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Original Research

An Experimental Investigation to Enhance the Strength of Recycled Aggregate Concrete Using Silica Fume

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ABSTRACT

Burying construction waste in the soil causes a negative environmental impact. Therefore, it is essential to find effective disposal methods, such as recycling and reuse. This study investigates the effect of using recycled concrete aggregate (RCA) at 25%, 50%, and 75% on the mechanical properties of new concrete, as well as substituting of a 10% and 20% of the cement with silica fume to compensate for the expected decrease in concrete strength when using RCA. The results showed that replacing 25% of the natural coarse aggregate (NCA) with RCA does not significantly affect compressive strength. Replacement percentages of 50% and 75% caused a greater decrease in strength. These ratios have a greater impact on tensile and flexural strength than on compressive strength. A 25% replacement ratio yields better results than other ratios. Adding silica fume has a positive effect; replacing 10% of the cement with silica fume increases compressive strength by 12% as compared to ordinary concrete, by 8% compared to concrete treated with 25% RCA, and by 9% compared to concrete treated with 50% RCA. However, replacing 20% of the cement with silica fume reduces strength compared to ordinary concrete. Therefore, the reductions resulting from replacing 25% and 50% of the RCA with NCA can be repaid by replacing 10% of the cement with silica fume.

Keywords: Sustainability, recycled concrete aggregate, normal coarse aggregate, silica fume, mechanical properties

1. Introduction

Concrete is widely used as a building material worldwide due to its ease of formation, low cost, and the availability of local raw materials. It is used in the construction of multiple structures and infrastructure types, like residential, commercial, and high-rise buildings, water facilities, roads, bridges, and others [1]. However, the high consumption of cement and natural resources such as aggregate harms the environment and life on Earth. Therefore, the high production and use of concrete have negative environmental impacts due to its contribution to greenhouse gas emissions and the exhaustion of natural resources [2], [3]. Although concrete production results in the release of fewer embodied carbon units compared to the manufacturing of other substances, such as glass and steel, the high use of concrete in the construction industry has made it a major contributor to greenhouse gas emissions [4]. This is due to the production of cement, which is an essential component of concrete and the main binding agent in concrete and building processes. Concrete consumes the most Portland cement, at an estimated 70%, while the remaining 30% is used in other building processes, such as mortar, plaster, and others [5]. About 4 billion tons of Portland cement are annually produced worldwide [6], and this amount is expected to increase by up to 23% annually to reach 5 billion by 2050 [7] due to rapid urbanization and population growth. Furthermore, urban renewability in many regions around the world has recently resulted in large-scale production of demolition and construction waste, which detrimentally impacts the environment and life [8]. One of the optimal choices involves applying these wastes to concrete aggregate. Therefore, applying recycled aggregate in concrete production can assist in reducing its negative impact.

Due to these reasons, great efforts have been made by researchers and manufacturers worldwide to reduce these negative impacts. The primary objective of these efforts was to reduce cement and natural aggregate consumption through alternative materials. Recycled aggregate can be an alternative to reduce the amount of conventional aggregate used in concrete construction [9]. Mineral supplementary cementitious materials, on the other hand, were utilized to replace a cement portion [8], [10].
According to the reports of the United Nations Environment Program (UNEP), demolition and construction waste occupies (25% - 30%) of the overall global solid waste, annually producing around 2.2 billion tons [7], [11]. This great volume is expected to rise by more than 40% by 2030 due to the acceleration. The U.S. Environmental Protection Agency (EPA) reported that 67% of waste from urban growth comes from concrete alone, making it the most influential ingredient of that waste category. Demolished or old concrete waste particularly causes serious challenges to the environment, as it is an intensive and heavy substance that is difficult to decompose naturally. Therefore, researchers and manufacturers have focused efforts on utilizing these industrial wastes; one of these benefits is using them in the production of concrete [12].
Debris from the buildings and structures resulting from natural disasters, renovations, and other activities has become one of the most significant pollutants of the environment and air, causing problems for life on Earth. This debris includes residues from building substances, such as concrete and brick. Debris processing systems are increasingly stressed due to the huge quantities resulting from construction and demolition processes, causing a stack of debris in landfills or randomly thrown down into the soil [13], [14]. This stacking not only deteriorates expanded lands but also contributes to the release of pollutants that affect air, water, and soil quality. Therefore, the use of recycled aggregates in new construction has become increasingly attractive due to their potential as an environmentally friendly material. Furthermore, the shortage of supplying the normal aggregates in some regions around the world encourages the development of recycled aggregates as a substitute for aggregate sources [15]. However, the use of RA in concrete reduces its strength and increases porosity, which makes concrete susceptible to attack by sulfates and acids. Many studies [16], [17], [18], [19], [20], [21], [22], [23], [24] found that the reduction in strength due to the application of recycled concrete aggregate at a constant w/c ratio can be minimized if good concrete is used as the coarse recycled aggregate, in addition to adding a proportion of fine recycled aggregate.
Supplementary cementitious materials, including silica fume, fly ash, metakaolin, and blast-furnace slag, have been frequently used as additives to cement concretes or to replace a cement portion [25], [26], [27]. Its use was because of its high pozzolanic activity; the implication of silica fume in concrete can improve its mechanical and durability properties [26].
This research presents an experimental study to demonstrate the impact of using silica fume to replace part of the cement on the mechanical properties of concrete manufactured using recycled concrete aggregates (RCA) resulting from the demolition of old concrete structures.

2. Experimental Program

Two parameters were adopted in this study, both of which look at sustainability in concrete production. The first involved replacing proportions of coarse aggregate with recycled concrete aggregate, and the second involved replacing a proportion of cement with silica fume. Therefore, twelve concrete mixes were produced. The experiments also discussed adjusting the superplasticizer dosage to maintain fresh concrete workability when the recycled aggregate content increased.
Increasing the percentage replacement of recycled concrete aggregate and/or adding silica fume reduces the workability of the fresh concrete mix [28]. This is due to the recycled aggregate's ability to absorb water. Additionally, the microsize of the silica fume particles results in a high surface area, allowing them to absorb a high number of water molecules [29]. However, in this study, the water-to-cement ratio was maintained at a constant ratio of 0.5%, while workability was modified by raising the superplasticizer content. Silica fume is a cementitious substance that can enhance the mechanical properties of concrete. On the other hand, silica fume can also compensate for the weakness resulting from using RCA in the mixture. Therefore, two ratios of silica fume were used to replace a percentage of the cement content. These ratios were 10% and 20%; besides, no silica fume (0%) in the reference mix

3. Materials and Mix Proportion

The mixes were classified into three groups. The first group consisted of four mixtures with a 450 kg/m³ cement content, without silica fume, and with the coarse aggregate replaced by recycled concrete aggregate at 0%, 25%,

50%, and 75%.
The second group included four mixtures with a cement content of 405 kg/m^3 and 45 kg/m^3 silica fume, which match a 10 % replacement of cement content. Also, the coarse aggregate has been replaced with recycled concrete aggregate using four ratios: 0%, 25%, 50%, and 75%.
The third group consisted of four mixtures with a cement content of 360 kg/m^3 and 90 kg/m^3 silica fume, representing a 20% replacement of cement content. Also, the coarse aggregate has been replaced with recycled concrete aggregate using four ratios: 0%, 25%, 50%, and 75%.
The fine aggregate remained fixed at 820 kg/m^3 for all mixtures. The superplasticizer dosage was modified for each mix, depending on the recycled concrete aggregate and silica fume content. Table 1 clarifies the mix proportions of all mixtures used in this study.

Table 1. Mix proportions of the twelve mixtures

Group	Mix ID	Cem.	Water	RCA		NCA		FA	Silica Fume		Superplasticizer	
		kg	kg	%	Wt. kg	%	Wt. kg	kg	%	Wt. kg	%	Wt. kg
G1	MR	450	225	0	-	100%	850	820	0	-	0.5	2.25
	M1	450	225	25%	212.5	75%	675.5	820	0	-	1	4.5
	M2	450	225	50%	425	50%	425	820	0	-	1.25	5.625
	M3	450	225	75%	675.5	25%	212.5	820	0	-	1.5	6.75
G2	M4	405	225	0	-	100%	850	820	10%	45	1	4.5
	M5	405	225	25%	212.5	75%	675.5	820	10%	45	1.25	5.625
	M6	405	225	50%	425	50%	425	820	10%	45	1.5	6.75
	M7	405	225	75%	675.5	25%	212.5	820	10%	45	1.75	7.875
G3	M8	360	225	0	-	100%	850	820	20%	90	1	4.5
	M9	360	225	25%	212.5	75%	675.5	820	20%	90	1.25	5.625
	M10	360	225	50%	425	50%	425	820	20%	90	1.5	6.75
	M11	360	225	75%	675.5	25%	212.5	820	20%	90	1.75	7.875

Ordinary Portland cement (ASTM Type I) of the Mass brand manufactured in Iraq was used throughout the experimental work. Tables 2 and 3 list the test results of chemical analysis and physical properties of the cement, respectively.

Table 2. Chemical Analysis of Cement

Oxides composition	Content, %	ASTM C150-16 [30]	IQS No.5 / 2019 [31]	Main Compounds		
				Main Compounds	Content, %	ASTM C150-16
CaO	61.61	-	-	C_3A	6.15	8.0 (max.)
SiO_2	20.08	-	-			
Al_2O_3	4.62	6.0 (max.)	-	C_3S	54.29	-
Fe_2O_3	3.60	6.0 (max.)	-			
MgO	2.12	6.0 (max.)	5.0 (max.)	C_2S	16.61	-
SO_3	2.71	3.0 (max.)	2.5 (max.)			
Loss on Ignition, L.O.I	2.40	3.5 (max.)	4.0 (max.)	C_4AF	10.95	-
Lime Saturation Factor	0.93	-	0.66-1.02			

Table 3. Physical Properties of Cement

Physical Properties	Test results	ASTM C150-16 [30]	IQS No.5 / 2019 [31]
Specific surface area (Blaine method), m^2/kg	368	260 (min.)	230 (min.)
Setting time (Vigat test)			
-Initial setting time (hrs.: minutes)	01:45	0:45(min.)	≥ 0:45
-Final setting time (hrs.: minutes)	02:50	6:15 (max.)	≤ 10:00
Compressive strength, MPa			
- 3 days	18.40	12.0	15.0 (min.)
- 7 days	26.50	19.0	23.0 (min.)

Densified micro-silica produced by CONMIX-Construction Chemical Company, of a type of MegaAdd MS(D), was used in the mixtures of the experimental work. The chemical composition of silica fume applied in this study is listed in Table 4. The silica fume applied in this work conforms to the chemical and physical requirements of ASTM C1240-03a [30], as shown in Tables 4 and 5.

Table 4. Chemical Composition of Silica Fume concerning ASTM C1240 Requirements [32]

Oxide component	Oxide percentage,%	Specification limits, ASTM C1240 [32]
SiO_2	90.65	85.0 (min.)
Al_2O_3	0.57	-
Fe_2O_3	0.89	-
Na_2O	1.33	-
K_2O	1.97	-
CaO	2.50	-
MgO	1.14	-
SO_3	0.34	-
Moisture ratio, %	0.5	3.0 (max.)
Loss on Ignition, %	lower than 1.6 %	6.0 (max.)

Table 5. Physical Characteristics of Silica Fume at 25 °C

Properties	Value of applied silica fume *
Status	Amorphous, micro-powder
Color	Dark to medium grey powder
Density, Specific	2.00-2.40
Density, Bulk, kg/m^3	510-710
Surface area per unit mass, m^2/kg	15000
Pozzolanic Activity Indicator, at 7 days	104 %
Oversized particles hold on a 45-micrometer sieve	≤ 10 %

* Values provided by the manufacturer

The recycled aggregate was produced from concrete cubes that were tested and broken in the concrete laboratory at the College of Engineering, University of Wasit. More than 600 cubes with 150 mm side dimensions were crushed using a steel hammer and a crushing machine, then sieved to determine the size of the coarse aggregate. The retained aggregate on a 4.75 mm sieve and passing through a 14 mm sieve was used as coarse RCA. The compressive strength of the concrete cubes used to produce RCA ranged from 20 to 25 MPa, as tested by the Schmidt hammer. The RCA was sieved to achieve the required grading in compliance with ASTM C33. The bulk density was 1370 kg/m^3. Figure 1 illustrates the grading of RCA.

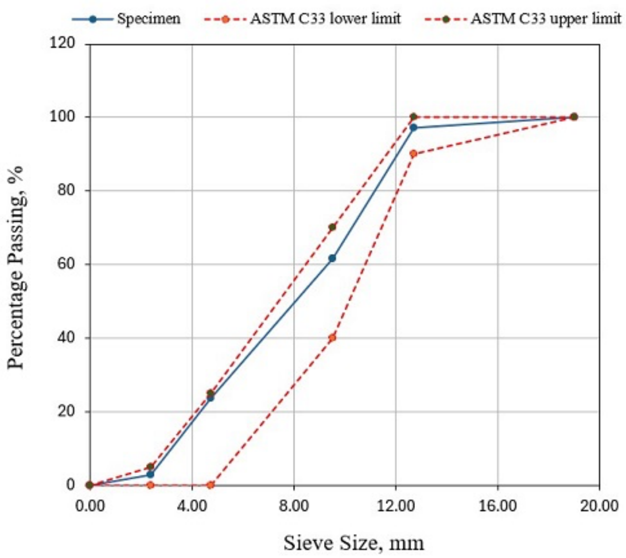

Figure 1. Sieve analysis of RCA

Natural sand was utilized as a fine aggregate in all mixes. Sieve analysis shows that the fine aggregate is a fine sand in zone 2 according to Iraqi Specification No. 45/1984. The fineness modulus of the fine aggregate was 2.53, and the bulk density was 1660 kg/m^3. Figure 2 illustrates the sieve analysis of fine aggregate. Natural crushed gravel was used as a natural coarse aggregate in the mixtures. The maximum gravel size was 14 mm. The sieve analysis is consistent with the Iraqi Specifications No. 45/1984. The bulk density was 1577 kg/m^3.

Figure 3 illustrates the coarse aggregate's sieve analysis.

Ordinary potable tap water was used to blend all the mixes applied throughout the works and for curing all the specimens. Sika ViscoCrete -180 GS, a high-range water reducer, retarder, and slump retainer, was used as a superplasticizer material to modify the workability of fresh mixtures. It conforms to the requirements of ASTM C494-Type F and G [33]. Upon adding the admixture, particle surface adsorption and steric effects act on the separation of cement particles, which cause a long workability time and flowable mixture. Table 6 lists the properties of the admixture.

Table 6. Properties of Viscocrete -180 GS [34]

Properties	Characterization*
Appearance/color	brown liquid
Chemical base	Hydrous solution of polycarboxylates
pH range	4 - 6
Density	1.07 +/- 0.02 gm/cm^3
Total Chloride ion content	Max. 0.1 % Chloride-free (TS EN 934-2)
Recommended dosage	For plastic mix: 0.5-1 % by weight of binder For self-compact mix:1-2 % by weight of binder

* The properties are provided by the manufacturer

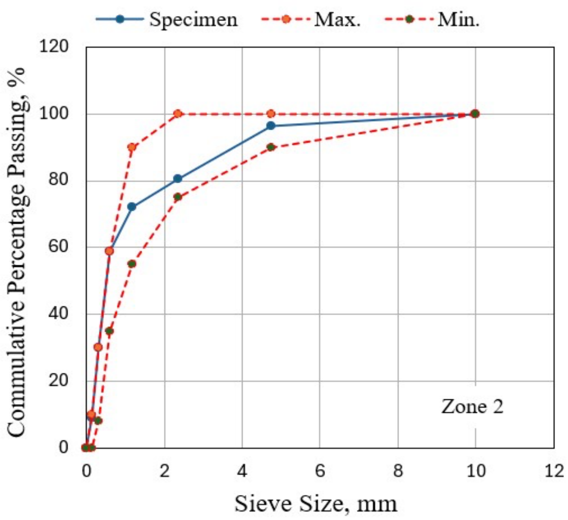

Figure 2. Sieve analysis of the fine aggregate

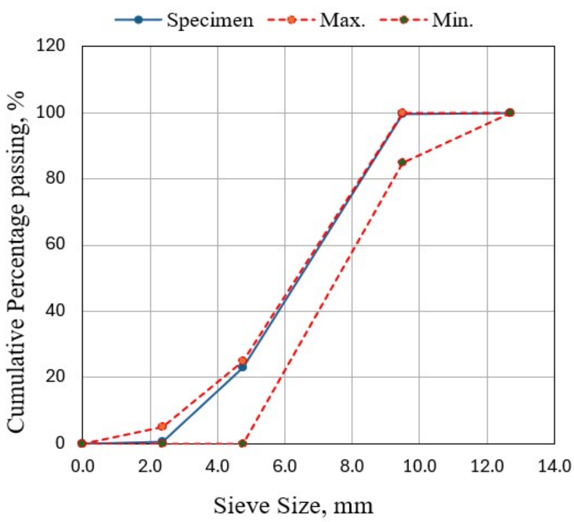

Figure 3. Sieve analysis of the natural coarse aggregate

4. Mixing Procedure and Curing

A Rotary Drum Mixer with a capacity of 125 liters was used to prepare the concrete mixtures. The mixing procedure was initiated by adding the two types of coarse aggregates (RCA and gravel) and sand to the mixer and mixing for a minute. Then, cement was added to the mixer and mixed for another minute. Next, half of the mixing water was added to the mixer with continuous mixing to moisturize the mix, followed by gradual addition of the second half of mixing water, which had been premixed with superplasticizer, with progressive mixing. The mixing time was approximately 5 to 7 minutes. When using silica fume in the mixture, it was premixed with cement before adding to the mixer to ensure that the fine powder of silica fume was thoroughly dispersed among the cement particles.

Before casting the concrete, the specimen molds were cleaned and slightly oiled to prevent adhesion of hardened concrete to the mold's surfaces. Then the internal surfaces were swabbed with a cloth to eliminate extra oil. The concrete was poured into prism and cylindrical molds in two equal layers. Each layer was compacted using a shaking table. The top surface of the samples was equalized via a steel trowel.

After completing casting, the specimens were entirely covered by polyethylene sheets to prevent water evaporation. 24 hours later, the hardened samples were demolded. Thereafter, they were cured using water for 28 days.

5. Experimental Results and Discussion

The mechanical properties of the twelve concrete types were determined, including compressive, tensile, and flexural strengths for each mixture type. An average value of three or more specimens was taken to represent the mechanical properties of each mixture type at 70-day age. The test was conducted at 70 days to allow for reactions between SiO_2 in the silica fume and the calcium hydroxide produced by the cement hydration. These reactions require a relatively long period to achieve the benefit of using the silica fume.

Concrete cylindrical specimens were used to determine the compressive strength, using (100×200) mm cylinders, according to ASTM C39/C39M-18 [35]. The loading rate was controlled at 2.0 kN/sec, which means approximately 0.25 MPa/sec, according to ASTM C39/C39-18. Cylindrical specimens with dimensions of (100 × 200) mm were also prepared and tested according to ASTM C496/C496M-11 [36] to determine the splitting tensile strength of concrete. The tests were performed using an Matest Digital Compression Testing Machine with 2000 kN capacity, as shown in Figure 4.

Prism specimens with dimensions of (100 ×100 × 400) mm were prepared and tested according to ASTM C78/C78M-16 [37] for all specimens, using a Matest Flexural Test Apparatus with 50 kN capacity, as shown in Figure 5. The loading rate was fixed at 0.02 kN/sec throughout the test, which was equivalent to 1.10 MPa/min, as recommended by ASTM C78/C78M-16. A four-point loading test was applied to test the prisms with a clear span of 300 mm.

Figure 4. Matest apparatus for compressive and tensile strength tests

Figure 5. Matest apparatus for flexural strength tests

Table 7 shows the test results of the mechanical properties of all specimens, including percentages of variation relative to the natural coarse aggregate concrete.

Table 7. Test results of the specimens

Group	Mix ID	RCA %	SF %	f'c MPa	% variation	fspt MPa	% variation	fr MPa	% variation
G1	MR	0	0	39.81	0.00	4.94	0.00	5.70	0.00
	M1	25%	0	39.55	-0.65	4.40	-10.93	5.43	-4.74
	M2	50%	0	35.50	-10.83	4.10	-17.00	5.36	-5.96
	M3	75%	0	30.24	-24.04	3.83	-22.47	4.91	-13.86
G2	M4	0	10%	44.74	0.00	5.07	0.00	5.78	0.00
	M5	25%	10%	42.58	-4.83	4.59	-9.47	5.48	-5.19
	M6	50%	10%	38.77	-13.34	4.42	-12.82	5.43	-6.06
	M7	75%	10%	32.22	-27.98	4.06	-19.92	5.11	-11.59
G3	M8	0	20%	37.26	0.00	4.49	0.00	5.52	0.00
	M9	25%	20%	36.54	-1.93	4.44	-1.11	5.04	-8.70
	M10	50%	20%	32.21	-13.55	3.98	-11.36	4.63	-16.12
	M11	75%	20%	29.72	-20.24	3.71	-17.37	4.60	-16.67

RCA: Recycled Concrete Aggregate; SF: Silica Fume Percentage; f'c: compressive strength;
fspt: Splitting tensile strength; fr: flexural strength (modulus of rupture).

5.1. Slump Test Results

A slump test was performed to assess the workability of concrete mixtures. The results showed that decreasing the slump upon increasing the RCA percentage. Therefore, the superplasticizer dosage should be increased to maintain the workability. When no cement replacement with silica fume (i.e., silica fume content was zero), the results showed a 31% reduction in slump when 25% of the natural aggregate was replaced with coarse RCA, along with a 100% increase in superplasticizer content. The reduction in slump increased further to 37% with 50% and 75% RCA content, along with 150% and 200% increase in superplasticizer content, respectively, as illustrated in Figures 6 and 7. The reduction in slump is due to the high porosity of recycled aggregate, which absorbs more water. To maintain convenient workability, the mixing water should be increased, or the dosage of plasticizing admixtures should be increased. In this work, the w/c ratio remained constant, while the plasticizing admixtures were increased to modify the mix's workability.

When cement was replaced with 10% silica fume, the results showed an increased need for superplasticizer. The superplasticizer content increased by 30% at 25% RCA, by 43% at 50% RCA, and by 57% at 75% RCA.

Upon replacing cement with 10% silica fume, the superplasticizer content needed to be increased by 180% to achieve 66% of the slump value of the mix without RCA, maintaining the same w/c ratio, as shown in Figures 6 and 7.

Replacing cement with 20% silica fume reduced the slump by 17% when NCA was replaced with coarse RCA, and the superplasticizer content was increased to 19%. The decrease in slump increased to 33% and 39% when the RCA content increased to 50% and 75%, respectively, despite increasing the superplasticizer content to 31% and 41%, respectively. Replacing cement with 20% silica fume required increasing the superplasticizer content by 220% to achieve a slump rate of 51% of that of ordinary concrete. The reason for this additional increase in plasticizers is due to the use of micro-silica, which has a high surface area.

In general, slump results coincided with results obtained by some researchers. Younis et al. [38] found that adding 20% silica fume to the concrete mix lowered the slump value by (110 – 55) mm. Sobuz et al. [39] stated that incorporating silica fume into the concrete mix decreases the slump from 120 mm to 30 mm. Meraz et al [40] stated that the concrete mix loses its workability at a certain rate upon adding micro-silica. However, the slump results for all mixes used in this study remained within the desired range from 55 mm to 115 mm to reach the required workability, as shown in Figure 8.

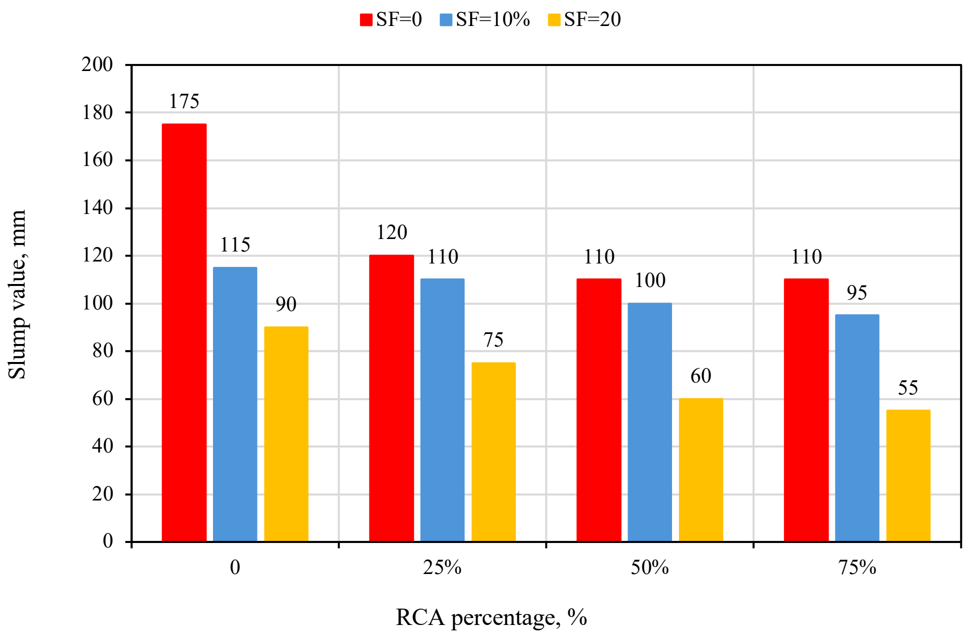

Figure 6. The relationship between RCA percentages and slump value

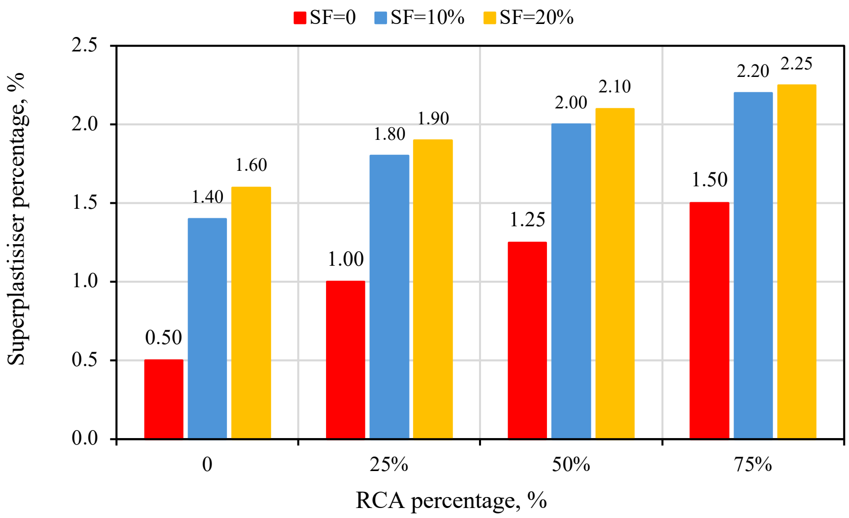

Figure 7. The relationship between superplasticizer percentage and RCA percentage

(a) Slump of MR (b) Slump of M6 (c) Slump of M7

Figure 8. Measurement of mixtures' slump via the cone test

5.2. Impact of replacing natural coarse aggregate (NCA) with RCA on the mechanical properties

This study involved replacing NCA with RCA from old concrete, using four weight ratios for replacement: 0%, 25%, 50%, and 75%. Additionally, a portion of the cement content was replaced with silica fume at rates of 10% and 20%. The impact of each parameter will be discussed separately, along with the mutual effect of each on the mechanical properties of hardened concrete.

5.2.1. Impact of replacing NCA with RCA on the mechanical properties of concrete without Silica Fume

Figure 9 illustrates the compressive, splitting tensile, and flexural strengths of concrete specimens without silica fume, with RCA replacing NCA at varying percentages. It appears that replacing 25% of NCA with recycled aggregate does not significantly affect compressive strength, as the decrease in strength is no more than 0.65%, as indicated in Table 7. However, when the replacement percentage increases to 50% and 75%, the compressive strength decreases by a relatively higher percentage, reaching 11% and 24%, respectively.

Regarding tensile strength, Figure 9 shows that substituting NCA with RCA has a significant impact on tensile strength than on compressive strength. Tensile strength decreases by 11%, 17%, and 22% when the aggregate is replaced by 25%, 50%, and 75%, respectively. This apparent decrease in tensile strength is due to the composition of the recycled concrete aggregate, which consists of natural coarse aggregate mixed with the old mortar layer, resulting in increased porosity, higher water absorption, and consequently, a weak interfacial transition zone, as illustrated in Figures 10 and 11. Therefore, that weakness reduces tensile strength more than compressive strength. This also applies to flexural strength, but to a lesser degree, where the reduction in modulus of rupture is less than that of tensile strength. The modulus of rupture decreases by 5%, 6%, and 14% when the aggregate is replaced by 25%, 50%, and 75%, respectively. This indicates that the impact of natural aggregate remains dominant and that the stress distribution has not been significantly affected by the replacement ratio of RCA.

The reason for reducing the RAC strengths more than those of normal concrete may be due to the premature collapse of the old mortar, besides accumulation failure in the bonding areas between the new mortar and the recycled aggregate. The bonding strength of the interfacial transition zone decreases, and the old-cracked mortar becomes weaker, causing rapid crack propagation and loss of cohesion. The tensile and flexural strengths depend primarily on the integrity of the interfacial transition zone, and not just the strength of the aggregate.

As compared to the results of other researchers, Riaz et al. [41] found that the concrete cylinder compressive strength decreases by 2%, 11%, and 19% when NCA was replaced with RCA at rates of 25%, 50%, and 75%, respectively. Al-Azzawi [41] found that the cube compressive strength decreased by 7%, 13%, and 19% when normal aggregate was substituted with recycled aggregate at rates of 25%, 50%, and 75%, respectively. Meanwhile, the tensile strength decreased by smaller percentages of 2%, 3%, and 11% when natural aggregate was replaced with recycled aggregate by the same ratios. Etxeberria [22] reported that the compressive strength of concrete made with 100% of RCA was lower than the 28-day NCA concrete by 20–25%, at the same w/c ratio and cement content.

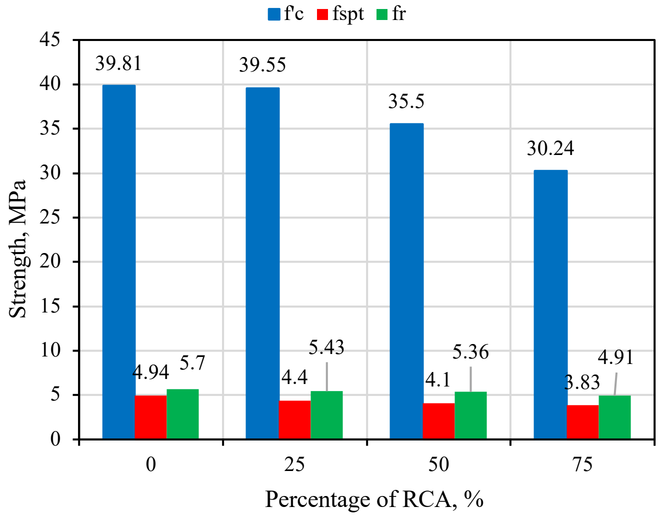

Figure 9. Compressive, tensile, and flexural strength of zero silica fume content at different percentages of RCA

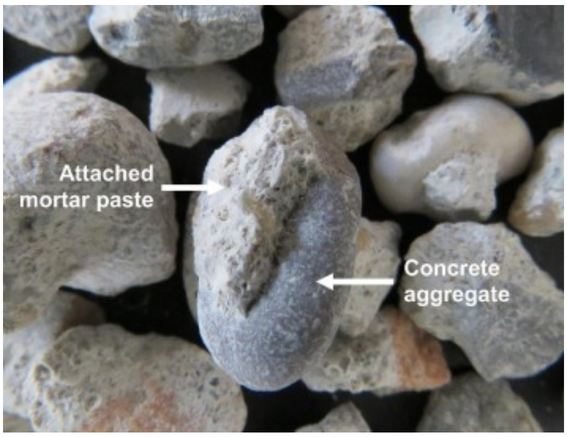

Figure 10. The attached mortar to the gravel in the RCA

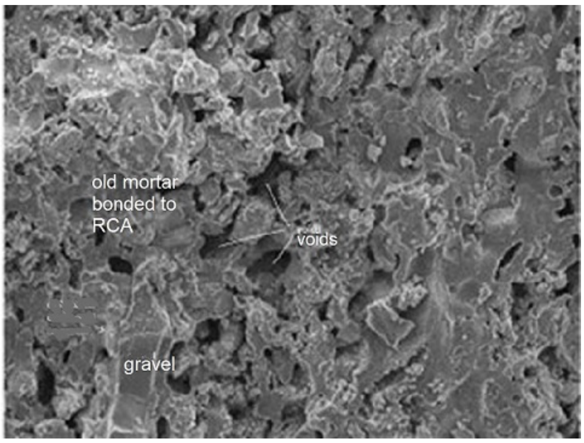

Figure 11. A microscopic image of RCA

5.2.2. Impact of replacing NCA with RCA on the concrete mechanical properties with 10 % Silica Fume

Figure 12 shows compressive, splitting tensile, and flexural strengths of concrete specimens in which 10% of the cement content was replaced with silica fume, and NCA was replaced with RCA at three percentages: 25%, 50%, and 75%. It appears that replacing 25% of NCA with RCA has a slight effect on compressive strength, as the strength decreases by about 5%. However, when the replacement percentage increases to 50% and 75%, the compressive strength decreases by relatively large amounts, reaching 13% and 28%, respectively. This verifies that replacing cement with 10% silica fume and replacing coarse aggregate with 25% recycled aggregate increases compressive strength, resulting in a value higher than that of conventional concrete by 7%. Furthermore, it compensates for the deficiency when using recycled aggregate at a rate of 50%, yielding a strength very close to that of normal concrete, as illustrated in Table 7.

Regarding tensile and flexural strength, it is clear that replacing NCA with RCA at 25% and 50%, along with silica fume to replace cement content at 10 %, results in higher tensile strength than that of normal concrete. Generally, the tensile strength decreases by 9.5%, 13%, and 20% when the normal aggregate is replaced by RCA at 25%, 50%, and 75%, respectively, compared to normal concrete with a 10% silica fume replacement ratio. Flexural strength decreases by 5%, 6%, and 12 % when the aggregate is replaced by 25%, 50%, and 75%, respectively. It can be said that the use of silica fume enhances tensile and flexural strength more than compressive strength at 50% and 75% replacement of ordinary aggregate with RCA.

However, replacing NCA with 25 % and 50% RCA, along with replacing cement with 10% silica fume, can enhance the compressive, tensile, and flexural strengths of concrete compared to those of ordinary concrete. Anyway, a 75% replacement ratio causes a slight decrease in those strengths compared to normal concrete strengths, which can be attributed to an increase in the overall porosity of the resulting concrete, weak bonding in the interfacial transition zone, and the transmission of cracks through the old mortar.

The improvement in the strength of concrete containing 10% silica fume is due to the effectiveness of the reaction between the silicate oxides in the silica fume and the calcium hydroxide produced by cement hydration, which forms calcium silicate hydrate products similar to those formed by cement hydration; therefore, increasing strength.

5.2.3. Impact of replacing NCA with RCA on the mechanical properties of concrete with 20 % Silica Fume

Replacing cement with 20% silica fume generally results in a decrease in all three strengths compared to those of normal concrete. however, at 20% silica fume to replace cement content, the compressive strength decreased by 2%, 14%, and 20%, respectively, tensile strength reduced by 1%, 11%, and 17%, respectively, flexural strength decreased by 9%, 16%, and 17%, respectively, upon replacing NCA with RCA at 25%, 50%, and 75%, respectively, as illustrated in Figure 13.

Replacing 20% of the cement content with silica fume did not show a significant improvement in concrete strength. This is attributed to the reduced cement content, which can produce calcium hydroxide that may react with relatively high silica oxides. Furthermore, increasing the content of fine-grained silica fume increases water demand, thus hindering the completion of pozzolanic reactions between silica fume and the cement hydration products, which are calcium hydroxide.

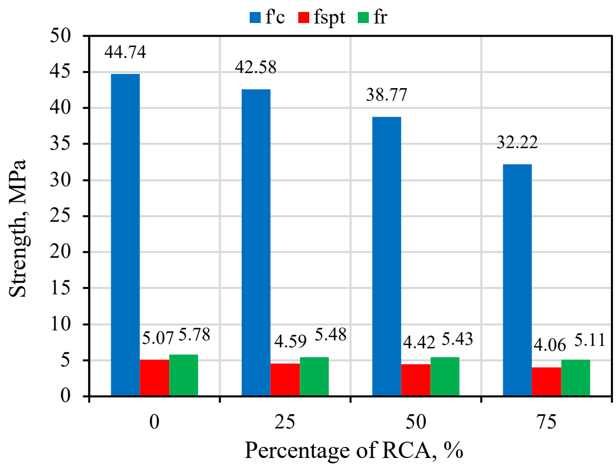

Figure 12. Compressive, tensile, and flexural strength of 10% silica fume at different percentages of RCA

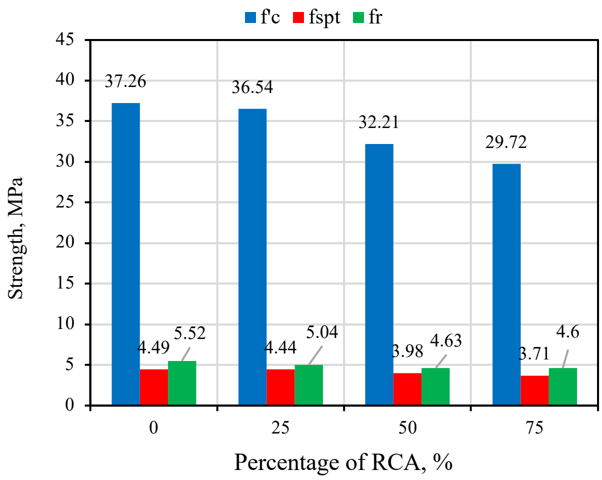

Figure 13. Compressive, tensile, and flexural strength of 20% silica fume at different percentages of RCA

5.3. Impact of replacing a proportion of cement with Silica Fume on the mechanical properties of concrete

The study involved replacing 10% and 20% of cement content with silica fume, along with replacing NCA with recycled one at different percentages. That was to compensate for the expected decrease in the strength of concrete containing recycled aggregate. Besides the concrete with zero silica fume for comparison. Thus, three proportions were regarded for silica fume.

5.3.1. Impact of replacing a proportion of cement with Silica Fume on the mechanical properties of concrete without RCA

Amorphous silica has pozzolanic properties that facilitate its reaction with calcium hydroxide produced by cement hydration to form calcium silicate hydrates (C-S-H), which, in turn, enhance strength and reduce porosity in the concrete microstructure.

The results show that the improvement rate of hardened concrete depends on the ratio of silicate dioxide and calcium hydroxide for the reaction that occurs between them to form extra C-S-H. If the ratio of calcium hydroxide resulting from the cement hydration in the mix is equal to the ratio of silicate, a great improvement will be achieved. However, if the ratios are not balanced, there will be a partial improvement, as shown by the study results. Figure 14 shows that a 10% silica fume content improved strength more than a 20% content. At 10% silica fume, the compressive, tensile, and flexural strength increased by 12 %, 3%, and 1.4%, respectively, as illustrated in Figure 15. The improvement of compressive strength is more pronounced than tensile and flexural strength. That is related to the mechanisms of stress transferring and fracture in concrete. The compressive strength primarily depends on density and strength of cement paste and interfacial transition zone between paste and aggregate, whereas tensile strength mainly relies on the progressive distribution of microcracks in a concrete microstructure, as well as the concrete's ability to hinder or delay crack development. Silica fume enhances cement paste and transition zone density, besides strength, while not affecting the mechanism of brittle cracking of concrete.

On the other hand, increasing silica fume content and decreasing the cement content reduces the reaction between SiO2 and Ca(OH)2 due to the decrease in calcium hydroxide resulting from cement hydration, and consequently, the density and strength of the cement paste and the transition zone decrease. Therefore, the compressive, tensile, and flexural strength decrease by 6.4%, 9%, and 3 %, respectively, below the counterparts of conventional concrete, upon replacing 20% of cement content by silica fume, as illustrated in Figure 15.

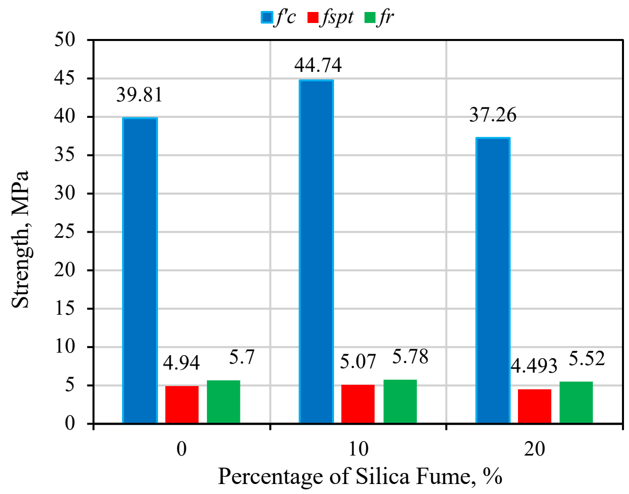

Figure 14. Compressive, tensile, and flexural strength of zero RCA and different percentages of silica fume

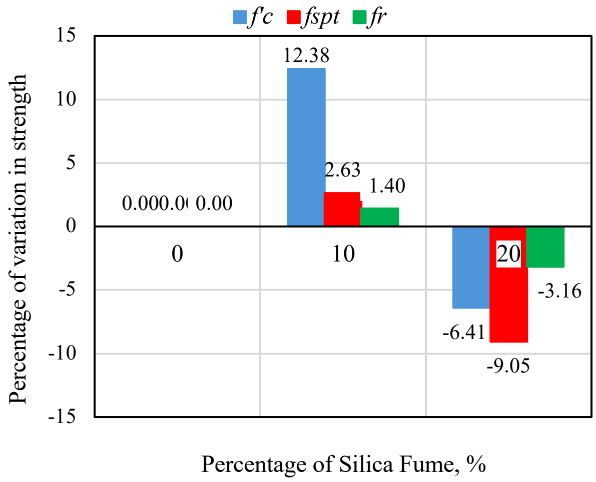

Figure 15. Variation of compressive, tensile, and flexural strength at 10% and 20 % silica fume and zero RCA.

5.3.2. Impact of replacing a percentage of cement with Silica Fume on the mechanical properties of concrete with 25 % RCA

Replacing 25% of NCA with RCA causes a slight decrease in compressive, tensile, and flexural strength. Whereas the replacement of 10% cement with silica fume, along with 25% recycled aggregate, improves compressive strength by 8%, tensile strength by 4%, and flexural strength by 1%, as illustrated in Figures 16 and 17. That is due to the same causes mentioned above. In contrast, replacing cement with 20 % silica fume reduces compressive strength by 8 %, flexural strength by 7 %, but it slightly increases tensile strength by 1 %, as shown in Figures 16 and 17. This behavior is due to the same causes mentioned above in paragraph 5.3.1.

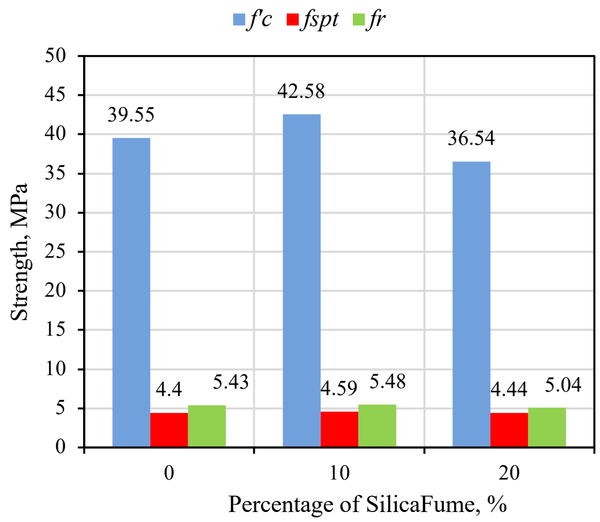

Figure 16. Compressive, tensile, and flexural strength of 25% RCA with variable percentages of silica fume

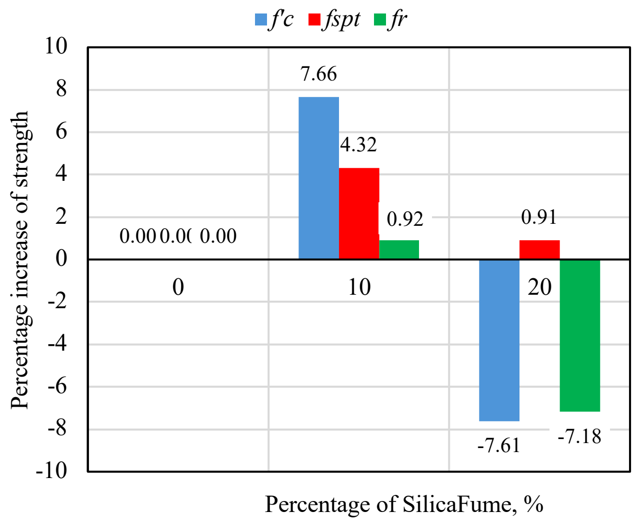

Figure 17. Variation of compressive, tensile, and flexural strength at 10% and 20 % silica fume and 25 % RCA.

5.3.3. Impact of replacing a percentage of cement with Silica Fume on the mechanical properties of concrete with 50 % RCA

Replacing 50% of NCA with recycled aggregate causes a moderate decrease in compressive, tensile, and flexural strength, but replacing 10% cement with silica fume along with 50% recycled aggregate improves compressive strength by 9%, tensile strength by 8%, and flexural strength by 1%, as illustrated in Figures 18 and 19. Replacing NCA with 50% RCA, along with the substitution of cement with 10% silica fume, slightly reduces compressive strength by 2.7 %, tensile strength by 12%, and flexural strength by 5% compared to the conventional concrete counterpart strengths. In contrast, replacing cement with 20 % silica fume reduces compressive strength by 9 %, tensile strength by 3 %, and flexural strength by 14 %, as shown in Figures 18 and 19. This behavior is due to the same causes mentioned earlier, in paragraph 5.3.1.

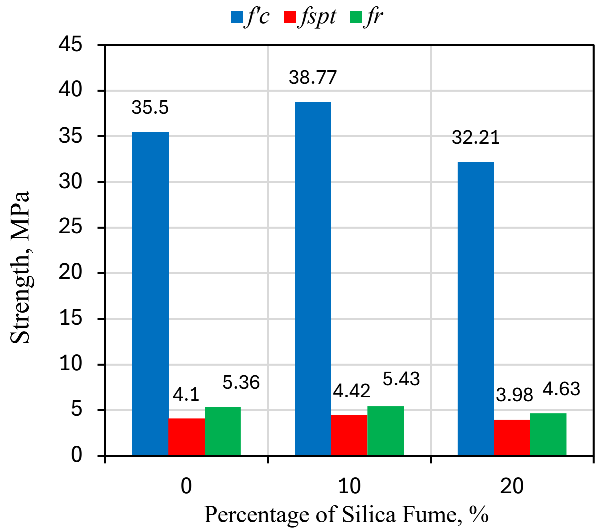

Figure 18. Compressive, tensile, and flexural strength of 50% RCA and different percentages of silica fume

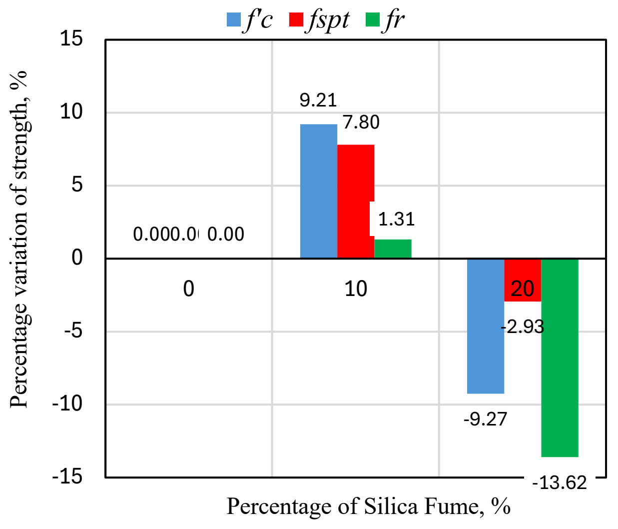

Figure 19. Variation of compressive, tensile, and flexural strength at 10% and 20 % silica fume and 50 % RCA.

5.3.4. Impact of replacing a percentage of cement with Silica Fume on the concrete mechanical properties with 75 % RCA

Replacing NCA with 75% RCA reduces compressive, tensile, and flexural strengths by 24%, 23%, and 14% as compared to normal concrete. However, replacing cement with 10% silica fume enhances those strengths; the compressive, tensile, and flexural strengths increase by 7%, 6%, and 4%, respectively. In contrast, replacing cement content with 20% silica fume, along with replacing NCA with 75% RCA, further reduces strength. The compressive, tensile, and flexural strength decreases by 2%, 4%, and 6%, respectively, as illustrated in Figures 20 and 21.

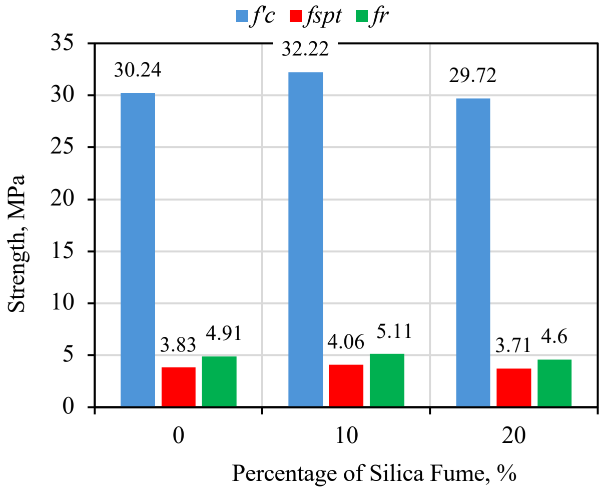

Figure 20.Compressive, tensile, and flexural strength of 75% RCA and different percentages of silica fume

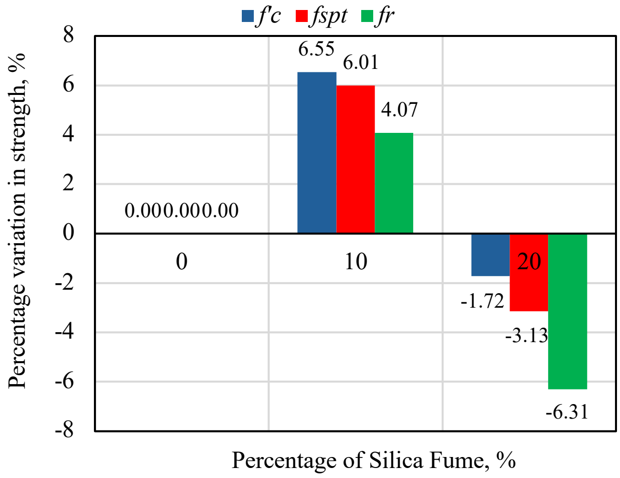

Figure 21.Variation of compressive, tensile, and flexural strength at 10% and 20 % silica fume and 75 % RCA

6. Conclusions

This study experimentally demonstrates the impact of using silica fume to replace part of the cement on the mechanical properties of concrete manufactured with recycled concrete aggregates (RCA) to replace normal aggregate at ratios of 25%, 50%, and 75%. The following conclusions can be drawn;

Increasing the replacement ratio of recycled concrete aggregate (RCA) instead of natural coarse aggregate (NCA) reduces the workability of fresh concrete more with each increase, necessitating an increase in the plasticizing admixture dosage or water content in the mix to maintain the required workability.

Substituting 25% NCA with RCA did not significantly affect compressive strength. At 50% and 75% replacement ratios, a further increase in strength loss occurred. Replacing NCA with RCA has more impact on tensile and flexural strength than on compressive strength. However, the reduction in flexural strength is less than that of tensile strength. indicating that the effect of natural aggregate remains dominant and the stress distribution has not been significantly affected by the 25% replacement ratio of RCA on flexural strength.

Clearly, the 25% replacement ratio of NCA with RCA awards the better results than the other ratios.

Replacing cement with 10% silica fume contributes to improving compressive strength when 25% of NCA is replaced with RCA, resulting in compressive, tensile, and flexural strengths greater than those of normal concrete by 7%, 4%, and 1%, respectively. Replacing 50% of NCA with RCA, along with a 10% replacement of silica fume, results in tensile and flexural strengths higher than those of normal concrete by 8% and 1%. Thus, 10% silica fume can compensate for the deficiency when using recycled aggregate at a rate of 50%, yielding a strength very close to that of normal concrete.

The use of 10% silica fume enhances tensile and flexural strength more than compressive strength.

Furthermore, substituting 10% cement with silica fume increases compressive strength higher than normal concrete by 12%, concrete with 25% RCA by 8%, and concrete with 50% RCA by 9%. Therefore, substituting cement with 10% silica fume can compensate for the deficiency of replacing NCA with 25% and 50% RCA.

In general, the decrement ratio in flexural strength is lower than that of tensile strength.

The improvement rate of hardened concrete properties relies on the blending ratio of silicate dioxide and $Ca(OH)2$ resulting from cement hydration. Substituting 20% of cement with silica fume decreases compressive, tensile, and flexural strengths compared to normal concrete. Therefore, 10% substitution ratio of silica fume improves concrete strengths by more than 20%. The improvement in compressive strength exceeds that of tensile and flexural strength.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Author Contributions

Zahraa G. Jebur: Data curation, Investigation, Writing- Original draft preparation. **Adil M. Jabbar**: Conceptualization, Methodology, Validation, Supervision. **Thaar S. Al-Ghasham**: Visualization, Writing- Reviewing and Editing.

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