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Review

Compressive strength retention of recycled aggregate concrete: A systematic review

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Abstract: The utilization of recycled coarse aggregate in concrete offers a practical pathway toward more sustainable construction, yet its wider engineering adoption remains constrained by concerns regarding mechanical performance consistency. This systematic review synthesizes recent experimental evidence on the compressive strength behavior of recycled aggregate concrete produced with raw, unmodified recycled coarse aggregates. A strength retention normalization approach relative to natural aggregate concrete controls was adopted to enable meaningful cross-study comparison while reducing bias associated with absolute strength class, specimen geometry, and testing conditions. A total of 18 eligible studies were identified through a PRISMA guided screening process, yielding 77 individual mix configurations extracted from the included papers. Of these, 56 mix configurations reported sufficient information to compute compressive strength retention relative to companion controls and were therefore included in the categorical comparison (low n = 14, medium n = 17, high n = 25). The results indicate that no systematic reduction in mean compressive strength retention can be attributed solely to increasing recycled aggregate replacement. Instead, low to moderate replacement levels generally exhibit more consistent strength retention behavior, whereas higher replacement levels are primarily associated with increased variability rather than uniformly inferior performance. The findings demonstrate that recycled aggregate replacement level alone is insufficient as a deterministic predictor of compressive strength performance. Variability observed at higher replacement levels highlights the importance of material quality and mix design considerations, including water demand control, aggregate particle size distribution, and matrix densification strategies. From an engineering perspective, the compiled evidence indicates that high recycled aggregate utilization does not inherently preclude acceptable strength retention, although performance stability appears more sensitive to material quality and mix design controls. Overall, the results support a performance-based approach to recycled aggregate concrete design that balances structural reliability with sustainability considerations.

Keywords: compressive strength; recycled aggregate concrete; recycled coarse aggregate; strength retention; concrete materials

1. Introduction

The construction sector is increasingly required to deliver structural performance while simultaneously reducing its reliance on virgin raw materials and mitigating construction and demolition waste. Concrete production, in particular, consumes large quantities of natural aggregates, making it a critical target for material circularity strategies [1]. One of the most direct approaches to improving sustainability in concrete construction is the partial or full replacement of natural coarse aggregates with recycled coarse aggregates (RCA) derived from construction and demolition waste. As a result, recycled aggregate concrete (RAC) has attracted sustained research interest as a practical pathway for resource conservation and waste reduction in structural applications [2,3].

Despite its potential environmental benefits, the widespread engineering adoption of RAC remains limited by concerns related to mechanical performance consistency and reliability. Recycled aggregates differ fundamentally from natural aggregates due to the presence of adhered mortar, microcracking induced during crushing, and increased porosity and water absorption [4,5]. These characteristics affect both fresh and hardened concrete behavior, influencing water demand, interfacial transition zone quality, and compressive strength development. Consequently, experimental studies on RAC frequently report a wide dispersion in compressive strength outcomes, even at comparable RCA replacement levels, which complicates engineering interpretation and design decision making [6].

Compressive strength remains one of the most widely used and practically relevant indicators for concrete quality control and structural design. However, direct comparison of compressive strength values across different studies is inherently challenging due to variations in strength class, mixture proportions, specimen geometry, curing regimes, and testing standards [7]. To address this limitation, several studies have adopted normalization approaches in which the compressive strength of RAC is expressed relative to a corresponding natural aggregate concrete (NAC) control within the same experimental programmed. Such strength retention indices reduce inter-study bias and enable more meaningful comparison of the relative influence of RCA incorporation on concrete performance [8,9].

Existing literature indicates that the performance of RAC is not governed by RCA replacement level alone. Factors such as parent concrete quality, aggregate grading and particle size distribution, water-to-binder ratio control, curing conditions, and the use of supplementary cementitious materials all contribute to observed strength variability [10–12]. As RCA replacement levels increase, these factors tend to exert a stronger influence, leading to greater sensitivity of compressive strength outcomes to mix design and material selection. This complexity challenges simplified assumptions that associate higher RCA content directly with inferior mechanical performance.

Within this context, systematic synthesis of recent experimental evidence is necessary to clarify how compressive strength retention varies across different RCA replacement levels and to assess whether consistent trends can be identified. The present systematic review focuses on RAC produced using raw, unmodified recycled coarse aggregates and emphasizes experimental comparability by requiring the presence of NAC control mixes. Compressive strength outcomes are analyzed using a strength retention index to enable cross-study comparison while minimizing bias associated with absolute strength differences.

Accordingly, the objectives of this study are fourfold. First, to provide an overview of eligible RAC mix configurations extracted from recent peer reviewed experimental studies and to characterize their distribution across RCA replacement levels. Second, to compare compressive strength retention behavior across low, medium, and high RCA replacement categories using a consistent normalization framework. Third, to examine whether a systematic relationship exists between RCA replacement level and strength retention across the compiled dataset. Finally, to interpret the engineering implications of these findings for practical RAC adoption, while acknowledging limitations arising from data heterogeneity and incomplete reporting of long-term performance indicators. Unlike prior reviews that focus primarily on absolute compressive strength trends, this study emphasizes strength retention and variability to reassess the role of recycled aggregate replacement level from an engineering performance perspective.

The remainder of this paper is organized as follows. Chapter 2 reviews the current understanding of RCA characteristics and their influence on RAC mechanical performance, with particular emphasis on mechanisms contributing to strength variability. Chapter 3 describes the systematic methodology, including the search strategy, eligibility criteria, and data processing procedures. Chapter 4 presents and discusses the results, focusing on strength retention patterns across RCA replacement levels and their engineering interpretation. The paper concludes by summarizing key findings and outlining directions for future research to support reliable and sustainable use of recycled aggregates in structural concrete.

2. Literature review

2.1. Characteristics of recycled coarse aggregates

Recycled coarse aggregates (RCA) differ fundamentally from natural aggregates in terms of physical structure and surface characteristics. RCA particles are typically composed of natural aggregate cores partially or fully coated with adhered cement mortar originating from the parent concrete. This residual mortar increases aggregate porosity, reduces density, and significantly elevates water absorption compared with natural aggregates [4,9]. In addition, the crushing and processing stages involved in RCA production often introduce microcracks within both the aggregate core and the adhered mortar, further contributing to variability in aggregate quality [5].

The quality of RCA is therefore strongly dependent on the properties of the parent concrete, including its original strength class, age, and exposure history. Studies have consistently shown that RCA sourced from high-strength parent concrete tends to exhibit lower water absorption and improved mechanical performance relative to RCA derived from low-strength or deteriorated concrete [10]. However, such information is not always reported in experimental studies, limiting the ability to directly compare RCA quality across investigations.

These intrinsic differences mean that RCA cannot be regarded as a uniform material. Instead, RCA should be considered a heterogeneous composite aggregate whose behavior is influenced by both the natural aggregate core and the attached mortar phase. This heterogeneity underpins many of the challenges associated with predicting the mechanical performance of recycled aggregate concrete (RAC), particularly at higher replacement levels.

2.2. Influence of RCA on compressive strength of concrete

Compressive strength has been the most extensively investigated mechanical property of RAC, owing to its central role in structural design and quality control. Numerous experimental studies have reported reductions in compressive strength with increasing RCA replacement levels when compared with corresponding natural aggregate concrete (NAC) mixes [6]. These reductions are commonly attributed to the lower stiffness and strength of the adhered mortar, as well as to the formation of a more porous interfacial transition zone (ITZ) between RCA and new cement paste.

Nevertheless, the magnitude of compressive strength reduction reported in the literature varies widely. While some studies indicate pronounced strength losses at relatively low replacement levels, others report comparable or even slightly improved strength at moderate replacement levels, particularly when appropriate mix design adjustments are implemented [2,11]. This variability suggests that RCA replacement level alone does not uniquely determine compressive strength performance.

Several mechanisms have been proposed to explain the observed trends. The presence of old mortar increases overall paste content and porosity, which may weaken the load transfer capacity of the concrete matrix. Conversely, the rougher surface texture of RCA particles can enhance mechanical interlocking and bonding with new cement paste, partially compensating for the weaker mortar phase under certain conditions [13]. The balance between these competing effects depends on RCA quality, grading, and the surrounding matrix properties.

2.3. Variability and dispersion in RAC strength performance

A recurring observation in RAC research is the substantial dispersion in compressive strength results reported across studies, even for similar RCA replacement levels. Xiao et al. and Silva et al. highlighted that inter-study variability often exceeds the average strength reduction attributed to RCA incorporation, complicating attempts to establish universal performance trends [6,9].

This dispersion arises from multiple interacting factors. Variations in water-to-binder ratio, aggregate pre-soaking practices, curing regimes, and specimen geometry all influence measured strength outcomes [7]. Moreover, differences in testing standards and specimen sizes introduce additional uncertainty, particularly when absolute strength values are compared across studies.

As RCA replacement levels increase, the influence of these secondary factors tends to become more pronounced. High replacement mixes are more sensitive to fluctuations in effective water content and aggregate moisture state, which can lead to inconsistent hydration conditions and strength development [14]. Consequently, higher RCA replacement levels are frequently associated with wider strength distributions rather than uniform reductions in mean strength.

2.4. Normalization approaches for cross-study comparison

To address the limitations associated with direct comparison of absolute compressive strength values, several researchers have proposed normalization approaches in which RAC strength is expressed relative to a NAC control produced within the same study. Strength retention indices, defined as the ratio of RAC compressive strength to NAC compressive strength, have been shown to reduce inter-study bias arising from differences in mix design and testing conditions [8,9].

Normalization enables systematic synthesis by focusing on the relative effect of RCA incorporation rather than absolute performance levels. This approach is particularly valuable in review studies, where the objective is to identify overarching patterns across heterogeneous datasets rather than to replicate specific experimental programmers. However, even when normalized, strength retention values exhibit considerable scatter, indicating that other material and mix-related variables continue to play an important role.

2.5. Role of aggregate particle size and grading

Aggregate particle size distribution is a well-established factor influencing the mechanical performance of conventional concrete. In RAC systems, particle size effects are further complicated by the heterogeneous nature of RCA. Smaller RCA particles generally contain a higher proportion of adhered mortar, while larger particles tend to retain more intact natural aggregate cores but may also include larger internal defects [15].

Experimental studies examining the influence of RCA particle size have shown that smaller coarse aggregate sizes can promote denser packing and more uniform stress distribution within the concrete matrix, leading to improved strength stability [16]. Conversely, larger RCA particles may amplify the influence of adhered mortar quality and internal microcracking, particularly at high replacement levels, resulting in greater variability in mechanical performance.

Despite its recognized importance, aggregate particle size distribution is not consistently controlled or reported in RAC studies. Many investigations focus primarily on replacement level while treating aggregate size as a fixed or secondary parameter. This inconsistency limits the ability to isolate particle size effects and may contribute to the wide dispersion observed in reported strength retention outcomes.

2.6. Research gaps and motivation for the present review

The existing body of literature demonstrates that compressive strength performance of RAC is governed by a complex interaction of factors, including RCA quality, replacement level, mix design parameters, and aggregate particle size characteristics. While numerous experimental studies have investigated individual aspects of RAC behavior, systematic synthesis that explicitly accounts for variability and normalized performance remains limited.

In particular, there is a need to clarify whether consistent patterns in strength retention can be identified across different RCA replacement levels when results are expressed relative to NAC controls. Furthermore, understanding whether higher replacement levels are associated primarily with reduced mean performance or with increased variability has direct implications for engineering practice and sustainable material adoption.

Against this background, the present systematic review seeks to synthesize recent experimental evidence using a consistent normalization framework, with the aim of providing engineering-relevant insights into strength retention behavior of RAC across different replacement levels. By focusing on raw, unmodified RCA and experimentally comparable datasets, the review addresses key sources of uncertainty and supports more informed decision making for practical RAC applications.

3. Methodology

3.1. Protocol and reporting standard

This systematic review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [17]. A transparent and reproducible screening framework was adopted to identify experimental studies examining the compressive strength performance of recycled coarse aggregate concrete (RAC). The review process comprised database searching, stepwise refinement, abstract screening based on predefined eligibility criteria, full-text assessment, and final data extraction.

3.2. Information source and initial search strategy

The literature search was performed using the Web of Science Core Collection as the primary database. Only peer-reviewed journal articles published between 2021 and 2025 were considered. The search was restricted to the following Web of Science categories: Construction & Building Technology, Engineering, Civil, and Materials Science, Multidisciplinary.

An initial broad (“balloon”) topic search was conducted using the following query:

(“recycled concrete aggregate” OR “RCA concrete” OR “recycled aggregate concrete” OR “recycled coarse aggregate”)
AND
(“compressive strength” OR “mechanical strength” OR “strength performance”)
AND
(concrete)

This initial search yielded 1328 records.

3.3. Sequential refinement of search results

To progressively focus the dataset on experimentally relevant studies, a multi-stage refinement procedure was applied within the initial search results. First, records explicitly addressing compressive strength and coarse aggregate were retained, reducing the dataset to 727 records. Subsequently, studies involving non-relevant aggregate systems were excluded by removing records associated with fine aggregates, brick, ceramic, rubber, powder-based materials, geopolymer binders, and asphalt, resulting in 439 records. Finally, to ensure an experimental focus, records related to numerical analysis, simulation, modelling, and finite element methods were excluded. As a result, 395 records entered the abstract screening stage prior to formal PRISMA eligibility assessment.

3.4. Eligibility criteria

3.4.1. Inclusion criteria

Studies were eligible for inclusion only if all of the following criteria were satisfied:

1) I1. Raw recycled coarse aggregate (RCA): The study must employ raw, unmodified recycled coarse aggregate, without surface treatment, strengthening, carbonation, coating, chemical agents, mechanical processing, or biological or

nano modification.

2) I2. RCA as a primary independent variable: RCA must be the principal variable under investigation, with at least one RCA-related parameter varied, including replacement level, particle size distribution, or RCA source/type.
3) I3. Experimental mechanical testing: The study must report original experimental mechanical testing, with compressive strength data as a mandatory outcome. Additional tests, such as stress–strain behavior or elastic modulus, were acceptable but not required.
4) I4. OPC-based normal concrete: Concrete mixtures must be based on ordinary Portland cement (OPC) and represent conventional concrete systems. Mineral admixtures were permitted only if they were not the primary research variable. A natural aggregate concrete (NAC) control mix was required.

3.4.2. Exclusion criteria

Studies failing to meet the inclusion criteria were excluded using a strict six-category exclusion framework, with each excluded study assigned a single primary exclusion code:

1) E1—Modified or Treated RCA: Studies employing carbonated, coated, chemically treated, mechanically processed, biologically modified, or otherwise enhanced RCA.
2) E2—Special Concrete Types: Self-compacting concrete, UHPC/RPC, geopolymer concrete, or binder-dominated systems beyond conventional OPC concrete.
3) E3—Composite Systems: Incorporation of fibers, nano-materials, bacteria, or hybrid modifiers preventing isolation of RCA effects.
4) E4—Structural-Level Studies: Investigations focused on reinforced concrete elements or structural behavior rather than material-level mechanical properties.
5) E5—Modeling-Only or Non-Experimental Studies: Studies lacking original experimental compressive strength testing, including machine learning models and numerical simulations.
6) E6—Insufficient or Inappropriate Data: Absence of compressive strength data, lack of NAC control, unclear RCA parameters, inadequate methodological detail, non-English, or non–peer-reviewed publications.

These inclusion and exclusion criteria were subsequently applied during the abstract screening and full-text assessment stages to ensure that only experimentally comparable studies investigating raw recycled coarse aggregate concrete were retained for the final synthesis.

3.5. Study selection and final inclusion

Following stepwise search refinement, 395 records were screened at the title and abstract level. A total of 339 records were excluded, leaving 56 studies eligible for full-text retrieval. Records excluded at the abstract screening stage were removed based on the predefined exclusion categories from E1 to E6. These categories were applied to ensure experimental relevance and data comparability. Of these, seven articles could not be accessed in full text, and the remaining 49 studies were assessed for eligibility. After full-text evaluation and verification of data extractability, 18 studies met all inclusion criteria and were included in the final qualitative synthesis. The complete study selection process is illustrated in the PRISMA flow diagram (**Figure 1**).

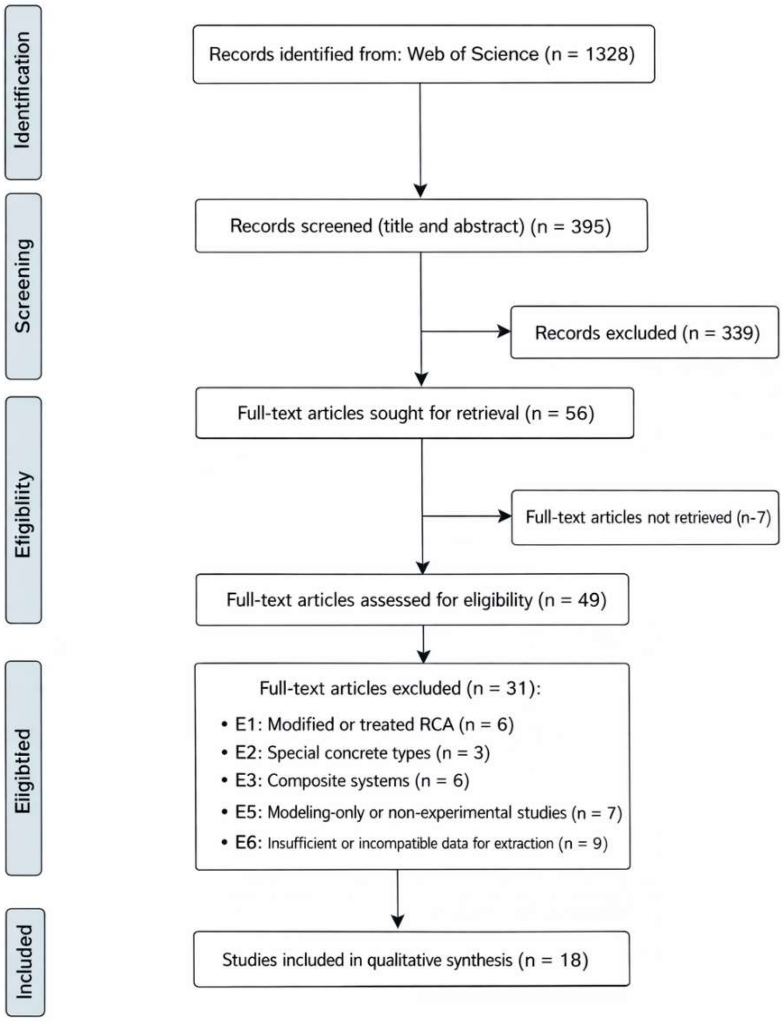

Figure 1. PRISMA 2020 flow diagram illustrating the literature search, screening, eligibility assessment, and final study inclusion process for the systematic review.

3.6. Data extraction and variable definition

Data extraction was performed at the mix-level, rather than the study-level, to preserve the experimental granularity of the original investigations. Each row in the master database represents one concrete mixture incorporating a specific RCA condition, allowing studies that reported multiple RCA replacement levels or mix designs to contribute multiple data entries.

For each eligible study, the following variables were systematically extracted and recorded:

1) Study: First author and year of publication.
2) Country: Country or region where the experimental work was conducted.
3) RCA (%): Replacement level of recycled coarse aggregate by mass or volume, as reported in the original study.

4) RCA_Level: Categorical grouping of RCA replacement level used for comparative analysis.
5) fc $_{\mathrm{NAC}}$ (MPa): Compressive strength of the natural aggregate concrete (control mix).
6) fc $_{\mathrm{RAC}}$ (MPa): Compressive strength of the recycled aggregate concrete mixture.
7) Strength Retention (%): Normalized compressive strength expressed as the ratio of RAC to NAC strength.
8) Specimen: Specimen geometry used for compressive testing (e.g., cube or cylinder).
9) Age (days): Curing age at which compressive strength was measured, with emphasis on 28-day results where available.
10) W/B: Water-to-binder ratio of the concrete mixture.
11) SCM (Type & %): Type and replacement level of supplementary cementitious materials, where applicable.
12) RCA Absorption (%): Water absorption capacity of the recycled coarse aggregate.
13) RCA Density (kg/m^3): Bulk or apparent density of the recycled coarse aggregate.
14) Remarks: Additional experimental notes relevant to interpretation, including target strength class, air entrainment, or mix design considerations.

3.7. Strength normalization strategy

To enable meaningful comparison across studies with different absolute strength levels, specimen geometries, and mix proportions, compressive strength results were normalized using a strength retention index, defined as:

$$\text{Strength Retention (\%)} = \frac{f_{c,\mathrm{RAC}}}{f_{c,\mathrm{NAC}}} \times 100$$

where $f_{c,\mathrm{RAC}}$ is the compressive strength of the recycled aggregate concrete and $f_{c,\mathrm{NAC}}$ is the corresponding natural aggregate control strength reported within the same study.

This normalization approach minimizes inter-study variability associated with absolute strength class, testing standards, and curing conditions, while isolating the relative effect of RCA incorporation on compressive strength performance. Only comparisons within the same study were used for normalization to avoid cross-study bias.

3.8. Data consistency and handling of multiple entries

When a single study reported multiple RCA replacement levels, curing ages, or mix designs that satisfied the eligibility criteria, each configuration was treated as an independent data entry. This approach ensured that trends associated with RCA replacement level and material properties were retained without averaging or aggregation that could obscure underlying relationships.

Where necessary, compressive strength values were extracted directly from tables or digitized from figures. All extracted data were cross-checked for internal consistency, and ambiguous or non-reproducible values were excluded at the full-text assessment stage.

3.9. Data grouping strategy

RCA replacement level was classified into three categorical levels (≤30%, >30–50%, and >50%) to facilitate structured comparison across heterogeneous experimental datasets. The upper boundary of 30% was selected because it represents the most frequently adopted low-replacement level in the extracted studies **(Appendix)**, with 30% appearing consistently as a benchmark test point across multiple experimental programs. Similarly, 50% and 100% replacement levels were repeatedly used as intermediate and full replacement scenarios in prior experimental and review literature [6,8], and were also prominently represented in the compiled dataset.

Accordingly, the selected grouping reflects both commonly investigated experimental replacement intervals and the natural clustering characteristics observed within the extracted mix-level data. The categorization was not intended as a normative classification derived from external design standards, but rather as an analytical framework to enable consistent comparison of strength retention behavior and variability patterns across frequently investigated replacement ranges.

4. Results and discussion

4.1. Overview of extracted mix configurations

An overview of the experimental studies included in the review is provided in **Table 1**.

Table 1. Overview of included experimental studies.

Study	Country	No. of mixes	RCA range (%)	Specimen type	Test age (days)
Chang et al., 2022 [18]	China	10	0–100	Prism	128
You et al., 2022 [19]	China	3	0–100	Prism	118
Mahmood et al., 2023 [20]	Pakistan	4	0–30	Cylinder	28
Hadjari et al., 2025 [21]	Algeria	4	0–100	Cylinder	28
Jia et al., 2022 [22]	China	3	0–100	Cube	28
Liu et al., 2025 [23]	China	3	0–100	Hollow prism	28
Jiang et al., 2022 [24]	China	3	0–100	Cube	28
Fu et al., 2024 [25]	China	3	0–100	Cylinder	28
Huang et al., 2024 [26]	China	4	0–100	Cube	28
Wang et al., 2025 [27]	China	3	0–100	Cube	28
Yu et al., 2024 [28]	China	3	0–100	Cube	28
Datta et al., 2022 [16]	Bangladesh	8	0–45	Cylinder	28
Zhu et al., 2024 [29]	China	3	0–100	Cube	28
Liang et al., 2021 [30]	China	11	0–100	Cube	28
Zhang et al., 2023 [31]	China	4	0–100	Cube	28
Tulimaa et al., 2025 [32]	Finland	2	0–50	Cored cylinder	28
Gaurav et al., 2023 [33]	India	3	0–100	Cube	28
Chamani et al., 2025 [34]	Iran	3	0–100	Cube	160

After full-text eligibility assessment, a total of 77 concrete mix configurations were extracted and included for analysis. The dataset comprised both control natural aggregate concrete (NAC) mixes and recycled aggregate concrete (RAC) mixes, enabling comparative assessment of strength retention behavior relative to corresponding control systems.

Among the extracted configurations, control mixes constituted a smaller proportion of the dataset, while the majority involved partial or full replacement of natural coarse aggregates with recycled coarse aggregates. Based on the reported replacement levels, RAC mixes were categorized into Low, Medium, and High RCA replacement groups, following commonly adopted classification approaches in previous synthesis and review studies [8,9].

All three replacement categories were represented within the dataset. Medium and High replacement levels accounted for a substantial share of the extracted mixes, reflecting the increasing research emphasis on higher RCA utilization in structural concrete applications. The numerical distribution of control, Low, Medium, and High RCA mixes is summarized in **Table 2**.

Table 2. Distribution of extracted concrete mix configurations by RCA replacement level.

RCA replacement level	Number of mix configurations (n)
Control (0%)	21
Low	14
Medium	17
High	25

Note: Classification follows the grouping strategy defined in Section 3.9.

4.2. Strength retention across RCA replacement levels

The strength retention ratios of RAC relative to corresponding control mixes were evaluated across Low, Medium, and High RCA replacement levels. As presented in **Table 3**, the mean strength retention values of the three groups were broadly comparable, indicating that increasing RCA replacement did not result in a systematic reduction in average strength retention.

Despite the similarity in mean values, marked differences were observed in the dispersion of strength retention outcomes. The High RCA replacement group exhibited a substantially wider minimum–maximum range than the Low and Medium groups. This trend was clearly illustrated in the boxplot shown in **Figure 2**, where the High replacement group displayed a larger interquartile range and more extreme values.

In contrast, the Low and Medium replacement groups showed relatively clustered distributions, suggesting more consistent strength retention behavior across studies.

Table 3. Summary statistics of strength retention ratios across RCA replacement levels.

RCA replacement level	Number of mix configurations (n)	Mean strength retention (%)	Minimum (%)	Maximum (%)
Low	14	89.1	76.4	102.2
Medium	17	88.4	67.1	105.8
High	25	90.7	71.5	112.0

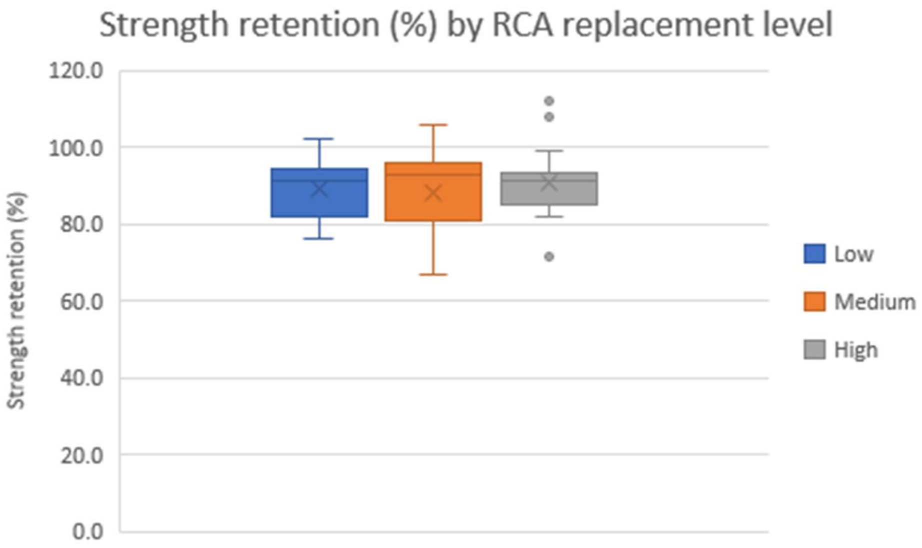

Figure 2. Boxplot of strength retention ratios grouped by RCA replacement level.

The pronounced variability observed at high RCA replacement levels is consistent with the inherently heterogeneous nature of recycled aggregates. Unlike natural aggregates, RCA properties are strongly influenced by parent concrete quality, residual mortar content, crushing processes, and storage conditions, leading to wide variations in porosity, density, and water absorption capacity [6,10,12].

At elevated replacement levels, the influence of the interfacial transition zone (ITZ) becomes increasingly significant. Previous experimental studies have shown that RCA introduces a weaker and more porous ITZ due to the presence of adhered old mortar, which can amplify sensitivity to mix design parameters and curing conditions [4,13]. In particular, the higher water absorption of RCA increases the susceptibility of RAC performance to variations in effective water-to-binder ratio, especially when replacement levels are high [14].

In addition to RCA quality, coarse aggregate particle size and grading represent an important but often inconsistently reported factor across studies. Experimental evidence indicates that smaller coarse aggregate sizes promote denser aggregate packing and more homogeneous stress distribution within the cement matrix, resulting in more stable mechanical responses. Conversely, larger RCA particle sizes tend to magnify the influence of adhered mortar quality and internal defects, particularly at higher replacement levels, thereby increasing performance variability [16]. As particle size distributions were not uniformly controlled across the extracted studies, this factor likely contributed to the wider dispersion observed in the High replacement group.

Importantly, the present results do not imply that high RCA replacement inherently leads to inferior strength retention. Rather, they demonstrate that high replacement mixes are more condition-dependent, with performance governed by a combination of RCA properties, aggregate size characteristics, and mix design optimization. This interpretation is consistent with recent studies reporting comparable strength performance at high RCA contents when aggregate characteristics and binder systems are carefully controlled [8,11].

To move beyond descriptive comparison and explore potential explanatory factors underlying this increased dispersion, additional exploratory subgroup analyses were conducted within the High replacement category using selected extracted mix-level variables.

To further examine potential sources of dispersion within the High replacement category (>50%), two extracted mix-level parameters were explored descriptively, namely RCA water absorption and water-to-binder ratio, and the corresponding subgroup statistics are summarized in **Table 4**.

When the High group was stratified by the median RCA absorption value (5.8%), mixes with lower absorption (≤5.8%, n = 13) demonstrated higher mean strength retention (92.72%) and a comparatively narrower dispersion range (82.38%–112.03%) than higher-absorption mixes (>5.8%, n = 12; mean 88.58%; range 71.49%–107.78%).

A similar exploratory stratification based on the median W/B ratio (0.47) revealed that mixes with W/B > 0.47 (n = 12) exhibited substantially higher mean strength retention (96.37%) compared with those at ≤0.47 (n = 13; mean 85.52%).

Although these subgroup analyses remain descriptive in nature, the observed patterns suggest that variability at elevated RCA replacement levels may be partially associated with aggregate absorption characteristics and mixture proportioning parameters rather than replacement level alone.

Table 4. Exploratory subgroup statistics within the High RCA replacement category (>50%) based on median stratification of absorption and water-to-binder ratio.

Variable	Subgroup	*n*	Mean (%)	Min (%)	Max (%)	SD
RCA Absorption	≤5.8%	13	92.72	82.38	112.03	7.38
RCA Absorption	>5.8%	12	88.58	71.49	107.78	9.15
W/B ratio	≤0.47	13	85.52	71.49	93.55	5.80
W/B ratio	>0.47	12	96.37	89.60	112.03	7.02

4.3. Relationship between RCA replacement level and strength retention

The relationship between RCA replacement level and strength retention was further examined using a scatter plot (**Figure 3**). Across the full range of replacement levels, no clear monotonic or linear relationship between RCA replacement level and strength retention was observed. A second-order polynomial smoothing curve was added for visual guidance only and does not represent a fitted predictive model.

At lower replacement levels, strength retention values were relatively concentrated. In contrast, the higher RCA replacement region exhibited a noticeably wider scatter, indicating that similar replacement percentages could correspond to substantially different strength outcomes.

The absence of a clear linear relationship highlights the limitation of using RCA replacement percentage as a standalone predictor of RAC performance. While replacement level is often treated as a primary design parameter, the present findings indicate that it does not adequately capture the complex interactions governing strength retention.

Previous research has demonstrated that parameters such as water-to-binder ratio, use of supplementary cementitious materials, and physical characteristics of RCA, including particle size distribution, exert significant influence on compressive strength development [2,9,12]. In particular, studies focusing on coarse aggregate size effects have shown that smaller aggregate fractions can partially mitigate the adverse effects associated with RCA porosity and ITZ weakness by improving packing density and reducing stress concentration [15,16].

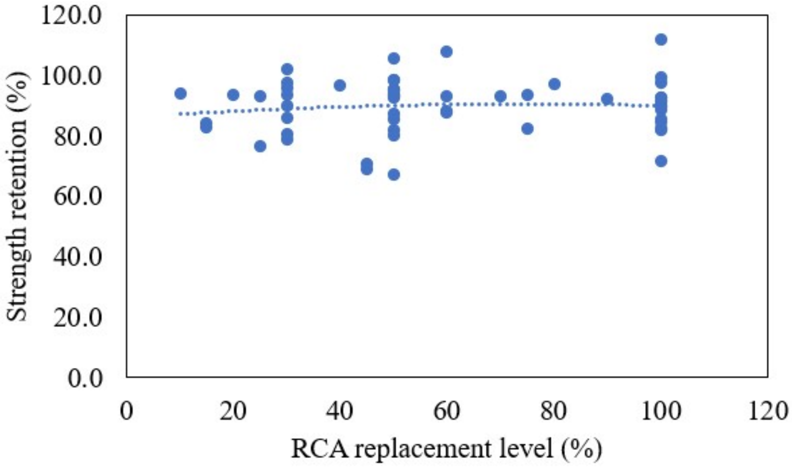

Figure 3. Scatter plot showing the relationship between RCA replacement level and strength retention ratio. A second-order polynomial smoothing curve is included for visual interpretation only.

The exploratory subgroup analyses presented in Section 4.2 further support this interpretation. Within the High replacement category, stratification by RCA water absorption and W/B ratio revealed discernible differences in mean strength retention between subgroups, indicating that mixture proportioning parameters and aggregate quality characteristics contribute to the dispersion observed in Figure 3. These findings reinforce that the scatter at higher replacement levels is not random, but reflects sensitivity to condition-dependent variables embedded within the dataset.

From an engineering perspective, these results reinforce that no single "percentage rule" can reliably predict RAC strength retention. Instead, RCA replacement level should be interpreted within the broader context of aggregate size, aggregate quality, and overall mix design strategy. This understanding is essential for avoiding overly simplified assumptions in RAC design and assessment.

4.4. Engineering implications and limitations

From an engineering practice perspective, the findings presented in Sections 4.2 and 4.3 provide several implications relevant to material selection and mix design decisions. At relatively low to moderate RCA replacement levels, typically up to approximately 30%, strength retention behavior was found to be more consistent across studies. This level of replacement may therefore be considered a conservative and robust option for structural applications where performance reliability and predictability are prioritized, in line with recommendations commonly reported in design-oriented studies and technical guidelines [10,35].

At the same time, the present results indicate that higher RCA replacement levels are not precluded from practical use, but require more deliberate design control. In engineering terms, high replacement levels should be approached as condition-sensitive systems rather than direct extensions of low-replacement practice. Adequate control of water demand, appropriate consideration of coarse aggregate particle size distribution, and the incorporation of supplementary cementitious materials to enhance matrix densification and interfacial transition zone quality are critical prerequisites for achieving acceptable and stable performance. Under such conditions, high RCA replacement should not be regarded as inherently inferior, but rather as more dependent on material quality and mix design optimization.

In the context of sustainable construction, these findings underscore the need to balance circular economy objectives with structural performance requirements. Increasing RCA utilization contributes directly to resource conservation and construction waste reduction; however, the observed variability at high replacement levels highlights the importance of performance-based design approaches over prescriptive replacement limits. Engineering decisions regarding RCA use should therefore be guided by demonstrated material performance rather than fixed percentage thresholds [3]. By clarifying the role of strength variability rather than replacement level alone, this review provides an engineering basis for increasing recycled aggregate utilization in line with circular economy objectives.

Several limitations of the present study should also be acknowledged. The extracted dataset reflects considerable heterogeneity in aggregate sources, curing regimes, and testing standards, which may contribute to the observed dispersion in strength retention outcomes. Critically, several key parameters that could plausibly explain dispersion at higher replacement levels were either missing or inconsistently reported across studies. These included parent concrete strength class, adhered mortar content or residual mortar fraction, detailed grading curves, aggregate pre saturation or moisture conditioning protocols, and full water adjustment procedures to account for RCA absorption. The lack of systematic reporting of these variables limited the feasibility of more refined quantitative synthesis (for example, meta regression style exploration) and required the present subgroup analyses to remain descriptive in nature. Moreover, the analysis focuses primarily on compressive strength retention, while other performance indicators, particularly durability-related properties, remain insufficiently and inconsistently reported in the existing literature. Future studies with more systematic reporting of aggregate characteristics, including particle size distribution, as well as long-term durability metrics, would further support the development of practical and reliable guidance for high-RCA concrete applications.

5. Conclusion

This systematic review synthesized recent experimental evidence on the compressive strength performance of recycled aggregate concrete produced with raw, unmodified recycled coarse aggregates. By adopting a strength retention normalization approach relative to natural aggregate concrete controls, the study enabled meaningful cross-study comparison while reducing bias associated with differences in strength class, specimen geometry, and testing conditions.

Based on the analysis of 77 extracted mix configurations from 18 eligible studies, no systematic reduction in mean strength retention was observed solely as a function of increasing recycled aggregate replacement level. Instead, low to moderate replacement levels were generally associated with more consistent and predictable strength retention behavior, whereas higher replacement levels primarily exhibited increased variability rather than uniformly inferior performance. These findings indicate that recycled aggregate replacement level alone is insufficient as a deterministic predictor of compressive strength performance.

The observed dispersion at higher replacement levels highlights the importance of material and mix design factors that govern recycled aggregate concrete behavior, including recycled aggregate quality, water demand control, aggregate particle size distribution, and matrix densification strategies. High replacement levels should therefore be approached as condition-sensitive systems that require deliberate mix design optimization, rather than as direct extensions of low-replacement practice. When appropriate controls are applied, the compiled evidence indicates that high recycled aggregate utilization does not inherently preclude acceptable strength retention, although performance stability appears more sensitive to material and mix design parameters.

From an engineering and sustainability perspective, the findings emphasize the need to balance circular economy objectives with structural performance requirements. While increased use of recycled aggregates supports resource conservation and construction waste reduction, fixed replacement thresholds may not adequately reflect the complexity of recycled aggregate concrete behavior. Performance-based evaluation frameworks that account for material variability and mix sensitivity are therefore more appropriate for guiding practical implementation.

Several limitations of the present review should be acknowledged. The available literature exhibits substantial heterogeneity in aggregate sources, curing regimes, and reporting practices, which constrains the generalizability of specific design implications. In addition, the present synthesis focused primarily on compressive strength retention, while durability-related properties remain insufficiently and inconsistently reported. Future research incorporating systematic characterization of recycled aggregate properties, together with long-term durability performance, would further strengthen the evidence base for reliable and sustainable adoption of recycled aggregate concrete.

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Appendix: Master table of extracted mix-level data

This appendix presents the complete mix-level dataset extracted from the studies included in the systematic review. Each row represents an individual concrete mixture that satisfied the eligibility criteria, enabling traceability between the synthesized results and the original experimental data.

Table A1. Complete mix-level dataset extracted from the included experimental studies for the analysis of recycled aggregate concrete compressive strength retention.

Study	**Country**	**RCA replacement (%)**	**RCA category**	**fc $_{NAC}$ (MPa)**	**fc $_{RAC}$ (MPa)**	**Strength Retention (%)**	**Specimen geometry**	**Test age (days)**	**Water-to-binder ratio**	**SCM (type and content)**	**RCA water absorption (%)**	**RCA Density (kg/m³)**	**Remarks**
Chang et al., 2022 [18]	China	0	Control	43.4	43.4	100	Prism 150×150×300	128	0.45	None	7.16	2629	NAC (control), C30
		25	Low (≤30%)	43.4	40.4	93.1	Prism 150×150×300	128	0.45	None	7.16	2629	C30
		50	Medium (30–50%)	43.4	37	85.3	Prism 150×150×300	128	0.45	None	7.16	2629	C30
		75	High (>50%)	43.4	40.6	93.5	Prism 150×150×300	128	0.45	None	7.16	2629	C30
		100	High (>50%)	43.4	39.7	91.5	Prism 150×150×300	128	0.45	None	7.16	2629	C30
		0	Control	73.2	73.2	100	Prism 150×150×300	128	0.31	None	7.16	2629	NAC (control), C50
		25	Low (≤30%)	73.2	55.9	76.4	Prism 150×150×300	128	0.31	None	7.16	2629	C50
		50	Medium (30–50%)	73.2	59.9	81.8	Prism 150×150×300	128	0.31	None	7.16	2629	C50
		75	High (>50%)	73.2	60.1	82.1	Prism 150×150×300	128	0.31	None	7.16	2629	C50
		100	High (>50%)	73.2	62.6	85.5	Prism 150×150×300	128	0.31	None	7.16	2629	C50
You et al., 2022 [19]	China	0	Control	44.9	44.9	100	Prism 100×100×300	118	0.55	Fly ash 20%	5.1	2620	NAC (control), Baseline only
		50	Medium (30–50%)	44.9	47.5	105.8	Prism 100×100×300	118	0.55	Fly ash 20%	5.1	2620	Baseline only
		100	High (>50%)	44.9	50.3	112.0	Prism 100×100×300	118	0.55	Fly ash 20%	5.1	2620	Baseline only
Mahmood et al., 2023 [20]	Pakistan	0	Control	44	44	100	Cylinder 100×200	28	0.4	None	4.5	2430	NAC (control), Unexposed control
		30	Low (≤30%)	44	37.86	86.0	Cylinder 100×200	28	0.4	None	4.5	2430	Unexposed control
		0	Control	30.22	30.22	100	Cylinder 100×200	28	0.43	None	4.5	2430	NAC (control), Unexposed control
		30	Low (≤30%)	30.22	27.14	89.8	Cylinder 100×200	28	0.43	None	4.5	2430	Unexposed control

Table A1. (*Continued*).

Study	Country	RCA replacement (%)	RCA category	fc_{NAC} (MPa)	fc_{RAC} (MPa)	Strength Retention (%)	Specimen geometry	Test age (days)	Water-to-binder ratio	SCM (type and content)	RCA water absorption (%)	RCA Density (kg/m^3)	Remarks
Hadjari et al., 2025 [21]	Algeria	0	Control	41.89	41.89	100	Cylinder 110×220	28	0.51	None	6.23	2520	NAC (control)
		30	Low (≤30%)	41.89	42.81	102.2	Cylinder 110×220	28	0.51	None	6.23	2520	Baseline only
		60	High (>50%)	41.89	45.15	107.8	Cylinder 110×220	28	0.51	None	6.23	2520	Baseline only
		100	High (>50%)	41.89	40.83	97.5	Cylinder 110×220	28	0.51	None	6.23	2520	Baseline only
Jia et al., 2022 [22]	China	0	Control	46.2	46.2	100	Cube 100×100×100	28	0.42	None	5.8	2550	NAC (control), Initial strength only
		50	Medium (30–50%)	46.2	42.7	92.4	Cube 100×100×100	28	0.42	None	5.8	2550	Initial strength only
		100	High (>50%)	46.2	39.1	84.6	Cube 100×100×100	28	0.42	None	5.8	2550	Initial strength only
Liu et al., 2025 [23]	China	0	Control	32.7	32.7	100	Hollow prism 100×100×300	28	0.6	None	4.2	2550	NAC (control), Baseline only
		50	Medium (30–50%)	32.7	31.1	95.1	Hollow prism 100×100×300	28	0.6	None	4.2	2550	Baseline only
		100	High (>50%)	32.7	32.5	99.4	Hollow prism 100×100×300	28	0.6	None	4.2	2550	Baseline only
Jiang et al., 2022 [24]	China	0	Control	54.7	54.7	100	Cube 100×100×100	28	0.4	None	9.8	2670	NAC (control), Baseline only
		50	Medium (30–50%)	54.7	51.1	93.4	Cube 100×100×100	28	0.4	None	9.8	2670	Baseline only
		100	High (>50%)	54.7	44.8	81.9	Cube 100×100×100	28	0.4	None	9.8	2670	Baseline only
Fu et al., 2024 [25]	China	0	Control	36.09	36.09	100	Cylinder Ø76×300	28	0.49	None	4.8	2580	NAC (control), Baseline only
		50	Medium (30–50%)	36.09	31.42	87.1	Cylinder Ø76×300	28	0.49	None	4.8	2580	Baseline only
		100	High (>50%)	36.09	31.96	88.6	Cylinder Ø76×300	28	0.49	None	4.8	2580	Baseline only
Huang et al., 2024 [26]	China	0	Control	38.6	38.6	100	Cube 100×100×100	28	0.48	None	5.3	2540	NAC (control), Baseline only
		30	Low (≤30%)	38.6	36.9	95.6	Cube 100×100×100	28	0.48	None	5.3	2540	Baseline only
		60	High (>50%)	38.6	34.1	88.3	Cube 100×100×100	28	0.48	None	5.3	2540	Baseline only
		100	High (>50%)	38.6	31.8	82.4	Cube 100×100×100	28	0.48	None	5.3	2540	Baseline only

Table A1. (*Continued*).

Study	Country	RCA replacement (%)	RCA category	fc_{NAC} (MPa)	fc_{RAC} (MPa)	Strength Retention (%)	Specimen geometry	Test age (days)	Water-to-binder ratio	SCM (type and content)	RCA water absorption (%)	RCA Density (kg/m³)	Remarks
Wang et al., 2025 [27]	China	0	Control	32.5	32.5	100	Cube 100×100×100	28	0.38	None	7.11	2441	NAC (control), Baseline only
		50	Medium (30–50%)	32.5	30.4	93.5	Cube 100×100×100	28	0.38	None	7.11	2441	Baseline only
		100	High (>50%)	32.5	29.8	91.7	Cube 100×100×100	28	0.38	None	7.11	2441	Baseline only
Yu et al., 2024 [28]	China	0	Control	54.97	54.97	100	Cube 100×100×100	28	0.4	None	6.8	2642	NAC (control), Baseline only
		50	Medium (30–50%)	54.97	44.07	80.2	Cube 100×100×100	28	0.4	None	6.8	2642	Baseline only
		100	High (>50%)	54.97	39.3	71.5	Cube 100×100×100	28	0.4	None	6.8	2642	Baseline only
Datta et al., 2022 [16]	Bangladesh	0	Control	50.64	50.64	100	Cylinder 100×200	28	0.33	Silica fume 10%	5.05	1389	12–20 mm
		15	Low (≤30%)	50.64	42.6	84.1	Cylinder 100×200	28	0.34	Silica fume 10%	5.05	1389	12–20 mm
		30	Low (≤30%)	50.64	40.7	80.4	Cylinder 100×200	28	0.35	Silica fume 10%	5.05	1389	12–20 mm
		45	Medium (30–50%)	50.64	35.8	70.7	Cylinder 100×200	28	0.35	Silica fume 10%	5.05	1389	12–20 mm
Datta et al., 2022 [16]	Bangladesh	0	Control	52.26	52.26	100	Cylinder 100×200	28	0.33	Silica fume 10%	5.89	1337	5–12 mm
		15	Low (≤30%)	52.26	43.2	82.7	Cylinder 100×200	28	0.34	Silica fume 10%	5.89	1337	5–12 mm
		30	Low (≤30%)	52.26	41.1	78.6	Cylinder 100×200	28	0.35	Silica fume 10%	5.89	1337	5–12 mm
		45	Medium (30–50%)	52.26	36.1	69.1	Cylinder 100×200	28	0.35	Silica fume 10%	5.89	1337	5–12 mm
Zhu et al., 2024 [29]	China	0	Control	51.1	51.1	100	Cube	28	0.52	FA+SF	0.9	2654	NAC (control), C40, air-entrained
		50	Medium (30–50%)	51.1	47.6	93.2	Cube	28	0.52	FA+SF	6.7	2305	First-generation RCA
		100	High (>50%)	51.1	45.9	89.8	Cube	28	0.52	FA+SF	6.7	2305	First-generation RCA
Liang et al., 2021 [30]	China	0	Control	30.93	30.93	100	Cube 150 mm	28	0.55	None	0.31	2714	NAC (control), Baseline only

Table A1. (*Continued*).

Study	**Country**	**RCA replacement (%)**	**RCA category**	**fc_{NAC} (MPa)**	**fc_{RAC} (MPa)**	**Strength Retention (%)**	**Specimen geometry**	**Test age (days)**	**Water-to-binder ratio**	**SCM (type and content)**	**RCA water absorption (%)**	**RCA Density (kg/m^3)**	**Remarks**
		10	Low (≤30%)	30.93	29.01	93.8	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		20	Low (≤30%)	30.93	28.96	93.6	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		30	Low (≤30%)	30.93	30.23	97.7	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		40	Medium (30–50%)	30.93	29.85	96.5	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		50	Medium (30–50%)	30.93	30.45	98.4	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		60	High (>50%)	30.93	28.84	93.2	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		70	High (>50%)	30.93	28.74	92.9	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		80	High (>50%)	30.93	29.96	96.9	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		90	High (>50%)	30.93	28.52	92.2	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
		100	High (>50%)	30.93	28.67	92.7	Cube 150 mm	28	0.55	None	1.68	2579	First-generation RCA
Zhang et al., 2023 [31]	China	0	Control	42.8	42.8	100	Cube 100 mm	28	0.45	None	0.6	2680	NAC (control), Baseline only
		30	Low (≤30%)	42.8	40.1	93.7	Cube 100 mm	28	0.45	None	5.9	2340	First-generation RCA
		60	High (>50%)	42.8	37.6	87.9	Cube 100 mm	28	0.45	None	5.9	2340	First-generation RCA
		100	High (>50%)	42.8	35.2	82.2	Cube 100 mm	28	0.45	None	5.9	2340	First-generation RCA
Tulimaa et al., 2025 [32]	Finland	0	Control	52	52	100	Cored cylinder	28	0.6	None	0.3	2700	NAC (control), Baseline only
		50	Medium (30–50%)	52	34.9	67.1	Cored cylinder	28	0.6	None	6.5	2680	First-generation RCA
Gaurav et al., 2023 [33]	India	0	Control	32.35	32.35	100	Cube 150 mm	28	0.54	None	1	1645	NAC (control), Baseline only

Table A1. (*Continued*).

Study	**Country**	**RCA replacement (%)**	**RCA category**	**fc_{NAC} (MPa)**	**fc_{RAC} (MPa)**	**Strength Retention (%)**	**Specimen geometry**	**Test age (days)**	**Water-to-binder ratio**	**SCM (type and content)**	**RCA water absorption (%)**	**RCA Density (kg/m^3)**	**Remarks**
		50	Medium (30–50%)	32.35	31.87	98.5	Cube 150 mm	28	0.54	None	5.7	1393	First-generation RCA
		100	High (>50%)	32.35	29.91	92.5	Cube 150 mm	28	0.54	None	5.7	1393	First-generation RCA
Chamani et al., 2025 [34]	Iran	0	Control	47.1	47.1	100	Cube 150 mm	160	0.5	None	1.81	2600	Baseline only
		50	Medium (30–50%)	47.1	44.9	95.3	Cube 150 mm	160	0.5	None	5.66	2430	Baseline only
		100	High (>50%)	47.1	42.2	89.6	Cube 150 mm	160	0.5	None	5.66	2430	Baseline only