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An Evaluation of the Strength for Recycled Fine Aggregate Replacement in Cementitious Mortars

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Abstract: This research investigates the viability of high-strength Recycled Concrete Aggregate (RCA) sourced from demolished structures containing high-strength concrete as a substitute for natural fine aggregates (NA) in cementitious mortar applications. Concrete specimens (40 × 40 × 160 mm) were prepared in a controlled environment with varying percentages of RCA replacing NA, ranging from 0% to 100% in 10% increments. The resulting RCA aggregates exhibited lower weight for sizes from 0.01 to 1 mm compared to NA, and for 1 to 3 mm sizes, RCA weights were 145% to 177% higher than SS aggregates. After curing for 28 days, flexural and compressive strength tests were conducted on the batches. The average compressive strength for the 0% RCA batch was 66.26 MPa, while the 50% RCA batch showed the closest average compressive strength at 63.10 MPa. Batches with varying RCA levels displayed compressive strengths between 49.52 and 58.18 MPa. The highest flexural strength was observed in the 0% RCA batch, with the closest result for a batch containing RCA being the 50% RCA batch.

Keywords: recycled mortar; recycled mortar aggregate; fine recycled aggregate; circular construction; sustainable construction materials

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1. Introduction

Demand for aggregates in construction applications has been on the rise, with approximately 34 billion metric tonnes of aggregate per person extracted on an annual basis [1]. However, the methods used to extract these materials are associated with various environmental impacts. These impacts include deterioration of the landscape, the production of dust, and pollution of water bodies or water courses [1–3]. To match the industry requirements for circular construction, research studies investigated the use of recycled concrete recovered from demolition sites to be used as Recycled Concrete Aggregates (RCA) in various applications [4–7]. The shift in interest in this research domain has increased by approximately 94% between 2015 and 2020 [8]. Figure 1 reflects this shift of interest. This shift also correlates with the European Commission Waste Framework Objective, which sets a target of 2020 for the preparation and re-use of up to 70% of construction waste in the form of recovery material. However, the results varied significantly from one member state to the next, with over half achieving this target between 2013 and 2015 [9,10]. To assess the viability of wide implementation of RCA as a substitute for NA, a life cycle assessment must be conducted [11]. For this purpose, ref. [12] conducted a life-cycle assessment of RCA applications in pavement design mixes. The results estimated that the impact of utilising RCA pavements can lead to a reduction in various economic, social, and environmental aspects during the extraction and construction phases. This is further highlighted by [13], in which it was estimated that by utilising RCA, reduction in either conversion or occupation of land are improved. However, ref. [12] estimated that during the operational phase, the impact of RCA compared to that of plain pavements yielded similar results. In some instances, RCA pavements led to increased energy consumption.

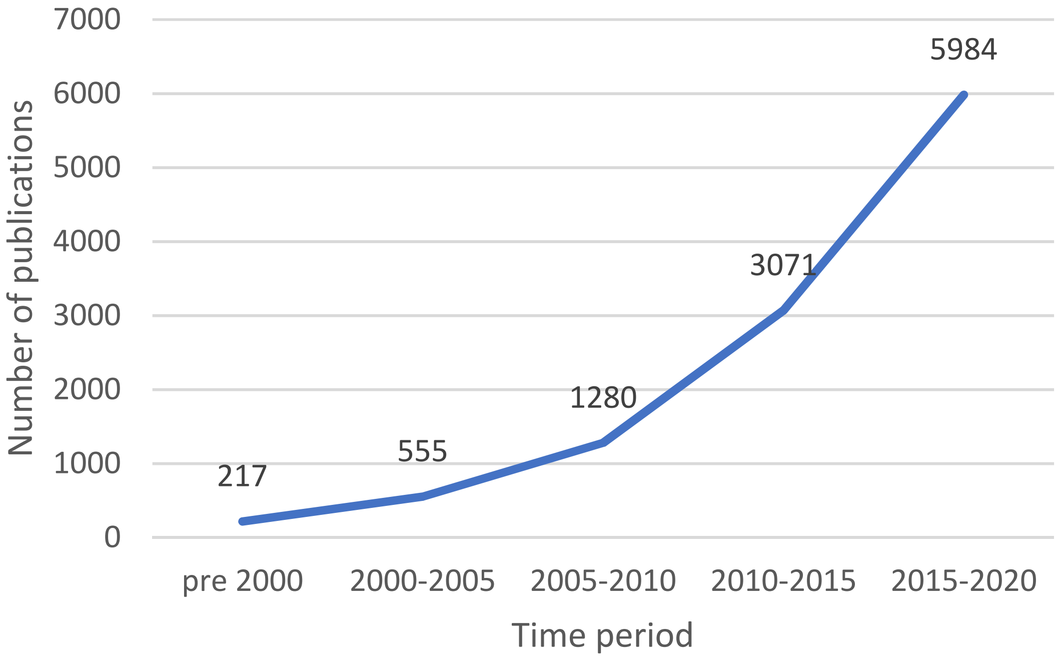


Figure 1. Published articles in RCA [8]. Adapted with permission from Ref. [8]. Copyright Feb 06, 2024, copyright Bo Wang, Libo Yan, Qiuni Fu, Bohumil Kasal.

1.1. Aim

The aim of this study is to assess the behaviour of RCA made from high-strength concrete specimens using recycled mortar aggregates as a replacement for natural sand in concrete mortar to replicate the long-term strength and durability in mortar applications. As such, this study will build upon the previous works of literature to attempt to answer the question of whether utilizing RCA at various replacement ratios as a fine aggregate can have similar strength properties to those of the SS.

1.2. Contribution and Significance of the Study

Previous studies published by other researchers have investigated the strength characteristics of concrete specimens incorporating Recycled Concrete Aggregates (RCA), as outlined in Table 1. The majority of laboratory-generated samples in these studies have employed ordinary Portland cement, specifically Type I 42.5 N and Type II cement 32.5 N [14–17]. This study focused on using white Portland cement type I 52.5 N to identify the effect of superior strength characteristics in mortar mixes in the presence of recycled aggregates. In terms of recycled aggregates, most of the work from other researchers focused on mixes obtained from construction demolition waste [18–20]. In contrast, this present study focused on identifying the effects of structural concrete derived from recycled aggregates. Notably, the preceding literature has often focused on a limited range of recycled aggregate replacement ratios. Ref. [21] explored RCA replacement ratios ranging from 0% to 40%; ref. [15] investigated replacement ratios of 0%, 25%, 50%, and 100%; and [14] utilized replacement ratios of 20%, 50%, and 100%. In contrast, this study spans all replacement ratios, starting at 0% and incrementing by 10% up to 100%. This would allow for a better capture of the effect of RCA. Consequently, this research aims to address gaps in the existing literature by exploring the use of high-strength concrete specimens as RCA in the context of cementitious mortar applications, incorporating a comprehensive range of RCA replacement ratios.

Table 1. Most recent studies in the field of RCA.

Authors	Focus	Type of Parent Material Used for Creating RCA	RCA Replacement Ratio (%)
[22]	Fine aggregates in concrete	Ordinary Portland type I 42.5 N	0, 20, 45, 70, 100
[5]	Construction demolition waste in concrete	Construction demolition waste	0, 30, 50, 100
[23]	Recycled coarse aggregates with mineral additives	Ordinary Portland type I 42.5 N	0, 25, 50, 75, 100
[24]	Cement additives on recycled concrete	Ordinary Portland type I 42.5 N	0, 20, 50, 100
[14]	Recycled fine aggregates in mortar	Portland Type II cement 32.5 N	0, 20, 50, 100
[15]	Cement mortars with RCA	Portland Type II cement 32.5 N	0, 25, 50, 100
[18]	Geopolymer mortar with RCA	Construction demolition waste	0, 100
[25]	Evaluating mechanical properties of cement mortar with fine recycled aggregates	Ordinary Portland type I 42.5 N	0, 25, 50, 100
[26]	Strength and durability cycled fine aggregates in mortar applications	Recycled sand obtained from recycling platform	0, 10, 20, 30, 50, 100

1.3. Performance of RCA

A study conducted by [5] investigated the structural performance of RCA in various structural applications. It was estimated that 30% RCA replacement in concrete mixes would yield the closest strength to that of NA concrete. However, this study also highlighted that in some applications, a 50% RCA replacement can be suitable. The structural performance However, it may be impacted by an increased risk of steel corrosion [27]. Steel reinforcement corrosion is attributed to various factors. Furthermore, ref. [5] estimated that the influencing factors for steel corrosion include carbonation, permeability, and chloride penetration. Furthermore, ref. [28] estimated that Fine Recycled Aggregates (FRA) allowed for up to a 227% increase in the Alkali Silica Reaction (ASR). Chloride penetration presents another issue that may detriment performance. However, this study determined that utilizing 60% and higher contents of FRA did not pose a risk to steel reinforcement corrosion compared to NA mixes. Additionally, low- to medium-FRA mixes can reach the desired compressive strength over the long term. A study by [29] estimated that, due to its high water absorption rate, increasing the water content would avoid excessive absorption. Additionally, the absorption rate depends on the capacity and size of the RCA. As the size decreases, the absorption increases [30]. As a result, the concrete slump may show greater workability rates compared to that of the concrete mix with NA [29]. Additionally, ref. [31] further elaborated that RCA mixes would increase the shrinkage due to drying, concrete permeability, and creep. As a result, the mechanical properties and modulus of elasticity decreases [32].

1.4. Additives and Plasticisers

To mitigate the reduced performance of concrete with RCA, various studies have investigated the use of additive materials [33]. A study by [34] researched the impact of RCA mixes with fly ash. This study estimated that by mixing 30% fly ash as a partial substitute within an RCA mix, a comparable design strength to that of NA can be achieved. This finding is further elaborated by the findings of [35], in which it was estimated that 25% substitution with a Class F fly ash lowered the pH rate up to 13.28. In geopolymer concrete; however, the inclusion of fly ash in mixes with fine or coarse RCA may not be sufficient to reach the desired strength. As such, the inclusion of micro carbon fibre may present a potential solution to this issue [36]. Furthermore, ref. [37] estimated that with the increase in W/C ratio, there is a linear increase in the level of porosity. As such, this study suggested introducing a correction method to enhance the assessment of the water/cement ratio. The correction formula for the water absorption rate is shown in Equation (1). This formula is based on the water absorption rate of RCA measured at 105 degrees.

$$Absorption\ rate\ of\ RCA = Absorption\ rate\ measured\ at\ 105\ °\mathrm{C} \times 0.75 \quad (1)$$

In mortar applications, ref. [36] estimated that a 0.2% carbon fibre mixed with a 100% RCA geopolymer mortar resulted in an increase in compressive and tensile strengths. However, it was estimated from this study that 50% RCA mixed in geopolymer mortar along with 0.2 carbon fibre generated the highest flexural strength. Other additive materials used to enhance the RCA concrete mix were mineral additives such as glass and mineral wool and ground granulated blast furnace slag [23,38]. However, the resulting mixes did not significantly increase the strength up to the standards. In some cases, the inclusion of these additive materials led to a decrease in strength in certain RCA design mixes [39].

2. Materials and Methods

2.1. Materials

2.1.1. Cement

The cement used in this experiment was Type I general-purpose Portland cement, which complies with British Standards BS EN 480 [40]. The chemical composition of the cement is found in Table 2. The cement used in this study has a strength of 52.5 N and is known as Extra Strong Snow-Crete Cement due to its high strength compared to ordinary Portland cement. This type of cement conforms with the British Standards for ordinary cement as per BS EN 197-1:2011 [41]. However, this type of cement is ideally suited for mortar and other non-structural applications [42].

Table 2. Chemical composition of cement type I.

Chemical Characteristics	Portland Cement Type I 52.5 N (%)	Portland Cement Type I 42.5 N (%) [20]
SiO_2	22.44	22.43
CaO	62.16	56.40
Al_2O_3	4.80	6.83
Fe_2O_3	3.44	2.82
MgO	1.43	2.11
SO_3	3.20	3.04
Na_2O	0.57	-
K_2O	0.62	-
Cl	0.07	-
Fineness (m^2/kg)	353	369
Setting time (mins)	113	190
Soundness (mm)	1.00	-

2.1.2. Aggregates

The fine RCA samples were derived from concrete specimens produced under controlled laboratory conditions specifically for the purpose of crushing into standard-sized aggregates thereafter. The resulting mass of the recycled aggregates obtained was estimated to be 1407 kg/m^3, indicating a 16% decrease compared to the mass of SS, which was estimated to be 1642 kg/m^3. To ensure that the RCA sizes conformed to the standard size dimensions of fine aggregates, the collected aggregate samples were passed through a Controls Sieving Machine. The estimated frequency of the sieved materials was 5 min per interval. This would allow for the correct separation of particles. The results from the Controlled Sieving Machine estimated that the weight of the passing aggregates for RCA for aggregate sizes between 0.01 and 1 mm was comparatively lower than that of SS aggregates. However, for aggregate sizes larger than 1 mm, the results showed a significant increase in aggregate passing. Both the SS and RCA aggregates exhibited a 100% passing rate through the 4 mm sieve. Table 3 depicts the detailed results of the sieving analysis.

When comparing the percentage of aggregates retained for both RCA and SS to the BS 993-2 [43] upper and lower limits, it can be observed that the passing RCA aggregates fall within the acceptable boundaries for sieve sizes 2 and 1 mm. Conversely, the SS sample approached the upper limit boundary for the 1 mm sieve. However, for sieve sizes less than 1 mm, the RCA aggregates passing are much closer to the lower range of the BS 993-2 range. Additionally, both the SS and RCA samples were matching the upper limit range of the BS 993-2, as shown in Figure 2.

Table 3. Aggregate sieving analysis.

Aggregate Size (mm)	Weight Retained (g)		Weight Passing (g)		Percentage Passing (%)	
	SS	RCA	SS	RCA	SS	RCA
4	0	0	10,000	10,000	100.00%	100.00%
2	1590.7	2731	8011.7	6585	80.12%	65.85%
1	8011.7	2084	6580.7	4501	65.81%	45.01%
0.01 < 1.00	6580.7	4401	874.3	100	8.75%	1.00%
Pan	874.3	100	0	0	0.00%	0.00%

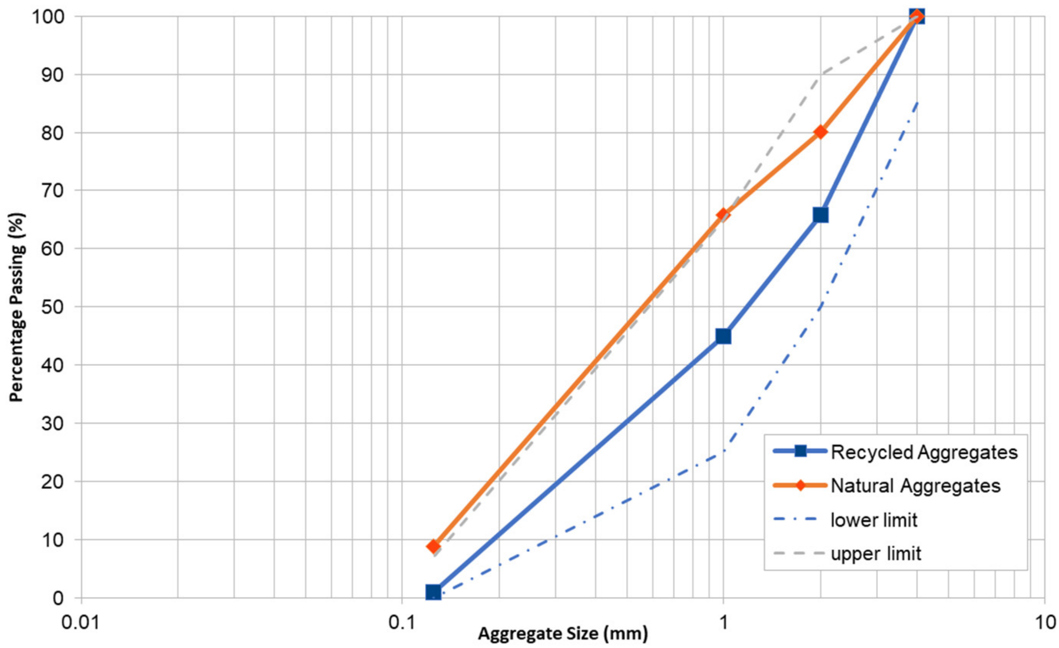


Figure 2. Sieve analysis of RCA and SS compared to BS 993-2 upper and lower limits.

2.2. Mortar Design Mixes

Mortar mixes incorporating varying levels of Recycled Concrete Aggregates (RCA) were systematically produced in a laboratory setting, adhering to the guidelines outlined in BS 998-1:2016 [44]. A total of 11 batches were prepared, with each batch consisting of three beam samples, except for the control batch, which comprised six samples. The batches spanned from 0% RCA in the first batch to 100% RCA in the final one, with each batch incrementing the RCA ratio by 10%. To ensure optimal workability, water ratios were meticulously assessed. Following this evaluation, a mix design with a 5% water ratio was deemed suitable for achieving the desired workability. Consequently, each batch was furnished with a consistent amount of water (270 g) and cement (600 g). Notably, no super-plasticizers were employed throughout this process. The composition of each mix batch is detailed in Table 4.

Table 4. Mortar batch mix composition.

Batch No.	Batch Size	Cement (g)	Natural Sand (g)	RCA (g)	RCA (%)	Water (g)	Slump Flow (mm)
Control	6	600	1200	0	0	270	225
2	3	600	1080	120	10	270	222
3	3	600	960	240	20	270	196
4	3	600	840	360	30	270	191
5	3	600	720	480	40	270	178
6	3	600	600	600	50	270	170
7	3	600	480	720	60	270	155
8	3	600	360	840	70	270	145
9	3	600	240	960	80	270	142
10	3	600	120	1080	90	270	125
11	3	600	0	1200	100	270	110

2.3. Specimen and Curing

The batch beams were manually mixed and cast in a 40 × 40 × 160 mm cast mould for the purposes of evaluating the tensile and compressive strength of the mortar. These beams were fully submerged in water to cure. Samples taken from each batch were tested at 7 days to assess their initial strength. The remaining samples from each batch were tested at 28 days.

2.4. Tests

Compressive and Flexural Strength

To assess the strength of the mortar batches, experimental tests were conducted at 28 days in accordance with BS 1015-11:2019 [45]. To assess the flexural strength of the samples, a three-point loading test was utilised (shown in Figure 3). The machine utilised for this purpose had a test speed of 30 N/s and was pre-loaded with 5 N. BS 1015-11:2019 provides a formula to assess the strength based on the setup configuration. This formula was adapted in this study for the purpose of assessing the flexural strength, as follows:

$$f = 1.5 \times \frac{F \times L}{b \times d^2} \quad (2)$$

where:

f = design flexural strength
F = maximum applied load to the beam in N
L = the distance between the supports in mm
b = beam width in mm
d = beam depth in mm

Figure 3. Flexural test 3-point test.

The compressive strength test conducted in this study is in accordance with BS 1015-11:2019. The resulting samples from the flexural strength test were used in this experiment to increase the sample numbers per batch to 6, as depicted in Figure 4. As such, the cross-sectional areas for each sample were measured manually, as shown in Table 5 [14]. The compressive machine utilised in this experiment has a loading rate of 400 N/s and was pre-loaded with 5 N. The compressive stress is assessed based on Equation (3). The compressive force in this equation refers to the maximum force recorded prior to compressive failure.

$$Compressive\ Strength = \frac{Compressive\ force}{Cross - sectional\ Area} \quad (3)$$

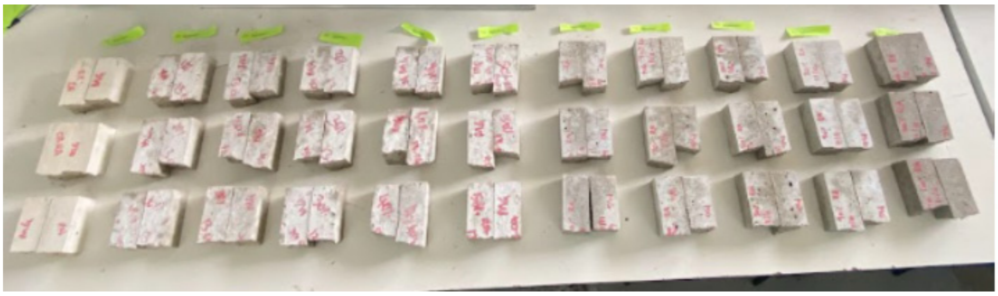


Figure 4. Compressive strength samples tested after 28 days of curing.

Table 5. Cross-sectional area for samples tested for compressive strength.

Sample Type	Sample No.	Cross-Sectional Area (mm^2)	Sample Type	Sample No.	Cross-Sectional Area (mm^2)	Sample Type	Sample No.	Cross-Sectional Area (mm^2)
SS	1	3362	40% RCA	1	3241	80% RCA	1	3082
	2	3001		2	3129		2	3314
	3	3144		3	3096		3	3294
	4	3256		4	3298		4	3055
	5	3313		5	2815		5	3210
	6	3065		6	3564		6	3189
10% RCA	1	3266	50% RCA	1	2928	90% RCA	1	3105
	2	3119		2	3444		2	3294
	3	3444		3	2852		3	3161
	4	2956		4	3545		4	3236
	5	3203		5	3171		5	3051
	6	3196		6	3188		6	3339
20% RCA	1	3076	60% RCA	1	3443	100% RCA	1	3153
	2	3313		2	2945		2	3238
	3	3423		3	3170		3	3242
	4	2903		4	3223		4	3157
	5	3183		5	3111		5	3408
	6	3216		6	3287		6	2979
30% RCA	1	3160	70% RCA	1	3335			
	2	3231		2	3045			
	3	3338		3	2722			
	4	3059		4	3675			
	5	3074		5	3092			
	6	3318		6	3305			

3. Results

3.1. Compressive Strength

The compressive strength tests of the control samples were tested at 7 days and 28 days of curing. Each test contained three samples. The findings revealed a notable enhancement in strength, with the 28-day results exhibiting an estimated 50% increase compared to the samples tested at 7 days, as outlined in Table 6. Consequently, a strategic decision was made to assess the compressive strengths of the samples exclusively at the 28-day mark, aiming to obtain more precise and reliable results.

Table 6. Mean and standard deviation for the compressive strength of 7 days vs. 28 days natural Sand samples.

Sample Type	Mean Compressive Strength (MPa)	Standard Deviation
7 days	43.90	10.42389
28 days	66.25	11.28284

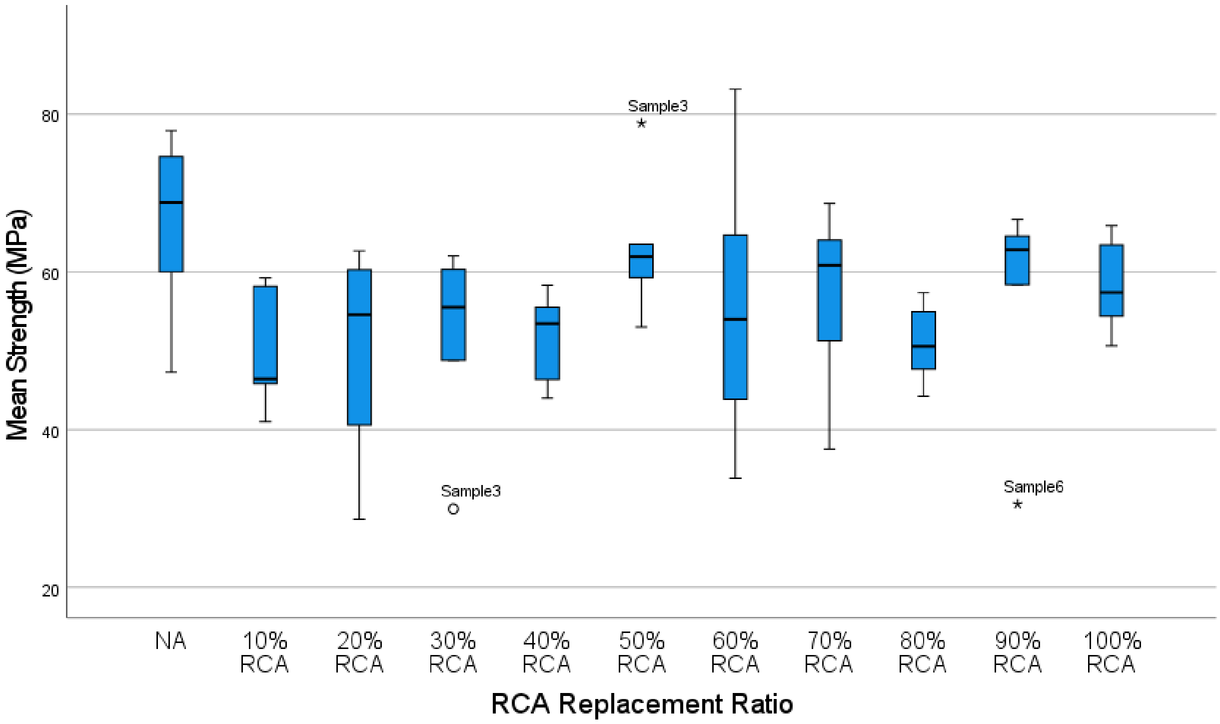
When examining the average compressive strength of SS samples after 28 days of curing in comparison to those containing RCA, an overarching trend indicates a reduction in strength across all tested samples. The samples incorporating 50% RCA aggregates exhibited the closest average strength (63.10 MPa) relative to the SS samples (66.25 MPa), representing an estimated 5% decrease. The 100% RCA samples ranked second in compressive strength (58.19 MPa) compared to the SS samples, reflecting an approximate decrease of 12%. Notably, the greatest decline in strength was observed in samples containing 10% RCA aggregates, with the average strength estimated to be 33% lower than that of the SS samples. Table 7 presents the mean and standard deviation of the strengths obtained from the compressive strength tests, while Figure 5 visually depicts the statistical analysis through boxplots.

Table 7. Mean and standard deviation for compressive strength for samples tested at 28 days.

Sample Type	Mean Compressive Strength (MPa)	Standard Deviation
SS	66.25	11.28284
10% RCA	49.52	7.40859
20% RCA	50.23	13.29850
30% RCA	52.85	11.93912
40% RCA	51.85	5.59013
50% RCA	63.10	8.60569
60% RCA	55.58	17.15341
70% RCA	57.22	11.26280
80% RCA	50.91	4.79873
90% RCA	57.64	13.56803
100% RCA	58.19	5.64774

3.2. Flexural Test

When contrasting the average flexural strength of SS aggregate samples cured for 7 days with those cured for 28 days, a notable strength increase of up to 74% was observed, as illustrated in Table 8. The boxplot in Figure 6 serves to visually underscore the statistical distinctions among the sample strengths. Aligning with the approach taken in the compression test, a strategic decision was made to exclusively assess the flexural strengths of the samples at the 28-day mark, aiming to enhance the precision and reliability of the results.



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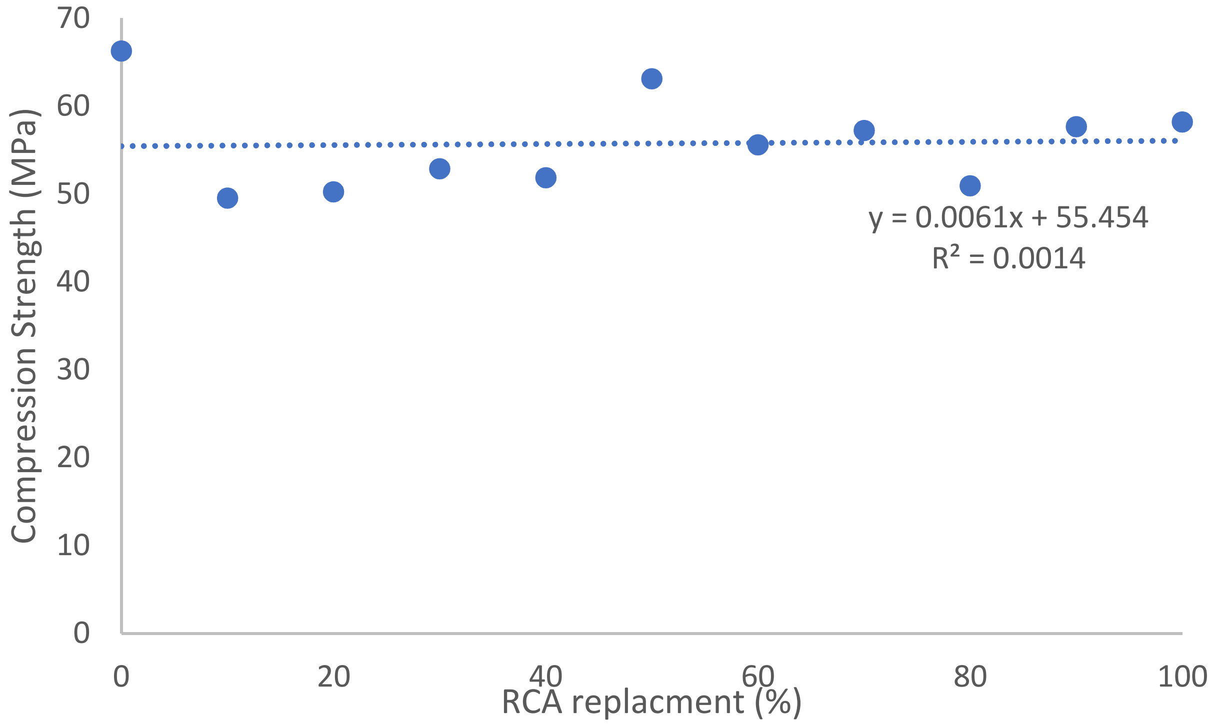

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Figure 5. Compressive strength results (**a**) Graphical display of the distribution and skewness using boxplots (**b**) Compressive strength relative to RCA replacement with a trendline. The ○ and * present sample outliers.

Table 8. Mean and standard deviation for the flexural strength of 7 days vs. 28 days natural Sand samples.

Sample Type	Mean Flexural Strength (MPa)	Standard Deviation
7 days	7.00	0.38734
28 days	12.23	1.25831

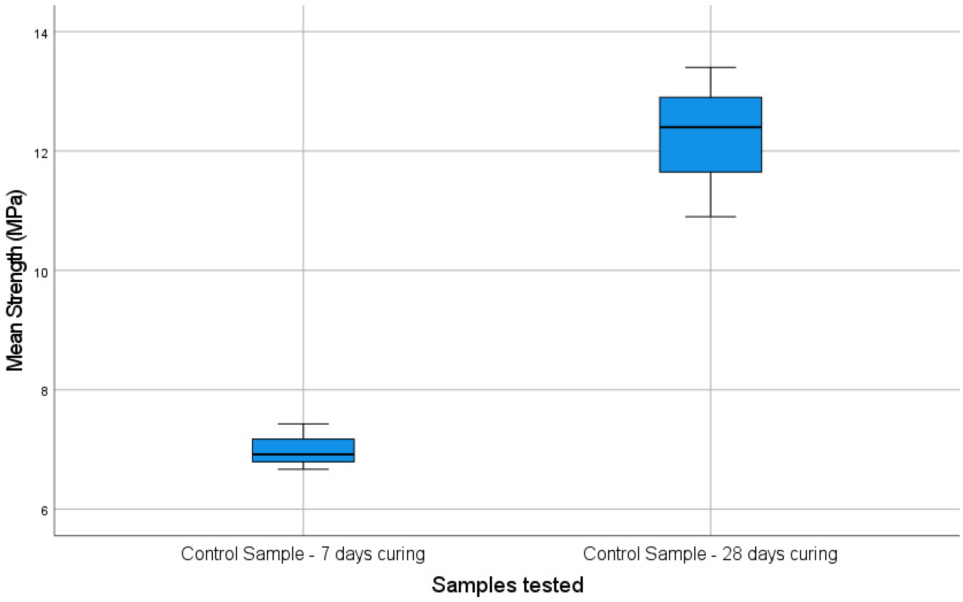
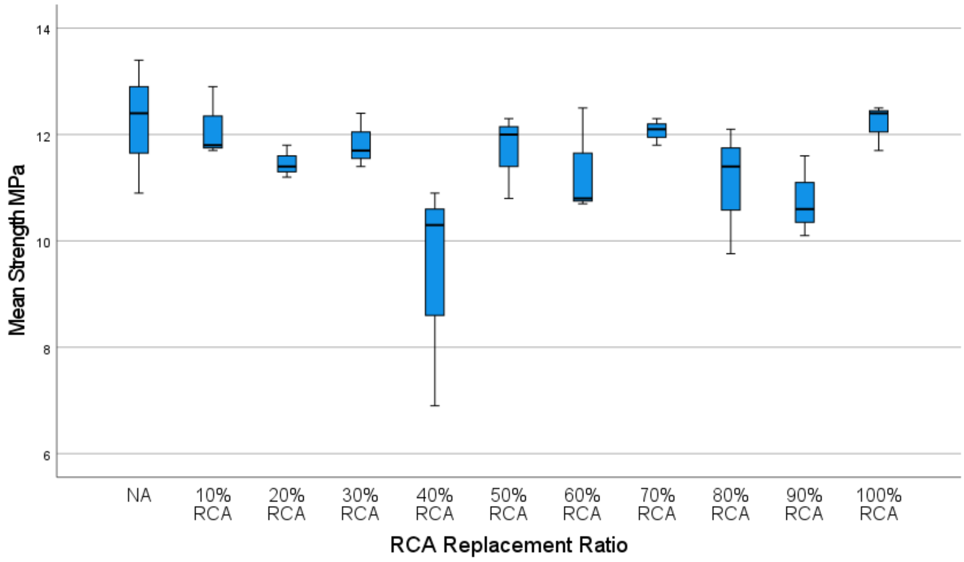


Figure 6. boxplot for 7-day vs. 28-day flexural strength for SS samples.

Upon testing samples incorporating RCA, it was determined that the average flexural strength for 100% RCA aggregates (12.20 MPa) closely paralleled that of SS aggregates (12.23 MPa). Following closely, the second-highest average strength was observed in the 10% RCA samples (12.13 MPa). Notably, these 10% RCA samples displayed a more compact dispersion (0.66583) in comparison to the SS samples (1.25831). Conversely, the weakest flexural strength was recorded for the 40% RCA aggregates, with the mean strength estimated at 9.37 MPa. The standard deviation in strength for the 40% RCA samples exhibited a more extensive dispersion (2.15716) when contrasted with the other samples of varying aggregate compositions. A comprehensive overview of the mean and standard deviation for all tested samples is presented in Table 9, while Figure 7's boxplots provide a visual representation of the statistical analysis for each sample.

Table 9. Mean and Standard Deviation for 28-day flexural strength.

Sample Type	Mean Flexural Strength (MPa)	Standard Deviation
SS	12.23	1.25831
10% RCA	12.13	0.66583
20% RCA	11.47	0.30551
30% RCA	11.83	0.51316
40% RCA	9.37	2.15716
50% RCA	11.70	0.79373
60% RCA	11.33	1.01160
70% RCA	12.07	0.25166
80% RCA	11.09	1.20106
90% RCA	10.7667	0.76376
100% RCA	12.20	0.43589



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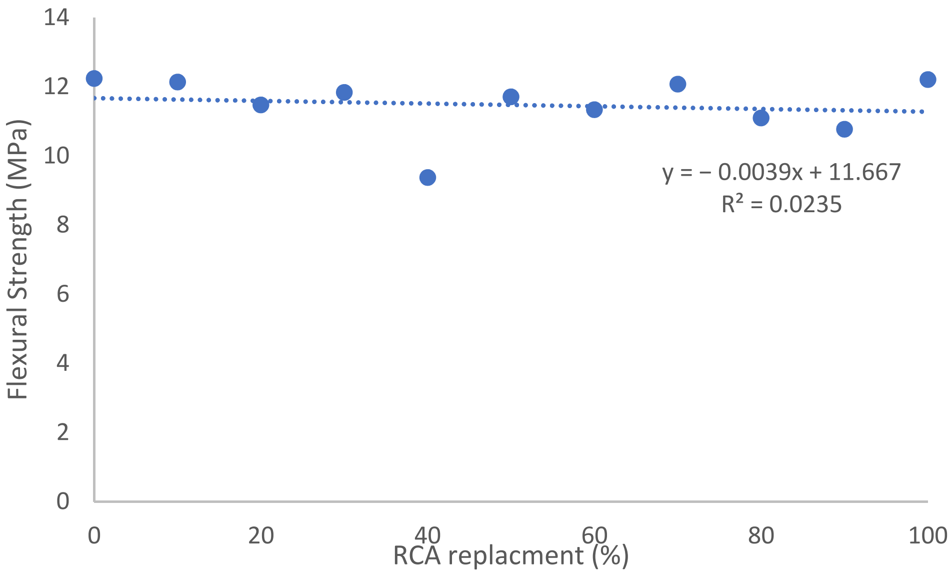

(**b**)

Figure 7. Flexural strength results (**a**) Graphical display of the distribution and skewness using boxplots (**b**) Flexural strength relative to RCA replacement with a trendline.

4. Discussion

The flexural test results obtained from specimens incorporating varying degrees of RCA consistently demonstrated comparable strength to that of the SS samples. The introduction of RCA aggregates did not significantly impact flexural strength, maintaining a consistent pattern across most replacement ratios. An exception to this trend was observed in the case of 40% RCA aggregates, where the mean sample strength was estimated to be 23% lower than that of the SS samples. The overall trend in the flexural test results aligns with findings from the previous literature, particularly [14,46]. Additionally, ref. [14] reported the highest flexural strength for the 100% RCA samples, a trend consistent with the outcomes of the present study. However, it is noteworthy that the observed flexural strength pattern differs from the findings of [20,26], where the strength steadily decreased with increasing RCA content. Figure 8 visually compares the flexural strengths obtained in this study with those reported by [26].

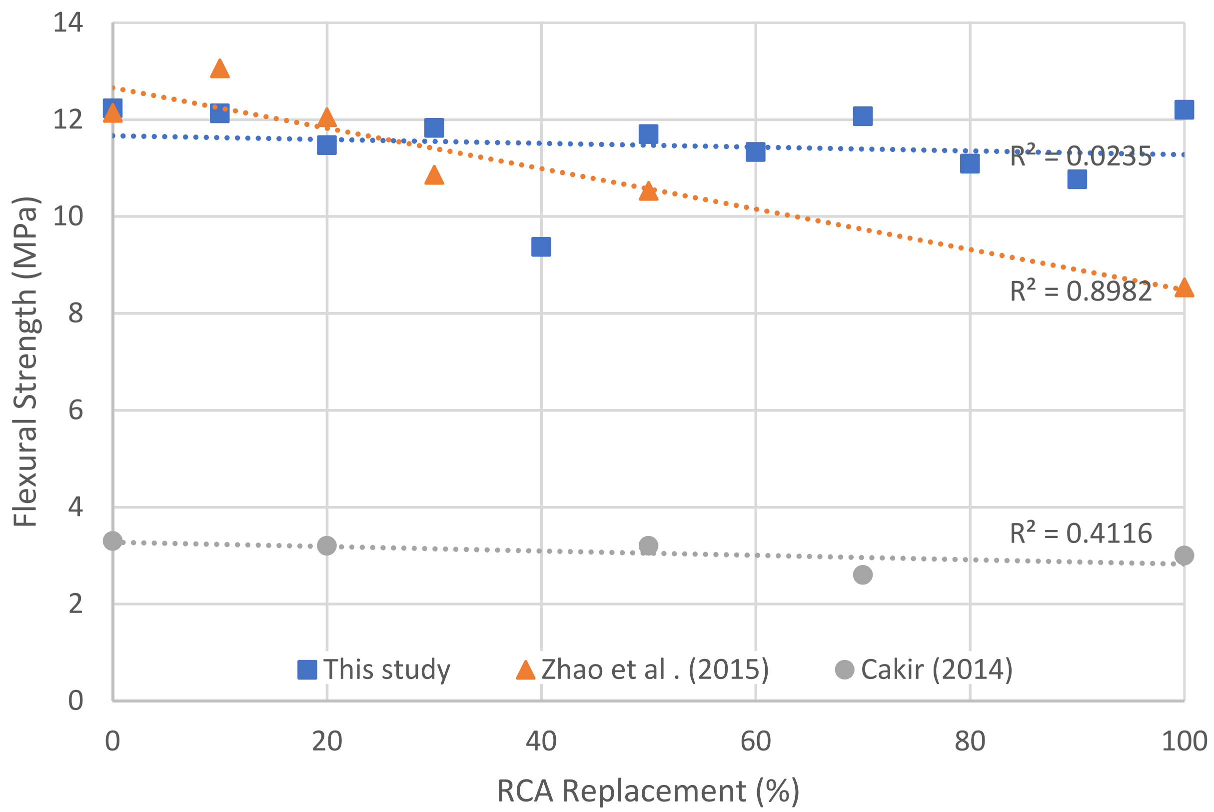

Figure 8. Flexural strength compared to [23,26]. Adapted with permission from Ref. [23]. Copyright Feb 06, 2024, copyright Ö. Çakır. Adapted with permission from Ref. [26]. Copyright Feb 06, 2024, copyright Zengfeng Zhao, Sébastien Remond, Denis Damidot, Weiya Xu.

The compression strength results in this study exhibit a similar pattern to the findings in flexural strength, as illustrated in Figure 9. As such, a comparative analysis between the compression strength results of RCA and SS suggests that a 50% RCA replacement stands out as an optimal solution, despite a marginal reduction in flexural strength of approximately 5% compared to SS samples. It is noteworthy that the resulting compressive and flexural strengths exhibit a weak correlation (depicted in Figures 5b and 7b) between the RCA aggregate replacement percentages and the strength values. This contrasts with the previous literature, where a strong correlation between RCA replacement and strength was observed [26]. As per the findings of this study, a complete replacement of SS with RCA (i.e., 100% RCA) is predicted to have an insignificant reduction in both compressive and flexural strength of the mortar. This finding does align with the findings of previous works in the literature [5,14,26], which also indicated a strong correlation between RCA replacement ratios and strength. For instance, ref. [14] estimated the greatest compressive strength to be in 100% RCA samples, indicating a 143% increase compared to the results for 50% RCA in that study. Conversely, refs. [26,47] concluded that the highest compression strength was at 10% RCA. The discrepancy between the current study and [26,47] can be attributed to differences in the materials used as fine aggregates, specifically the source of recycled fine aggregates and the mix design, particularly the water-cement ratio (W/C). In this study, the recycled fine aggregates were produced in a controlled laboratory setting, whereas [26] utilised recycled sand obtained from a third party. Furthermore, this study utilised a W/C ratio of 0.45 for suitable workability in the design mix. In contrast, ref. [26] utilized a W/C ratio of 0.5 and further testing at a W/C ratio of 0.6, which did not achieve the desired strength.

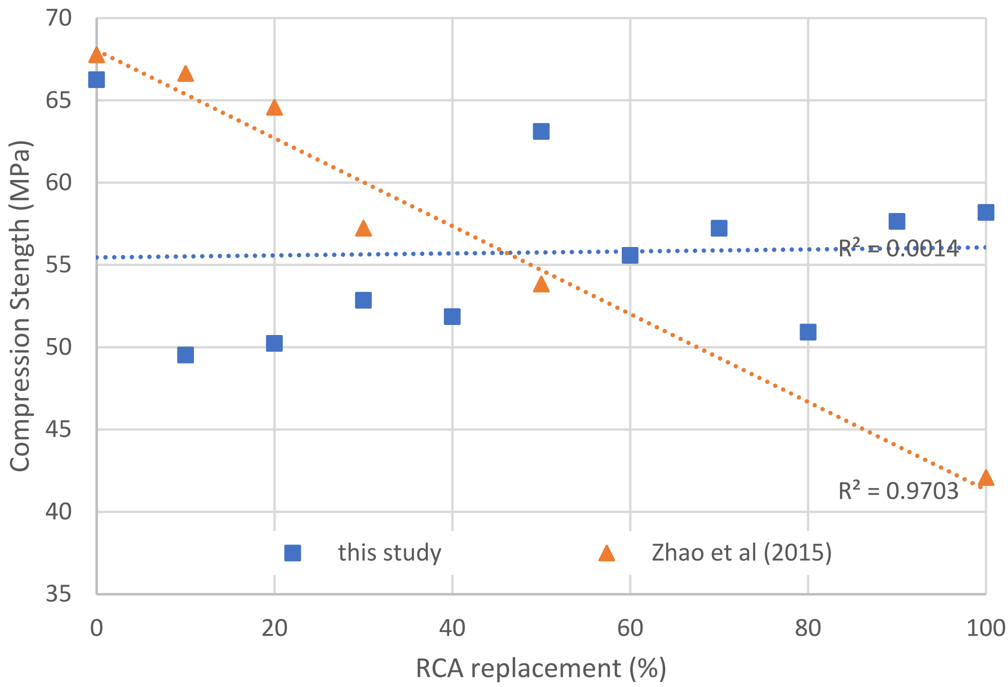

Figure 9. Compression strength comparison with [26]. Adapted with permission from Ref. [26]. Copyright Feb 06, 2024, copyright Zengfeng Zhao, Sébastien Remond, Denis Damidot, Weiya Xu.

5. Conclusions

This study explored the use of recycled fine aggregates as a replacement for SS aggregates in mortar applications. Based on the results and discussion, the following conclusions can be drawn:

1. In the context of the mix designs, workability can be achieved by incorporating 5% water. As such, the water-to-cement ratio needed to achieve the desired workability is 0.45.
2. The compressive tests conducted on aggregates containing Recycled Concrete Aggregates (RCA) at various percentages did not reveal a significant reduction in strength compared to findings in the previous literature. Furthermore, the correlation between the amount of RCA in a mix and strength was found to be insignificant. Consequently, incorporating any amount of RCA using the materials in this study is not anticipated to impact strength significantly. A similar conclusion can be drawn for flexural strength, although it is worth noting that the results for the 40% RCA exhibited a notable reduction when compared to the flexural strength of Standard Sand (SS) samples.
3. The compressive strength values obtained in this study for samples with RCA, when compared to those of SS, were closest in value for the 50% RCA. This finding aligns with results from the previous literature, indicating that adopting a 50% RCA replacement can provide compressive and flexural strengths nearly identical to those of SS samples.

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