100+
Specific gravity (25 oC/25 oC)	1.03	-
Flash point (oC)	310	-
Fire point (oC)	330	230 min.
Loss on heat (85 min., l63 °C, %)	0.299	1 max.
Rotational viscosity at 135°C, cP	2138	3000 max.
DSR (G/sin (δ), @ 10ra/sec, kPa: Original binder (G/sin δ) RTFO (G/sin δ) PAV (G*sin δ))	 1.881 3.355 1500	 1.0 min 2.2 min. 5000 max.
Creep stiffness, S, -6 °C, MPa m-value @ 60 sec, -6 °C	64.65 0.3435	300 max. 0.3 min.

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 utilized a D5 dense asphalt mixture that met ASTM D3515 specifications (ASTM, 2 The aggregate was sieved into various sizes before being recombined with sulfur waste to match the mid-range ASTM D3515 surface course gradation requirements sizes (ASTM, 2015). The blended aggregate with varied filler ratios is graded according to Table 4. The Marshall Method was applied to make the asphalt mixture (ASTM, 2015). In order 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 performed, yielding an optimal binder content (OBC) of 5.2% of the aggregate weight for an asphalt concrete (AC) reference mixture containing 5% CaCO3 filler. This OBC was used to produce all asphalt mixtures examined in this study to maintain consistency throughout the investigation. Following a mixture design method, three AC containing SW (SWAC4, SWAC5, and SWAC6) and AC containing CaCO3 combinations were selected. The sulfur waste concentration and asphalt binder types were evaluated. The mixing and compaction temperatures of PG76-16-containing AC and SWAC mixtures were 180 5 and 165 5 degrees Celsius, respectively. These numbers were derived utilizing the relationship between viscosity and temperature. Fig. 1 depicts the strategies utilized to achieve the study's objectives.

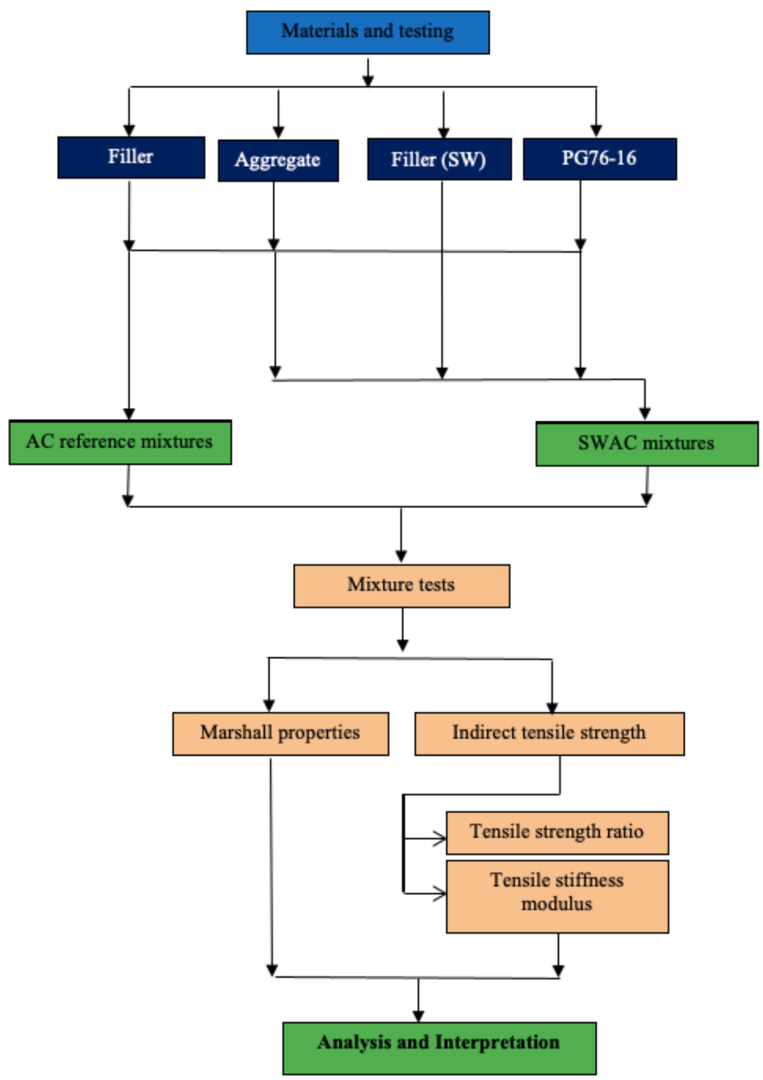


Figure 1: Flowchart of Experimental Work of the Study

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 Ffow tests

For both binder types, Marshall stability and flow experiments were done on compacted specimens containing varying amounts of sulfur waste in accordance with ASTM D6927 (2015). 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 prior to being compressed to failure using curved steel loading plates at a constant rate of 51 mm/min. Marshall stability is a force unit given in kilogram-newtons (kN), representing the amount of compression pressure exerted on an object. The flow unit is measured in millimeters. It is used to describe the pressure produced when something is compressed. To measure stiffness, the Marshall quotient (kN/mm) is used, which is the stability (kN) divided by the flow (mm). Bituminous mixtures test protocols for hot mix are included in Draft BSEN 12697-34. Pavement - Part 34: The MQ has been restored for the Marshall test. It is to be superseded by the previously mentioned BS 598-Part 107 (BS 598, 1990).

2.4 Tensile characteristics and moisture susceptibility tests

Moisture-sensitive mixes are susceptible to bitumen stripping (bitumen detachment from aggregate). In dense asphalts and macadams with low void contents, stripping is extremely unlikely. Even in very dense water-permeable materials, stripping happens, resulting in losing internal cohesiveness and possible collapse. The affinity of the aggregate with the bitumen and its resistance to water displacement determines the stripping potential.

The purpose of immersion mechanical testing is to evaluate the mechanical properties of a compacted bituminous mixture after its water immersion. Therefore, the ratio of the property after immersion to the original property serves as an indirect indicator of stripping. The indirect tensile strength (ITS) is likely the most commonly employed 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.

In accordance to ASTM D6931, the tensile characteristics and moisture susceptibility of the AC and SWAC combinations was measured using indirect tensile strength (ITS) (2015). The average air void content of the compressed mixes was seven percent. For the ITS test, the AC and SWAC samples were divided into two subsets: unconditioned (U) and conditioned (C) (C). Unconditioned samples were stored at 25°C for two hours, while conditioned samples were held at 60°C for 24 hours and then returned to 25°C for two hours. The samples were then examined at a 51 mm/min rate using the Marshall apparatus until they failed. The specimen's maximum load has been established, and the ITS has been calculated using Eq (1).

$$ITS = 2P/\pi dt \qquad (1)$$

Where ITS is the indirect tensile strength (N/mm2), 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 the ITS test at 25oC as given in Eq. (2).

$$TSR (\%) = ITSC / ITSU \times 100 \quad (2)$$

Where ITSC and ITSU are the indirect tensile strength (N/mm2) of conditional and unconditional specimens, respectively.

An important performance parameter of the base and road layers is their stiffness modulus. Bituminous layers are put through a load-spreading capacity test in this manner. To prevent fatigue cracking and permanent subgrade deformation, control traffic-induced tensile and compressive stresses at the road foundation's underside. The maximum stress to maximum strain ratio calculates a material's stiffness modulus under uniaxial loading. At 25°C and 60°C, TSM values (N/mm2) were calculated using the peak of the applied vertical load and the mean of the horizontal deformation (Eq (3)).

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

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

3. Test results and discussions

3.1 Considerations for Statistics

In this analysis, AC and SWAC-mixes were compared using an analysis of variance (ANOVA) with the null hypothesis (H0 = 0) and a significance level of 0.05. (SPSS, 1999). The least significant difference value (LSDV) was provided to assess if there is a significant difference between the two means. If the difference between the two averages is greater than or equal to the LSDV, and vice versa, the difference is significantly different. The average differences between alphabet letters are shown in Table 5. Averages with identical letters suggest that they were not statistically significant.

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

Property	AC	SWAC4	SWAC5	SWAC6
Marshall stability at 60°C, kN	22.2±1.58A	20.73±1.48AB	21.82±1.39A	18.93±1.30B
Marshall flow, mm	2.84±0.43A	3.2±0.35A	3.01±0.39A	3.37±0.42A
Air voids, %	4±0.30AB	4.5±0.29A	4.2±0.25AB	3.8±0.40B
VMA, %	15.25±2.03A	15.2±1.97A	14.9±1.58A	14.6±1.83A
It's at 25°C, MPa	1.777±0.29A	1.683±0.25A	1.659±0.30A	1.611±0.24A
It's at 60°C, MPa	1.652±0.17A	1.497±0.23A	1.501±0.26A	1.345±0.3A

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 anticipated (Fig. 2), the compacted densities of sulfur waste mixtures were similar to those of the control mixture. Due to its decreased density, the sulfur waste contains an additional 6 percent of airspace. A 5% sulfur waste by weight of aggregate results in a 5% reduction in air gaps in the compacted mix (Fig. 3). At higher temperatures, sulfur waste polymerizes and forms a two-radical chain, decreasing density and air space. When radicals interact with asphalt, they can produce carbon-sulfur bonds or absorb hydrogen, leading to dehydrogenation.

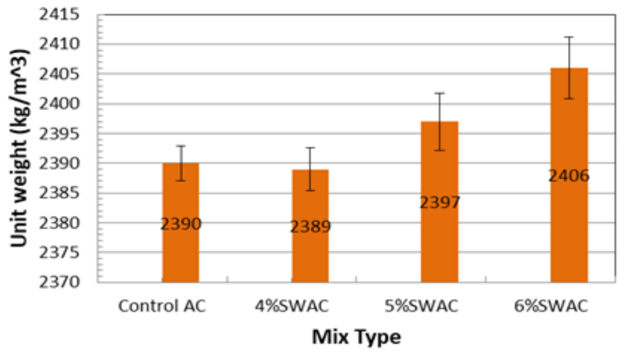


Figure 2: Unit weight of control AC and SWAC mixtures

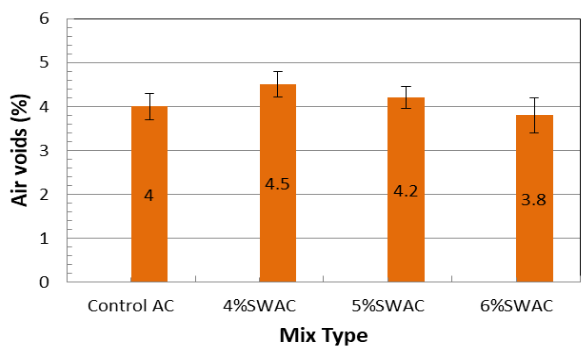


Figure 3: Air voids of control AC and SWAC mixtures

3.3 Marshall stability, flow, and Marshall quotient

Sulfur waste mixtures possess marginally lower Marshall stability ratings than the AC reference mix (Fig. 4a). SWAC5 has a nearly equivalent stability value to the AC control mix among SWAC combinations. This strength (stability) is made feasible by combining and crushing sulfur waste at precisely set temperatures. ANOVA and LSDV (2.879) suggest that there was no statistically significant difference between the averages of AC, SWAC4, and SWAC5 for Marshall stability; however, there was a statistically significant difference between the averages of AC and SWAC6 for Marshall stability.

The sulfur waste combinations showed a greater flow value (Fig. 4b) than the AC control mixtures, showing less brittle than the sulfur waste samples. As a result, the likelihood of premature cracking was diminished. At the same optimal binder content, all sulfur waste combinations meet the minimal ASTM (2015) and NCCL (2018) requirements of 8kN stability, 2-4mm flow, 35% air voids, and 14% VMA (Fig. 4c).

A high Marshall quotient (MQ) in typical dense-graded mixtures (Fig. 4d) suggests a stiffer mixture capable of dispersing applied load and resisting creep deformation. Due to their reduced tensile strain capacity to failure, mixtures with high stiffness must be treated with care, since they are more likely to fail when put on improperly supported foundations. Even though the Marshall stability of the sulfur waste mixtures is lower than that of the control mixtures, the flow values are higher, indicating a more significant potential for strain-induced breakdown. The sulfur waste mixtures have a lower MQ value compared to the control mixtures. MQ (pseudo stiffness) is a well-known parameter representing a material's resistance to shear loads, persistent deformation, and rutting (Zoorob and Suparma, 2000).

Compared to the AC mixture, the MQ values for the SWAC4, SWAC5, and SWAC6 mixtures are reduced by approximately 17.2%, 7.3%, and 28.2%, respectively. The drop in MQ is related to the lower stability and higher flow values of SWAC combinations.

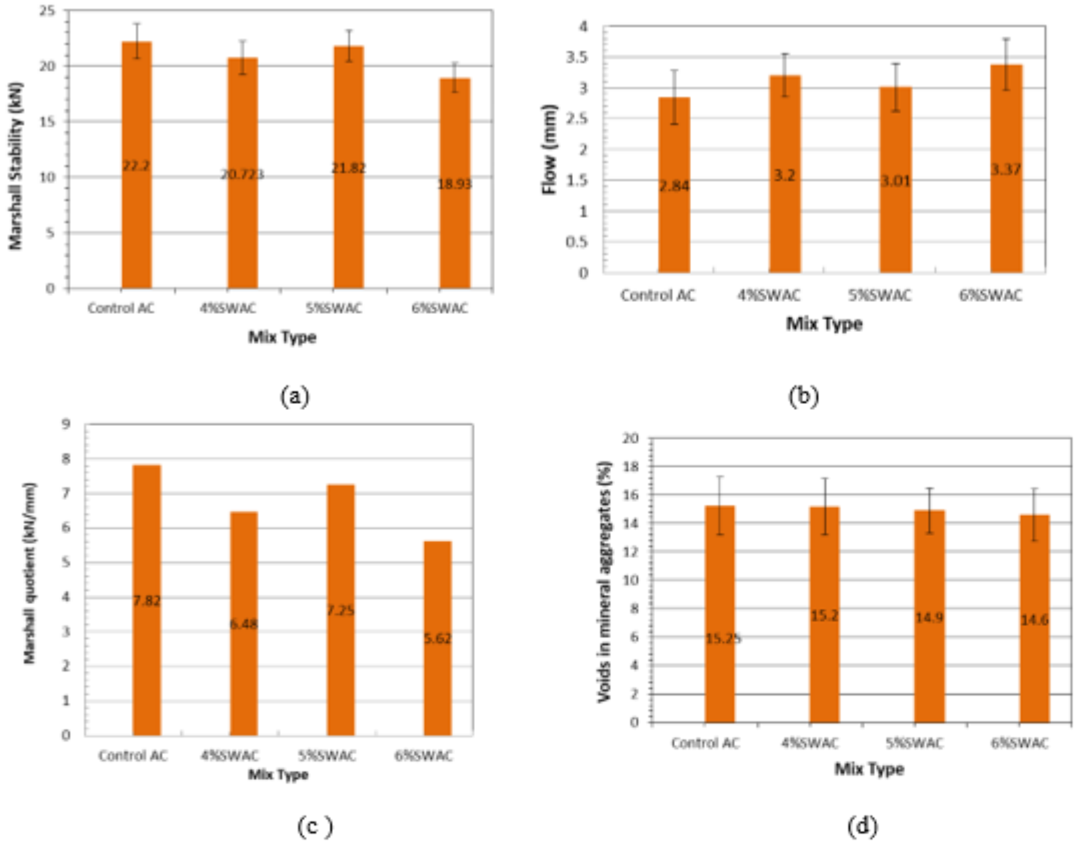


Figure 4: Marshall parameters of control AC and SWAC mixtures

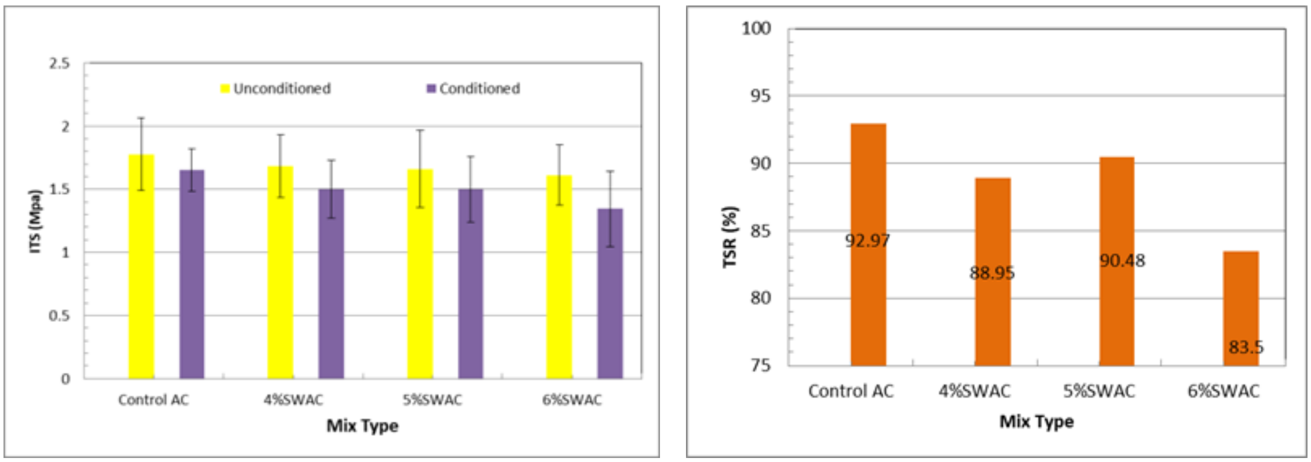
(a- stability, b- flow, c- voids in mineral aggregate, & d- Marshall quotient)

3.4 Indirect tensile strength (ITS)

The ITS test was conducted to assess the impact of humidity and temperature on sulfur waste mixes' tensile strength. Figure 5a depicts the unconditioned and conditioned tensile strengths of various combinations. As seen in the graph, the magnitudes of ITS are reduced for both conditioned and unconditioned sulfur waste samples compared to control AC mixtures. When utilized in asphalt mixtures, unconditioned asphalt samples containing sulfur waste have a lower ITS value.

Compared to the AC mixture, the ITS levels of unconditioned specimens fall by approximately 5.3%, 6.7%, and 9.4% when exposed to the SWAC4, SWAC5, and SWAC6 combinations. Similarly, the average ITS values of conditioned SWAC4, SWAC5, and SWAC6 combinations fall by 9.4%, 9.2%, and 18.6%, respectively. Using sulfur waste in asphalt mixtures decreases the ITS values of both unconditioned and conditioned samples. At intermediate temperatures, sulfur waste may have diminished the binder's ductility and elongation. The previous study has yielded comparable results (Al-Hadidy, 2022). ANOVA and LSDVs (0.541 and 0.489, respectively) demonstrate no significant difference in the averages of AC, SWAC4, SWAC5, and SWAC6 for both unconditional and conditional ITS samples (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 researchers 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%, 3.6%, and 8.5%, respectively, when compared to the AC mixture.

A minimum TSR value of 0.85 is usually specified to identify the mixtures with acceptable moisture susceptibility worldwide and this minimum value is applicable for application in Iraq (Van Hung and Van Phuc, 2019). Interestingly, the TSR values of SWAC6 mixtures are less than 0.85, indicating moisture susceptible mixtures, whereas the TSR value of SWAC4 and SWAC5 mixture (0.88 and 0.90, respectively) is greater than 0.85, indicating adequate moisture resistance. The reason for the increase in TSR of SWAC4 and SWAC5 is that the viscosity decreases when sulfur waste is added. However, when the sulfur waste concentration exceeds 5%, the asphalt's value approaches that of fresh asphalt. When the sulfur waste concentration is increased further, the viscosity lowers once again. Previous studies have also shown this type of conduct (Al-Hadidy, 2009).



(a) **(b)**

Figure 5: Indirect tensile strength properties of control AC and SWAC mixtures

(a- Indirect tensile strength & b- tensile strength ratio)

3.5 Tensile stiffness modulus (TSM)

Figure 6 depicts the tensile stiffness modulus (TSM) values obtained at 25 and 60 degrees Celsius. On average, three measurements are made for each type of mixture. The sulfur waste mixtures have lower TSM values than the control mixtures at 25 °C and 60 °C. The graph demonstrates that the TSM of the SWAC4, SWAC5, and SWAC6 mixtures examined at 25°C is 27.5 percent, 26.7 percent, and 36.2% less than the AC control mixture, respectively. Similarly, the average TSM values of SWAC4, SWAC5, and SWAC6 mixed specimens decreased by 26,6%, 19.6%, and 36%, respectively, at 60 °C. This test checks the results of the ITS test.

In contrast, the TSM of the sulfur waste samples was lower than that of the reference mixtures. This shows that even while the sulfur waste mixtures are less rigid than the control mixtures, which would imply higher strain values, their tensile strength at failure ITS values are lower. This would also indicate that sulfur waste mixtures are more resistant to fracture under tensile stress.

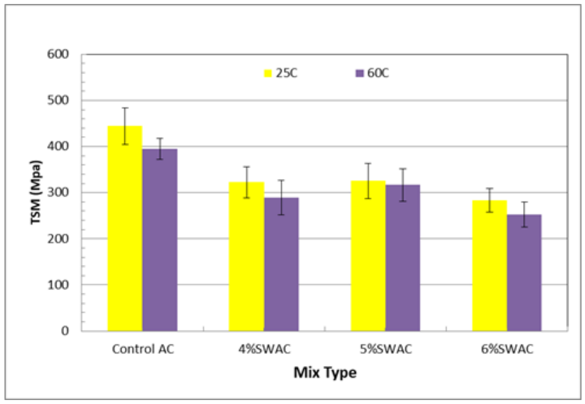


Figure 6: Indirect tensile stiffness modulus of control AC and SWAC mixtures

4. Conclusions

This study aimed to assess the efficacy of sulfur waste (SW) as a mineral filler in dense-graded asphalt mixtures. The laboratory examined the influence of sulfur waste at three different concentrations (4%, 5%, and 6% by aggregate weight) on an AC mixture's mechanical and durability parameters containing a PG76-16 binder. Using indirect tensile strength, tensile stiffness modulus, and moisture damage tests, we studied the impact of SW on the mechanical and durability properties of an AC blend. The following is a summary of the study's results and recommendations:

1. When sulfur waste is utilized as a mineral filler, the Marshall properties meet ASTM and NCCL requirements. However, calcium carbonate ($CaCO3$) offers marginally superior results. The tensile stiffness modulus also indicates that the flow values of sulfur waste asphalt mixtures are greater than those of AC control mixtures. This implies that sulfur waste combinations can endure greater tensile stresses before breaking than AC waste mixtures.
2. The implicit and explicit tensile strengths and tensile strength ratios of sulfur waste asphalt mixtures are less than those of AC reference mixtures. The required minimum tensile strength ratio for AC mixtures, including 4 percent and 5 percent SW mineral filler and PG76-16 asphalt, was determined by tensile strength ratio testing. This suggests that these combinations are more resistant to moisture deterioration (and therefore have a longer service life) than waste asphalt mixtures containing 6 percent sulfur.
3. It can be assumed that an AC mixture with an SW content between 4% and 5% can display essentially equivalent mechanical and durability qualities.

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 the PG76-16 binder, at varying loading rates and temperatures.

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