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Review Article

Recycled Concrete Aggregates from Construction and Demolition Waste: A Systematic and Critical Review of a Sustainable Construction Material

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Abstract

The construction sector is a major consumer of natural aggregates and a significant contributor to carbon emissions. Recycled Concrete Aggregates (RCA), sourced from Construction and Demolition (C&D) waste, offer a sustainable alternative that supports circular economy principles. However, the inferior quality of RCA, mainly due to adhered mortar and weak interfacial transition zones (ITZs), limits its structural application. This study aims to (1) systematically identify and classify RCA enhancement methods, (2) evaluate the impact of RCA on concrete performance, particularly strength and durability, and (3) highlight key barriers and opportunities for its broader implementation in structural concrete. A systematic review of 77 peer-reviewed articles published between 2000 and 2024 was conducted using PRISMA guidelines. The review analyzed diverse RCA treatment methods, mechanical, chemical, thermal, and biological, and their influence on concrete properties. Findings show that untreated RCA can reduce compressive strength by 10–30% and increase shrinkage by up to 50%. However, acid soaking, mechanical polishing, and carbonation significantly improve RCA quality. When combined with supplementary cementitious materials (SCMs) and an optimized mix design, treated RCA enables concrete to perform comparably to conventional mixes. Recent studies support the technical viability of high-performance RAC well. The remaining challenges lie in standardization, quality control, and adoption at scale. This review concludes that while technical solutions are mature, the primary barrier to widespread adoption is the lack of integrated, performance-based regulatory frameworks, shifting the challenge from materials science to implementation science.

Keywords: Circular Economy; Concrete Durability; Interfacial Transition Zone (ITZ); Lifecycle Assessment (LCA); RCA Treatment Methods; Sustainable Construction.

1. INTRODUCTION

Sustainable construction has become a global imperative in response to escalating urbanization, resource depletion, and environmental degradation [1], [2]. Concrete, currently the most widely used construction material worldwide, is responsible for approximately 8% of global CO_2 emissions, primarily due to cement production and the extensive consumption of natural aggregates [3], [4]. To mitigate these sustainability challenges, the integration of recycled materials, particularly aggregates derived from construction and demolition (C&D) waste, has garnered increasing attention in both academic and industrial contexts [5], [6].

Among the various recycling strategies, Recycled Concrete Aggregate (RCA) from demolished concrete structures offers a promising substitute for virgin aggregates. Industrialized regions generate more than 900 million tons of C&D waste annually, with concrete comprising the majority of this volume [7], [8]. Converting this waste into RCA not only diverts significant quantities from landfills but also reduces reliance on quarrying and energy-intensive processing of virgin materials, thereby supporting the principles of a circular economy in the construction sector [9]–[11].

RCA is typically produced by crushing discarded concrete elements, and its incorporation into new concrete, commonly referred to as Recycled Aggregate Concrete (RAC), has been extensively studied. Numerous experimental investigations have demonstrated that RAC can achieve compressive strengths suitable for both structural and non-structural applications, particularly when the proportion of RCA is kept within acceptable limits [12], [13]. Life cycle assessments further confirm that RAC can significantly reduce environmental impacts, including carbon emissions and embodied energy, mainly when RCA is sourced locally [14]–[16]. Moreover, the use of RCA aligns with internationally recognized sustainability frameworks such as LEED, BREEAM, and Green Public Procurement standards [17], [18].

Despite its proven technical feasibility, the adoption of RCA in real-world construction remains limited across many countries. For example, in Japan, less than 1% of newly produced concrete utilizes recycled aggregates, primarily due to conservative design codes and concerns regarding long-term durability [19]. Even in jurisdictions with supportive regulatory environments, such as the European Union and Australia, usage rates are often constrained by inconsistent RCA quality and the lack of standardization among suppliers [20], [21]. Engineers typically restrict RCA content to less than 30% in structural applications to mitigate risks associated with performance variability [19], [22].

This cautious approach is grounded in well-documented challenges. Compared to conventional natural aggregate concrete (NAC), RAC generally exhibits lower workability, increased water demand, and higher shrinkage attributable to the porous and micro-cracked nature of the adhered mortar on RCA particles [23], [24]. These deficiencies are mainly due to the presence of two weakened Interfacial Transition Zones (ITZs): (1) the "old ITZ" between the original natural aggregate and the residual mortar, and (2) the "new ITZ" formed between RCA and the fresh cement paste. These ITZs are more porous and mechanically inferior, resulting in reductions in compressive strength (up to 30%), increases in drying shrinkage (20–50%), and heightened permeability and carbonation susceptibility [25]–[27].

Over the past two decades, researchers have explored various enhancement strategies to improve RCA quality and RAC performance. These approaches can be broadly categorized into two domains: (1) enhancing RCA quality through techniques aimed at reducing or modifying the adhered mortar using mechanical, thermal, or chemical treatments [28], [29]; and (2) compensating for RCA's deficiencies at the mix design level through the use of admixtures, supplementary cementitious materials (SCMs), and optimized proportioning methods [30], [31]. Despite their demonstrated efficacy, the practical application of these techniques remains sporadic, mainly due to the absence of standardized guidelines, variability in research outcomes, and economic constraints.

A persistent gap remains between laboratory research and field implementation. Variability in RCA source characteristics, lack of unified testing standards, and concerns over cost-effectiveness impede confidence in RCA's performance, particularly for high-grade structural applications. Furthermore, previous reviews have focused narrowly on specific performance metrics such as strength or durability, without encompassing broader considerations such as long-term serviceability, integrated mix design strategies, or system-level behavior.

The present review systematically evaluates 77 peer-reviewed studies investigating methods for enhancing RCA quality and RAC performance to address this gap. Adhering to PRISMA guidelines, we conducted a transparent and methodical literature search to ensure the comprehensiveness and reproducibility of our findings. We propose a novel multi-level analytical framework spanning material properties (RCA characteristics), mix design strategies, and system-level performance to guide practitioners and researchers in effectively implementing RCA in construction.

Ultimately, this study seeks to answer a critical question: under what conditions can RCA be reliably employed in structural concrete while satisfying performance, durability, and sustainability requirements? This review aims to support evidence-based decision-making and promote the broader adoption of sustainable construction practices by synthesizing the existing body of knowledge and highlighting areas of convergence and divergence.

2. MATERIAL AND METHODS

2.1. Research Framework

This study employs a rigorous and transparent systematic review methodology based on the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which is widely recognized as the gold standard for evidence-based reviews in engineering and applied sciences. The application of this framework ensures that the identification, selection, and analysis of the literature are conducted in a methodical, replicable, and unbiased manner, enhancing the credibility, reproducibility, and academic robustness of the findings [32], [33].

2.2. Literature Identification

A comprehensive search was conducted across multiple academic databases, Scopus, Web of Science, and Google Scholar, to identify relevant peer-reviewed literature published between January 2000 and April 2024. The search used Boolean combinations of keywords such as "Recycled Concrete Aggregate", "Recycled Aggregate Concrete", "Construction and Demolition Waste", "RCA treatment", "Concrete durability", "RAC mechanical properties", and "Interfacial Transition Zone". Additional records were manually identified through the bibliographies of key review articles and thesis repositories, yielding 450 records.

2.3. Screening and Eligibility Criteria

After removing approximately 50 duplicate entries, 400 unique records underwent a systematic title and abstract screening process. Clearly defined inclusion criteria guided this initial screening to ensure that only methodologically sound and thematically relevant studies were retained for further evaluation. A study was considered eligible for full-text assessment if it met all the following criteria:

- It involved the application of Recycled Concrete Aggregate (RCA), either coarse or fine, in the production of concrete mixtures;
- It reported quantitative or qualitative effects on concrete performance, such as mechanical properties, durability metrics, or microstructural characteristics;
- It presented a specific method or strategy for enhancing RCA quality or for modifying the mix design of Recycled Aggregate Concrete (RAC);
- It was published in English in a peer-reviewed journal or refereed conference proceedings between 2000 and 2024.

During this screening phase, 310 articles were excluded based on irrelevance, such as those focused solely on unbound applications of RCA (e.g., road base), studies involving non-concrete recycled aggregates (e.g., brick or ceramic), or conceptual papers lacking experimental validation. Figure 1 provides a detailed visualization of this multi-stage selection process.

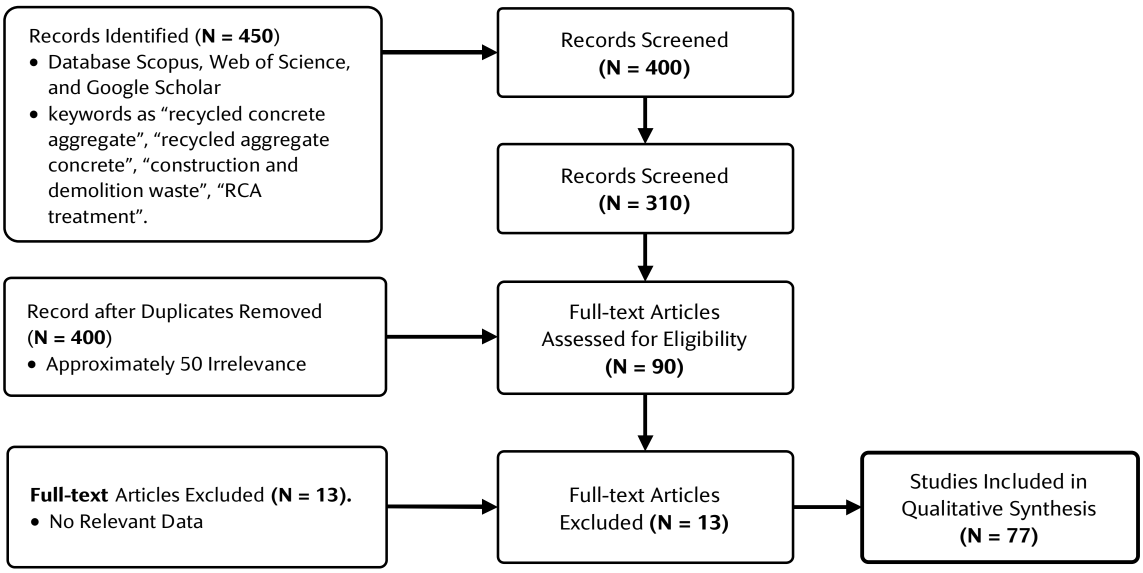

Figure 1. PRISMA Flow Diagram for Current Study

This resulted in 90 full-text articles deemed potentially eligible and subjected to a second-level evaluation. Each of these articles was critically appraised for alignment with the scope and quality standards of the review. A further 13 studies were excluded at this stage due to one or more of the following reasons:

- Insufficient or ambiguous reporting of experimental data;
- Lack of focus on concrete incorporating RCA;
- Duplication with previously included studies (e.g., extended versions or conference-to-journal replications);
- Incomplete methodological documentation.

Ultimately, 77 studies fulfilled all eligibility requirements and were incorporated into the final qualitative synthesis. These studies form the empirical basis for the comparative analysis and thematic discussions presented in the subsequent sections.

2.4. Data Extraction and Coding

Data from the selected studies were systematically extracted using a structured spreadsheet template. The following parameters were recorded:

- Source of RCA (parent concrete quality, demolition source);
- RCA treatment method (mechanical, chemical, thermal, surface coating, etc.);
- Mix design variables (RCA replacement level, water-cement ratio, admixtures, SCMs);
- Tested performance metrics (compressive strength, shrinkage, permeability, ASR, modulus, carbonation depth);
- Key findings and conclusions;
- Limitations or caveats reported by authors.

Each study was assigned thematic tags based on the nature of the intervention (e.g., "thermal-mechanical pretreatment", "polymer coating", "CO_2 curing", "nano-modification") and performance focus (e.g., "durability", "workability", "long-term creep").

2.5. Synthesis and Comparative Analysis

A narrative synthesis approach allowed for qualitative aggregation and thematic clustering of findings. Studies were grouped into categories based on the type of enhancement method and the specific performance outcomes addressed. These clusters formed the foundation for detailed comparative analysis, as presented in Table 1 and subsequent sections.

Key performance metrics, such as compressive strength reduction at 50% RCA replacement, drying shrinkage differentials, and chloride ion penetration rates, were benchmarked across studies, allowing for cross-validation of claims. Possible explanatory variables (e.g., parent concrete quality, moisture preconditioning, curing regime) were explored in cases where results diverged.

3. COMPARATIVE ANALYSIS OF RAC METHODS

Table 1 presents a comparative summary of several notable RCA improvement methods from the literature, highlighting their mechanisms and practical considerations. These examples illustrate the range of approaches from mechanical to chemical to CO_2 curing (carbonation) that researchers have employed to enhance recycled aggregate performance. As presented in Table 1, each treatment method exhibits a distinct mechanism for addressing the persistent issue of adhered mortar in recycled concrete aggregate (RCA). Mechanical treatments such as additional crushing, grinding, or specialized equipment like the Advanced Dry Recovery (ADR) system physically remove the attached mortar. The efficacy of this approach is evident in methods such as multi-stage crushing, which has been shown to significantly reduce mortar content and produce RCA with properties approaching those of natural aggregates [36], [37]. Moreover, in situ mobile recycling techniques offer additional advantages by minimizing transportation costs and emissions through on-site processing of demolition waste [34].

Table 1. Summary Of Selected Methods for Improving RCA Quality, with Their Mechanisms and Limitations

Authors	Treatment Method	Concrete Source	Key Findings (Aggregate & Concrete)	Mechanism	Limitations / Considerations
Lotfi et al., [34]	Mechanical: multi-stage crushing, autogenous milling, and ADR (Advanced Dry Recovery)	End-of-life high-rise concrete (in-situ mobile recycling)	Multi-stage crushing and sorting produced RCA suitable for structural concrete, meeting market specs. Autogenous grinding removed most attached mortar; ADR further reduced waste transport. The resulting RCA was nearly equivalent to natural aggregate for structural use.	Physical removal of adhered mortar through crushing and milling; ADR used air classification to isolate high-density (mortar-free) particles. On-site processing maintains aggregate integrity by reducing handling.	Requires capital-intensive mobile equipment. Efficiency depends on project scale and a consistent waste stream.
Tam et al., [28]	Chemical: Acid Soaking (pre-soaking in weak acid solutions)	Lab concrete specimens (mix of various sources)	Acid-treated RCA showed drastically lower water absorption and improved concrete strength by >20% compared to untreated RCA. Compressive strength of RAC improved to near control concrete when optimal acid treatment was applied.	Acids dissolve calcium hydroxide and other cement hydrates in the old mortar, exposing a cleaner aggregate surface and reducing the porosity of RCA.	Safety and environmental issues include acid handling and disposal of acidic waste. If not controlled, over-etching can damage the aggregate.
Kalinowska-Wichrowska et al., [35]	Thermal–Mechanical: heat at 650°C + Los Angeles abrasion ("waste-free recycling" method)	Demolition concrete rubble (mixed sources)	Thermal-mechanical treatment yielded high-quality RCA similar to natural aggregate, with slightly higher absorption and crushing. Concrete with 100% treated RCA had 10% higher compressive and 6% higher flexural strength, and better frost resistance than control concrete. Recycled cement mortar showed potential as a supplementary cementitious material.	High-temperature heating causes mortar cracks; abrasion disintegrates and separates mortar from aggregate. Fine residual powder is produced as a separate stream.	It requires heating energy and may not be "zero-waste" unless fine powder is reused. Thermal exposure must be controlled to avoid damaging the aggregate.
Sonawane & Pimplikar [36]	Mechanical: multiple crushing + abrasion (drum)	Lab concrete (M20) broken to simulate waste	Multi-stage crushing followed by drum polishing reduced adhered mortar content by ~60%. RAC with 30% RCA had strength equal to control; 100% RCA mix had ~15% lower strength (but still above target).	Repeated impact and abrasion dislodge mortar. Enhances aggregate quality incrementally with each cycle.	Aggregate size reduction occurs; the process can generate excess fines—diminishing returns beyond specific repetitions.
Pacheco & de Brito [37]	Surface Treatment: Autogenous cleaning (saturation-dry cycle)	Lab concrete (varied mixes)	A saturation and rapid-drying treatment ("micro-cracking") removed some of the mortar. Treated RCA showed 10–15% lower absorption. RAC with treated	Water saturation causes mortar swelling; rapid drying induces micro-cracks at the ITZ, causing mortar flaking.	Efficacy depends on the original mortar quality. Not all mortar is removed; improvement is moderate. The process

Authors	Treatment Method	Concrete Source	Key Findings (Aggregate & Concrete)	Mechanism	Limitations / Considerations
			RCA had ~5% higher 28-day strength than untreated RCA.		needs multiple cycles for a significant effect.
Medina et al., [38]	Polymer Coating: impregnation of RCA with polymer latex	Mixed demolition waste (concrete and masonry)	Polymer-coated RCA showed a 50% reduction in water absorption and significantly enhanced durability in RAC, such as lower chloride permeability and reduced shrinkage, compared to untreated RCA. When the optimal polymer dosage was applied, the compressive strength of RAC with coated RCA matched that of control concrete.	Thin polymer film blocks pores on the RCA surface and glues residual mortar particles together, strengthening the RCA and improving ITZ with new cement paste.	Added cost for polymer; needs uniform application. Long-term stability of polymer in concrete (under heat, UV if exposed) needs verification.
Fang et al., [39]	Mineral Carbonation: CO_2 curing of fine RCA powder ("two-step" process)	Recycled cement paste powder (from RCA fines)	Two-step carbonation converted waste cement paste into 71 wt% $CaCO_3$ residue and silicate gel, recovering about 99% of CaO as calcite. The residue can be used as filler or cement substitute, sequestering around 14% of CO_2 by mass. This process is carbon-negative when used in RAC production, with CO_2 uptake exceeding emissions.	CO_2 reacts with portlandite and C–S–H in paste, forming solid $CaCO_3$ and a separate silica-rich phase. This upcycling stabilizes CO_2 in mineral form and yields usable by-products.	The process directly applies to the fine paste fraction, not the coarse RCA. Requires CO_2 supply and a reactor. Economic viability depends on scaling and the value of the by-products ($CaCO_3$, silica gel).

A critical insight is that the strength and maturity of the parent concrete substantially influence the ease with which the mortar can be detached. High-strength, well-cured concrete often results in more tenaciously adhered mortar, posing greater challenges for removal. Autogenous milling, where aggregates abrade each other during tumbling, can address this issue, albeit at the expense of substantial energy input [13].

Chemical treatments, including acid soaking and other reactive solutions, aim to dissolve or soften the old cement paste—for example, Tam et al. [28] demonstrated that acid-treated RCA exhibits significantly reduced water absorption and improved compressive strength, with enhancements exceeding 20% in some cases. These improvements are attributed to the dissolution of portlandite and other permeable phases within the residual mortar, which exposes cleaner aggregate surfaces and reduces overall porosity. Strong acids pose safety and environmental risks, necessitating careful neutralization and disposal of the resultant waste solutions. Recent investigations into milder chemical agents such as carbonic acid via accelerated carbonation or biochemical treatments involving microbial activity suggest that alternative, environmentally benign methods may also achieve comparable surface densification [40], [41].

Thermal treatments, including conventional oven heating and microwave irradiation, have also been explored to induce thermal stresses that crack the mortar or promote differential expansion at the interfacial transition zone (ITZ). These processes weaken the mortar bond, facilitating easier removal via subsequent mechanical abrasion [42]. However, such methods require high energy input and pose the risk of inadvertently damaging the natural aggregate if not precisely controlled [43].

Emerging frontiers in RCA enhancement include biological and nano-scale interventions. These novel approaches do not remove the residual mortar but aim to modify or strengthen it in situ. For instance, biomineralization techniques, particularly microbially induced calcium carbonate precipitation (MICP), have shown promising results in sealing pores and microcracks within the residual mortar matrix. Wang et al. [44] reported significant reductions in water absorption in RCA treated with *Sporosarcina pasteurii*, attributed to the deposition of calcite crystals. Similarly, nano-material additives such as nano-silica can penetrate and react with the existing cementitious matrix to form additional calcium–silicate–hydrate (C–S–H) gel, thereby densifying the ITZ and enhancing durability [45], [46].

These enhancement strategies, ranging from polymers and biomineralization to pozzolanic nano-additives, primarily focus on improving the intrinsic quality of RCA rather than removing deleterious phases. Importantly, they may be integrated synergistically with removal-based techniques; for example, carbonation or polymer treatments can be applied post mechanical pre-treatment to achieve compounded performance benefits. A diverse suite of treatment methods now exists to improve the quality and performance of RCA. The subsequent section synthesizes how these treatment-enhanced aggregates, combined with tailored mix designs, influence recycled aggregate concrete's mechanical and durability performance, as demonstrated across a broad spectrum of recent empirical studies.

4. MECHANICAL PROPERTIES

4.1. Compressive Strength

Compressive strength is the most frequently reported mechanical property in studies concerning recycled aggregate concrete (RAC). A consistent finding across the literature is that compressive strength tends to decline without specific interventions as the replacement ratio of recycled concrete aggregate (RCA) increases. This reduction is primarily attributed to weaker adhered mortar and the additional interfacial transition zones (ITZs) introduced by RCA particles. However, the extent of strength loss varies significantly depending on multiple factors—a meta-analysis by Silva et al. [47], based on a large dataset, revealed an approximately linear decline in compressive strength, with 100% coarse RCA replacement typically resulting in a strength reduction of 20–25% relative to equivalent natural aggregate concrete (NAC). In the studies reviewed, mixes with 30% RCA replacement commonly retained 85–95% of the compressive strength of NAC, while 100% RCA mixes retained approximately 70–90%, contingent on RCA quality.

The quality of RCA emerges as a critical determinant. RAC from high-strength parent concrete performs substantially better than RCA sourced from low-strength or deteriorated concrete. Notably, studies reporting strength losses of less than 10% at 100% RCA replacement, such as Kalinowska-Wichrowska et al. [48] consistently utilized RCA derived from high-strength (>50 MPa) parent concrete, combined with advanced mechanical and/or thermal treatments. In contrast, studies documenting losses exceeding 25% typically used RCA from unknown or poor-quality sources with minimal processing. This trend suggests a quantifiable relationship among parent concrete strength, treatment intensity, and RAC performance, which may be a foundation for predictive modeling.

Several mitigation strategies have proven effective in narrowing or eliminating the strength gap. Pre-treatment of RCA, whether mechanical, thermal, or chemical, can substantially improve compressive strength outcomes. In many cases, treated RCA yielded RAC compressive strengths within 0–10% of control mixes, even at high replacement levels. Exceptional processing techniques have even resulted in strength parity or enhancement; for instance, Kalinowska-Wichrowska et al. [49] reported slightly higher compressive strength in RAC containing 100% thermally and mechanically treated RCA. In general, if the water absorption of RCA is reduced to below 2% and the amount of adhered mortar is minimized, the compressive strength of RAC can approach or match that of conventional concrete.

4.2. Mix Design Adjustments

Adjustments in mix design also play a vital role in mitigating strength reductions. Increasing cement content or reducing the water-to-cement (w/c) ratio can help restore strength, though these approaches may compromise economic feasibility. More sustainable and technically compelling alternatives include supplementary cementitious materials (SCMs) such as fly ash, slag, silica fume, or metakaolin. These materials improve the microstructure of the ITZ and the overall cement matrix, thereby counteracting the deleterious effects of RCA. For instance, Kurad et al. [50] demonstrated that incorporating high-volume fly ash (50% cement replacement) in RAC could completely negate the strength reduction at 50% RCA content, due to refinement of the ITZ and reduced porosity. Similarly, adding 10–15% metakaolin has enhanced RAC strength by improving matrix cohesion and ITZ bonding. Alternative binder systems such as geopolymers have been employed in more advanced approaches. For example, achieved compressive strengths exceeding 60 MPa in RAC containing 100% RCA by using a geopolymer binder composed of fly ash, ground granulated blast furnace slag (GGBS), and metakaolin, thus circumventing limitations associated with Portland cement [51].

4.3. Tensile and Flexural Strength

Tensile and flexural strengths generally follow trends similar to compressive strength but are often more sensitive to the presence of RCA. This increased sensitivity arises because tensile failure is more influenced by flaws such as microcracks in the ITZ, which are more prevalent in RAC. The reviewed studies indicate that, without specific treatment measures, splitting tensile strength and modulus of rupture decrease by approximately 10–20% at 50% RCA replacement and by up to 25–30% at 100% replacement. However, the application of appropriate enhancement strategies can mitigate these reductions. For example, Velardo et al., [38] reported that polymer-coated RCA resulted in tensile strengths equivalent to control concrete, primarily due to improved bonding at the RCA–paste interface. Likewise, adding silica fume is particularly effective in enhancing tensile properties by densifying the ITZ and reducing crack propagation.

4.4. Elastic Modulus

RAC's elastic modulus (E) typically decreases more markedly (in percentage terms) than compressive strength as RCA content increases. This is because coarse natural aggregates contribute significantly to concrete stiffness; replacing them with RCA characterized by adhered mortar and inherent microcracks results in a more compliant composite material. A general guideline from the literature indicates a reduction in E of approximately 5–10% at 25% RCA, 10–20% at 50% RCA, and up to 25% at 100% RCA. However, actual values vary depending on the original aggregate type and RCA quality. Several studies have proposed empirical models to estimate RAC modulus based on NA and RCA content. Importantly, the variability in modulus data is high: while some studies report only minor reductions, particularly when using high-quality RCA, others observe more significant declines.

In contrast to compressive and tensile strength, mix design interventions such as lowering paste volume or adding SCMs have a relatively limited impact on elastic modulus. Instead, improving RCA quality remains the most effective strategy. In the reviewed dataset, RAC mixes incorporating thermally or mechanically treated RCA frequently exhibited modulus values only 5–10% lower than control concrete, even at 100% RCA replacement. Conversely, untreated RCA mixes showed reductions of up to 20% or more.

5. DURABILITY AND PERFORMANCE

Durability represents a critical aspect of recycled aggregate concrete (RAC), as the presence of inferior aggregates and a more porous interfacial transition zone (ITZ) can adversely affect properties such as drying shrinkage, creep, permeability, freeze–thaw resistance, and susceptibility to alkali–silica reaction (ASR).

5.1. Drying Shrinkage and Creep

It is well-documented that RAC exhibits higher drying shrinkage and creep than conventional concrete. The elevated shrinkage, often reported to be 20–50% greater, is primarily attributed to the increased paste content from adhered mortar and higher initial water demand due to RCA's water absorption. Similarly, creep strains can increase by 20–30% at high RCA replacement levels. This is mainly due to RAC's reduced stiffness and the residual mortar's viscous deformation.

In our review, the trends align with existing literature. For instance, one study reported that concrete with 50% RCA exhibited approximately 20% higher one-year shrinkage, while 100% RCA led to 50–70% higher shrinkage. Creep coefficients showed similar proportional increases. Notably, several mitigation strategies have demonstrated success in reducing these effects. Lowering the water-to-cement (w/c) ratio and incorporating supplementary cementitious materials (SCMs), which refine the pore structure and reduce shrinkage potential, can significantly narrow the gap. Some studies have also reported effective use of shrinkage-reducing admixtures, reducing shrinkage by up to 30%. An alternative strategy is internal curing, achieved by incorporating saturated lightweight sand or internal fibers to offset self-desiccation.

A few studies in our review indicated that internal curing using fine lightweight aggregates successfully restored RAC shrinkage performance to levels comparable to natural aggregate concrete (NAC). While RAC generally demonstrates higher creep, its impact on serviceability is often manageable when the lower modulus and strength are adequately considered in structural design.

5.2. Permeability and Freeze–Thaw Resistance

The increased porosity of RAC typically results in higher water absorption and permeability, potentially compromising freeze–thaw durability and chloride ingress resistance. Several reviewed studies employed rapid chloride permeability tests (RCPT) and found that 100% RCA mixes often fall into a lower durability class (e.g., moderate instead of low permeability) under ASTM C1202 criteria. However, modified RAC mixtures incorporating SCMs such as fly ash and slag frequently exhibited permeability values similar to, or only slightly higher than, those of NAC.

An important finding by Wang et al. [44] revealed that carbonation treatment of RCA significantly reduced chloride penetration in RAC, likely due to densification of the ITZ and overall pore network, about freeze–thaw resistance, Kalinowska-Wichrowska et al. [35] demonstrated that concrete with 100% thermally treated RCA surpassed the durability of NAC under freeze–thaw cycling. The literature generally indicates that RAC can attain freeze–thaw durability comparable to conventional concrete, provided sufficient compressive strength is achieved and an appropriate air-void system is established. The primary vulnerability arises from high residual mortar content, which may become saturated and prone to cracking during freezing cycles. Proper air entrainment and pre-treatment of RCA can effectively mitigate these issues.

5.3. Alkali–Silica Reaction (ASR)

Another durability consideration is the potential for alkali–silica reaction (ASR), particularly if the original aggregate was reactive or if the adhered mortar contributes additional alkalis. While relatively few studies have focused explicitly on ASR in RAC, a comprehensive review by Barreto Santos et al. [52] concluded that RAC exhibits similar ASR behavior to NAC when reactive components are present. The old mortar in RCA can act as a secondary source of alkalis, elevating ASR risk.

Mitigation strategies align with conventional concrete: employing SCMs such as fly ash and slag to bind available alkalis, and blending RCA with non-reactive aggregates. Notably, one study reported that incorporating 20% recycled glass into RCA blends effectively eliminated expansion in ASTM C1260 tests, suggesting that aggregate engineering can be a viable ASR control strategy. Overall, ASR is not an inherent issue in RAC but requires evaluating the source materials and the application of preventive measures, particularly in high-durability or critical infrastructure projects.

5.4. Carbonation and Steel Corrosion

The higher porosity of RAC also raises concerns about increased carbonation depth, which could accelerate the corrosion of embedded steel reinforcement. Several studies reported that carbonation depths were 1.5 to 2 times greater in RAC containing 100% RCA after equal exposure durations. However, this effect is strongly influenced by concrete grade, density, curing conditions, and aggregate treatment.

When RAC achieves compressive strength and density similar to NAC, particularly through low w/c ratios and high-quality treated RCA, the difference in carbonation depth narrows considerably. Xiong et al., [53] even suggest that the carbonation coefficient of high-strength RAC can be comparable to that of conventional concrete. In carbonating environments, best practices include ensuring adequate concrete cover, applying surface sealants, or selecting corrosion-resistant reinforcement where necessary.

Recent studies confirm that Recycled Aggregate Concrete (RAC) can match the durability of conventional concrete when supported by key interventions. These include lowering the water-to-cement (w/c) ratio to reduce permeability, adding Supplementary Cementitious Materials (SCMs) to enhance matrix durability and prevent ASR, and applying RCA treatments (e.g., carbonation, thermal, or polymer coatings) to improve aggregate quality. For freeze–thaw resistance, ensuring a proper air-void system is essential. Internal curing agents or shrinkage-reducing admixtures also help manage volumetric changes and minimize cracking. Collectively, these strategies optimize RAC's performance for long-term use. Table 2 summarizes typical performance ranges for RAC compared to NAC and the improvements achievable through these interventions.

Table 2. Performance Comparison of RAC vs NAC and Improvements with Treatments

Performance Metric	NAC (100% NA)	RAC (untreated)	RAC (with treatments)	Typical Code Limit / Standard	Sources
Compressive Strength (fc')	100% (baseline)	70–90% of NAC (at 100% RCA); 85–95% (at 50% RCA)	~95–105% of NAC (with high-quality RCA + SCMs)	Target design strength (project-specific)	Panghal et al., [42]; Kalinowska et al., [35]
Drying Shrinkage	600 με (example)	+20% (≈720 με at 50% RCA); +50% (≈900 με at 100% RCA)	+0–20% (with internal curing or SCMs reducing shrinkage)	≤800 με (typical limit for structural concrete)	Tam et al., [28]; Panghal et al., [42]
Chloride Permeability (RCPT) (Coulombs)	1200 (Low)	1500–2500 (Mod. – High at 100% RCA)	800–1500 (Low, with silica fume or densification treatments)	<2000 (Low per ASTM C1202)	Medina et al., [54]; Tam et al., [28]
Carbonation Depth (mm in 1yr accelerated)	2–4 mm	4–8 mm (100% RCA)	3–5 mm (with CO_2 curing of RCA or low w/c)	Cover based on exposure class (e.g., 25 mm for XC4, 50yr life)	Zhan et al., [55]; Xiao et al., [56]
ASR Expansion (ASTM C1260, % at 14d)	0.10% (non-reactive)	0.15–0.25% (if RCA contains reactive components)	0.05–0.10% (with 30% fly ash + non-reactive blend)	0.10% (ASTM limit for innocuous)	Barreto Santos et al., [52]; This study

The performance disparities between RAC and NAC can be substantially reduced and, in some cases, virtually eliminated through appropriate material processing and mix design strategies. High-performance RAC is no longer confined to laboratory-scale studies; numerous full-scale applications across Europe and Asia have demonstrated that structural-grade RAC can satisfy conventional design standards when produced with rigorous quality control. The key lies in adopting an integrated approach that considers aggregate treatment, water–cement ratio optimization, including SCMs, and control of air content and curing conditions. These findings underscore the potential of RAC as a viable, sustainable alternative to natural aggregate concrete in structural applications.

6. DISCUSSIONS

Synthesizing the findings presented in this review, a more integrated understanding of recycled concrete aggregate (RCA) as a sustainable construction material emerges. Technically, the incorporation of RCA in concrete is both feasible and promising. However, it is not a direct, one-to-one replacement for natural aggregate (NA); successful application requires deliberate consideration of RCA's distinct properties and appropriate modifications to the mix design. The classical challenges associated with RCA, such as higher water absorption, the presence of adhered mortar, and the formation of weaker interfacial transition zones (ITZs), are now well-documented [57], [58]. Equally, the solutions ranging from mechanical or chemical treatments to admixture optimization have become standardized across the literature [59], [60]. The field has matured to a stage where a well-defined "toolkit" of strategies exists; the remaining challenge is selecting and integrating the appropriate combination for a given context.

Central to achieving high-performance recycled aggregate concrete (RAC) is improving RCA quality. Nearly all advanced methods converge on this objective, either by removing deleterious phases (e.g., adhered mortar and contaminants) or by enhancing RCA's surface and internal properties through mechanical, chemical, or mineral-based treatments [35]. The ITZ, in particular, has emerged as a unifying concept in this domain. Given that RAC introduces both a new ITZ (between old and new mortar) and a potentially compromised legacy ITZ (within the RCA), strengthening or mitigating these zones is critical to enabling RAC to match conventional concrete's performance. Treatments such as carbonation have demonstrated significant benefits relative to cost, primarily due to their ability to densify the ITZ and refine pore structures [44], [61], [62].

Importantly, there is no universal "best method" for using RCA. Instead, optimal outcomes typically arise from a layered or hybrid approach. For example, a recycling facility may employ mechanical abrasion or thermal treatment to improve aggregate quality, while the concrete producer implements a tailored mix design using supplementary cementitious materials (SCMs), water-reducing admixtures, or particle packing optimization [59]. This multi-scale intervention strategy, which addresses macro-level impurities and micro-level bond quality, has yielded synergistic improvements in mechanical and durability properties.

An illustrative case uses the Compressible Packing Model (CPM) in RAC mix design. Kasulanati and Pancharathi [63] demonstrated that optimizing aggregate gradation using CPM, in conjunction with treated RCA, allowed for a reduction in paste content while achieving equal or greater compressive strength. Remarkably, the CPM-designed RAC outperformed an ACI 211.1-designed NAC mix in strength, despite using less cement, demonstrating clear gains in sustainability and structural performance.

Apparent contradictions in the literature, such as reports of poor and excellent RAC performance, are not factual inconsistencies but reflect the context-sensitive nature of RCA usage. Outcomes are heavily influenced by parent concrete quality, treatment methods, and specific mix designs [56], [64]. Hence, the pertinent research question is not “How does RAC perform generally?” but rather “How does RAC perform under specific material, processing, and environmental conditions?” These nuanced insights offer an opportunity to refine guidelines and performance models by identifying the key variables that govern successful RAC behavior.

From a practical implementation perspective, the most substantial obstacle is not technological but systemic. Bridging the gap between laboratory success and field-scale adoption requires alignment across the demolition, recycling, and construction sectors. Without integrated frameworks, the successful application of RCA remains fragmented. For instance, even if RCA is treated using Method X and performs well with Mix Design Y, it cannot be deployed widely unless supply chains are stable, quality standards are enforced, and market acceptance is in place. The entire lifecycle from concrete demolition and RCA processing to concrete production and placement must be considered holistically. A failure in any component, such as an inconsistent RCA supply or resistance from specifiers due to outdated codes, can compromise the system.

Nonetheless, current trends are favorable for the broader adoption of RCA. Increasing landfill costs, growing environmental awareness, and policy mechanisms like carbon pricing are all pushing the construction industry toward circular material flows [54], [57], [65], [66]. Advances in automation, sensor-based sorting, and treatment efficiency also reduce the technical and financial barriers associated with RCA processing.

From an economic standpoint, the viability of RCA depends on its competitiveness relative to natural aggregates [67]. Where natural aggregate prices are high or landfill disposal is taxed, as is the case in parts of Australia and the European Union, RCA is already economically attractive [59]. Governments can further incentivize their use through green procurement policies, setting minimum recycled content thresholds, or providing subsidies and certifications for recycling infrastructure.

7. IMPLICATIONS

The evidence synthesized in this review underscores that high-quality recycled aggregate concrete (RAC) is now technically viable for structural applications and can be specified within performance-based design codes. Technological barriers such as strength, durability, and workability have been mainly addressed at the laboratory scale through a combination of aggregate processing, optimized mix design, and supplementary cementitious materials (SCMs). The remaining challenges lie in institutional adoption: developing consistent standards, quality assurance protocols, and long-term performance data to convince stakeholders of RAC’s reliability.

This calls for a shift from prescriptive limits on RCA content to performance-driven qualification. Concrete mixes with high RCA proportions should be permitted if they meet established criteria for compressive strength, shrinkage, permeability, and service life expectations. Emerging European standards have begun to reflect this approach, classifying RCA by quality and linking it to allowable replacement levels.

For producers and contractors, using RCA implies manageable modifications to practice, such as adjusting mixing procedures or incorporating admixtures. The outdated perception that RAC is inherently inferior must give way to a more nuanced view: RAC can equal or exceed conventional concrete performance when best practices are applied.

The environmental implications are significant. RAC reduces the need for virgin aggregate and diverts waste from landfills, lowering the environmental footprint. Additionally, carbonation treatment of RCA offers potential for CO_2 sequestration, contributing to broader carbon neutrality goals. Research has shown that recycled paste or aggregate, when carbonated, can both improve material performance and capture CO_2, positioning RAC as a tool for not just reducing impact but potentially offering environmental benefit.

At the urban scale, RAC supports circular economy principles by closing the concrete loop, reusing demolition waste in local construction and reducing transport burdens. Projects in Europe, such as the Eco-Cement initiative and fully recycled pavements, demonstrate the feasibility of large-scale RAC implementation. RAC is no longer a marginal or alternative material. With appropriate standards and greater industry awareness, it can become a mainstream solution for sustainable construction. As performance-based design becomes the norm, RAC is well-positioned to meet modern structural and environmental demands.

8. FUTURE RESEARCH DIRECTIONS

Despite substantial advances in understanding and applying recycled concrete aggregates (RCA), several critical research avenues remain open to support the widespread and reliable adoption of recycled aggregate concrete (RAC) in structural applications.

A primary need is long-term durability studies in real-world environments, as most current data derive from accelerated laboratory testing. Field-scale investigations, particularly of RAC exposed to aggressive climates such as marine, freeze–thaw, or high-humidity environments, are essential to confirm its ability to meet service-life expectations of 50 to 100 years. Such studies should monitor creep, shrinkage, and microcracking in full-scale structural elements over time, providing the empirical foundation needed to refine design codes and serviceability models for RAC.

Another critical research direction involves mitigating alkali–silica reaction (ASR) in RAC, particularly when the source concrete contains reactive aggregates or alkali-rich mortar. While supplementary cementitious materials (SCMs) such as fly ash and slag have shown efficacy in suppressing ASR expansion, optimal dosages and combinations remain uncertain for RCA-rich mixtures. Hybrid aggregate strategies e.g., blending RCA with inert recycled glass or ceramic aggregates also warrant deeper investigation. Developing robust, ASR-resistant RAC formulations, especially at high replacement levels, would significantly enhance confidence in RAC use across a broader range of structural applications.

Integrating RAC in 3D concrete printing (3DCP) offers another frontier with circular construction potential. However, early experiments using fully recycled aggregate mixes in printable concrete have shown significant reductions in strength and challenges with water demand and rheology. Research is urgently needed to optimize particle gradation, admixture systems, and fiber reinforcement to enhance printability and mechanical performance. Understanding the interaction between recycled materials and the extrusion process will be critical in advancing this emerging application.

Moreover, there is growing interest in conducting comprehensive life-cycle assessments (LCA) of advanced RCA treatments. While innovations such as CO_2 curing, microbial calcite precipitation, and polymer coatings have demonstrated performance gains, their environmental trade-offs must be rigorously quantified. In particular, evaluating the CO_2 sequestration potential of carbonated RCA both in absolute terms and relative to process emissions could determine whether such technologies can contribute meaningfully to net-zero or even carbon-negative concrete pathways. Holistic LCA models incorporating energy use, transportation, treatment inputs, and long-term durability benefits are essential for guiding policy and practice.

Another practical focus should be scaling up promising laboratory techniques through field demonstrations. Casting and monitoring full-scale structural components with high RCA content in real projects can validate handling, constructability, and long-term behavior. Such demonstrations not only provide technical evidence but also help shift conservative industry attitudes by showing that RAC performs reliably when produced and implemented according to best practices.

Finally, exploring alternative binder systems and high-performance concrete technologies using RCA opens the door to greater innovation. For example, combining RCA with alkali-activated binders such as those based on fly ash and GGBS has shown promise in achieving high strength and durability [51], [68]. Likewise, designing ultra-high-performance concrete (UHPC) incorporating RCA and advanced pozzolans could enable recycled materials to be used in seismic, high-load, or infrastructure-critical applications. Understanding the unique ITZ chemistry and behavior in these systems remains a critical knowledge gap.

Pursuing these research directions will not only address the remaining technical and environmental concerns but will also support the refinement of codes and encourage industry adoption. In doing so, the construction sector can fully leverage RAC as a standard material for sustainable and resilient infrastructure.

9. CONCLUSIONS

This review has demonstrated that using recycled concrete aggregates (RCA) in structural concrete is no longer a conceptual proposition but a technically viable and increasingly mature solution. Advances in processing technologies, aggregate characterization, and mix design optimization have enabled the production of high-performance recycled aggregate concrete (RAC) that meets, and in some cases exceeds, the mechanical and durability performance of conventional concrete. Concerns about substantial strength loss, increased shrinkage, or compromised durability at moderate RCA replacement levels have been largely dispelled by empirical evidence over the past decade.

When best practices such as appropriate RCA grading, removal of deleterious components, mix proportioning with supplementary cementitious materials, and control of water absorption are achieved, RAC can achieve equivalent compressive strength, satisfactory workability, and long-term durability. Notably, several studies have reported that even concrete with 100% coarse RCA can fulfill structural requirements, particularly when enhanced by internal curing effects from residual mortar and optimized particle packing strategies.

The primary challenges now lie not in technical feasibility but in the standardization and institutionalization of RAC. Existing building codes and specifications often limit RCA usage to 20–30% replacement levels, reflecting outdated assumptions rather than current performance-based evidence. The findings of this review support a transition toward performance-based specifications, where the use of RAC is governed not by aggregate origin but by measurable outcomes such as strength, permeability, shrinkage, and durability. This approach aligns with modern engineering principles and enables a more rational, data-driven path for sustainable material adoption.

The implications are substantial from an economic and environmental perspective. RAC reduces dependence on natural aggregates, diverts construction and demolition waste from landfills, and when integrated with carbon-curing or low-embodied-carbon binders can contribute meaningfully to decarbonization goals. The potential to use RCA as both a material resource and a vehicle for CO_2 sequestration further strengthens its role in transitioning to a low-carbon, circular construction economy.

Realizing these benefits will require greater industry confidence, improved quality control mechanisms, and the proactive updating of design codes, procurement policies, and educational curricula. Encouragingly, several major contractors, precast producers, and municipalities are already conducting RAC trials, signaling growing acceptance. Policy instruments such as green procurement mandates or recycled content requirements can accelerate adoption.

High-quality RAC has moved beyond the laboratory and is poised to become a standard material in structural applications. Its integration into mainstream construction will depend on closing the gap between research and practice through continued field validation, demonstrative projects, and regulatory reform. If these steps are taken, RCA can be pivotal in reducing raw material consumption, minimizing construction waste, and achieving durable, resource-efficient infrastructure without compromising structural performance or safety.

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