Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 05, May, 2025

Revolutionizing Recycled Aggregate Concrete: A Dual Approach Using HCl Treatment and Silica Fume

Wajde S. Alyhya [1*], Ghazwan A. Salman [2], Awad Jadooe [1]

[1] *Civil Engineering Department, University of Kerbala, Karbala, Iraq.*

[2] *Contract Department, Ministry of Higher Education and Scientific Research, Baghdad, Iraq.*

Received 02 February 2025; Revised 19 April 2025; Accepted 26 April 2025; Published 01 May 2025

Abstract

Debris from building and demolition projects, as well as the shortage of natural resources, have become more pressing issues on a global scale in recent times. Even though concrete, the utmost adaptable building material, is a vital factor in the development of the infrastructural and industrial sectors, it has been claimed that it is not an environmentally friendly material due to its potential for profound environmental influence beyond its use and critical resource-consumption nature. Nevertheless, it will continue to be the dominant building material utilized globally. The present research aims to investigate the synergistic effects of the treatment of recycled concrete aggregate (RCA) by hydrochloric acid (HCl) and the replacement of cement by silica fume (SF) on the mechanical properties of produced concrete. Four groups of concrete mixes were prepared: (1) untreated recycled concrete aggregate (URCA), (2) HCl-treated recycled concrete aggregate (TRCA), (3) URCA with SF replacement, and (4) TRCA with SF replacement. The HCl treatment was applied at four molarities (0.2M, 0.4M, 0.6M, and 0.8M), while SF was used to replace cement by weight at four ratios (5%, 10%, 15%, and 20%). The results were evaluated in terms of the 7, 14, and 28-day compressive strength. The findings indicated that TRCA mixes significantly outperformed URCA mixes in terms of the mechanical properties, namely the 28-day compressive strength, in which the optimal mix was that with 100% TRCA by 0.4M HCl combined with 5% SF replacement. The results also demonstrated that 0.6M HCl treatment significantly enhanced the quality of RCA by removing weakly adhered mortar, leading to a nearly 21% rise in the 28-day compressive strength compared to URCA with complete replacement. Indeed, adding further SF enhanced the performance, as using 75% of TRCA+10% SF achieved the highest compressive strength of 38.7 MPa at 28 days, equalling around 25% improvement over the URCA with the same replacing level.

Keywords: HCL; Molarity; Silica Fume; Untreated Recycled Coarse Aggregate; Treated Recycled Coarse Aggregate.

1. Introduction

Today, the building industry follows a significant global development problem, which is one of the most sustainable development principles [1]. The advancement in manufacturing technology of concrete necessitates using superior raw material sources, particularly aggregates [2]. The ever-increasing scarcity of energy and resources and the new environmental regulations for environmental preservation make it challenging to address this problem. Thus, the now objective is to fully utilize trash deposits from various industries and low-quality raw materials [3]. Similarly, the demand for building materials is increasing worldwide, accelerating the consumption and loss of energy and raw materials. This has become a worldwide issue, compelling researchers to find a substitute substance to safeguard the environment and natural resources [3, 4]. The aforementioned issue could be primarily resolved by recycling and utilizing construction and demolition wastes and employing alternative mineral admixtures in concrete to reduce the

* Corresponding author: wajde.alyhya@uokerbala.edu.iq

http://dx.doi.org/10.28991/CEJ-2025-011-05-08

amount of aggregates and cement used [5]. Applications of wastes, as well as various mineral admixtures, such as recycled concrete aggregate (RCA) as well as fly ash, rice husk, metakaolin, and ground granulated blast furnace slag, that are derived from industrial wastes, have been tested worldwide in various applications with different blends [5, 6].

It was known from past publications that using RCA exhibits a reduction in strength by nearly 40% compared to control concrete. Indeed, such use could also significantly impact the workability, bonding, and durability properties [7]. According to the guidance for demolition and re-use of concrete and masonry RILEM TC 121-DRG (1994) statement, "replacing recycled materials for all classes of concrete strength was limited to just twenty percent. The presence of glued mortar and slack particles on RCA was the leading cause of their unfavorable outcomes. If the water absorption of aggregate is higher than 5%, utilizing RCA in a saturated surface dry condition or adding more water to the concrete improves the characteristics of fresh concrete [6-9]. Several earlier studies concluded that surface treatment techniques like surface impregnation and acid pre-soaking methods could effectively reduce the RCA's subpar performance. According to Tam et al. [10], the pre-soaking of RCA in an acidic environment such as hydrochloric acid (HCl) altered the surface of RCA by removing a large amount of the previously adhered mortar and enhancing RCA's properties [10-12].

Purushothaman et al. [11] stated that the quality of RCA treated with HCl was comparable to that of natural aggregate, and the pre-soaking treatment approach by HCl acid was more efficient than that carried out by H_2SO_4 acid in removing the adhered mortar. Additionally, they stated that RCA treated with HCl of low molarity (under 0.5M) produced superior characteristic strength compared to high-molarity acid-treated concrete. Kaushik and Bhan investigated in their paper on enhancing recycled concrete aggregates (RCA) through acidic treatments, specifically hydrochloric acid (HCl) and sulfuric acid (H_2SO_4), to enhance the hardened properties and durability of the produced concrete [13]. Forero et al. stated that HCl treatment effectively removes contaminants, such as adhered mortar, adversely affecting aggregate performance [14]. The HCl treatment effectively removed the adhered mortar from RCA, which is crucial for improving the aggregate's quality. Allal et al. stated that such treatment reduced water absorption and enhanced the concrete's mechanical properties, leading to better durability and performance [15]. Yan et al. investigated physical, chemical, and microbial strengthening methods for recycled aggregates, analyzing their effects on the concrete's mechanical and microstructural properties. They highlight improvements in durability and performance, providing insights for future research and technical standards [16]. While treated RCA can improve concrete properties, the inherent challenges of RCA, such as the quality of attached mortar, can still limit performance. Regarding the treatment technique by surface impregnation, Saravanakumar and Dhinakaran [17] compared the properties of concrete made with RCA treated with calcium metasilicate solution and those treated with nano silica. They found that the concrete treated with the former of 10% concentration had superior strength characteristics compared to those treated with the latter. Thus, ongoing research is essential to optimize treatment methods and fully realize the potential of recycled aggregates in sustainable construction [18, 19].

Moreover, several literature reviews stated that using mineral admixtures such as silica fume (SF) in concrete increased its durability. Allal et al. stated that incorporating SF in concrete mixes has significantly improved compressive and tensile strengths, with values reaching 43.5 MPa and 3.87 MPa, respectively [15]. It acts as a micro-filler, improving the bond between cement paste and aggregates, resulting in a denser microstructure and enhanced ITZ [20]. Indeed, the inclusion of SF can reduce the porosity of the ITZ by up to 44.22%, leading to a more compact structure [21]. Studies also showed that adding 10% SF can reduce water permeability by 87%, indicating a significant improvement in durability [22]. Moreover, SF contributes to the formation of calcium silicate hydrate (C–S–H), which enhances the binding of unreacted portlandite, further improving the microstructure [23]. The presence of SF has been linked to lower chloride ion penetration, which is critical for structures exposed to aggressive environments [22]. While SF offers substantial benefits, balancing its use with other admixtures is essential to avoid potential issues such as increased brittleness or cost implications in large-scale applications. It has been stated that the combined use of treated aggregates with SF achieved mechanical properties comparable to conventional concrete at replacement levels up to 50% [14, 24]. Indeed, the dual approach significantly improved acid resistance and reduced water absorption, making RCA more durable in aggressive conditions [13, 25-28]. Balasubramani and Palaniappan examined the influence of acids and slurries on RCA, primarily aiming to improve their quality by removing or strengthening the weakly adhered mortar. The results showed that such processes have enhanced RCA's physical and mechanical properties, making it more suitable for construction applications [29]. In addition, a great deal of previous research revealed that various suggested treatment approaches for RCA promote sustainable construction by reducing landfill waste and conserving natural resources [16, 30-33]. Despite these advancements, limited recycled aggregate replacement up to 50% has been suggested for optimal performance [14, 34-37]. Moreover, the dual use of SF and treatments did not perform, necessitating a need between performance improvements and economic feasibility.

This research aims to comprehensively evaluate the synergistic effects of HCl treatment and SF addition on the properties of concrete incorporating RCA. This was achieved by detailing the methodology and the procedures for HCl treatment of RCA, the mix design of concrete incorporating such treated aggregate and silica fume (SF), and the experimental techniques for assessing mechanical properties. It attempts to investigate the properties of concrete produced using RCA treated with HCL with various molarities and including silica fume (SF) at various cement replacement levels. The findings of the experimental study will be presented, focusing on the impact of such an approach on compressive strength, in addition to a thorough discussion of the findings, analyzing the underlying mechanisms responsible for the observed improvements, and comparing the results with existing literature. The conclusions will summarize the key findings, highlight the potential applications of this dual approach in sustainable concrete production, and suggest directions for future research. A comparison of the results of concrete properties produced with untreated RCA was also conducted.

2. Experimental Program

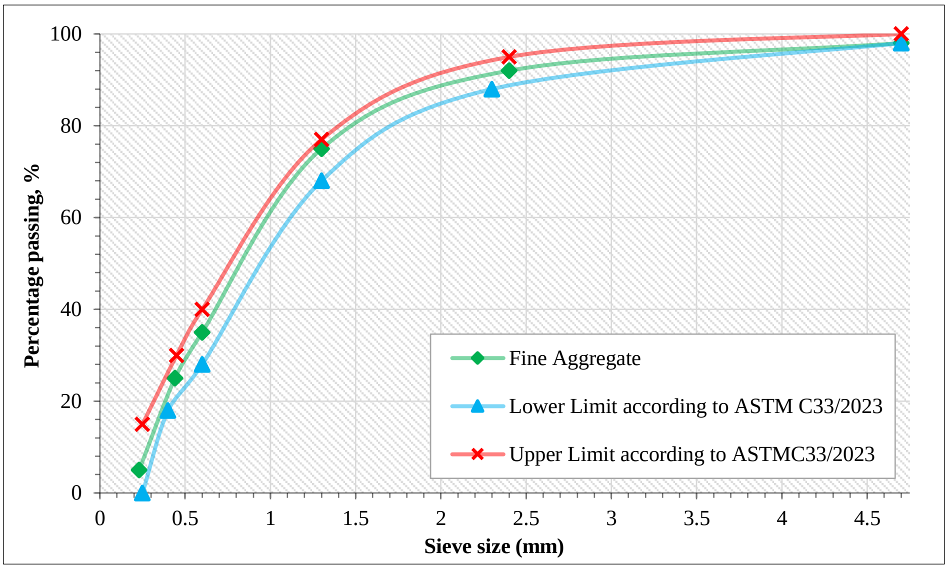
2.1. Materials

2.1.1. Cement

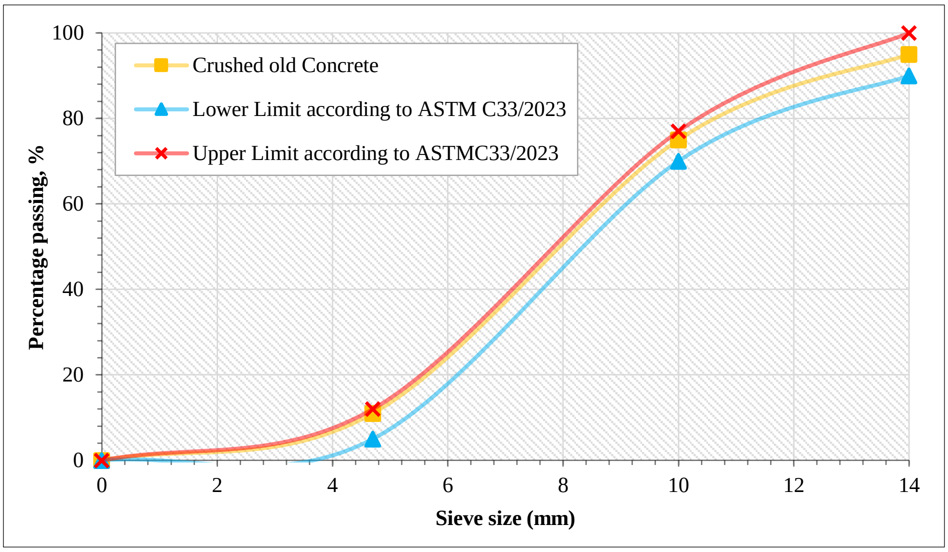
In the experimental work of this research, ordinary Portland cement (type I) was utilized, known locally (Aljisir). Karbala Cement Factory, Iraq, makes this kind of cement. It was kept in airtight plastic containers to prevent exposure to humid air conditioning and preserve consistent quality. The cement properties conformed to the ASTM C109-07 specification limits [38].

2.1.2. Fine Aggregate (Sand)

Natural sand from the Al-UKhaider region was used in this research as a fine aggregate with a maximum granule size of 4.75 mm. The grading of the sand confirmed the requirements of ASTM C33 [39], as shown in Figure 1-a.



(a)



(b)

Figure 1. (a) Grading curve of fine aggregate, (b) Coarse natural and recycled aggregate

2.1.3. Coarse Aggregate (Gravel)

A locally available coarse aggregate with a maximum particle size of no larger than 14 mm was used. After being cleaned of dust using tap water, it was allowed to be in its saturated surface dry condition before use. The grading of the coarse aggregate confirmed the requirements of ASTM C33 [39].

2.1.4. Recycled Concrete Aggregate (RCA)

According to the mix design and study parameters, waste concrete from demolishing old structures that had a density of 2.35-2.45 gm/cm^3 and water absorption of 5.25% was utilized as recycled concrete aggregate (RCA) at four different rates in place of the natural coarse aggregate (NCA), and it was graded to be similar to NCA. The grading of recycled concrete aggregate confirmed the requirements of ASTM C33 [39], as shown in Figure 1-b.

2.1.5. Silica Fume

Megaadd MS (D) UAE was the silica fume type employed in preparing all mixes [40]. This extremely fine pozzolanic material from amorphous silica was usually made as a side product in electric furnaces. It was sometimes referred to as condensed silica fume or micro silica. The findings indicate an agreement with the ASTM C1240 [41]. This investigation used silica fume instead of cement as a weight replacement. The sort of silica fume that will be used is depicted in Figure 2.

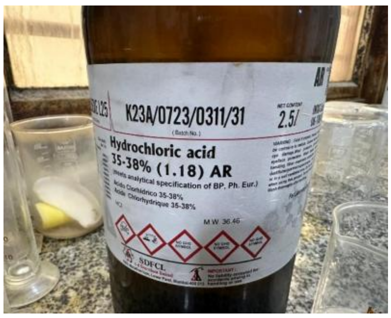
Figure 2. Sample of silica fume (SF)

2.1.6. Hydrochloric Acid (HCL)

Hydrochloric acid (HCL) could be defined as an aqueous solution of hydrogen chloride, sometimes called muriatic acid or spirits of salt. It is a colorless solution that smells strong and is under the strong acids class (the properties are shown in Table 1). RCA was immersed for 24-hour in four distinct molarities of HCL (0.2M, 0.4M, 0.6M, and 0.8M) at room temperature (23°C to 28°C), as shown in Figure 3. The current treatment protocol by HCL used in this study was based on Tam et al.'s methodology [11]. The pre-soaked RCA was washed thoroughly using tap water, dried in the sun for a day, and sieved. The loose mortars and acidic solutions were eliminated throughout this procedure.

Table 1. Properties of hydrochloric acid

Product Name	Hydrochloric acid
Grade	LR
Vapor density	1.3 (vs air)
Vapor pressure	2.23- 7.93 Psi
Product line	VETEC
Form	Liquid
Concentration	35-38%
PH	<1.0
Density	1.070 g/cm^3



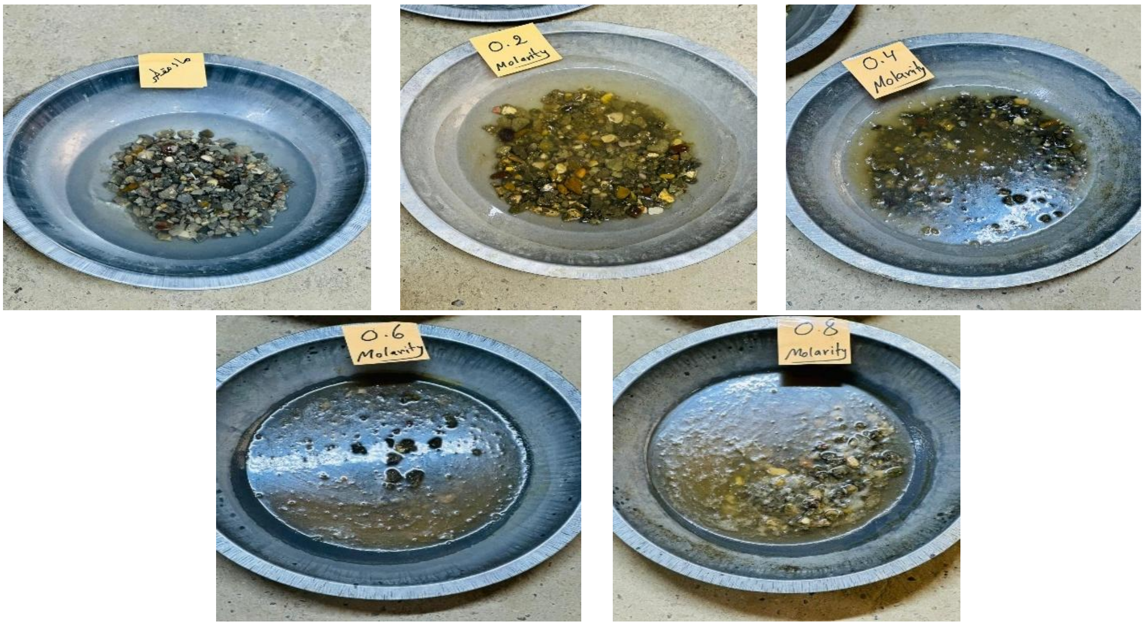


Figure 3. Pre-soaking treatment procedure for RCA

2.1.7. Water

Drinking tap water from the water supply project was used for the mixing and curing processes.

2.2. Preparation of Concrete Mixes

In order to achieve a 35 MPa 28-day compressive strength concrete, a mix was designed according to the British design approach BS 5328 part 2: 1991 specifications [42]. The concrete mix was made using the following weight-based proportions: 1 (cement), 1.5 (fine aggregate), and 2.8 (coarse aggregate), with a maximum aggregate size of 14 mm and a water/cement ratio of 0.38. According to ASTM C143-2012 [43], a standard range of workable slumps of 80 -100 mm was utilized in this investigation. In order to prevent water absorption by RCA during the mixing and hardening processes, saturated surface dry aggregates were used in the preparation of all mixes. There were four different mix groups: Mix 1 had no SF and treatment by HCL, Mix 2 had SF and had no treatment by HCL, Mix 3 had no SF and had treatment by HCL, and Mix 4 had SF and had treatment by HCL. The percentages of RCA substitution were 25%, 50%, 75%, and 100%, while the percentages of SF replacement were 5%, 10%, 15%, and 20%. Furthermore, RCA was treated using hydrochloric acid (HCl) in four molarities (0.2M, 0.4M, 0.6M, and 0.8M) before being used instead of NCA aggregate. The details of the mix proportion before using SF and treated RCA with HCL are shown in Table 2.

Table 2. Mix proportion of concrete mix (kg/m^3)

Mix	Cement	Fine Agg.	Coarse Agg.	W/C ratio (%)	Target Strength of Compression (MPa)
NC	400	728	1090	0.38	35

3. Results and Discussion

3.1. Compressive Strength of Mixes with Untreated Recycled Aggregate Concrete (URCA)

One purpose of this study is to determine how the compressive strength of normal concrete (NC) is affected when recycled concrete aggregate (RCA) is utilized in place of natural coarse aggregate (NCA). Four different ratios of RCA (25%, 50%, 75%, and 100%) were used to replace the NCA in the creation of the NC mixes using a constant water-cement ratio (w/c) of 0.38 in addition to a control mix with 0% of RCA for comparison. The values of the compressive strength of all mixes at different curing ages of 7, 14, and 28 days are given in Table 3 and shown in Figure 4. It can be revealed from the testing results that using RCA in place of NCA significantly reduced the concrete's compressive strength. In other words, the direct use of RCA achieved concrete with lower compressive strength by 8.5%, 10.7%, 12.4%, and 15% for the replacement percentages of 25%, 50%, 75%, and 100%, respectively, at 28 days of age compared to the control concrete (0% replacement level). Numerous previous research reported a similar pattern, with the existing mortar in the RCA being the reason for the declining strength [44]. Moreover, the given decline in the compressive concrete strength when using RCA instead of NCA at various replacement levels could be owing to the lesser quality of RCA as it frequently contains adhered mortar from its original concrete that can be more porous and weaker than NCA.

This can lead to a weaker bond between the aggregate and the new cement paste, lowering the overall compressive strength. Indeed, RCA can absorb higher amounts of water than NCA, resulting in higher water absorption, which can affect the ratio of water to cement in the mix, potentially leading to a weaker hardened structure. Moreover, RCA particles can have higher porosity due to their inherited old cracks and voids in the adhered mortar, which causes a reduction in strength.

Table 3. Compressive strength of mixes with untreated recycled aggregate concrete (URCA) at various replacement levels and curing ages

RAC %	7 days	14 days	28 days
0	22.7	26.9	34.5
25	19.2	24.7	31.6
50	18.7	23.9	30.8
75	17.1	22.6	30.2
100	16.4	21.5	29.3

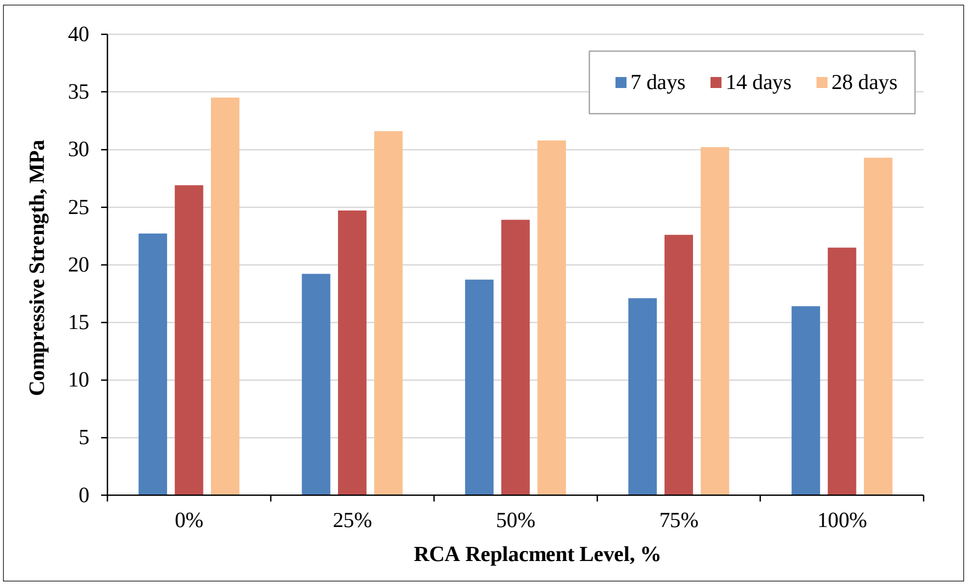


Figure 4. Compressive strength of mixes with untreated recycled aggregate concrete (URCA) at various replacement levels and curing ages

3.2. Compressive Strength of Mixes with Untreated Recycled Aggregate Concrete (URCA) Incorporating Silica Fume (SF)

Table 4 and Figures 5-a to 5-c present the compressive strength of all concrete mixes after 7, 14, and 28 days, highlighting variations in strength due to different percentages of untreated recycled coarse aggregates (URCA) and silica fume (SF) used as partial cement replacements by weight. As shown in Figure 5, regardless of the SF content, the compressive strength of concrete mixes without SF decreases progressively with increasing URCA content.

The control mix—containing neither RCA nor SF—achieved a 7-day compressive strength of 22.7 MPa. For mixes without RCA but with 5%, 10%, and 15% SF replacing cement, the compressive strengths were 23.1 MPa, 23.9 MPa, and 23.3 MPa, respectively, corresponding to increases of 1.7%, 5.3%, and 2.6%. However, a 20% cement replacement with SF led to a 2.6% decrease in strength for the same mix type.

All mixes showed strength gains as curing progressed due to ongoing hydration reactions, exhibiting consistent strength development patterns across curing ages. An exception was observed in the mix with 20% SF and 100% RCA, demonstrating lower compressive strength than the control mix.

At 28 days, mixes containing 5%, 10%, and 15% SF and up to 75% RCA substitution showed improved strength compared to the control mix (34.5 MPa). This enhancement is primarily attributed to the residual mortar on RCA surfaces, which, besides enhancing RCA properties, strengthens the bond between the cement paste and aggregate. This contributes to a more robust interfacial transition zone (ITZ), often the initial point of failure under loading.

Based on these results, increasing SF content up to 10% consistently improves the compressive strength of mixes with up to 75% RCA, regardless of curing age. These findings align with trends observed in previous studies [45].

Table 4. Compressive strength of concrete mixes with different levels of RCA and SF

		SF Replacement Level, %														
		0			*5*			*10*			*15*			*20*		
Age (days)		**7**	**14**	**28**	**7**	**14**	**28**	**7**	**14**	**28**	**7**	**14**	**28**	**7**	**14**	**28**
RCA replacement level %	**0**	22.7	26.9	34.5	23.1	27.7	35.7	23.9	29.2	37.3	23.3	27.9	34.5	22.1	27.1	33.8
	25	19.2	24.7	31.6	22.3	28.1	36.2	24.2	29.3	37.3	23.6	28.4	35.5	22.5	27.9	34.9
	50	18.7	23.9	30.8	23.8	29.3	37.7	26.3	30.1	39.1	23.1	27.2	34.8	21.7	26.2	33.5
	75	17.1	22.6	30.2	22	26.7	33.8	24.1	29.2	37.6	22.3	25.8	34.1	20.8	24.1	31.7
	100	16.4	21.5	29.3	20.7	24.8	32.2	22.9	27.9	31.1	21.5	20.9	29.4	19.7	19.5	17.7

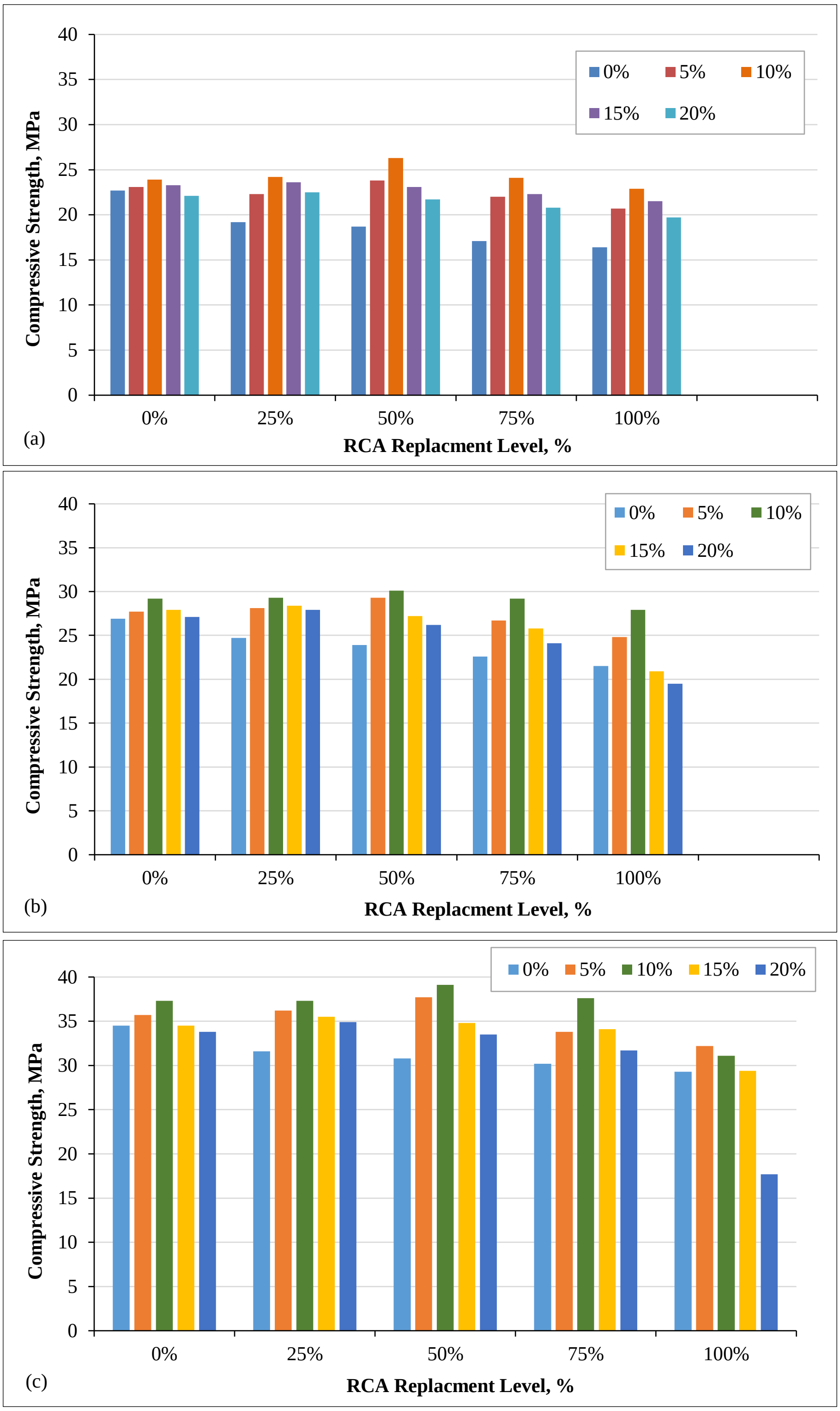


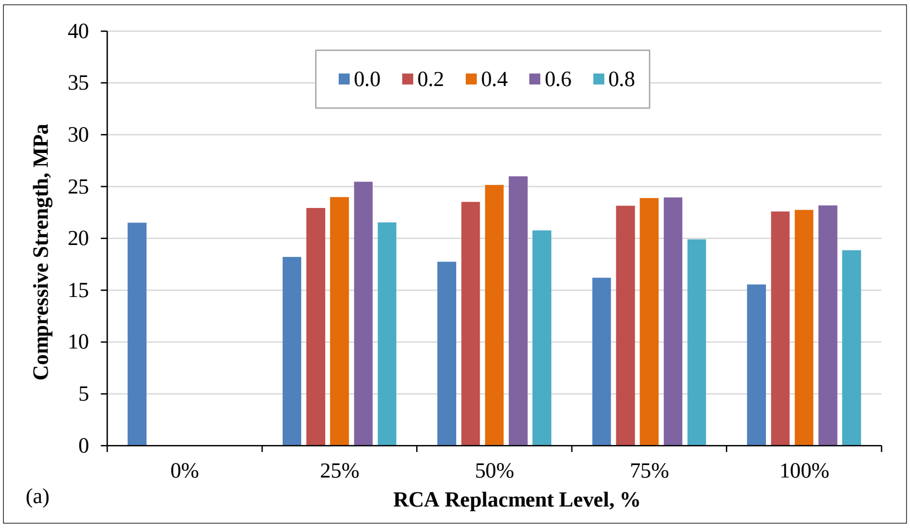
Figure 5. (a): Compressive strength with different levels of RCA and SF at age 7 days, (b): Compressive strength with different levels of RCA and SF at age 14 days, (c): Compressive strength with different levels of RCA and SF at age 28 days

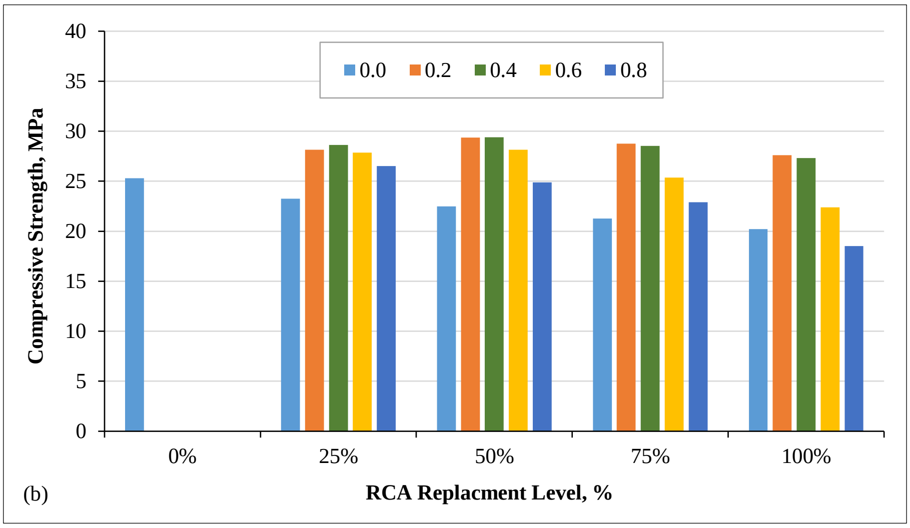
3.3. Compressive Strength of Mixes with Treated Recycled Aggregate Concrete (TRCA)

The main factor affecting the quality of RCA is the amount of cement mortar that remains on the aggregate's surface. This could produce RCA with high porosity and water absorption rates, which weakens the interfacial zone between the aggregates and new cement mortar, reducing the compressive strength in particular and the other mechanical performance of concrete in general. This work aimed to investigate the effect of treatment on RCA by using the pre-soaking approach, namely, using HCl to remove the adhered mortar on RCA. Pre-treating RCA was found to be useful and could increase its quality as the adhered mortar that is linked to them could be the primary component that lessens the mechanical behavior of the produced concrete from such materials. The variations in the compressive strength after 7, 14, and 28 days of all concrete mixes with RCA with different percentages previously treated by HCL of various molarities are shown in Table 5 and Figure 6-a to 6-c. Results revealed that treated RCA with 0.4M to 0.8M by HCL before use and, in particular, the inclusion of RCA with percentages of 50% and 75% have improved the compressive strength by 25% to 31%. This demonstrates how well the pretreatment process is as it removes a significant amount of the weak adhered mortar from RCA, strengthening the bond between RCA and the new cement mortar. The advantages of the pretreatment strategy were evident as the results showed an ideal strength enhancement of 32% with 50% RCA replacements at 28 days. RCA has been pre-treated, and the aggregate's interfacial zone behavior with fresh cement mortar can be improved. Such findings were in agreement with [46, 47].

Table 5. Compressive strength of mixes with treated recycled aggregate concrete (TRCA)

		HCL Molarity														
		0.0			0.2			0.4			0.6			0.8		
Age (days)		7	14	28	7	14	28	7	14	28	7	14	28	7	14	28
RCA Replacement Level %	0	22.7	26.9	34.5	-	-	-	-	-	-	-	-	-	-	-	-
	25	19.2	24.7	31.6	24.3	30	37.2	25.2	30.3	38.8	26.9	29.4	39.5	22.5	27.9	34.9
	50	18.7	23.9	30.8	24.8	31.3	38.7	26.3	31.1	40.4	27.6	29.9	40.8	21.7	26.2	33.5
	75	17.1	22.6	30.2	24.6	30.9	36.9	25.1	30.2	37.5	25.3	26.8	38.1	20.8	24.1	31.7
	100	16.4	21.5	29.3	24.1	29.8	30.2	23.9	28.9	36.2	24.5	23.9	35.4	19.7	19.5	17.7





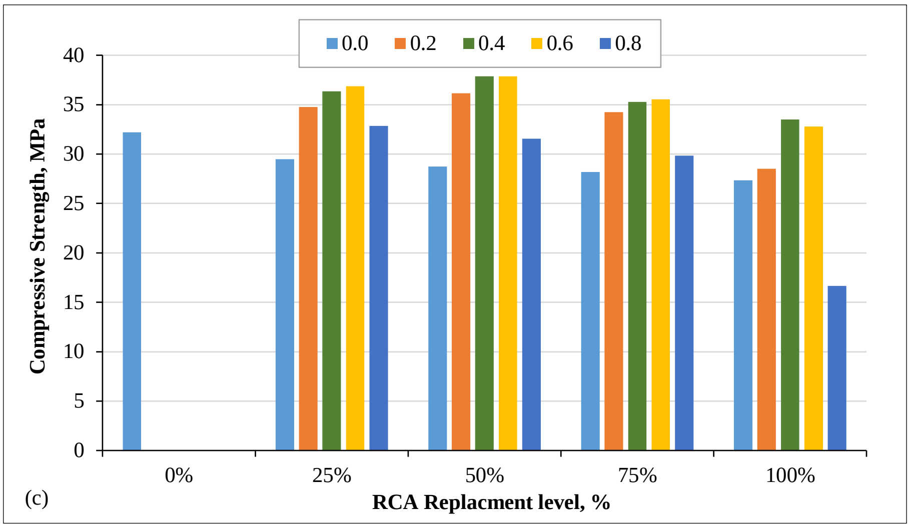


Figure 6. (a): Compressive strength of mixes with treated recycled aggregate concrete (TRCA) by HCL at 7 days with varying RCA ratios, (b): Compressive strength of mixes with treated recycled aggregate concrete (TRCA) by HCL at 14 days with varying RCA ratios, (c): Compressive strength of mixes with treated recycled aggregate concrete (TRCA) by HCL at 28 days with varying RCA ratios.

3.4. Compressive Strength of Mixes with Treated Recycled Aggregate Concrete (TRCA) Incorporating Silica Fume (SF)

Following the pre-soaking procedures, specimens of concrete in the shape of cubes measuring 100 mm were created using treated recycled concrete aggregate (TRCA). The outcomes are then compared with those obtained from the standard method, which does not involve pre-soaking in an environment of an acidic nature. Each experimental work was conducted three times to reduce the difference between samples and results, and the average values were calculated. Tables 6 to 9 and Figure 7 tabulate and show the improvement percentages in compressive strength at three different ages. The treatment strategy by pre-soaking should be considered profitable since it can straightly eliminate the old cement mortar and weak links of RCA at a relatively cheap cost. Various experimental studies have also demonstrated the improvement after implementing such an approach. Although this pre-soaking technique requires expenditure to apply, the overall quality for RCA is significantly enhanced and is on par with the normal aggregate.

Table 6. Compressive strength after treatment with different ratios of RCA and 5%SF

		HCL Molarity														
		0.0			0.2			0.4			0.6			0.8		
Age (days)		7	14	28	7	14	28	7	14	28	7	14	28	7	14	28
RCA Replacement Level %	0	24.4	28.6	36.4	-	-	-	-	-	-	-	-	-	-	-	-
	25	20.6	26.3	33.3	26.2	32.1	39.4	27.3	32.6	41.3	29.3	31.7	42.2	24.4	30.0	37.2
	50	20.1	25.5	32.5	26.8	33.5	41.0	28.5	33.4	43.0	30.1	32.2	43.6	23.6	28.2	35.7
	75	18.4	24.1	31.9	26.6	33.1	39.1	27.2	32.5	39.9	27.6	28.9	40.7	22.6	26.0	33.8
	100	17.6	22.9	30.9	26.0	31.9	32.0	25.9	31.1	38.6	26.7	25.8	37.8	21.4	21.0	18.9

Table 7. Compressive strength after treatment with different ratios of RCA and 10%SF

		HCL Molarity														
		0.0			0.2			0.4			0.6			0.8		
Age (days)		7	14	28	7	14	28	7	14	28	7	14	28	7	14	28
RCA Replacement Level %	0	23.5	27.7	35.4	-	-	-	-	-	-	-	-	-	-	-	-
	25	19.9	25.5	32.4	24.9	30.6	38.1	26.0	31.2	39.7	27.4	30.3	40.0	23.4	28.9	36.0
	50	19.4	24.6	31.6	25.6	32.0	39.6	27.4	32.0	41.4	27.9	30.5	41.0	22.6	27.2	34.6
	75	17.7	23.3	31.0	25.1	31.1	37.4	25.9	31.1	38.7	25.8	27.6	38.6	21.7	25.0	32.7
	100	17.0	22.2	30.1	24.4	29.9	31.4	24.7	29.8	36.4	25.0	24.2	35.4	20.5	20.2	18.3

Table 8. Compressive strength after treatment with different ratios of RCA and 15%SF

	HCL Molarity														
	0.0			0.2			0.4			0.6			0.8		
Age (days)	7	14	28	7	14	28	7	14	28	7	14	28	7	14	28
RCA Replacement Level % 0	22.8	26.9	34.4	-	-	-	-	-	-	-	-	-	-	-	-
25	19.3	24.7	31.5	24.2	29.8	37.0	25.3	30.3	38.6	26.7	29.4	38.9	22.8	28.1	35.0
50	18.8	23.9	30.7	24.8	31.1	38.5	26.6	31.1	40.2	27.2	29.7	39.9	21.9	26.4	33.6
75	17.2	22.6	30.1	24.4	30.3	36.3	25.2	30.2	37.6	25.1	26.8	37.5	21.0	24.3	31.8
100	16.5	21.5	29.2	23.7	29.1	30.5	24.0	28.9	35.4	24.3	23.6	34.5	19.9	19.6	17.7

Table 9. Compressive strength after treatment with different ratios of RCA and 20%SF

	HCL Molarity														
	0.0			0.2			0.4			0.6			0.8		
Age (days)	7	14	28	7	14	28	7	14	28	7	14	28	7	14	28
RCA Replacement Level % 0	21.5	25.2	32.1	-	-	-	-	-	-	-	-	-	-	-	-
25	18.1	23.2	29.4	22.9	28.1	34.7	23.9	28.6	36.3	25.4	27.8	36.9	21.4	26.4	32.8
50	17.7	22.4	28.7	23.4	29.3	36.1	25.0	29.3	37.8	26.0	28.1	37.9	20.7	24.8	31.5
75	16.2	21.2	28.1	23.1	28.8	34.3	23.8	28.5	35.2	23.9	25.3	35.6	19.8	22.8	29.8
100	15.5	20.2	27.3	22.6	27.7	28.4	22.7	27.2	33.6	23.2	22.4	32.9	18.8	18.5	16.6

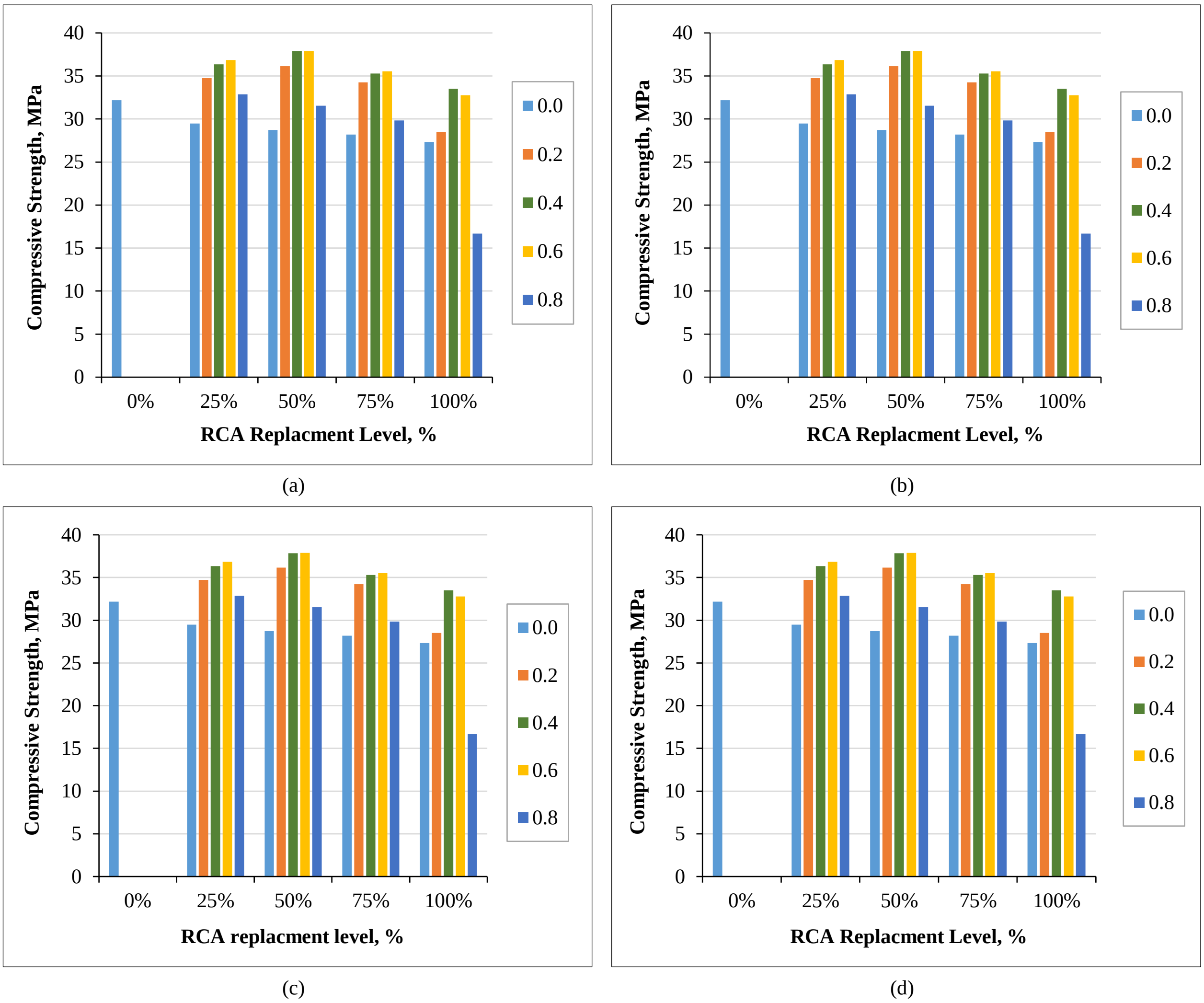


Figure 7. Compressive strength of mixes with treated recycled aggregate concrete (TRCA) incorporating silica fume (SF)(A: 5%; B: 10%; C: 15%; D:20%)

Compared with the control concrete mix involving RCA without treatment, it is evident that adding SF at rates of 5%, 10%, and 15% along with treatment RCA at 0.2M of HCL increases the compressive strength from 25% to 29%. Simultaneously, the compressive strength increased with HCl of 0.4M from 30% to 33%. Moreover, there was an increase in the compressive strength from 11% to 25% when utilizing TRCA at 0.6M of HCL. However, the increase in the compressive strength at all ages decreased when the RCA was treated at 0.8M of HCl. Using SF creates a dense and compact microstructure, decreases voids in concrete, and improves the bonding between pastes and aggregates, increasing the compressive strength. This tendency toward strength development is consistent with previous research findings [7-10]. Additionally, the SF contributes more to RCA mixes than NCA mixes, achieving the highest strength development when replacing 25% of the treated RCA at HCL with 0.6M. This behavior might be due to the adhering mortar of RCA, which has more pores than NCA and hydrates and strengthens the connection at the interface. Microstructural analysis from previous research revealed that the combination of HCl treatment and SF refined the interfacial transition zone (ITZ) and densified the concrete matrix, reducing porosity and improving durability. However, higher SF replacement ratios (15% and 20%) showed diminishing returns, likely due to excessive cement replacement.

4. Conclusions

The current study explores the effects of silica fume as a partial substitution of cement in concrete mixtures that substitute varying percentages of RCA instead of NCA. Enhancing the qualities of RCA made from coarse aggregate wastes by HCL and creating sustainable concrete with these materials are the primary goals of this research project. The following points provide the main conclusions after analyzing the experimental data:

- For all curing ages, the compressive strength decreases as the amount of RCA in concrete increases due to RCA's weaker characteristics than NCA. The 28-day compressive strength for 100% RAC shows the highest reduction of 15%.
- The inclusion of silica fume makes up for the decrease in the compressive strength of RCA concrete mixes as it increases the 28-day compressive strength by nearly 27% at 50% and 10% RCA and silica fume replacement levels, respectively. This increase in strength is ascribed to the filler effect of silica fume particles.
- The pretreatment by HCL for the RCA is a successful technique for enhancing RCA quality, especially for higher-grade utilization, which expands the range of RCA applications in various construction projects.
- The findings highlight the potential of combining HCl treatment and SF to produce high-performance, sustainable concrete. This approach enhances RCA's mechanical and durability properties and promotes industrial by-product use, contributing to a circular economy.
- The study concludes that 0.6M HCl treatment and 5% SF replacement of cement and 50% RCA represent the optimal combination for enhancing the performance of recycled aggregate concrete (RCA), making it suitable for structural applications in aggressive environments. Future work should consider the long-term durability and economic feasibility of this approach.

5. Declarations

5.1. Author Contributions

Conceptualization, W.S. and A.J.; methodology, W.S. and G.S.; validation, W.S., G.S., and A.J.; formal analysis, W.S. and G.S.; investigation, W.S., G.S., and A.J.; resources, W.S. and A.J.; data curation, W.S., G.S., and A.J.; writing—original draft preparation, W.S. and A.J.; writing—review and editing, W.S, G.S., and A.J.; visualization, W.S.; supervision, W.S., G.S., and A.J.; project administration, W.S., G.S., and A.J.; funding acquisition, W.S., G.S., and A.J. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgments

The experimental techniques were performed at the Constructional Materials Laboratory of Kerbala University. The authors would like to thank all the staff for their support.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Fediuk, R., Pak, A., & Kuzmin, D. (2017). Fine-Grained Concrete of Composite Binder. IOP Conference Series: Materials Science and Engineering, 262(1), 12025. doi:10.1088/1757-899X/262/1/012025.

[2] Fediuk, R. S., Lesovik, V. S., Svintsov, A. P., Mochalov, A. V., Kulichkov, S. V., Stoyushko, N. Y., Gladkova, N. A., & Timokhin, R. A. (2018). Self-compacting concrete using pretreatmented rice husk ash. Magazine of Civil Engineering, 79(3), 66–76. doi:10.18720/MCE.79.7.

[3] Klyuev, S. V., Klyuev, A. V., Khezhev, T. A., & Pukharenko, Y. V. (2018). High-strength fine-grained fiber concrete with combined reinforcement by fiber. Journal of Engineering and Applied Sciences, 13(S8), 6407–6412. doi:10.3923/jeasci.2018.6407.6412.

[4] de Brito, J., Agrela, F., & Silva, R. V. (2019). Construction and demolition waste. New Trends in Eco-Efficient and Recycled Concrete, 1–22, Woodhead Publishing, Sawston, United Kingdom. doi:10.1016/b978-0-08-102480-5.00001-4.

[5] Sivamani, J., Neelakantan, T. R., Saravana Kumar, P., Mugesh Kanna, C., Vignesh Harish, H., & Akash, M. R. (2021). Efficient Utilization of Recycled Concrete Aggregates for Structural Applications—An Experimental Study. Proceedings of SECON 2020. SECON 2020. Lecture Notes in Civil Engineering, 97. Springer, Cham, Switzerland. doi:10.1007/978-3-030-55115-5_52.

[6] TC, D. R. (1994). Specifications for concrete with recycled aggregates. Materials and Structures, 27(9), 557–559. doi:10.1007/BF02473217.

[7] Karim, Y., Khan, Z., Alsoufi, M. S., & Yunus, M. (2016). A review on recycled aggregates for the construction industry. American Journal of Civil Engineering and Architecture, 4(1), 32-38.

[8] González-Taboada, I., González-Fonteboa, B., Martínez-Abella, F., & Carro-López, D. (2016). Study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis. Materiales de Construccion, 66(323), e089. doi:10.3989/mc.2016.06415.

[9] Saravanakumar, P., & Dhinakaran, G. (2013). Strength Characteristics of High-Volume Fly Ash–Based Recycled Aggregate Concrete. Journal of Materials in Civil Engineering, 25(8), 1127–1133. doi:10.1061/(asce)mt.1943-5533.0000645.

[10] Tam, V. W. Y., Tam, C. M., & Le, K. N. (2007). Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resources, Conservation and Recycling, 50(1), 82–101. doi:10.1016/j.resconrec.2006.05.012.

[11] Purushothaman, R., Amirthavalli, R. R., & Karan, L. (2015). Influence of Treatment Methods on the Strength and Performance Characteristics of Recycled Aggregate Concrete. Journal of Materials in Civil Engineering, 27(5), 04014168. doi:10.1061/(asce)mt.1943-5533.0001128.

[12] Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. Construction and Building Materials, 44, 464–476. doi:10.1016/j.conbuildmat.2013.03.014.

[13] Kaushik, S., & Bhan, P. S. (2024). Chemical Modifications of Recycled Concrete Aggregate. International Journal of Emerging Science and Engineering, 12(7), 7–12. doi:10.35940/ijese.g9900.12060724.

[14] Forero, J. A., de Brito, J., Evangelista, L., & Pereira, C. (2022). Improvement of the Quality of Recycled Concrete Aggregate Subjected to Chemical Treatments: A Review. Materials, 15(8), 2740. doi:10.3390/ma15082740.

[15] Allal, M., Zeghichi, L., & Larkat, K. (2024). Improvement of mechanical and interfacial properties (ITZ) of concrete based on treated recycled aggregates. Studies in Engineering and Exact Sciences, 5(1), 955–973. doi:10.54021/seesv5n1-050.

[16] Yan, X., Liu, T., & Zhang, B. (2024). Study on Strengthening Treatment of Recycled Aggregate and the Effect on the Mechanical Properties of Concrete. Advances in Transdisciplinary Engineering, 62, 421–426. doi:10.3233/ATDE241016.

[17] Saravanakumar, P., & Dhinakaran, G. (2015). Mechanical and durability properties of slag based recycled aggregate concrete. Iranian Journal of Science and Technology Transactions of Civil Engineering, 39(C2), 271-282.

[18] Zhao, H., & Zhou, A. (2024). Effects of recycled aggregates on mechanical and fractural properties of concrete: Insights from DEM modelling. Composites Part A: Applied Science and Manufacturing, 186(0). doi:10.1016/j.compositesa.2024.108395.

[19] Irfan, M. (2024). Importance of RE Utilization of Aggregate in Developing Concrete from Demolition Concrete Waste: Review. International Journal for Research in Applied Science and Engineering Technology, 12(2), 911–914. doi:10.22214/ijraset.2024.58474.

[20] Sharma, R., Jang, J. G., & Bansal, P. P. (2022). A comprehensive review on effects of mineral admixtures and fibers on engineering properties of ultra-high-performance concrete. Journal of Building Engineering, 45(0). doi:10.1016/j.jobe.2021.103314.

[21] Wang, X., Li, X., Zhong, Y., Li, H., & Wang, J. (2024). Properties and Microstructure of an Interfacial Transition Zone Enhanced by Silica Fume in Concrete Prepared with Coal Gangue as an Aggregate. ACS Omega, 9(1), 1870–1880. doi:10.1021/acsomega.3c08560.

[22] Rabab'ah, S. R., Al Hattamleh, O. H., Tarawneh, A. N., & Aldeeky, H. H. (2024). Experimental and ANN Analysis of Shearing Rate Effects on Coarse Sand Crushing. Civil Engineering Journal, 10(3), 824-834. doi:10.28991/CEJ-2024-010-03-011.

[23] Iqbal, M., Zhang, D., Khan, K., Amin, M. N., Ibrahim, M., & Salami, B. A. (2023). Evaluating mechanical, microstructural and durability performance of seawater sea sand concrete modified with silica fume. Journal of Building Engineering, 72. doi:10.1016/j.jobe.2023.106583.

[24] Alamri, M., Ali, T., Ahmed, H., Qureshi, M. Z., Elmagarhe, A., Adil Khan, M., Ajwad, A., & Sarmad Mahmood, M. (2024). Enhancing the engineering characteristics of sustainable recycled aggregate concrete using fly ash, metakaolin and silica fume. Heliyon, 10(7), 29014. doi:10.1016/j.heliyon.2024.e29014.

[25] Trykoz, L., Zinchenko, O., Borodin, D., Kamchatna, S., & Pustovoitova, O. (2024). Effect of treatment types of recycled concrete aggregates on the properties of concrete. Construction and Architecture, 23(3), 129–137. doi:10.35784/bud-arch.6318.

[26] Madhavarao, D. G., Sai, T. V. D., Ramya, T., Mahesh, T., Divya, M., & Babu, B. V. (2023). Evaluating The Performance of Acid-Treated (Hcl-Hno3) Recycled Aggregate in Environmentally Friendly Concrete. International Journal of Innovative Research in Engineering and Management, 10(2), 99–102. doi:10.55524/ijirem.2023.10.2.18.

[27] Kadarla, N., Siempu, R., & Murali Krishna, B. (2024). Studies on Performance of the Treated Recycled Concrete Coarse Aggregate in High-Strength Concrete. Journal of Physics: Conference Series, 2779(1). doi:10.1088/1742-6596/2779/1/012019.

[28] Joseph, H. S., Pachiappan, T., Avudaiappan, S., Maureira-Carsalade, N., Roco-Videla, Á., Guindos, P., & Parra, P. F. (2023). A Comprehensive Review on Recycling of Construction Demolition Waste in Concrete. Sustainability (Switzerland), 15(6), 4932. doi:10.3390/su15064932.

[29] Balasubramani, G., & Palaniappan, M. (2025). Influence of acids and slurries on the properties of recycled concrete aggregates. Matéria (Rio de Janeiro), 30, e20240682. doi:10.1590/1517-7076-RMAT-2024-0682.

[30] Lv, D., Huang, K., & Wang, W. (2023). Influence of pretreatment methods on compressive performance improvement and failure mechanism analysis of recycled aggregate concrete. Materials, 16(10), 3807. doi:10.3390/ma16103807.

[31] Rama Rasagna, A. S. V. S., Siempu, R., & Murali Krishna, B. (2024). Studies on the Mechanical Properties of Recycled Aggregate Concrete using Treated Recycled Coarse Aggregates. Journal of Physics: Conference Series, 2779(1). doi:10.1088/1742-6596/2779/1/012046.

[32] Tam, V. W. Y., Soomro, M., & Evangelista, A. C. J. (2021). Quality improvement of recycled concrete aggregate by removal of residual mortar: A comprehensive review of approaches adopted. Construction and Building Materials, 288, 012046. doi:10.1016/j.conbuildmat.2021.123066.

[33] Ouyang, K., Liu, J., Liu, S., Song, B., Guo, H., Li, G., & Shi, C. (2023). Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review. Resources, Conservation and Recycling, 188. doi:10.1016/j.resconrec.2022.106717.

[34] Tang, A. J., De Jesus, R., & Cunanan, A. (2019). Microstructure and mechanical properties of concrete with treated recycled concrete aggregates. International Journal of GEOMATE, 16(57), 21–27. doi:10.21660/2019.57.4537.

[35] Panghal, H., & Kumar, A. (2024). Enhancing concrete durability and strength: An innovative approach integrating abrasion and cement slurry treatment for recycled coarse aggregates. Structural Concrete, 26(2), 1455–1476. doi:10.1002/suco.202400387.

[36] Panghal, H., & Kumar, A. (2024). Enhancing concrete performance: Surface modification of recycled coarse aggregates for sustainable construction. Construction and Building Materials, 411. doi:10.1016/j.conbuildmat.2023.134432.

[37] Feng, C., Wang, J., Cui, B., Ye, Z., Guo, H., Zhang, W., & Zhu, J. (2024). Evaluation of techniques for enhancing recycled concrete aggregates: Chemical treatment, biological modification and synergistic reinforcement. Construction and Building Materials, 420. doi:10.1016/j.conbuildmat.2024.135641.

[38] ASTM C109/C109M-11a. (2004). Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International, Pennsylvania, United States. doi:10.1520/C0109_C0109M-11A.

[39] ASTM C33/C33M-18. (2023). Standard Specification for Concrete Aggregates. ASTM International, Pennsylvania, United States. doi:10.1520/C0033_C0033M-18.

[40] Megaadd MS(D) Company. (2025). Densified micro silica construction chemical. Megaadd MS(D) Company, Sharjah, United Arab Emirates.

[41] ASTM C1240-20. (2003). Standard Specification for Silica Fume Used in Cementitious Mixtures. ASTM International, Pennsylvania, United States. doi:10.1520/C1240-20.

[42] BS 5328-2:1997. (1997). Concrete. Methods for specifying concrete mixes (AMD 9691) (AMD 10365) (AMD Corrigendum 10612) (AMD 13877). British Standards Institution (BSI), London, United Kingdom.

[43] Hansen, T. C., & Narud, H. (1983). Recycled concrete and silica fume make calcium silicate bricks. Cement and Concrete Research, 13(5), 626–630. doi:10.1016/0008-8846(83)90051-0.

[44] Li, J., Xiao, H., & Zhou, Y. (2009). Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete. Construction and Building Materials, 23(3), 1287–1291. doi:10.1016/j.conbuildmat.2008.07.019.

[45] Mukharjee, B. B., & Barai, S. V. (2014). Influence of incorporation of nano-silica and recycled aggregates on compressive strength and microstructure of concrete. Computers and Chemical Engineering, 71(30), 570–578. doi:10.1016/j.conbuildmat.2014.08.040.

[46] Skoyles, E. R. (2000). Material control to avoid waste. Building Research Establishment Digest, London, United Kingdom, 3(259), 1-8,

[47] Alexander, M. G. (1994). Effects of aging on mechanical properties of the interfacial zone between cement paste and rock. Cement and Concrete Research, 24(7), 1277–1285. doi:10.1016/0008-8846(94)90112-0.