Enhancing Sustainability in Construction through Recycled Concrete Aggregate (RCA): Technological and Policy Perspectives

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Abstract. In the context of the circular economy, the incorporation of construction and demolition (C&D) waste as recycled concrete aggregate (RCA) offers a crucial chance to promote sustainability in the building industry. This research investigates the technological, financial, and environmental effects of using construction and demolition waste as RCA in the manufacturing of concrete. The potential of RCA to lessen landfill usage, cut greenhouse gas emissions, and lessen dependency on natural aggregates is highlighted. The study examines life cycle assessment (LCA) measures, performance features of RCA-based concrete, and existing practices. The results show that although RCA could have worse mechanical qualities than virgin aggregates, these impacts can be reduced with the right processing and mix design changes. Additionally, by encouraging resource efficiency, waste reduction, and material reuse, RCA supports the tenets of the circular economy. In order to effectively reap the benefits of recycling construction and demolition waste in sustainable construction practices, this study emphasises the necessity of updated standards, legislative support, and industry collaboration.

Keywords: Recycled Concrete Aggregate, sustainable construction, circular economy, demolition waste, mix design, policy frameworks, lifecycle assessment.

INTRODUCTION

The global construction sector consumes vast quantities of raw materials, with aggregates alone accounting for more than 40 billion tons annually (McNeil and Kang, 2013). Simultaneously, construction and demolition (C&D) activities generate massive amounts of waste up to 35% of global solid waste streams (Mesgari *et al*., 2020). Increasing urbanization and infrastructure demand will exacerbate both extraction pressures and waste generation, making resource circularity a critical priority (Verian *et al*., 2018).

Recycled Concrete Aggregate (RCA) represents one of the most promising strategies to close material loops in the construction sector (Vieira Ramos *et al*., 2020). By reclaiming concrete from demolished structures, RCA can substitute for natural aggregates in a wide range of applications. While this approach reduces landfill waste and environmental degradation from quarrying, questions remain about technical performance, long-term durability, cost-effectiveness, and standardization. Furthermore, policy and regulatory mechanisms have yet to fully align with technological potential, leaving gaps between sustainability goals and on-ground practices (Ali *et al*., 2020).

This manuscript presents a dual-perspective analysis of RCA adoption. It reviews technological advances that enhance RCA quality and performance, while also evaluating the role of policy instruments in creating demand and ensuring quality control (Gupta *et al*., 2020). Together, these perspectives can accelerate the transition of RCA from niche use to mainstream construction practice (Issa and Salem, 2013).

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Objective

- To synthesize state-of-the-art technological practices in RCA production and utilization.
- To examine regulatory and policy frameworks that drive RCA adoption.
- To integrate environmental and economic assessments in evaluating RCA benefits.
- To propose a roadmap of recommendations bridging technology and policy.

Background and Rationale

The environmental benefits of RCA are clear: reducing quarrying impacts, conserving non-renewable aggregates, lowering embodied carbon, and diverting waste from landfills (Kashani *et al*., 2018). Yet challenges persist. RCA generally has higher porosity, lower density, and weaker interfacial transition zones compared to virgin aggregates due to residual mortar (Nuaklong *et al*., 2018). These characteristics can reduce mechanical performance and increase water demand in fresh concrete mixes. Furthermore, quality variability in feedstock and inconsistent regulations hinder confidence among designers and contractors (Ling *et al*., 2012).

Nevertheless, with advancements in processing, mix design, and supplementary cementitious materials (SCMs), RCA can meet the requirements of many structural and non-structural applications (Whiting *et al*., 2013). When coupled with strong policies such as landfill diversion mandates, procurement incentives, and performance-based standards RCA can deliver substantial environmental and economic value to the construction sector (Qi *et al*., 2016).

Technological Perspectives

Source Separation and Selective Demolition

The foundation of high-quality RCA lies in selective demolition practices. Traditional demolition often produces mixed waste streams contaminated with metals, wood, gypsum, or plastics, reducing RCA quality. Source separation and controlled dismantling ensure cleaner concrete streams, reducing downstream processing requirements. Pre-demolition audits and recovery plans are increasingly recognized as best practices (Vintimilla and Etxeberria, 2023).

Crushing and Beneficiation Technologies

Modern recycling plants employ primary jaw crushers, secondary impact crushers, and multi-stage screening systems to generate RCA with controlled particle-size distributions. Beneficiation techniques such as mechanical abrasion, heat treatment, or acid washing help remove adhered mortar and reduce water absorption. Magnetic separators remove metallic contaminants, while density separation techniques isolate lighter materials. These innovations significantly improve RCA consistency (Liu *et al*., 2016).

Grading, Particle Shape Control, and Blending

Aggregate grading and particle shape influence packing density, workability, and mechanical properties. Advanced crushers can produce cubical RCA particles similar to natural aggregates. Blending RCA with virgin aggregates at controlled ratios enhances consistency, particularly in structural applications, while gradually building industry confidence (Kirthika and Singh, 2020).

Surface Treatment and Pre-conditioning

Treatments such as carbonation curing, polymer coatings, or silane-based impregnations can reduce porosity and water absorption. Pre-soaking RCA before mixing minimizes rapid water uptake and stabilizes workability. While effective, cost and scalability of treatments remain areas for ongoing research (Kou and Poon, 2012).

Mix-Design Strategies

Effective mix-design strategies include:

- Adjusting water-to-cement ratios and accounting for RCA absorption capacity.
- Using higher paste volumes to improve workability.
- Incorporating SCMs such as fly ash, slag, or calcined clay to enhance durability and microstructure.
- Employing chemical admixtures (superplasticizers, shrinkage reducers) to address workability and strength. Partial replacement strategies, typically 20–50% substitution of coarse aggregates, are widely adopted to balance sustainability with performance.

Structural Performance and Durability

Studies indicate that RCA concrete can achieve comparable compressive strength to natural aggregate concrete with proper design adjustments. However, durability concerns — including freeze–thaw resistance, chloride ingress, and alkali-silica reaction require targeted testing and mitigation measures. Long-term monitoring projects in Europe and Asia have confirmed the viability of RCA in structural applications when quality-control measures are rigorously implemented.

Quality Control and Certification

Developing certification schemes for RCA quality classification (e.g., RCA Class I for structural use, Class II for non-structural) simplifies adoption. Regular testing protocols for density, water absorption, and residual mortar content build confidence among engineers and regulators.

Policy Perspectives

Standards and Technical Regulations

Performance-based standards allow flexibility in using RCA while ensuring structural safety. Countries such as Japan and the Netherlands have established specific RCA standards, while others still rely on restrictive guidelines. Harmonized international standards could accelerate adoption (Kumar *et al*., 2022).

Fiscal Incentives and Market Mechanisms

Landfill taxes, recycling credits, and reduced VAT rates for recycled materials make RCA more competitive. Pay-as-you-dispose systems discourage waste landfilling and incentivize recycling.

Green Public Procurement (GPP)

Governments, as major construction clients, can mandate RCA content in public infrastructure projects. Such procurement policies create large, stable markets for recycled materials (Chouksey *et al*., 2025).

Extended Producer Responsibility (EPR)

Requiring contractors and developers to take responsibility for end-of-life materials ensures higher recycling rates. Demolition permits tied to waste management plans with recovery targets further strengthen accountability.

Certification and Labelling Schemes

Material passports, digital tracking systems, and third-party certifications improve transparency. By linking RCA products to verified performance data, confidence among engineers, contractors, and clients grows.

Capacity Building and Knowledge Transfer

Training programs, guidelines, and demonstration projects bridge knowledge gaps. Public–private partnerships and academic collaborations are essential to share best practices and innovations.

Local Infrastructure and Zoning

Locating recycling plants close to urban centers minimizes transport emissions and costs. Urban planning policies can incentivize the creation of regional recycling hubs.

Environmental and Economic Assessments

Lifecycle Assessment (LCA)

LCA tools evaluate RCA's environmental benefits by accounting for avoided quarrying, reduced landfill use, and processing energy. RCA typically shows lower embodied carbon compared to virgin aggregates, especially when transport distances are minimized (Chouksey *et al*., 2022).

Life-Cycle Costing (LCC)

LCC analysis incorporates material costs, processing expenses, transport, maintenance, and disposal fees. While RCA may involve higher upfront costs, avoided landfill fees and reduced virgin material demand often yield net savings over the lifecycle (Kumar *et al*., 2022).

Multi-Criteria Decision Analysis (MCDA)

MCDA frameworks allow stakeholders to balance environmental, economic, and technical factors. Engaging diverse stakeholders ensures fair weighting and transparent trade-offs in decision-making (Upreti and Verma, 2022).

Case Studies and Best Practices

- **Japan:** Mandatory standards requiring RCA in road sub-bases and building foundations have led to recycling rates above 95%.
- **Netherlands:** National circular economy policies and landfill ban on untreated C&D waste have driven high RCA utilization.
- **European Union:** Green procurement directives and landfill diversion targets have improved RCA adoption in infrastructure projects. These case studies illustrate how policy, standards, and technology interact to create favourable conditions for RCA adoption.

Barriers and Challenges

- Inconsistent quality of RCA feedstock.
- Lack of harmonized international standards.
- Limited awareness and risk perception among structural engineers.
- Higher processing and certification costs compared to virgin aggregates.
- Insufficient recycling infrastructure in developing regions.

Recommendations

Technological Recommendations

- Promote selective demolition and source separation to ensure cleaner feedstock.
- Invest in advanced beneficiation technologies to reduce variability.
- Develop RCA classification systems linked to allowable applications.

- Encourage partial substitution strategies with long-term monitoring of field performance.
- Standardize pre-treatment and water absorption correction practices.

Policy Recommendations

- Implement performance-based RCA standards and harmonize across regions.
- Provide fiscal incentives such as landfill taxes and recycling subsidies.
- Mandate RCA content in public procurement.
- Require recovery targets in demolition permits.
- Fund training, demonstration projects, and certification schemes.

Research Gaps and Future Directions

- Optimizing surface treatments for cost-effectiveness and environmental benefits.
- Developing digital traceability systems for RCA materials.
- Long-term durability studies across diverse climatic conditions.
- Integrating RCA into ultra-high-performance concretes.
- Exploring carbon sequestration potential through accelerated carbonation of RCA.

CONCLUSION

RCA represents a critical strategy for aligning construction practices with sustainability goals. Technological advances are steadily overcoming performance limitations, while supportive policy frameworks can accelerate market adoption. By integrating demolition planning, advanced processing, quality certification, and targeted policies, RCA can transition from marginal use to a mainstream construction material. Achieving this vision requires coordinated efforts across stakeholders, underpinned by robust research, capacity building, and regulatory support. Together, these measures will enhance the sustainability of the construction sector while advancing the principles of the circular economy.

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Received on 16-11-2025 Accepted on 20-12-2025 Published on 29-12-2025

https://doi.org/10.65904/3083-3604.2025.01.07