Recycled concrete aggregates derived from construction waste: potential applications in structural engineering

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■ Received: 26/01/2026 ■ Revised: 26/02/2026 ■ Accepted: 07/03/2026

DOI: https://doi.org/10.66195/mtu.2026.16.160

ABSTRACT

Large amounts of waste concrete have been accumulated during construction activities, posing substantial environmental and resource concerns for the sector. Recycling this garbage into recycled concrete aggregates (RCA) helps to promote sustainable and circular structural construction. This paper critically reviews the processing, classification systems, physical and mechanical qualities, durability performance, and structural behavior of RCA. The presence of adhered mortar causes increased porosity and reduced stiffness when compared to natural aggregates; however, recent advances in processing techniques, supplementary cementitious materials, and optimized mix design show that RCA concrete can achieve reliable structural performance. Practical case studies from buildings, infrastructure, and precast construction demonstrate the viability of moderate RCA replacement ratios in load-bearing systems. Limitations, including long-term durability, variability control, and conservative design provisions, are determined. The study highlights future perspectives focused on performance-based design, improved material processing, and integration of RCA within circular economy frameworks to support resilient and sustainable structural engineering.

Keywords: waste concrete, recycled concrete aggregates, sustainable, circular structural engineering, control.

1. INTRODUCTION

The rapid expansion of the construction industry has significantly increased construction and demolition waste (CDW), in which waste concrete represents a major fraction. The growing environmental burden associated with landfill disposal and natural resource depletion has encouraged the recycling of concrete within sustainable construction and circular economy frameworks [1-3]. Recycled concrete aggregates (RCA) provide a significant alternative to natural aggregates by reducing raw material consumption, lowering carbon emissions, and minimizing waste disposal impacts [4, 5]. Despite these environmental benefits, the structural use of RCA remains limited due to concerns regarding higher porosity, increased water absorption, and variability caused by adhered mortar, which may influence strength, stiffness, and durability [2, 6]. Recent advances in processing methods, mix design optimization, and supplementary cementitious materials have demonstrated that RCA concrete can achieve performance comparable to conventional concrete under certain conditions, with studies covering both material behavior and structural response under static and dynamic loading [7].

Furthermore, adopting RCA has the potential to reduce greenhouse gas emissions throughout the concrete life cycle, yet current design rules are conservative and lack uniform advice for structural applications [3, 8]. As a result, this analysis provides a synthesis of RCA formed from construction waste, with an emphasis on production processes, mechanical and durability qualities, and structural performance, as well as outlining current constraints and future approaches for safe structural application.

2. OVERVIEW OF RECYCLED CONCRETE AGGREGATES (RCA)

2.1. Definition

Recycled concrete aggregates (RCA) are produced by crushing and processing waste concrete from construction, demolition, or rehabilitation works. After removing contaminants such as steel or wood, the material can replace natural coarse or fine aggregates in new concrete and other civil applications. RCA consists of original aggregate particles coated with residual mortar, which affects its density, water absorption, and mechanical properties compared with natural aggregate [9-11].

2.2. Generation, processing, and classification of RCA

2.2.1. Sources of construction waste concrete

- Most waste concrete comes from demolishing old or damaged structures such as buildings, bridges, pavements, and industrial facilities. These activities generate large volumes of reinforced concrete rubble that can be processed into recycled concrete aggregates (RCA) [12]. Demolition typically contributes a greater share of construction and demolition waste than new construction activities [13].

- New construction activities (on-site waste): Concrete waste arises during construction due to over-ordering, casting defects, rejected batches, formwork removal, and surplus materials [14].

- Renovation and repair works: Maintenance and structural upgrades generate concrete debris from removing or replacing slabs, columns, foundations, and other elements [15].

- Infrastructure reconstruction and urban redevelopment: Large-scale road, bridge, and transportation upgrades, as well as urban renewal projects, contribute significantly to waste concrete generation [16].

- Industrial and prefabrication waste: Precast and ready-mix plants produce waste from defective elements, test specimens, rejected batches, and manufacturing residues [14].

2.2.2. Processing techniques

- Crushing and size reduction techniques: Crushing is the primary stage in RCA production, where demolished concrete is fragmented into smaller particles using mechanical equipment such as jaw crushers, impact crushers, and cone crushers [3, 17].

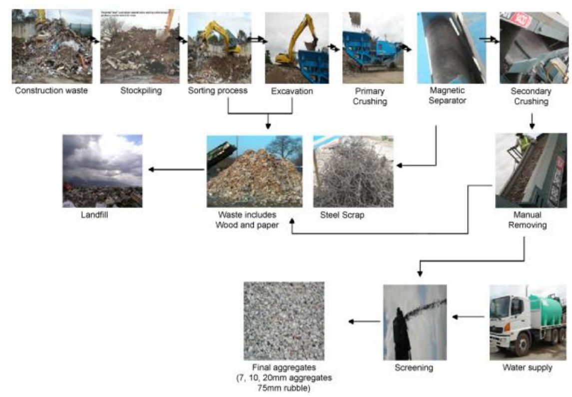

Figure 1. Flow chart of the concrete recycling method [18]

- Removal of adhered mortar from RCA: Mechanical abrasion, thermal treatment, and advanced liberation techniques used to reduce adhered mortar on RCA surfaces. Mortar removal decreases porosity and water absorption while improving mechanical performance [3, 19].

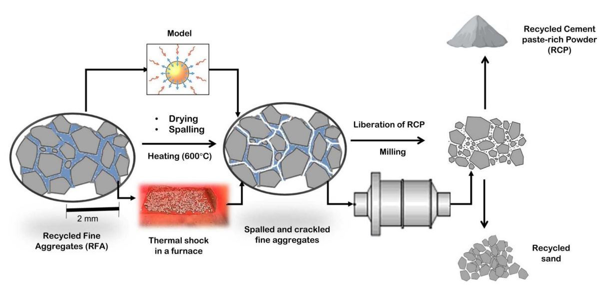

Figure 2. Enhancing the recovery of cement-rich powder from recycled fine aggregates through thermal shock [20]

- Treatment and improvement methods for RCA: Post-processing enhancement techniques for recycled concrete aggregates, including carbonation treatment, mineral slurry coating, and the two-stage mixing approach, which aim to improve the interfacial transition zone and durability properties [4].

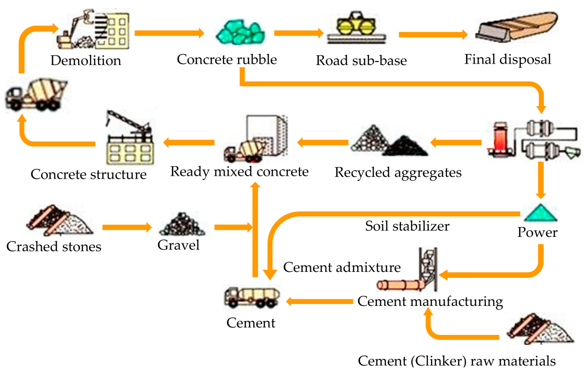

Figure 3. Process of destroyed buildings wastes production as RCAs [21]

2.2.3. Classification systems of RCA

- European classification system (EN standards): Under EN 12620 and EN 206, recycled aggregates are classified based on constituent composition, particularly the concrete and natural aggregate content (Rc). For structural use, RCA generally requires a high Rc content (often >90%) and strict limits on contaminants to ensure quality and performance [22].

- Japanese classification system (JIS A 5021 / JIS A 5022) [23]:

Japan classifies RCA into three quality grades based on density, water absorption, and impurity limits:

+ Class H (High quality): comparable to natural aggregate; suitable for structural concrete.

+ Class M (Medium quality): limited structural or precast use.

+ Class L (Low quality): road base, backfill, or non-structural applications.

- Chinese classification system (GB/T Standards) [24] uses GB/T 25177 and related standards classify RCA based on water absorption, crushing index, and density [24].

Typical grades:

+ Grade I: High-quality RCA for structural concrete.

+ Grade II: General concrete applications.

+ Grade III: Non-structural uses such as subbase or fill.

2.3. Physical characteristics of recycled concrete aggregates

Recycled concrete aggregates (RCA) are generally more angular, rougher, and less dense than natural aggregates due to adhered mortar, leading to higher porosity and water absorption (typically 2-15%) and slightly lower density (~2.32 g/cm³). These characteristics reduce workability and increase fines content, although they may help limit bleeding. Their properties vary depending on the source and processing quality, significantly influencing concrete mix design [25].

Figure 4. Classification of aggregate particles as per BS 812-110 (N: natural, R: recycled) [26]

2.4. Mechanical properties of concrete incorporating RCA

Concrete made with recycled concrete aggregates (RCA) typically shows lower compressive and flexural strength, reduced elastic modulus, and higher porosity and water absorption due to adhered mortar and weaker interfacial transition zones. However, performance can be significantly improved through proper processing (e.g., carbonation treatment), use of supplementary cementitious materials, fiber reinforcement, and strict quality control. With optimized mix design, RCA concrete can achieve mechanical and durability properties comparable to natural aggregate concrete, supporting its use as a sustainable construction material (Table 1 and Table 2). [27-29].

Table 1. Influence of RCA replacement ratio on mechanical properties of structural concrete [27-29]

RCA replacement ratio	Compressive strength	Elastic modulus	Tensile/ Flexural strength	Structural implication	Applications
0% (Control)	Reference	Reference	Reference	Conventional structural concrete	
≤ 30%	Slight reduction (≤ 10%)	Moderate reduction	Comparable	Suitable for most structural members	Reinforced concrete beams and slabs Columns in low- to mid-rise buildings Precast non-prestressed elements Residential and commercial structures
30-50%	Noticeable reduction	Significant reduction	Moderate loss	Requires mix optimization	Secondary structural elements; Shear walls; Parking structures; Lightly loaded slabs; Retaining walls
> 50%	Pronounced reduction	Large reduction	Reduced crack resistance	Limited to low-demand structures	Non-load-bearing walls; Mass concrete blocks; Temporary structures; Road base and subbase layers; Backfill materials

Table 2. Comparative performance of RCA-based concrete and natural aggregate concrete [5, 30-32]

Aspect	Natural aggregate concrete (NAC)	RCA-based concrete (RAC)	Typical trend / notes
Strength (compressive / tensile)	Baseline (higher, more consistent)	Often slightly lower at the same w/c, especially at high replacement	With coarse RCA at moderate replacement, strength loss is often small; with fine recycled aggregate, reductions can be more pronounced (e.g., reported ~15-30% in some studies).
Stiffness (modulus of elasticity, E)	Baseline (higher E)	Lower E due to adhered mortar + higher porosity	A commonly reported outcome is ~10-25% lower E at high RCA replacement.
Durability (permeability, carbonation, chloride ingress, freeze-thaw…)	Generally better transport resistance (lower permeability) at similar mix quality	Often higher water absorption/permeability → increased risk of carbonation and chloride ingress, unless mitigated	Reviews consistently report durability tends to worsen as RCA content increases, particularly for transport-related mechanisms. Some reports note carbonation/ chloride ingress can remain inferior even when SCMs help.
Environmental impact (resource use, landfill, CO_2)	Higher demand for virgin aggregate; quarrying impacts	Usually lower virgin aggregate demand and less landfill, often lower overall impacts in LCA- but transport + processing can offset benefits	LCA reviews show benefits are common but case-dependent (especially hauling distances and processing intensity).

2.5. Durability performance of RCA-based structural concrete

Recycled concrete aggregate (RCA) concrete has lower durability than natural aggregate concrete, owing to higher porosity and water absorption from adhered mortar, which increases the risk of carbonation, chloride ingress, and permeability, particularly at higher equivalent levels (e.g., >30%) [33]. However, quality control, coating treatments, or supplementary cementitious materials (SCMs) such as fly ash or metakaolin may significantly enhance performance, allowing it to meet structural requirements; however, increased creep and potential long-term issues such as steel corrosion remain concerns that necessitate careful mix design and monitoring [5, 30].

2.6. Structural behavior of RCA concrete members

Over the past two decades, many studies have examined reinforced concrete members with recycled concrete aggregates (RCA). Although adhered mortar and higher porosity may slightly reduce mechanical properties, properly designed RCA members can still achieve adequate strength, stiffness, and serviceability performance (Table 3).

Table 3. Structural behavior of reinforced concrete members incorporating RCA [6, 34, 35]

Structural Member	Observed Behavior	Comparison with NA Concrete	Key Findings
Beams	Similar failure modes	Slightly reduced stiffness	Ultimate capacity often maintained
Columns	Comparable axial strength	Reduced confinement efficiency	Sensitive to RCA quality
Slabs	Similar cracking patterns	Slightly larger deflections	Serviceability governs
Walls	Stable load transfer	Minor stiffness loss	Suitable with low-moderate RCA

3. PRACTICAL APPLICATIONS AND CASE STUDIES

3.1. Practical applications

3.1.1. Structural concrete in buildings

The use of recycled concrete aggregates (RCA) in structural components has progressed from laboratory studies to practical construction. Projects in Europe and Japan show that partial replacement levels (typically ≤30%) can deliver structural performance comparable to conventional concrete with proper mix design [2, 17]. Although RCA members exhibit similar flexural failure modes to natural aggregate concrete [34], reduced elastic modulus may lead to larger deflections and crack widths [4]. Therefore, serviceability considerations often control design, but RCA can be safely applied when stiffness reduction is properly addressed.

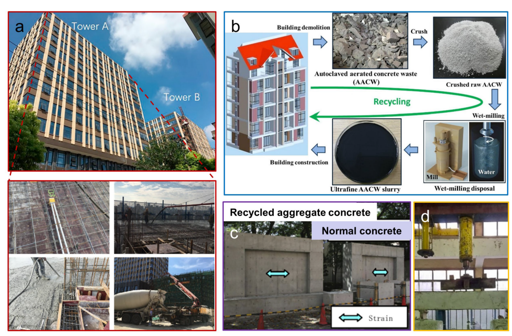

Figure 5. (a) Profile of the project-demonstration buildings and construction of the RAC structure; (b) AACW disposal procedure for recycling utilization; (c) mock-up RAC specimens; and (d) test setup and instrumentation layout of RAC concrete [36]

3.1.2. Infrastructure applications

RCA has been applied in bridges, precast girders, and retaining walls to enhance sustainability and material reuse. Full-scale tests show that, at moderate replacement levels, RCA concrete can maintain comparable load capacity and ductility [37]. The use of supplementary cementitious materials further improves durability by reducing permeability and chloride penetration [38]. These applications demonstrate that durability-focused mix design is essential for long-term performance (Fig. 6).

3.1.3. Precast and modular construction

Precast concrete production provides controlled conditions and strict quality control, making it suitable for RCA use. Research shows that precast elements with RCA achieve stable mechanical performance due to consistent mixing and curing [39]. The rough surface of RCA can also enhance mechanical interlock and bond strength in prefabricated components [34] in Fig. 7. Modular construction using RCA panels and blocks has demonstrated good structural reliability and sustainability, supporting circular economy goals by reducing raw material extraction and transport demands.

Figure 6. (a) General view of a typical fire test on a RAC composite slab, and (b) fire test one of the slabs [40]

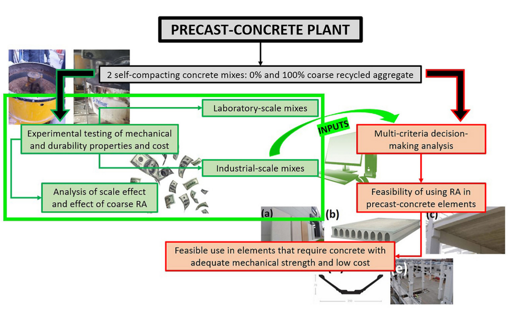

Figure 7. Using recycled aggregate concrete at a precast-concrete plant [41]

3.2. Key challenges, research gaps, and future directions

3.2.1. Variability and quality control of recycled concrete aggregates

A key limitation of recycled concrete aggregate (RCA) is its high variability, stemming from differences in source concrete quality, processing, and contamination. Unlike natural aggregates, properties such as density, water absorption, and strength largely depend on adhered mortar content and parent material characteristics [2, 39]. This variability introduces uncertainty in structural performance and long-term durability, limiting its use in critical load-bearing applications. Future research should prioritize standardized quality grading systems, improved treatment techniques, and comprehensive characterization methods to enhance the consistency and reliability of RCA for structural use.

3.2.2. Limited understanding of long-term structural performance

Many studies show that recycled concrete aggregate (RCA) concrete can achieve short-term strength and load capacity comparable to conventional concrete. However, its long-term performance remains uncertain, as RCA mixtures often exhibit higher shrinkage, creep, and carbonation due to greater porosity and weaker interfacial transition zones [38]. The combined effects of sustained loading, environmental exposure, and aging are still not well defined.

Future research should emphasize long-term field monitoring of full-scale members and the development of predictive models that integrate mechanical behavior, durability, and environmental interactions to enhance the reliability and wider adoption of RCA in structural applications.

3.2.3. Future research perspectives

Some priority research directions are recommended:

- Advancing RCA processing to reduce adhered mortar and improve aggregate quality.

- Conducting long-term full-scale field testing under realistic environmental and loading conditions.

- Developing performance-based design methods that address stiffness reduction and durability.

- Investigating seismic and dynamic behavior at the structural system level, including soil-structure interaction.

- Aligning experimental findings with international design codes and standards.

- Integrating RCA into digital and circular construction systems, such as BIM-based material tracking and life-cycle optimization.

4. CONCLUSIONS

Recycled concrete aggregates (RCA) derived from construction waste provide a sustainable alternative to natural aggregates by reducing landfill use, conserving resources, and lowering environmental impacts. Although RCA concrete has higher porosity and water absorption due to adhered mortar, proper processing and durability-focused mix design can achieve performance comparable to conventional concrete. Structural members with RCA generally maintain adequate load capacity, with serviceability (stiffness and crack control) often governing design. Moderate replacement levels (≤30%) are feasible under strict quality control. Further research on long-term durability, consistency, and performance-based design is needed to support broader structural applications.

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