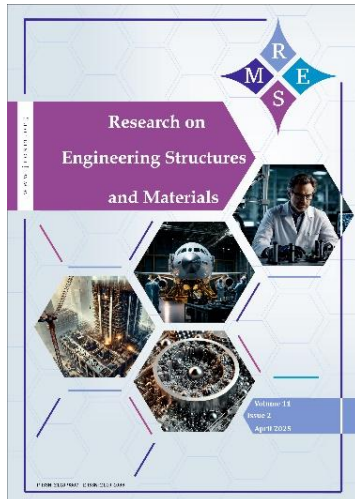




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Comparative evaluation of acid, mechanical, and thermal pre-treatment of recycled coarse aggregate in concrete

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Abstract

This study investigates the mechanical and selected durability-related performance of concrete incorporating recycled coarse aggregate (RCA) subjected to three pre-treatment methods, namely acid treatment (RCAA), mechanical treatment (RCAM), and thermal treatment (RCAT), with untreated RCA (RCAU) and conventional concrete (CC) used as reference groups. RCA replacement levels of 25, 50, 75 and 100% were considered. Workability, compressive strength, splitting tensile strength and flexural strength were evaluated at curing ages up to 365 days. Water absorption and sorptivity were evaluated for the conventional and untreated-RCA concrete series. The results show decreasing workability and strength with increasing RCA replacement, mainly because of higher porosity, adhered mortar and weaker interfacial transition zones. At 28 days, the 100% untreated-RCA concrete showed a compressive-strength reduction of about 17.1% relative to the control, while the 25% replacement level showed smaller reductions. Among the pre-treatment series, acid treatment gave the highest reported compressive-strength retention, followed by mechanical treatment, whereas thermal treatment gave lower values than the corresponding untreated-RCA series in the reported dataset. The durability-related results available in this study show that increasing untreated RCA replacement increased water absorption and sorptivity, indicating greater susceptibility to water ingress. The findings support the need for controlled RCA replacement and appropriate pre-treatment, while the durability benefit of the pre-treatment methods requires further experimental verification.

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1. Introduction

Rapid urbanization and large-scale infrastructure development have increased demand for construction materials, particularly natural aggregates (NA), which constitute a major volume fraction of concrete [1,2]. Intensive extraction of NA contributes to resource depletion and environmental impacts, while the generation of construction and demolition waste (CDW) creates additional disposal challenges. RCA produced from CDW has therefore emerged as a potential alternative to NA and as an important component of circular construction practices [3,4]. However, its structural application remains constrained by the presence of adhered old mortar (OM),

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microcracking and associated increases in porosity and water absorption [5–10]. Mechanical, chemical and thermal pre-treatment methods have been investigated to reduce adhered mortar and improve RCA quality [11–13]. Mechanical abrasion can remove part of the adhered mortar with comparatively low chemical waste [14–19], while acid treatment can dissolve calcium-rich hydration products but requires careful control of concentration, exposure and washing [20–24]. Thermal treatment can exploit differential thermal expansion to loosen adhered mortar, although excessive heating may damage aggregate and requires additional energy [25–29]. Hybrid treatments have also been reported [30–33]. Because the present study uses Portland Pozzolana Cement (PPC), the binder should also be considered when interpreting RCA performance. The pozzolanic constituents of PPC can participate in secondary reaction products and may contribute to matrix densification and interfacial development over extended curing periods. Previous studies on recycled aggregate concrete incorporating supplementary cementitious materials have reported changes in strength and durability associated with such binder systems [12,16]. PPC was therefore selected as the binder in the present investigation to examine RCA concrete under a commonly available blended-cement system rather than to imply equivalence with OPC.

The OM layer enclosing RCA particles changes dramatically in its properties. It increases porosity [6], water absorption and angularity and decreases specific gravity and strength [7]. Adhered mortar results in a weak interfacial transition zone (ITZ) between aggregate and fresh cement paste, which is a key factor for load transmission and overall concrete integrity [8]. In general, RCA absorbs 3–10% water which is substantially greater than 0.5–2% for NA leading to poorer density and reduction of 10–40% in compressive strength of concrete made using RCA known as recycled aggregate concrete (RAC) [9,10]. Therefore, pre-treatment techniques should be employed to enhance the RCA quality and to assure the structural reliability and durability of RAC. Various pre-treatment techniques have been proposed in an attempt to decrease adherent mortar and enhance aggregate surface characteristics including mechanical abrasion, chemical acid soaking and thermal exposure [11–13].

The physical technique of detaching the OM layer from the RCA particles by mechanical abrasion, ball milling or rotating friction is known as the mechanical treatment [14,15]. This method can remove 30–50% of the adhering mortar thereby decreasing porosity and increasing the strength and density of the aggregate [16]. However, severe wear may cause surface cracking and abnormalities in shape that are detrimental to the workability of concrete [17]. It has been shown that mechanical treatment optimization can boost the RCA crushing strength by 10–15% and enhance the RAC compressive strength by 10–20% [18]. The key advantages are the simplicity of operation, cost-effectiveness and little chemical waste, which makes it applicable for industrial large-scale applications [19].

Another potential option is the acid treatment that employs acidic solutions such as hydrochloric acid (HCl), sulfuric acid (H₂SO₄) or acetic acid (CH₃COOH) to dissolve calcium-rich hydration products in the OM [20,21]. The chemical reaction of acid with calcium hydroxide (Ca(OH)₂) or calcium silicate hydrate (C–S–H) phases, deteriorates the link between mortar and aggregate leading to its removal [22]. Studies have indicated that soaking RCA in 0.1–0.5 M HCl for 24 h can decrease adherent mortar by 20–30% and water absorption by 25–40%, leading to better aggregate quality [23]. However, the effectiveness of acid treatment is highly dependent on the acid content, the exposure time and the washing conditions. The aggregate surface can be damaged by overexposure and leftover acid can remain and impact the durability of concrete [24]. Therefore, the treatment parameters must be optimized to achieve a good compromise between mortar removal and aggregate integrity.

Thermal treatment is the application of heat at high temperatures (normally 250–600 °C) to RCA to create distinct thermal stress between natural aggregate and attached mortar to separate them [25,26]. It has been demonstrated that heating at ~300–400 °C, followed by mechanical abrasion or water quenching, can be successful in removing 25–45% of the mortar without harming the aggregate structure [27]. This procedure minimizes water absorption by up to 35% and increases the compressive strength of RAC by 10–25% compared to untreated RCA [28]. However, heating beyond 600 °C causes degradation of the mineral structure of the aggregate and micro-cracking

and damage due to expansion. Thermal treatment is energy expensive yet environmentally sound when used in conjunction with waste heat recovery systems in precast or cement industries [29].

Comparative investigations have indicated that these pre-treatment approaches have varying strengths and limitations. Mechanical treatment is inexpensive and scalable but less effective in mortar removal than acid or thermal treatment [30]. Acid treatment has more efficiency of mortar removal but increases environmental concern for handling of acids and disposal of effluents. Thermal treatment improves aggregate quality substantially but requires higher energy input [31]. To circumvent these limitations, hybrid treatments like mechanical–acid or thermal–mechanical combinations have been developed. For example, mild heating at 300 °C combined with mechanical abrasion led to a reduction in adhering mortar by up to 50% and an increase in the compressive strength of RAC by up to 25% [32,33].

The mechanical performance of RAC made with treated RCA is influenced by the quality of the aggregate, the mix design, the water-to-cement ratio and the curing regime. Studies have shown that strength recovery of 90–100% of conventional concrete can be obtained with optimum RCA treatment and replacement levels up to 50% [34]. Furthermore, treated RCA also improves durability parameters such as water absorption, chloride ion penetration, and shrinking [35]. SEM and XRD microstructural studies confirm a denser ITZ and a lower microcrack density, confirming the usefulness of RCA treatment in improving the overall performance [36].

Most previous studies have evaluated individual RCA treatment methods under different source concretes, replacement ratios and test protocols. The present work contributes a controlled comparison of untreated, acid-treated, mechanically treated and thermally treated RCA under a common M30 concrete framework, together with curing ages extending from 7 to 365 days. The extended curing period allows the evolution of strength to be followed beyond the conventional 28-day reference age. The experimental dataset is examined through direct descriptive comparisons and trend analysis to relate RCA replacement and treatment condition to concrete performance. These features provide a performance-oriented basis for interpreting the applicability of treated RCA, while recognizing the limitations of the available replicate-level dataset.

2. Research Objectives and Scope

The study aims to evaluate the influence of RCA replacement on concrete performance and to compare untreated RCA with acid-, mechanically-, and thermally treated RCA under common experimental conditions. The specific objectives are to: (i) evaluate workability and strength development at 7, 14, 28, 56, 90, 180, 270 and 365 days; (ii) compare the influence of RCA treatment on compressive, splitting tensile and flexural strengths; (iii) examine water absorption and sorptivity for the conventional and untreated-RCA series; and (iv) identify replacement levels and treatment conditions associated with improved strength retention. The study does not include direct SEM/XRD characterization or comparative durability testing of all treated-RCA concrete series; these are identified as areas for future research.

3. Materials and Methods

3.1 Cement

PPC conforming to IS 1489 was used as the binding material. The reported specific gravity of the cement was 3.15, as given in Table 1. This value is retained as the reported measured value in the supplied experimental dataset; no retrospective substitution with a typical PPC value has been made. The cement was selected to represent a blended-cement binder commonly used in practice. The possible contribution of pozzolanic reaction to continued matrix densification is considered when interpreting the long-term strength development. Table 2 represents the chemical properties of PPC.

3.2 Fine Aggregate

The fine aggregate used in this study was river sand conforming to IS 383, which is a naturally occurring material sourced from riverbeds. The sand was described as clean and free from organic impurities. The material was oven-dried prior to the reported physical-property measurements.

The fine aggregate passing the 4.75 mm sieve was used, with its measured properties provided in Table 3.

Table 1. Physical Properties of PPC

S.No.	Description	Result
1	Fineness (m^2/kg)	337
2	Standard consistency (%)	37
3	Setting time (minutes)	
	a. Initial	186
	b. Final	335
4	Soundness, mm	3
5	Specific gravity	3.15
6	Compressive strength, MPa	
	3 days	26.95
	7 days	35.70
	28 days	55.75

Table 2. Chemical properties of PPC*

S.No.	Description	Result
1	Insoluble residue (%)	29.85
2	Loss on ignition (%)	2.05
3	Sulphuric anhydride (%)	2.38
4	Magnesia (%)	1.24
5	Total chlorides (%)	0.021

*Source: Ultra Tech cements Ltd.

Table 3. Properties of fine aggregate

S.No.	Description	Result
1	Specific gravity	2.65
2	Bulk relative density, kg/m^3	1635
3	Bulking of sand	26%
4	Fineness modulus	2.64
5	Zone	II
6	Water absorption, %	1.35

3.3 Coarse Aggregate

Crushed granite coarse aggregate of 20 mm and 10 mm nominal sizes was used. The aggregates were angular, clean and free from deleterious materials, and conformed to IS 383 requirements. Physical properties including specific gravity and water absorption were determined using the relevant aggregate test procedures; coarse-aggregate specific gravity and water absorption were considered with reference to IS 2386 (Part III). The measured properties are presented in Table 4.

Table 4. Properties of coarse aggregate

S.No.	Description	Result
1	Specific gravity	2.65
2	Fineness modulus	2.43
3	Bulk density (kg/m^3)	1670
4	Crushing strength (%)	34
5	Impact value (%)	24
6	Water absorption (%)	0.50
7	Abrasion value (%)	30

3.4 Recycled Coarse Aggregate

3.4.1 Source of Construction and Demolition Waste

The RCA was produced exclusively from CDW, obtained from reinforced concrete structural elements of residential/commercial buildings in Chennai. No brick masonry, mortar debris, tiles, or mixed construction waste was included. The parent concrete was estimated to be of M25 grade, based on available construction records and field assessment, with an approximate service age of 25–30 years.

3.4.2 Crushing Procedure

The demolished concrete was initially broken into manageable sizes and subjected to mechanical crushing using a laboratory-scale jaw crusher for primary size reduction. Impurities such as steel, wood and plastic were manually removed. The crushing and subsequent processing were intended to produce RCA fractions suitable for concrete production. The RCA was then divided into untreated, acid-treated, mechanically treated and thermally treated groups for the experimental program described below.

3.4.3 Screening and Processing

The crushed material was sieved using conventional sieves, and the required size fractions were collected as RCA. Oversized particles were discarded or crushed again. The sieved RCA was air-dried and stored in closed containers to minimize moisture variation before testing and concrete production. The RCA used in the concrete consisted of 60% of the fraction passing 25 mm and retained on 20 mm, and 40% passing 12.5 mm and retained on 10 mm. The material was subsequently processed as untreated, acid-treated, mechanically treated and thermally treated RCA according to the experimental groups.

3.4.4 Physical Properties of RCA

The RCA exhibited lower density and higher water absorption than the natural coarse aggregate, consistent with the presence of adhered old mortar and micro-porosity introduced during crushing. The physical properties of the natural coarse aggregate and RCA were determined using relevant procedures of IS 2386. The measured physical properties of RCA are summarized in Table 5. These properties reflect the parent-concrete quality and the adopted crushing and screening process.

Table 5: Properties of recycled coarse aggregate

S.No.	Description	Result
1	Specific gravity	2.38
2	Fineness modulus	6.75
3	Bulk density (kg/m ³)	1380
4	Crushing strength (%)	26
5	Impact value (%)	21
6	Water absorption (%)	4.50
7	Abrasion value (%)	20

3.4.5 Treated Recycled Coarse Aggregate

The treated RCA groups were produced using the specified acid, mechanical and thermal pre-treatment procedures. Their measured physical properties are summarized in Table 6. The treatment processes did not improve every measured aggregate property uniformly; therefore, the treatment effects are interpreted parameter by parameter rather than assuming that all treatments enhance all properties.

Table 6. Properties of treated recycled coarse aggregate

S.No	Description	Acid	Mechanical	Thermal
1	Specific gravity	2.59	2.55	2.40
2	Aggregate crushing value (%)	7.20	7.10	6.80
3	Aggregate impact value (%)	29	26	22
4	Impact value (kj/m ²)	18	29	25
5	Abrasion value (%)	2.10	3.10	4.08
6	Abrasion	25	30	33

3.5 Water and Superplasticizer

Potable water suitable for drinking was used for mixing and curing. The superplasticizer SikaViscoCrete-SC 001 was used in the study, with dosage adjusted according to the workability requirement. The available manuscript records provide the product name, specific gravity and pH, but do not provide the manufacturer's dry-extract/solid-content value or the manufacturer's recommended dosage range. These values have therefore not been inferred or fabricated. The characteristics of superplasticizer are represented in Table 7.

Table 7. Technical data of superplasticizer

S.No.	Characteristics	Value
1	Color	Dark brown liquid
2	Specific gravity	1.08
3	Air entrainment	Maximum 1%
4	pH	7 to 8

3.6 Preparation and Curing of Specimen

The concrete mixtures were prepared using a laboratory pan mixer. The dry constituents were first blended to achieve homogeneous distribution, followed by the addition of water and superplasticizer. The fresh concrete was placed into moulds in layers and compacted using a table vibrator. Specimens were demoulded after 24 h and immersed in water at ambient temperature until the designated testing age. Exact mixing and vibration durations and the number of filling layers were not recorded in the supplied manuscript and are therefore identified as reproducibility limitations rather than supplemented with assumed values.

3.7 Test Methods

- Slump tests were performed to evaluate workability in accordance with IS 1199.
- Compressive strength tests were performed on 150 mm cube specimens using a 2000 kN compression testing machine at curing ages of 7, 14, 28, 56, 90, 180, 270 and 365 days. The reported test procedure was based on the applicable Indian Standard for concrete compressive strength (IS 516).
- Cylindrical specimens were cast to determine splitting tensile strength at the same curing ages. The applicable test procedure was based on IS 5816. The exact cylinder dimensions and loading rate were not reported in the supplied manuscript and have not been inferred.
- Prism specimens under third-point loading were evaluated for flexural strength at the reported curing ages. The applicable procedure was based on IS 516. The exact prism dimensions and loading rate were not reported in the supplied manuscript and have not been inferred.
- Durability-related performance was assessed through water absorption and sorptivity tests for the conventional and untreated-RCA concrete series. Water absorption was evaluated with reference to ASTM C642 and sorptivity with reference to ASTM C1585. The supplied manuscript does not contain corresponding concrete-level durability results for the acid-, mechanically- and thermally treated RCA series; therefore, no unsupported treated-series durability values have been added.

3.8 Statistical Analysis

Because the supplied dataset does not contain independent replicate-level observations for every treatment $\times$ replacement $\times$ curing-age combination, pooled standard deviations, coefficients of variation and inferential ANOVA results.

4. Concrete Mix Proportions

The concrete mixtures were designed for M30 grade in accordance with IS 10262:2019. The nominal water-to-cement ratio was kept at 0.45. Natural coarse aggregate was replaced by RCA at 0, 25, 50, 75 and 100% by mass in the experimental mixtures, while cement, water and fine aggregate contents were kept constant. The constituent ratio was 1: 1.48: 3.05, with a nominal w/c ratio of 0.45. Because the aggregates had different specific gravities, the reported mixtures are explicitly treated as mass-replacement mixtures; the supplied experimental record does not permit retrospective re-casting or reconstruction of the actual batches using an absolute-volume correction. This limitation is now stated to avoid implying volumetric equivalence. The detailed mix proportions in cubic meter of concrete are given in Table 8.

Table 8. Mix proportions of concrete with and without RCA (mass-based RCA replacement)

Mix ID	RCA Replacement (%)	Cement (kg/m ³)	Water (kg/m ³)	w/c Ratio	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Recycled Coarse Aggregate (kg/m ³)	Superplasticizer (% of cement)
M0	0	385	173	0.45	570	1174	0	0
M25	25	385	173	0.45	570	881	294	0.6
M50	50	385	173	0.45	570	587	587	0.8
M75	75	385	173	0.45	570	294	881	0.9
M100	100	385	173	0.45	570	0	1174	1

5. Concrete Properties

5.1 Fresh Concrete Properties

As illustrated in Figure 1, the reported slump value decreased from 100 mm for the control mix to 95, 81, 68 and 50 mm at 25, 50, 75 and 100% untreated RCA replacement, respectively. RCA has higher water absorption and a rougher, more angular surface than the natural aggregate. These characteristics increase particle-to-particle friction and interlocking and reduce the free water available for flow, thereby decreasing workability. The supplied dataset does not contain slump values for the acid-, mechanically- or thermally treated concrete series; consequently, Figure 1 and the discussion are limited to the conventional and untreated-RCA series.

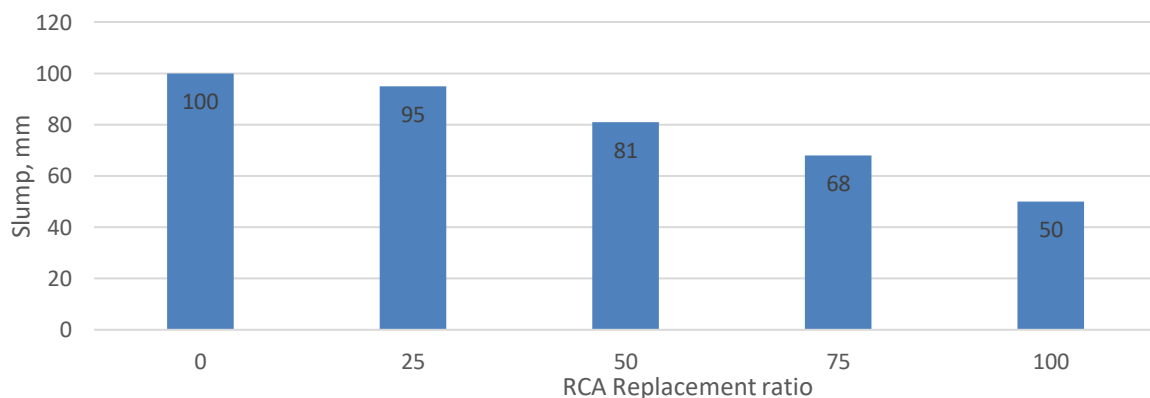


Fig. 1. Slump versus untreated RCA replacement

5.2 Hardened Concrete Properties

5.2.1 Compressive Strength

The compressive-strength values in Table 9 show progressive strength development from 7 to 365 days for the conventional and RCA concrete series. The control mix reached 34.50 MPa at 28 days and 43.00 MPa at 365 days. The results indicate that increasing RCA replacement generally reduced compressive strength, while the magnitude of reduction depended on treatment and replacement level. At 100% replacement, the untreated-RCA mixture reached 28.60 MPa at 28 days, compared with 34.50 MPa for the control, corresponding to a reduction of about 17.1%. The reduction is associated with the higher porosity, adhered mortar and weaker interfacial transition zones of untreated RCA. Among the treated-RCA mixtures, the acid-treated series generally retained the highest compressive strength in the reported dataset. At 25% replacement, RCAA25% reached 34.00 MPa at 28 days, compared with 33.20 MPa for RCAU25%. The results indicate that acid treatment improved strength retention relative to untreated RCA under the conditions investigated.

Mechanical treatment also improved strength relative to the corresponding untreated RCA in the reported dataset; for example, RCAM25% reached 33.40 MPa at 28 days. In contrast, the thermally treated series was consistently lower than the corresponding untreated series in the reported strength; for example, RCAT25% and RCAT100% reached 32.80 and 28.00 MPa at 28 days, compared with 33.20 and 28.60 MPa for RCAU25% and RCAU100%, respectively. Accordingly, thermal treatment should not be described as superior to untreated RCA in this study. The 25% replacement level generally provided the smallest strength reduction across the reported treatment series, whereas higher replacement levels produced larger reductions. The long-term data show continued strength development up to 365 days; however, this does not eliminate the initial strength penalty associated with higher RCA replacement. Overall, the results indicate that appropriate RCA pre-treatment can improve strength retention compared with untreated RCA, with acid treatment showing the highest reported retention in the present dataset.

Table 9. Compressive strength of various treated and untreated RCA

S.No	Replacement Ratio of CA	Compressive Strength, N/mm ²							
		7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	270 Days	365 Days
1	CC	22.50	27.80	34.50	36.80	38.20	40.50	41.80	43.00
2	RCAU25%	21.80	26.90	33.20	35.10	36.50	38.20	39.50	40.60
3	RCAU50%	20.60	25.40	31.80	33.60	35.00	36.50	37.80	38.90
4	RCAU75%	19.20	23.90	30.20	31.90	33.30	34.80	36.00	37.20
5	RCAU100%	18.00	22.50	28.60	30.10	31.50	33.00	34.20	35.50
6	RCAA25%	22.10	27.30	34.00	36.20	37.60	39.80	41.00	42.20
7	RCAA50%	21.50	26.60	33.00	35.00	36.50	38.50	39.80	41.00
8	RCAA75%	20.80	25.80	32.00	33.80	35.20	36.80	38.00	39.20
9	RCAA100%	19.60	24.20	30.50	32.20	33.60	35.20	36.50	37.80
10	RCAM25%	21.60	26.70	33.40	35.40	36.80	38.60	39.90	41.10
11	RCAM50%	21.00	25.90	32.30	34.10	35.60	37.20	38.50	39.70
12	RCAM75%	20.00	24.50	31.00	32.70	34.10	35.60	36.90	38.00
13	RCAM100%	18.80	23.20	29.50	31.10	32.50	34.00	35.30	36.50
14	RCAT25%	21.20	26.20	32.80	34.60	36.00	37.50	38.80	40.00
15	RCAT50%	20.20	24.80	31.20	32.90	34.30	35.80	37.00	38.20
16	RCAT75%	19.00	23.40	29.80	31.40	32.80	34.20	35.50	36.70
17	RCAT100%	17.80	22.00	28.00	29.60	31.00	32.40	33.60	34.80

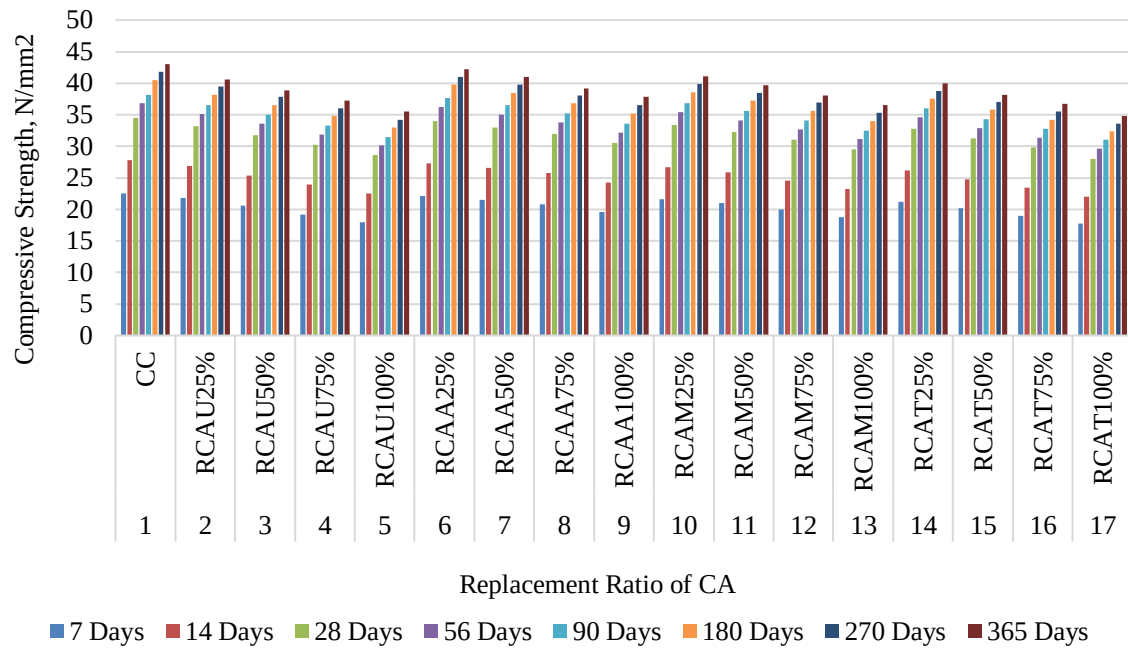


Fig. 2. Compressive strength versus curing age and RCA replacement

The statistical metrics given in Table 10 provide a better insight of the consistency, dependability and overall performance of RCA than CC. The average compressive strength of the CC was 35.64 MPa, with a standard deviation of 7.22 MPa (coefficient of variation (COV) = 20.26%). This implies a considerable degree of variability often associated with conventional concrete mixtures.

The use of recycled coarse materials causes a little decrease in the mean strength for all categories. RCAU has the lowest mean strength of 32.34 MPa, which corresponds to 9.25% drop compared to CC. This reduction is due to the deficiencies of the untreated recycled aggregates, such as high porosity, microcracks, and the presence of adhering mortar, which degrade the interfacial bonding in the concrete matrix. Better performance was observed for processed RCA mixes in comparison. The mean strength of RCAA is 33.94 MPa with only 4.77% reduction, which indicates that chemical treatment is an efficient method to improve the aggregate quality by removal of adhering mortar and improvement of surface texture. Similarly, the RCAM exhibits a moderate reduction of 6.20% which indicates that mechanical processing enhances aggregate integrity but is somewhat less effective than chemical treatment. RCAT shows a decrease of 8.30% showing it is less efficient in enhancing the overall performance.

The standard deviation values for all combinations are very close, from 6.95 to 7.22 MPa, indicating that the variation in strength is constant across all categories. This is also evidenced by COV values in the range of 20.26 to 21.58%. The minor rise of COV of RCA mixes suggests a somewhat higher variability, which can be justified by the heterogeneous character of recycled aggregates. However, the deviation is still within acceptable engineering limitations. This shows that the use of RCA does not affect the homogeneity of the concrete appreciably.

Table 10. Mean strength, standard deviation and standard reduction and COV

RCA (%)	Mean Strength (MPa)	Standard Deviation (MPa)	Standard Reduction (%)	COV (%)
CC	35.64	7.22	-	20.26
RCAU	32.34	6.98	9.25	21.58
RCAA	33.94	7.05	4.77	20.78
RCAM	33.43	7.01	6.20	20.97
RCAT	32.68	6.95	8.30	21.27

5.2.2 Split Tensile Strength

The split tensile strength data exhibited a steady increase with curing age across all mixtures, analogous to the behavior of compressive strength. The control mix attained a 28-day tensile strength of 3.40 MPa, whereas RAC demonstrated a decrease contingent upon the replacement level and treatment procedure. Untreated RCA mixes showed the lowest performance, with a reduction of approximately 17–20% at 100% replacement. Among the treatment methods, RCAA exhibited the best performance, with only an 11.8% reduction compared to the control mix at 28 days. Mechanical treatment showed moderate improvement, whereas thermal treatment resulted in comparatively lower strength due to microstructural damage caused by heating. The reduction in tensile strength is primarily attributed to the ITZ and increased porosity associated with RCA. However, treatment methods effectively enhanced bonding characteristics and reduced strength loss. Overall, up to 50% replacement of natural coarse aggregate with treated RCA can be recommended without significant compromise in tensile performance. The results are presented in Table 11.

Table 11. Split tensile strength of various treated and untreated RCA

S.No	Replacement Ratio	7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	270 Days	365 Days
1	CC	2.10	2.60	3.40	3.60	3.75	3.95	4.05	4.15
2	RCAU25%	2.00	2.50	3.25	3.45	3.60	3.80	3.90	4.00
3	RCAU50%	1.90	2.35	3.10	3.30	3.45	3.60	3.70	3.80
4	RCAU75%	1.75	2.20	2.95	3.10	3.25	3.40	3.50	3.60
5	RCAU100%	1.60	2.00	2.80	2.95	3.10	3.25	3.35	3.45
6	RCAA25%	2.05	2.55	3.35	3.55	3.70	3.90	4.00	4.10
7	RCAA50%	2.00	2.50	3.25	3.45	3.60	3.80	3.90	4.00
8	RCAA75%	1.90	2.40	3.15	3.30	3.45	3.60	3.70	3.80
9	RCAA100%	1.75	2.20	3.00	3.15	3.30	3.45	3.55	3.65
10	RCAM25%	2.00	2.50	3.30	3.50	3.65	3.85	3.95	4.05
11	RCAM50%	1.95	2.45	3.20	3.35	3.50	3.70	3.80	3.90
12	RCAM75%	1.85	2.30	3.05	3.20	3.35	3.50	3.60	3.70
13	RCAM100%	1.70	2.15	2.90	3.05	3.20	3.35	3.45	3.55
14	RCAT25%	1.95	2.40	3.20	3.35	3.50	3.70	3.80	3.90
15	RCAT50%	1.85	2.30	3.05	3.20	3.35	3.50	3.60	3.70
16	RCAT75%	1.75	2.15	2.90	3.05	3.20	3.35	3.45	3.55
17	RCAT100%	1.60	2.00	2.75	2.90	3.05	3.20	3.30	3.40

5.2.3 Flexural Strength

The flexural strength results exhibited a consistent increase with curing age for all concrete mixes as shown in Table 12. The control mix exhibited a 28-day flexural strength of 4.80 MPa, whereas the flexural strength of recycled aggregate concrete gradually diminished with increased replacement. RCAA exhibited optimal performance, achieving a 28-day strength of 4.75 MPa at a 25% replacement rate, equivalent to the control mix. Mechanical treatment marginally enhanced strength, however thermal treatment diminished strength due to microstructural degradation after heating. The ITZ and diminished crack resistance in recycled aggregates decrease flexural strength. Treatment protocols significantly enhanced bonding, minimizing strength degradation. Processed RCA can substitute up to 50% of natural aggregates without compromising flexural performance.

Table 12. Flexural strength of various treated and untreated RCA

S.No	Replacement Ratio	7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	270 Days	365 Days
1	CC	3.20	3.80	4.80	5.10	5.30	5.60	5.80	6.00
2	RCAU25%	3.10	3.70	4.60	4.90	5.10	5.30	5.50	5.70
3	RCAU50%	2.95	3.50	4.40	4.70	4.90	5.10	5.30	5.50
4	RCAU75%	2.80	3.30	4.20	4.40	4.60	4.80	5.00	5.20
5	RCAU100%	2.60	3.10	4.00	4.20	4.40	4.60	4.80	5.00
6	RCAA25%	3.15	3.75	4.75	5.00	5.20	5.50	5.70	5.90
7	RCAA50%	3.05	3.65	4.60	4.85	5.05	5.30	5.50	5.70
8	RCAA75%	2.95	3.50	4.45	4.70	4.90	5.10	5.30	5.50
9	RCAA100%	2.80	3.30	4.20	4.45	4.65	4.90	5.10	5.30
10	RCAM25%	3.10	3.70	4.65	4.90	5.10	5.35	5.55	5.75
11	RCAM50%	3.00	3.60	4.50	4.75	4.95	5.20	5.40	5.60
12	RCAM75%	2.85	3.40	4.30	4.55	4.75	5.00	5.20	5.40
13	RCAM100%	2.70	3.20	4.10	4.35	4.55	4.80	5.00	5.20
14	RCAT25%	3.05	3.60	4.55	4.80	5.00	5.25	5.45	5.65
15	RCAT50%	2.90	3.45	4.35	4.60	4.80	5.00	5.20	5.40
16	RCAT75%	2.75	3.25	4.15	4.40	4.60	4.80	5.00	5.20
17	RCAT100%	2.60	3.05	3.95	4.20	4.40	4.60	4.80	5.00

5.3. Durability Properties

5.3.1 Water Absorption

The water absorption consistently rises with the increasing amount of RCA. The control concrete exhibited a minimum absorption of 1.5%, while the concrete containing 100% RCA had the highest absorption at 4.5%, representing an estimated 200% increase compared to the control concrete, as detailed in Table 13 and Figure 3.

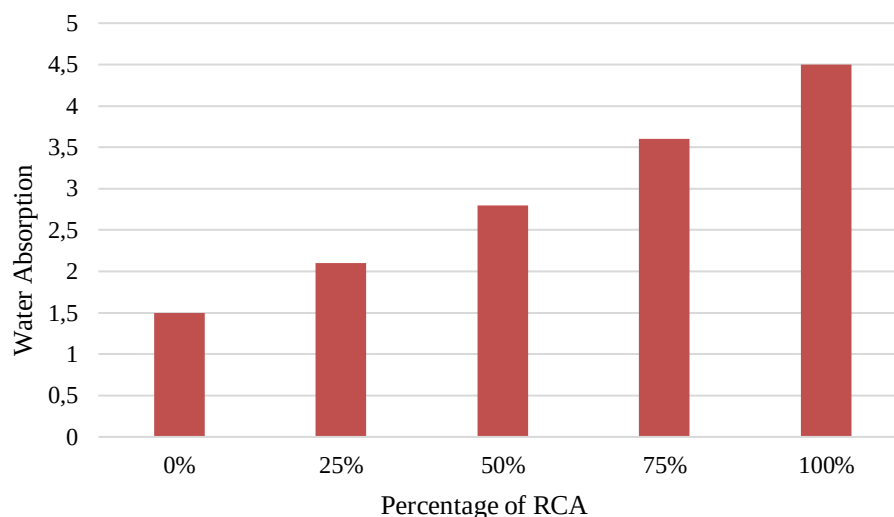


Fig. 3. Water absorption versus untreated RCA replacement

The incremental rise in water absorption with the increase in RCA concentration is mainly ascribed to the porous nature of RCA and the presence of adherent OM on their surfaces. These features develop more capillary holes in the concrete matrix resulting in higher water absorption than

typical concrete manufactured with natural sand. The results of water absorption clearly show that the inclusion of RCA considerably enhances the porosity of concrete. The control mix had a water absorption of 1.50%, whereas those with 25, 50, 75, and 100% RCA had values of 2.10, 2.80, 3.60, and 4.50%, respectively. This means the concrete water absorption is increased by 40%, 86.70%, 140% and 200%, respectively, in comparison to the traditional concrete. The increase in water absorption is mainly due to the existence of adherent mortar and microcracks in recycled aggregates resulting in high permeability. The results show that greater RCA replacement levels negatively affect durability-related attributes and consequently suitable treatment methods are needed to reduce the water absorption in RAC.

Table 13. Water Absorption (%)

RCA (%)	0%	25%	50%	75%	100%
Absorption	1.50	2.10	2.80	3.60	4.50
Increase in Absorption (%)	—	40.00	86.70	140.00	200.00

5.3.2 Sorptivity

The increase in water absorption with untreated RCA replacement is attributed to the porous nature of RCA, adhered old mortar and microcracks. These features provide additional pathways for water ingress. The term 'higher' or 'increased water absorption' is used rather than 'better water absorption'.

Table 14. Sorptivity Test

RCA (%)	0%	25%	50%	75%	100%
Sorptivity (mm/ $\sqrt{\text{min}}$)	0.12	0.16	0.21	0.27	0.34
Increase in Sorptivity (%)	—	33.30	75.00	125.00	183.30

The sorptivity results are for the conventional and untreated-RCA concrete series. Sorptivity increased from 0.12 mm/ $\sqrt{\text{min}}$ for the control mix to 0.34 mm/ $\sqrt{\text{min}}$ at 100% untreated RCA, corresponding to an increase of approximately 183.3%. The increase indicates greater capillary suction and potential susceptibility to water ingress with increasing untreated RCA content. Comparative sorptivity performance of treated-RCA concretes remains to be established in future experimental work. The results are presented in Table 14 and Figure 4.

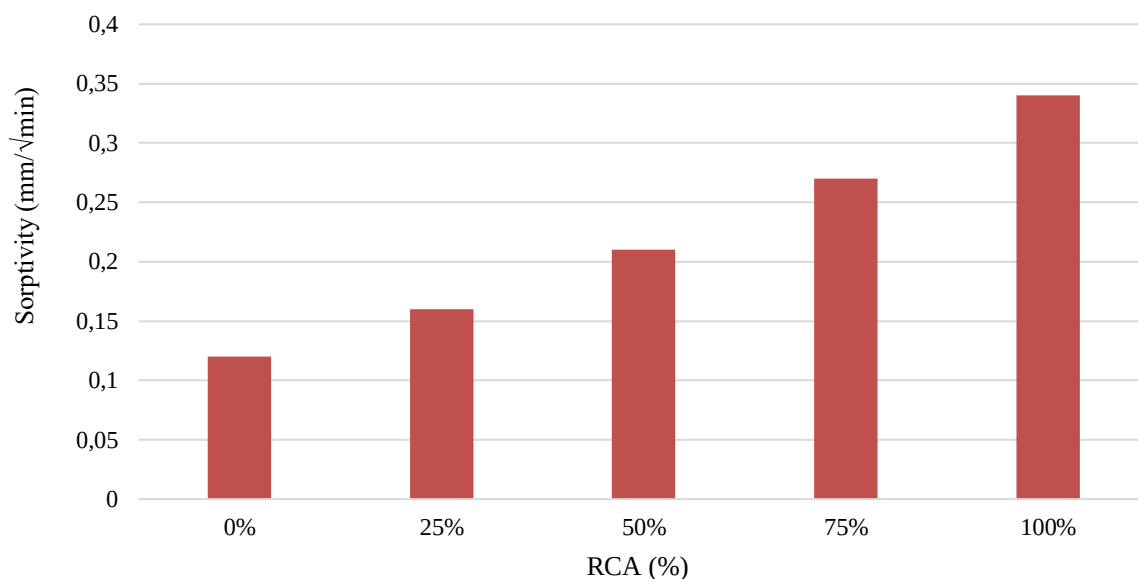


Fig. 4. Sorptivity versus untreated RCA replacement

6. Conclusions

This study compared untreated, acid-treated, mechanically treated and thermally treated RCA in M30 concrete over curing ages up to 365 days. The reported results show that increasing RCA replacement generally reduces workability and mechanical strength, while treatment effects depend on the treatment method and replacement level. Acid treatment gave the highest reported strength retention among the investigated treatments, whereas thermal treatment produced lower values than the corresponding untreated series. The available durability data are limited to conventional and untreated-RCA concrete; therefore, conclusions regarding durability benefits of the treatment methods are intentionally limited.

The comparative results indicate that acid treatment improved strength retention by reducing the influence of adhered mortar under the tested conditions. Mechanical treatment also provided strength retention benefits relative to untreated RCA. Thermal treatment did not improve the reported compressive, splitting tensile or flexural strengths relative to the corresponding untreated series and therefore requires further optimization before its effectiveness can be established.

- 1. RCA can be used as a partial substitute for natural coarse aggregate, but the suitable replacement level depends on the required performance and treatment condition.
- 2. At 28 days, compressive strength decreased from 34.50 MPa for the control to 28.60 MPa for RCAU100%, while lower replacement levels showed smaller reductions.
- 3. Acid-treated RCA showed the highest reported compressive-strength retention among the three pre-treatment methods. Mechanical treatment showed intermediate retention, while thermal treatment produced lower values than the corresponding untreated RCA series in the reported dataset.
- 4. Splitting tensile strength decreased with increasing untreated RCA replacement; at 28 days, the control and RCAU100% values were 3.40 and 2.80 MPa, respectively. Acid-treated RCA showed higher retention than untreated RCA at comparable replacement levels.
- 5. Flexural strength also decreased with increasing RCA replacement. At 28 days, the control and RCAU100% values were 4.80 and 4.00 MPa, respectively, while RCAA25% reached 4.75 MPa.
- 6. Water absorption increased from 1.50% for the control to 4.50% for RCAU100%, representing a 200% increase. This result indicates increased water-ingress susceptibility with increasing untreated RCA replacement.
- 7. Sorptivity increased from 0.12 to 0.34 mm/ $\sqrt{\text{min}}$ between the control and RCAU100%, representing an increase of approximately 183.3%.
- 8. RCA recycling can contribute to resource conservation and CDW diversion. Practical application should be based on the required performance, quality of the RCA source, treatment condition and replacement level.

7. Future Research

Future research should focus on comparative durability testing of concrete incorporating acid-, mechanically- and thermally treated RCA, microstructural characterization using SEM/XRD, optimization of thermal and mechanical treatment parameters, detailed life-cycle and energy assessment, and field-scale validation.

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