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The Moisture Resistance of Sustainable Asphalt Mixtures Modified with Silica Fume

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ABSTRACT

The administration of waste from constructing-demolition and the reuse of industrial waste materials are the main focuses of the sustainability initiatives. There are economic and environmental benefits to using recycled concrete aggregates (RCA). Nevertheless, the RCA mixes' poor performance necessitates the addition of more enhanced substances. This study investigated the moisture resistance of asphaltic mixes that included RCA and silica fume (SF). Coarse aggregates were replaced with RCA at three different percentages 15%, 30%, and 45%, which were pre-treated by immersing it in acid with a concentration of 0.1 mol. for a duration of 24 hours. Then the mixes containing RCA were incorporated with various amounts of SF, with 3%, 6%, and 9% of the binder's weight. These mixes were used to measure the Marshall characteristics and evaluate moisture resistance using indirect tensile strength, compresive strength tests. A thermal camera was employed to assess the modified asphalt's homogeneity. The thermal images demonstrated that after 30 minutes of mixing SF at 160 °C, the asphalt cement has been uniformly distributed SF particles, as evident by the colour convergence. The findings revealed that the addition of RCA to the asphalt mix increased TSR and IRS levels by 6.68% and 8.93%, respectively, at RCA 30% compared to the original mixture. Additionally, the inclusion of silica fume led to a rise in TSR and IRS until 6%, after which there was a drop, but the levels remained above the original mix. The use of 30% RCA ratio with 6% silica fume resulted in the highest improvement in TSR and IRS, with a rise of 13.72% and 14.13%, respectively.

Keywords: moisture resistance, silica fume, RCA, thermal images.

INTRODUCTION

Moisture degradation is a complicated and frequent failure in an asphalt pavement. The breakdown of the bond between the aggregate and asphalt or weakening of asphalt itself, is the reason for the loss of asphalt mix properties, including stiffness, strength, and durability (Kakar et al., 2015; Mirhosseini et al., 2016). In order to achieve optimal efficiency, asphalt pavements must be both durable and sustainable throughout their service life (Omar et al., 2020; Ismael et al., 2021). Temperature, water, and air are some of the environmental factors that affect this, coupled with other asphalt properties including cohesion and adhesion between aggregates and binder (Behiry, 2013; Mirabdolazimi et al., 2021). Recently, there has been a significant push to embrace sustainable technology in many different kinds of construction projects, such as asphalt concrete pavement, due to growing construction costs as well as increased environmental regulations and awareness (Albayati et al., 2018). Consequentially, a sustainable substitute material for asphalt mixes is presented: recycled concrete aggregate (RCA)(Ismael et al., 2023). Nevertheless, the substandard quality of RCA frequently restricts its utilisation to low-quality applications. The primary contributor that effects RCA is the overabundance quantity of cement mortar connected to the aggregate interface, causing higher porosity, lower density, higher absorption, and a weaker interfacial zone, which impairs the strength and mechanical performance of RCA (Tam et al., 2007; Xu et al., 2022). Technical benefits can be obtained at a reasonable cost by using appropriate pre-treatment techniques (Al-Bayati and Ismael, 2023). Currently, the majority of RCA pre-treatment methods primarily involve either eliminating or fortifying the adhering mortar (Shi et al., 2016; Kazemian et al., 2019). To maintain the good characteristics of asphaltic mix and reduce susceptibility to moisture and permanent deformation, stripping employed an anti-stripping agent (Alhamali et al., 2016; Hamedi and Tahami, 2018). The results of using the silica fume additive were demonstrated by a reduction in penetration, increased viscosity, softening point, and stability (Shafabakhsh et al., 2015; Naser et al., 2023).

Al-Bayati et al. (2016) examined how RCA affected the volumetric characteristics of asphalt mixes; different percentages of RCA were utilized (0%, 15%, 30%, and 60%). 30% of RCA had the strongest effects in terms of moisture resistance. The moisture sensitivity of mixes containing 10%, 20%, 30%, and 40% of RCA was assessed by Fatemi and Imaninasab, 2016). The result shows that using RCA increases, optimal asphalt content and improves resistance to moisture degradation, with 30% being the best enhancement when compared with the original mixture. Nazal and Ismael (2019) evaluated the moisture susceptibility of the control mixture and used different RCA percentages – 10%, 20%, 30%, 50%, 70%, 100% by the amount of coarse aggregate. They found the optimum percent of RCA is 30%, which recorded a higher increase in TSR and IRS, consequently a higher resistance to degradation caused by moisture. Kavussi et al. (2019) investigated the RCA changes in the mechanical properties of asphalt mixes. Asphalt mixes constructed using RCA components showed some moisture sensitivity. According to the results, treating RCA with HCL acid may improve the RCA's sensitivity to moisture.

Al-Taher et al. (2018) looked at how applying silica fume affected the characteristics of hot mix asphalt at various percentages 2%, 4%, 5%, 6%, 7%, 8%. The findings showed that adding 6% silica fume to the binder improved direct compression and indirect tensile strength, which in turn strengthened asphalt mixes' resistance to moisture damage and improved Marshall stability.

MATERIALS AND TESTING METHODS

Materials

All raw components that were utilized in this research brought from local resources. (asphalt cement with a 40/50 penetration grade, fine and coarse aggregate from Al-Nibaai quarry, limestone dust as mineral filler) are tested according to the Iraqi criteria (SCRB/R9, 2003). Table 1. exhibits the characteristics of both RCA and virgin coarse aggregate. It has been noted that RCA has a lower density and a higher water absorption rate compared to virgin aggregate due to its high porosity and the cement mortar adhered to it. The demolished concrete waste pieces were crushed to produce coarse aggregate with a size range of 19 to 4.75 mm. RCA therapy includes three stages. First, it is submerged in water for a full day to separate any dirt or impurities. Following that, a specified quantity of hydrochloride acid (HCL) at a dose of 0.1 mole was mixed with water, and the mix was socked for a whole day in order to treat the RCA's poor cement mortar and minimize it. It is then re-soaked in water to reduce the impact of the remaining acid solution. prior to usage, the entire quantity of RCA had been dried at 110 °C for four hours in the furnace, and then it was sieved to obtain the proper gradation and mix it with the virgin aggregate (Ugla and Ismael, 2023). Three different of silica fume percentages (3%, 6%, and 9% by the weight of the binder) were utilized to improve the adherence between aggregate and binder. The X-ray fluorescence (XRF) test was utilized to find out the chemicals were in SF, the outcomes of XRF test are listed in Table 2. The effect of the treatment on RCA has been determined using a scanning electron microscope (SEM). Images from SEM of treated and untreated RCA are displayed in Figure 1. The

Table 1. Physical features of coarse aggregate

Properties	Designation No.	Virgin	RCA
Bulk sp. gr.	C127	2.58	2.34
Water absorption%	C127	0.55	2.76
Abrasion%	C131	16	22

Table 2. Chemical characteristics of silica fume

The oxide compounds	%
SiO_2	94.5
SO_3	0.11
CaO	2.04
Fe_2O_3	0.37
Al_2O_3	0.11
LOI	Max 6%

Note: XRF test.

figure clearly illustrates that acid treatment reduces surface irregularity, but remains some mortar clinging to the RCA. Figure 2 shows the aggregate variation for the wearing course. According to this gradation, 52% of the aggregate that is coarse, except for original mix, has been substituted with RCA at rates of 15%, 30%, and 45%.

Mixing of silica fume (SF) with asphalt cement

To achieve efficient mixing of silica fume with asphalt cement, many instruments were utilized, as depicted below: a thermal camera, tachometer, and mixer.

Thermal camera

In this research, the UTi120P thermal camera was used. Thermal imagers transform imperceptible infrared into observable thermal images. The precision of a camera is mostly determined by emissivity, which refers to an object's capacity to reflect its surface temperature through the infrared radiation it emits (Albatici et al., 2013). The emissivity of many materials, such as concrete, asphalt, water, bricks, and copper, was identified for this camera. The determined emissivity value for asphalt is 0.96. To clarify, if the emissivity value were 1, the infrared sensor of the camera would perfectly estimate the real temperature by precisely capturing the infrared rays released by the material.

Digital laser tachometer instrument

The digital tachometer was employed to quantify the rotational speed, expressed in revolutions per minute, of a rotary apparatus. The reflective strips were employed to ascertain the revolutions per minute (rpm) of the shear mixer. The strips were affixed to the rotating component in order to reflect the laser signal emitted by the tachometer device, enabling precise reception of the signals from the rotating component. The mixer achieved a rotational speed of 1500 rpm. Figure 3 displays SF particles, tachometer device, shear mixer that were utilized in this study.

The experimental method of combining asphalt and silica fume

An experimental approach was utilized to ascertain the optimal blending temperature. The required consistency was ensured by employing a thermal imaging instrument. At 1500 rpm, three temperatures 150 °C, 160 °C, and 170 °C were employed. The images revealed that the uniformity of asphalt containing silica fume becomes apparent after 45 minutes at a temperature of 150 °C, whereas it becomes clear after 30 minutes at 160 °C. While at 170 °C, the state of being homogeneous is achieved within a duration of 30 minutes, but the presence of bubbles was observed. Thus, it was determined that 160 °C was the ideal temperature to reach the required homogeneity quickly. Figure 4, Figure 5, Figure 6 show thermal images for mixing SF and the required homogeneity. The homogeneity of surface

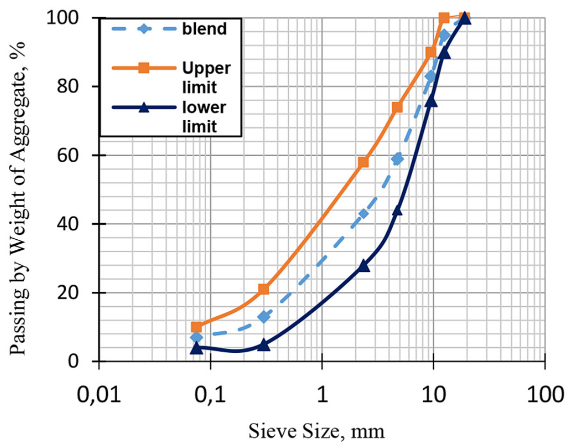

Figure 2. Aggregate gradation

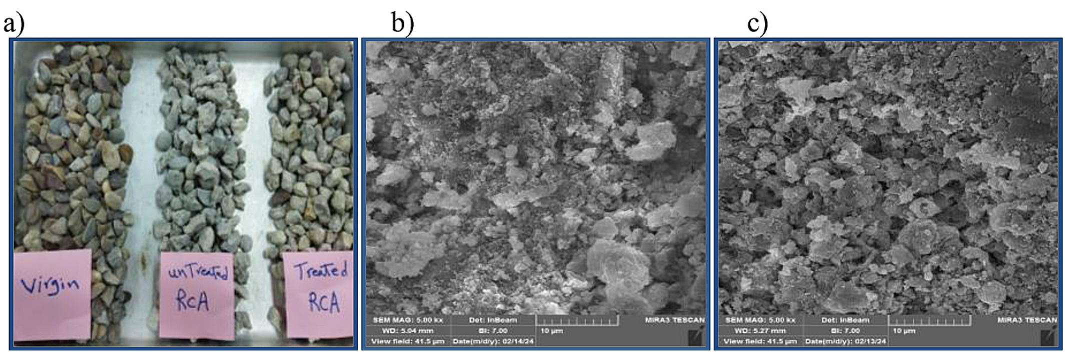

Figure 1. Aggregate utilized and SEM images: (a) virgin and RCA sample, (b) untreated RCA, (c) treated RCA

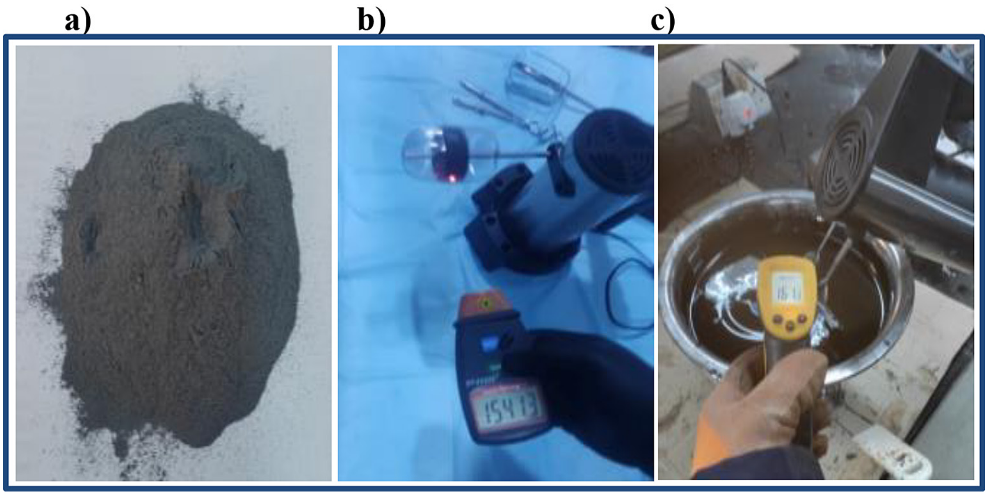

Figure 3. Silica fume, tachometer device and shear mixer: (a) silica fume, (b) device at 1500 rpm, (c) mixing SF with binder

temperatures of asphalt augmented with silica fume was assessed using the thermal analysis program connected to the thermal camera. The main material shown in these images is a mixture of silica fume and asphalt. Thermal analysis allows for the observation of temperature changes at different phases of mixing, ultimately indicating the successful attainment of desired homogeneity throughout the process. Upon analyzing all the images, both step (a) and (b), it was observed that a diverse spectrum of colors is present, spanning from low to high intensities. However, as the mixing process progresses, the mixture becomes increasingly homogeneous. Homogeneity is evident when temperatures measured at different places and for distinct hues during thermal analysis converge, indicating that they are suitable for the mixing process. Thus, the decision to select 160 degrees was based on the close resemblance in temperature across the majority of the surface.

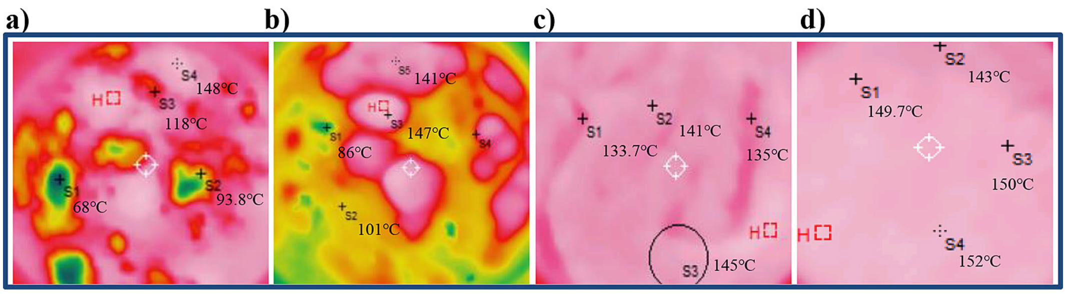

Figure 4. Silica fume mixed with asphalt at 150 °C is captured in thermal analysis images after: (a) 0.5 minute, (b) 5 minute, (c) 15 minute, (d) 45 minute

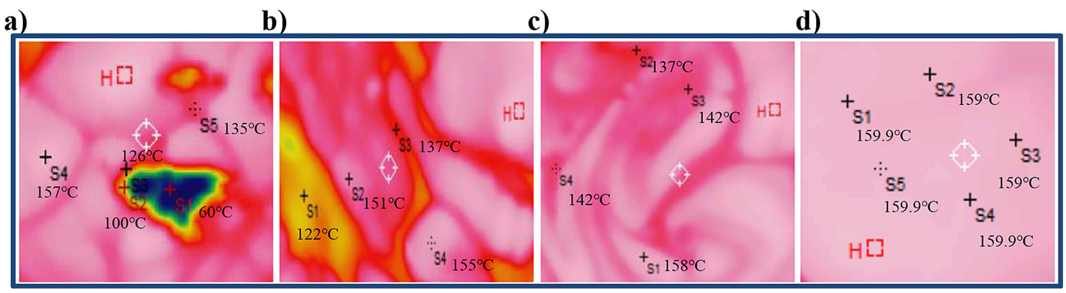

Figure 5. Silica fume mixed with asphalt at 160 °C is captured in thermal analysis images after: (a) 0.5 minute, (b) 5 minute, (c) 15 minute, (d) 30 minute

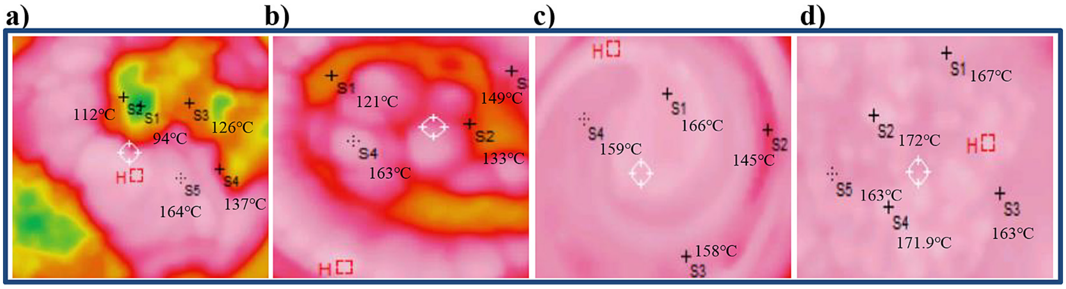

Figure 6. Silica fume mixed with asphalt at 170 °C is captured in thermal analysis images after: (a) 0.5 minute, (b) 5 minute, (c) 15 minute, (d) 30 minute

In order to finalize the mixing process, a mixer was utilized to incorporate SF into the asphalt. Firstly, the asphalt is heated to 160 °C, SF has been slowly added while the mixer was running at 500 rpm to make sure the SF bits were spread out evenly. The mixing speed was then sped up to 1500 rpm for thirty minutes, during which time it stayed steady (Ezzat et al., 2016; Taher and Ismael, 2022).

Mix design

The Marshall method was employed to identify the optimal asphalt content (OAC) for the designed aggregate gradation. A sample of 101.6 mm by 63.5 mm, weighing approximately 1200 g, was subjected to the ASTM D6926 procedure. A 4.53 kg compaction hammer was used to deliver 75 blows to both the top and bottom of the sample. Five different asphalt cement contents (4–6%) by weight of mixture was utilized with a 0.5 increment for the wearing course type IIIA according to the Iraqi criteria (SCRB/R9, 2003). 4% of air voids had been selected as the key consideration for choosing the O.A.C in this design procedure in accordance with the Asphalt Institute's guidelines. To determine the necessary specifications, all other attributes, including Marshall stability, bulk density and flow, voids were examined in

Figure 7. Marshall prepared specimens

the criteria (Islam, 2020). Figure 7 shows Marshall prepared specimens.

Marshall test

In accordance with the testing procedure outlined in ASTM D6927. It was utilized to caculate the Marshall stability and flow on the original mix and with treated RCA 15%, 30%, and 45% and silica fume (3%, 6%, and 9%). Additionally, the bulk, maximum specific gravity were calculated accordance with the ASTM D2726 and D2041, respectively. Figure 8 presented Marshall test.

Tensile strength ratio

In order to investigate the degree to which asphalt mixes are sensitive to moisture, indirect tensile strength test (ASTM D4867) was implemented. Six specimens have been produced following the Marshall compaction method for each mix.For the prepared samples (101.6 mm in diameter × 63.5 mm in height), the intended air voids was 7% ±1. The six specimens were split equally into two groups of three. Tests were conducted on one group, known as unconditioned samples, at 25 °C. The other group was placed in a flask under a vacuum for five minutes in order to get a (55–80) saturation degree, known as the conditioned specimens. The samples were then frozen and thawed for 16 hours at -18 ± 2°C, then they were left at 60 ± 1 °C for 24 hours, and they were evaluated at 25 °C, as shown in Figure 9. Equations 1 and 2 were utilized to calculate the ITS and TSR values.

$$ITS\% = \frac{2Pu}{\pi\ tD} \times 100 \quad (1)$$

$$TSR\% = \frac{ITS\ con}{ITS\ uncon} \times 100 \quad (2)$$

where: *Pu* – the ultimate load failure (N), *t* – sample's height (mm), *D* – sample's diameter (mm), ITS – indirect tensile strength (kPa), *TSR* – tensile strength ratio, *ITS con.* – wet samples' indirect tensile strength, *ITS uncon.* – dry samples' indirect tensile strength.

Compressive strength test

Index of retaining strength (IRS) can be used to measure the sensitivity to moisture damage. Samples 101.6 mm by 101.6 mm were utilized in the procedures in accordance with ASTM D1074. According to the ASTM D1075 standard, this test was essentially used as a moisture sensitivity indicator for the bitumen-aggregate mixtures. This procedure was employed to produce a trial mix in order to determine the appropriate component weight, which was found to be approximately 1900 gm. After preheating each specimen in the

Figure 8. Marshall test

Figure 9. Indirect tensile strength test

oven, the necessary weight of asphalt cement and the hot aggregates were rapidly combined. Then, to avoid honeycombing, half of the asphalt mixture was put into the mold, and a hot spatula was utilized to vigorously spade (10) times at random throughout the asphalt mixture and (15) times around the mold's edge. With rapidity, the remaining part was put into the mold cylinder and spaded similarly. After compacting at 150 psi, the mix was subjected to 3000 psi pressure. After that, allow the sample to reach ambient temperature for a whole day. The specimens were then treated in the kiln for a whole day at 60 °C. Six specimens are required for each mix, separated into two groups of three each , three of the samples were tested dry, whereas the other set was tested wet to determine how moisture damage affected compressive strength. Once vertically positioned, the specimens allowed for the application of an axial force at a rate of 5.08 mm/min to the original surface of the specimen until it failed (Ismael and Ismael, 2019). Figure 10 presents compressive strength test specimens.

RESULT AND DISCUSSION

Marshall properties results

Table 3 presents the findings of the Marshall test performed on mixes incorporating recycled concrete aggregates and silica fume at different proportions. It is noteworthy that a rise in the amount of RCA led to a corresponding increase in the optimal asphalt content. This phenomenon may occur because of the adhesion of mortar to aggregates, which in turn absorb a portion of the asphalt cement. The findings from the tests indicated that RCA mixtures without any additive exhibit higher levels of stability and flow values compared to the control mixtures. Including 45% RCA resulted in the highest rise in stability, 21.23% above the control mixture. The fragmentation of the RCA faces resulted in enhanced contact with the binder. Additionally, the value of flow increased by 13.41%. This outcomes agree with (Nwakaire et al., 2020; Xu et al., 2022). A decrease in bulk density observed in every mix included RCA compared with the control mixture was attributed to

Figure 10. Compressive strength test

Table 3. Marshall test outcomes

RCA (%)	S.F (%)	O.A.C (%)	Stability (kN)	Flow (mm)	Density (gm/cm³)	A.V (%)	V.M.A (%)	V.F.A (%)
0	0	4.92	9.89	3.28	2.333	4	14.71	72.80
15	0	5	10.74	3.35	2.325	4	14.64	72.55
	3	5.04	11.19	3.29	2.326	4	14.59	72.58
	6	5.18	11.48	3.20	2.329	4	14.52	72.85
	9	5.26	11.11	3.55	2.337	4	14.82	73.00
30	0	5.07	11.59	3.58	2.317	4	14.60	72.21
	3	5.12	11.69	3.44	2.319	4	14.48	72.41
	6	5.26	12.61	3.17	2.331	4	14.41	72.52
	9	5.31	10.94	3.63	2.336	4	14.85	73.10
45	0	5.16	11.99	3.72	2.307	4	14.50	71.98
	3	5.21	12.31	3.65	2.311	4	14.40	72.22
	6	5.28	12.52	3.45	2.321	4	14.31	72.41
	9	5.38	11.05	3.87	2.324	4	15.05	73.42

the cement mortar clinging to aggregate and high porosity of RCA. Because of the higher absorption of asphalt from the mix by the RCA's surface pores, the proportion of V.M.A. and V.F.A. was lower in the RCA-containing mixtures compared to the standard mixes due to the higher absorption of RCA for binder as a result of the porous surface. The incorporation of silica fume at percentages 3%, 6%, and 9% resulted in an increase in stability until 6%, after which it decreased. In comparison with control mix, the highest increase of 27.50% was observed at 6% when the RCA percentage was 30%, as well as the flow decreasing till 6% and then rising; the greatest decrease was found at the same percent by 3.35%. In addition to using treated RCA, the larger surface area of SF raises the binder stiffness, which results in an improvement in stability and a subsequent decrease in flow. Every RCA mix showed an increase in bulk density as the percentage of SF reached 9%. As a consequence of the substantial amount of SF that was introduced to the binder, the mixture began to become more dense. The ratio of air voids (AV%) in the end result remained within the specified limits. In RCA mixes, the VMA was first lowered until it reached a 6% SF percentage before it started to increase again. This could be due to the higher bulk density and roughness of the RCA. While RCA inclusion reduced VFA, SF inclusion increased it. The SF's large surface area led to a higher quantity of voids being filled with bitumen. It has to be mentioned that each outcome in Table 3, satisfies with SCRB R/9 standards. Figure 11 illustrate the effect of RCA and SF on Marshall characteristics.

Indirect tensile strength test

The findings of the TSR have been utilized to evaluate the mixes' resistance to the 80% required moisture level. RCA was initially introduced to the standard mix at 15%, 30%, and 45% to investigate the resistance of RCA mixes to moisture damage. Figure 12a displays the variation in

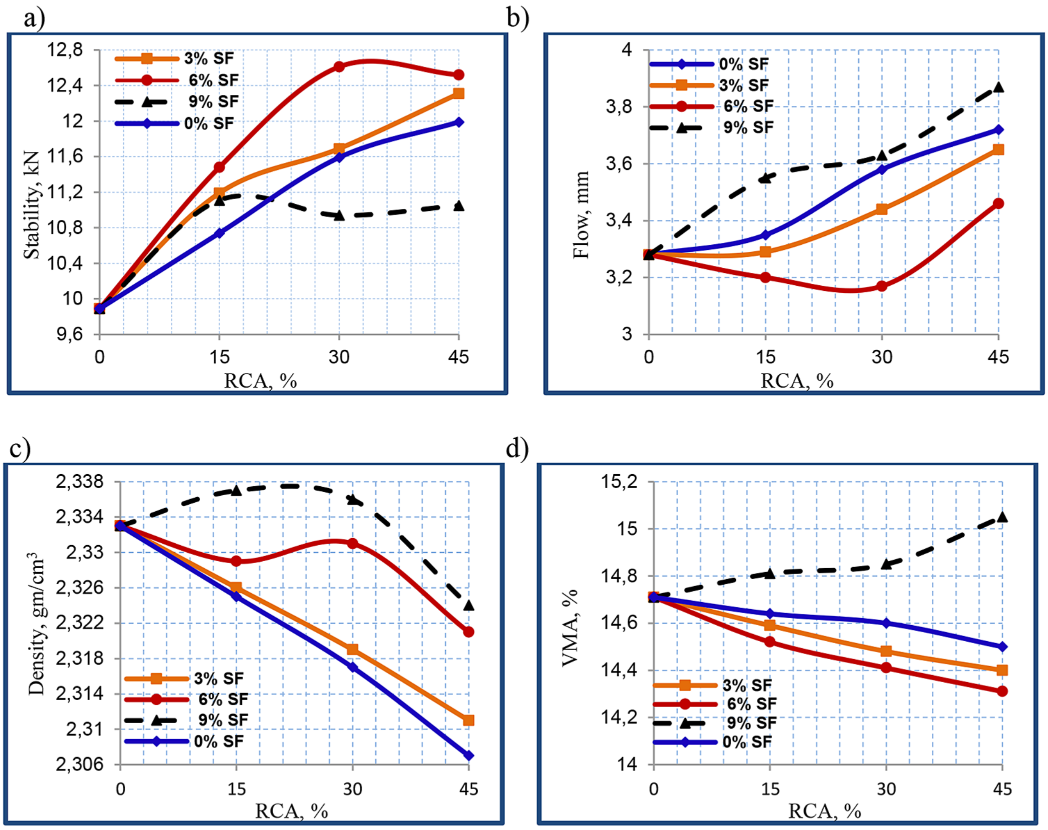

Figure 11. The effect of RCA and SF on Marshall results: (a) stability, (b) flow, (c) density (d) VMA%

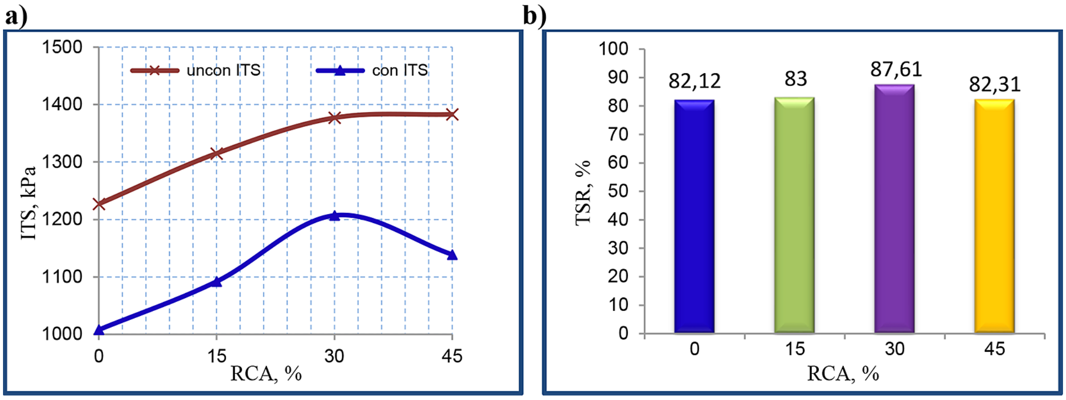

Figure 12 Indirect tensile strength findings: (a) Influence of RCA on ITS, (b) Influence of RCA on TSR

unconditioned and conditioned indirect tensile strength (ITS) and the best percentage of RCA. It is clear that introducing RCA to the standard mix raises the amount of dry and wet ITS. The addition of 15%, 30%, and 45% RCA to the dry samples resulted in an increase in ITS of 7.17%, 8.96%, and 12.71%, respectively. The ITS grows by 8.33%, 19.74%, and 12.99% for samples that are 15%, 30%, and 45% wet, respectively. As displayed in Figure 12b, the highest value of TSR occurred at 30% RCA. TSR rose by 6.68% above standard mix. This findings in line with (Topal et al., 2006; Fatemi and Imaninasab, 2016).

The resistance to damage caused by moisture was enhanced in the second stage by the addition of silica fume at percentages of 3%, 6%, and 9%. From Figure 13 TSR readings for mixes including SF climbed until they peaked at 6% SF, at which point they started to decline when the SF level was raised to 9%. For the mixture containing 15% RCA, the amount of TSR increased by 3.47%, 7.16%, 1.1% for 3, 6% and 9% SF compared with the control mix. Regarding the 30% RCA , the TSR rates had climbed to 10.53%, 13.72%, and 4.38% for the silica fume concentrations of 3%, 6%, and 9%, respectively. At a 45% RCA, the TSR readings experienced a slight rise to 2.29%, 5.33%, and 1.9% for 3%, 6%, and 9% correspondingly. The use of 30% RCA ratio with 6% silica fume resulted in the greatest improvement in TSR, with a rise of 13.72%. The presence of silica fume in the binder allowed for a sufficient amount of asphalt to adhere to the RCA. Consequently, this led to a rise in the cohesive strength between the asphalt and RCA. However, when the silica content reached 9%, its performance declines. This could be attributed to the increased absorption of asphalt caused by higher silica levels, which in turn impairs the adhesion and binding between the different components of the asphaltic mixture. The outcomes of percent 6% in line with (Al-Taher et al., 2018; Zhu and Xu, 2021).

Index of retained strength (IRS)

In order to assess the level of damage caused by moisture in the asphalt mix, the Iraqi standard used IRS factor. According to SCRB R/9, the IRS could not be less than 70%. It is therefore possible to consider every mix as being vulnerable to moisture damage if IRS% is less than this. Figure 14a presents the outcomes of the compressive strength test that was performed on the samples that containing RCA. Like the increasing trend observed in the indirect tensile strength, the addition of 15%, 30%, and 45% recycled concrete aggregate (RCA) improves both the wet and dry compressive strength readings. At 30% RCA, the maximum achieved (IRS) value was 8.93% above the control mix as illustrated in Figure 14b. Figure 15 depicts the results obtained from the IRS test. The inclusion of silica fume at percentages 3%, 6%, and 9% led to a rise in IRS until 6%, then a drop but still above the control mix. When SF was added by binder weight and RCA was used in place of coarse aggregate, the IRS increased by (3.36%, 7.51%, 2.42%) for 15% of samples with 3%, 6%, 9% SF and (10%, 14.13%, 6.44%) for 30% of the samples with 3, 6, 9% SF and (4.75%, 8.69%, 1.9%) for 45% of the samples with 3%, 6%, 9% SF, respectively. The IRS raised by 14.13% when 30% RCA and 6% silica fume were used. This was the greatest enhancement. The findings of percent 6% a complied with (Al-Taher et al., 2018; Zheng et al., 2020).

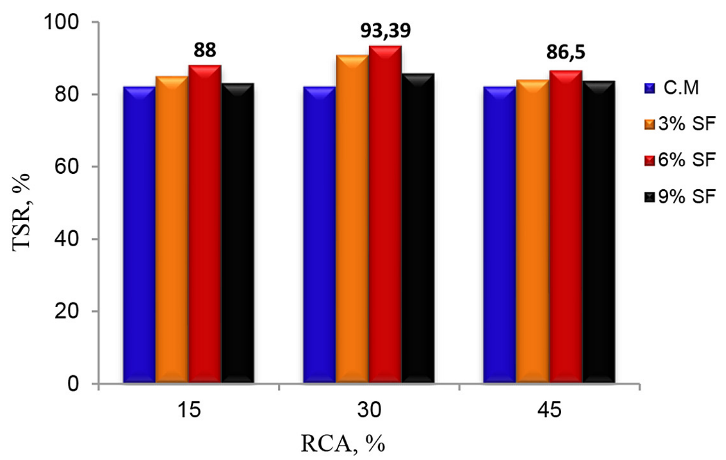

Figure 13. Influence of RCA and SF on the TSR findings

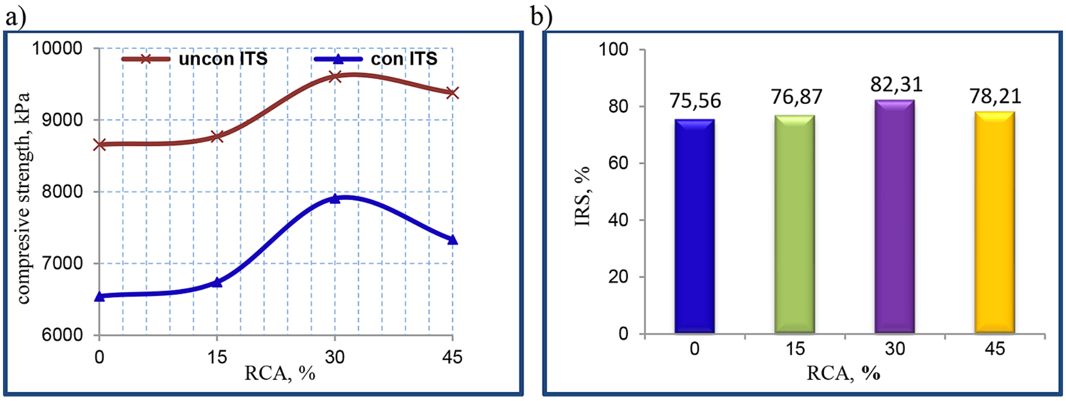

Figure 14. Compressive strength outcomes: (a) influence of RCA on compressive strength, (b) influence of RCA on IRS

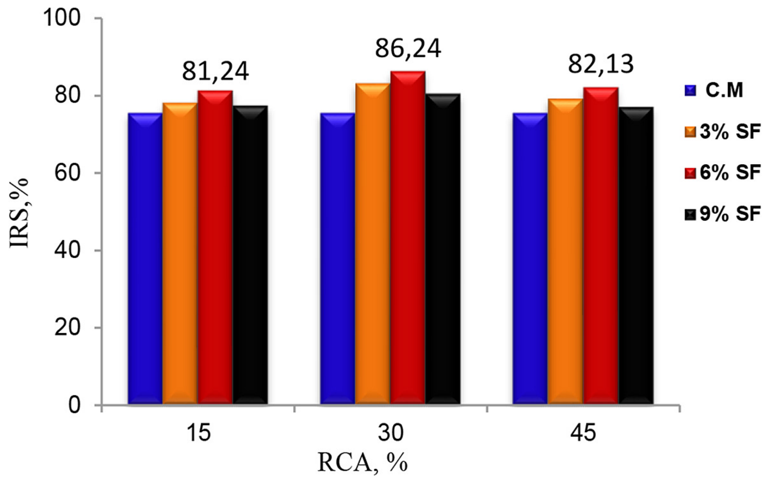

Figure 15. Influence of RCA and SF on IRS findings

CONCLUSIONS

TSR and IRS levels increased by 6.68% and 8.93%, respectively, at RCA 30% when using RCA at 15%, 30%, and 45% by weight of coarse aggregate, in comparison to the original mix.

The inclusion of silica fume at percentages 3%, 6%, and 9% led to a rise in TSR and IRS until 6%, then a drop but still above the original mix. The use of a 30% RCA ratio with 6% silica fume resulted in the highest improvement in TSR and IRS, with a rise of 13.72% and 14.13%, respectively. This revealed a stronger resistance against moisture degredation. The thermal images showed that after 30 minutes of mixing SF at 160 °C, the asphalt cement has been uniformly distributed SF particles, evident by the colour homogeneity.

When the original aggregate in the conventional asphalt mix is replaced with RCA, the resulting mix exhibits a rise in stability with 11.99 kN and lower density with 2.307 gm/cm^3 at RCA 45% as a result of the low weight of RCA.

The incorporation of silica fume at percentages 3%, 6%, and 9% resulted in an increase in stability until 6%, after which it decreased. In comparison with the original mix recorded at 9.89 kN, the highest increase measuring 12.61 kN by 27.50% was observed at 6% when the RCA percentage was 30%, as well as the flow decreasing till 6% and then rising; the greatest decrease was found at the same percent by 3.35% noted 3.17 mm.

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