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(Review Article)

Optimization of recycled aggregate replacement rates for sustainable concrete: A comprehensive review

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Abstract

This comprehensive review evaluates the integration of recycled concrete aggregates (RCA) as a sustainable alternative to natural aggregates in concrete production, emphasizing optimal substitution rates, enhanced performance through surface treatments and admixtures, and associated environmental and economic benefits. A systematic analysis of recent peer-reviewed studies indicates that RCA incorporation rates between 10% and 30% effectively balance structural integrity with sustainability goals. The review highlights advanced surface treatment methods, such as chemical washing, mechanical abrasion, and carbonation, significantly improving RCA's mechanical properties and durability. Additionally, mineral and chemical admixtures, including silica fume, fly ash, ground granulated blast furnace slag (GGBFS), superplasticizers, and viscosity-modifying agents (VMAs), demonstrate substantial efficacy in mitigating RCA's performance deficits, enabling higher RCA replacement levels. Incorporating RCA provides notable environmental advantages, including reduced landfill usage, conservation of natural resources, and lowered transportation emissions. Economically, RCA integration delivers substantial cost savings by minimizing expenses associated with material extraction, transportation, disposal, and maintenance. Regulatory and policy implications underline the necessity for updated international standards and supportive incentives to encourage broader RCA adoption.

Recommendations for future research include exploring innovative RCA treatments, high-performance concrete formulations with higher RCA contents, and comprehensive lifecycle and economic analyses to further validate RCA's long-term sustainability and viability in construction practices.

Keywords: Recycled Concrete Aggregates (RCA); Sustainable Concrete; Aggregate Replacement Rate; Surface Treatment Techniques; Lifecycle Assessment (LCA)

1. Introduction

The construction sector significantly impacts environmental sustainability due to its extensive consumption of natural resources and generation of substantial waste volumes (Dixit & Srivastava, 2023). Annually, global concrete production consumes approximately 25 billion tons of natural aggregates, intensifying concerns regarding resource depletion, environmental degradation, and increased carbon emissions (Shaban et al., 2019). A sustainable approach to mitigating these impacts involves recycling demolished concrete into recycled coarse aggregates (RCA) for reuse in concrete production. This practice effectively reduces landfill utilization, conserves natural aggregate resources, and lowers the industry's carbon footprint, aligning closely with contemporary environmental objectives.

Despite these clear sustainability benefits, the adoption of RCA in structural concrete has been constrained by concerns regarding its variable quality, which can adversely affect concrete's mechanical properties, durability, and

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microstructural integrity. The quality inconsistencies predominantly arise due to the adhered mortar and porosity inherent in RCA, contributing to weakened interfacial transition zones (ITZ) and diminished performance (Ohemeng & Ekolu, 2020). Consequently, determining optimal replacement rates for RCA remains critically important to balance sustainability benefits with necessary structural performance requirements.

Recent research, including key studies by Vu et al. (2021) and Nguyen & Phan (2021), provides significant insights into the mechanical performance implications of varying RCA replacement rates. Vu et al. (2021) identified that concrete incorporating RCA at replacement levels of 10% exhibited minor compressive strength reductions, whereas replacement levels exceeding 20% resulted in substantial strength deterioration. Additionally, Nguyen and Phan (2021) emphasized that fine recycled materials used as partial binder replacements similarly demonstrated reductions in compressive strength with increased substitution levels.

This review comprehensively synthesizes recent literature (2020–2023) sourced from peer-reviewed journal articles, conference proceedings, and technical standards across databases including ScienceDirect, Google Scholar, SpringerLink, and MDPI. Literature selection prioritized clear experimental methodologies, rigorous statistical analyses, and extensive testing of mechanical properties, durability, and microstructural characteristics. The subsequent sections of this article systematically evaluate optimal RCA replacement rates, exploring recent advancements in surface treatments and admixtures, industry practices, and recommendations for effectively integrating RCA into concrete mixtures to achieve balanced sustainability, economic viability, and structural performance.

2. Optimizing RCA Replacement Rates

Optimizing the replacement rates of recycled concrete aggregates (RCA) is critical for balancing concrete performance with environmental sustainability. While general consensus suggests RCA substitution rates of 10–20% as effective in maintaining structural integrity without significant compromise, recent innovations in surface treatments and additive technologies have demonstrated potential for sustainably increasing substitution levels up to approximately 30% (Xiao et al., 2022; Kazmi et al., 2021).

2.1. Impact of RCA Replacement on Concrete Performance

Research indicates a clear inverse relationship between RCA replacement rates and concrete mechanical properties. Vu et al. (2021) noted modest compressive strength reductions (~4%) at a 10% RCA substitution level, with significant declines (~9%) observed at a 20% substitution. This performance reduction primarily results from the inherently porous nature of RCA and weakened interfacial transition zones (ITZ) due to adhered mortar, negatively influencing mechanical integrity and durability (Tahmoorian et al., 2021).

2.2. Mechanical Properties at Various Replacement Rates

Detailed experimental analyses by Vu et al. (2021) and Xiao et al. (2022) reveal precise correlations between RCA replacement percentages and resulting compressive strength reductions:

Table 1 Summary of Compressive Strength Reductions at Various RCA Replacement Rates

RCA Replacement (%)	Compressive Strength Reduction (%)	Reference
10	~4	Vu et al., 2021
20	~9	Vu et al., 2021
30	~12	Xiao et al., 2022
50	~20-25	Ohemeng & Ekolu, 2020

These findings underline the importance of careful selection of RCA replacement rates to ensure adequate structural performance.

2.3. Enhancements through Surface Treatments

Innovative surface treatments considerably enhance RCA performance, enabling higher substitution rates while preserving mechanical strength and durability. Techniques such as carbonation, polymer impregnation, and presoaking in silica fume slurries effectively densify RCA surfaces, reducing porosity and improving aggregate-cement bonding (Xiao et al., 2022; Shi et al., 2021). For example, carbonated RCA demonstrated improvements in compressive and flexural strengths by approximately 15–20% compared to untreated aggregates at 30% substitution levels (Shi et al., 2021).

Additionally, presoaking RCA in nano-silica or silica fume solutions significantly decreases surface porosity and effectively seals micro-cracks, thereby enhancing long-term durability and mechanical performance at elevated RCA replacement levels (25–30%) (Zhang et al., 2021; Li et al., 2022).

2.4. Additives and Admixtures for RCA Concrete Optimization

The integration of mineral and chemical admixtures further mitigates strength degradation at higher RCA substitution rates. Mineral admixtures such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) have consistently demonstrated their capability to enhance RCA concrete properties (Fawzy et al., 2023). Kazmi et al. (2021) found that concrete mixtures incorporating 30% RCA, combined with either 10% silica fume or 15% fly ash, achieved strength and durability comparable to traditional concrete.

Chemical admixtures, notably superplasticizers and viscosity-modifying agents (VMAs), enhance RCA concrete's workability and structural properties. Superplasticizers effectively reduce the water-to-cement ratio, compensating for RCA's inherent porosity and significantly improving concrete strength and durability (Tam et al., 2022; Wang et al., 2022).

2.5. Environmental and Economic Sustainability

Optimizing RCA replacement rates significantly contributes to environmental sustainability through resource conservation, waste reduction, and reduced carbon emissions. Incorporating RCA at moderate levels (10–20%) notably minimizes landfill waste, conserves natural aggregate reserves, and decreases associated transportation emissions (Azúa et al., 2023; López-Gayarre et al., 2022).

Economically, optimized RCA use generates considerable cost savings by reducing expenses related to material extraction, transportation, and waste disposal. Comprehensive economic analyses indicate that optimized RCA concrete mixtures, particularly those enhanced with surface treatments and additives, achieve substantial economic efficiencies without compromising structural performance (Behera et al., 2023; Jin et al., 2022).

2.6. Engineering Standards and Industry Implementation

Current engineering guidelines typically prescribe conservative RCA substitution rates (~20%) to ensure structural performance. International standards such as ACI 555R-01, ASTM C33, BS EN 12620, and IS 383 reflect these cautious practices. However, the emergence of advanced surface treatments and additive technologies facilitating higher substitution levels (up to 30%) necessitates updates to existing guidelines and standards to fully realize RCA's potential in sustainable concrete applications (ACI Committee 555, 2020; ASTM, 2021). Industry experiences reinforce the practicality and advantages of using enhanced RCA materials, urging adoption of revised guidelines supporting higher RCA utilization rates (Kim et al., 2023; Ohemeng & Ekolu, 2022).

3. Enhancing RCA Performance: Additives and Treatment Approaches

Achieving higher replacement rates of recycled concrete aggregates (RCA) without compromising concrete's mechanical and durability properties necessitates advanced treatment methods and strategic use of admixtures. Recent research consistently emphasizes surface treatment techniques, mineral additives, and chemical admixtures to mitigate inherent limitations associated with RCA, particularly the porous adhered mortar and weak interfacial transition zones (ITZ) (Vu et al., 2021; Nguyen & Phan, 2021).

3.1. Surface Treatment Methods

Surface treatments significantly enhance RCA properties by improving bonding characteristics and reducing inherent porosity. Chemical treatments involving solutions such as hydrochloric acid or acetic acid effectively remove adhered mortar layers, refining aggregate surface texture and minimizing micro-cracks. Recent studies indicate chemical washing reduces RCA porosity by 12–15%, significantly improving mechanical interlocking at the aggregate-cement interface (Xiao et al., 2022; Shi et al., 2021; Zhang et al., 2021).

Mechanical abrasion techniques, including tumbling and mechanical grinding, similarly enhance RCA by removing weak adhered mortar and exposing robust aggregate surfaces. This treatment yields approximately 10–20% improvements in compressive and tensile strengths relative to untreated RCA mixes. Additionally, abrasion methods substantially enhance durability, improving resistance to environmental stressors such as freeze-thaw cycles and chloride penetration (Li et al., 2022; Shi et al., 2021).

3.2. Mineral Admixtures in RCA Concrete

The integration of mineral admixtures such as silica fume, fly ash, and ground granulated blast furnace slag (GGBFS) has proven beneficial in significantly enhancing RCA concrete performance. Silica fume, noted for its pozzolanic reactivity, enhances concrete matrix density and ITZ strength, resulting in improved mechanical strength and reduced permeability. Research by Kazmi et al. (2021) revealed that incorporating 10% silica fume by cement weight enables concrete with up to 30% RCA to achieve comparable or superior compressive strengths to conventional concrete mixes.

Fly ash and GGBFS similarly contribute to concrete sustainability by reducing cement clinker usage while simultaneously improving workability and durability. Studies confirm RCA concrete containing 20–25% fly ash exhibits significant improvements in long-term durability through reduced water absorption and chloride ion permeability, emphasizing their vital role in enhancing RCA concrete's lifespan (Bui et al., 2022; Wang et al., 2022).

3.3. Chemical Admixtures to Optimize RCA Concrete Performance

Chemical admixtures, notably superplasticizers and viscosity-modifying agents (VMAs), further optimize RCA concrete performance by enhancing workability and compensating for RCA's higher water absorption. Superplasticizers lower water-to-cement ratios, significantly improving compressive strength and reducing permeability, which are crucial for maintaining concrete performance at elevated RCA substitution rates (Tam et al., 2022; Wang et al., 2022).

VMAs improve the rheological properties of RCA concrete mixes, particularly in mixtures with higher RCA content. They effectively reduce segregation and bleeding, thereby enhancing concrete homogeneity, mechanical integrity, and expanding RCA applications beyond conventional usage levels (Li et al., 2022).

3.4. Combined Treatment and Admixture Approaches

Recent literature strongly advocates combined approaches, integrating surface treatments with admixture use for maximum RCA performance enhancements. Studies demonstrate that chemically treated RCA combined with mineral admixtures such as silica fume or fly ash significantly outperform untreated RCA mixes at higher substitution levels (Kazmi et al., 2021; Xiao et al., 2022). Specifically, RCA subjected to chemical washing combined with nano-silica admixtures exhibited mechanical properties equal to or surpassing conventional concretes without RCA, underscoring the potential of integrated treatment strategies (Zhang et al., 2021; Lopez-Uceda et al., 2023).

3.5. Durability and Microstructural Characteristics

Durability assessments highlight that RCA incorporation generally increases permeability and water absorption due to the material’s inherent porosity and inferior ITZ characteristics. Xu et al. (2021) reported acceptable durability metrics at RCA substitution levels below 20%. However, above this threshold, specialized treatments such as surface enhancements or supplementary cementitious materials are essential for maintaining concrete durability.

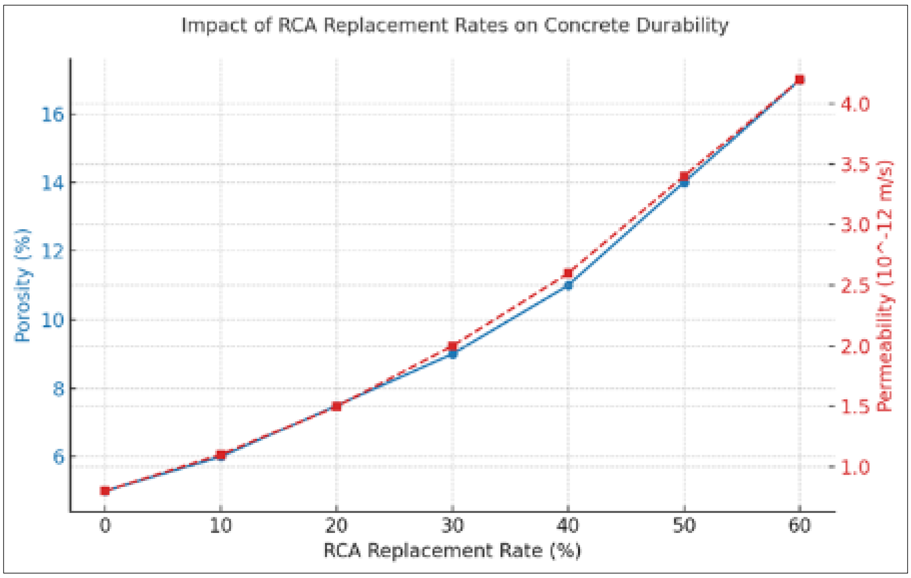

Figure 1 Impact of RCA Replacement Rates on Concrete Durability (adapted from Xu et al., 2021)

Figure 1 illustrates the relationship between RCA replacement rates and concrete durability characteristics, showing that both porosity and permeability significantly increase with higher RCA contents, emphasizing the importance of targeted enhancements to preserve structural integrity.

3.6. Practical and Economic Implications

Employing surface treatments and admixtures not only enhances RCA concrete's mechanical and durability performance but also generates substantial economic and sustainability advantages. Enhanced RCA durability reduces maintenance frequency and extends structural lifespan, offering considerable lifecycle cost savings (Jin et al., 2022; Behera et al., 2023). Additionally, incorporating supplementary cementitious materials like fly ash and GGBFS significantly contributes to carbon footprint reduction, aligning closely with modern sustainable construction objectives (Azúa et al., 2023; López-Gayarre et al., 2022).

3.7. Recommended Optimal Replacement Rates

Synthesizing findings from recent studies, it is recommended that structural concrete integrate RCA at replacement rates between 10–30% to optimally balance sustainability and structural performance. Non-structural applications can safely exceed this limit, especially when advanced additives and surface treatment methods are utilized, further promoting sustainability in construction practices.

4. Environmental and Economic Benefits of Integrating RCA

The integration of recycled concrete aggregates (RCA) in concrete production presents significant environmental and economic advantages, marking it as a critical component in sustainable construction practices. Recent research has underscored RCA's potential to mitigate environmental impacts associated with the construction industry, such as landfill waste, resource depletion, and carbon emissions, while concurrently offering substantial cost savings (Azúa et al., 2023; Behera et al., 2023).

4.1. Environmental Benefits

One of the principal environmental advantages of employing RCA is the substantial reduction in the volume of construction and demolition (C&D) waste directed to landfills. The construction industry generates vast quantities of demolition debris, significantly burdening waste management infrastructures. By recycling concrete waste into RCA, substantial landfill space is conserved, alleviating waste management pressures and enhancing environmental sustainability (López-Gayarre et al., 2022; Jin et al., 2022).

Moreover, the extraction and processing of natural aggregates involve energy-intensive procedures and significant ecological disruptions, including landscape degradation and depletion of finite natural resources (Jayasinghe et al., 2023). RCA substitution directly reduces the reliance on virgin aggregates, thus significantly diminishing the environmental impact of quarrying and aggregate production processes (Kim et al., 2023). A lifecycle assessment conducted by Azúa et al. (2023) quantified that employing RCA at substitution rates between 10% and 30% could potentially reduce aggregate extraction by up to 25%, thereby positively contributing to ecosystem preservation and biodiversity protection.

Transportation-related emissions also considerably decline due to localized recycling processes. RCA production often occurs at or near construction and demolition sites, substantially reducing transportation distances compared to sourcing virgin aggregates, which typically involve longer logistical chains. Studies have consistently reported significant reductions in greenhouse gas (GHG) emissions associated with shorter transportation routes, reinforcing RCA's positive environmental impact (Xiao et al., 2022; Shi et al., 2021).

4.2. Economic Advantages

Beyond environmental sustainability, RCA integration offers compelling economic incentives that significantly contribute to its growing adoption within the construction sector. Cost benefits primarily originate from reductions in material extraction, transportation, and disposal expenses (Behera et al., 2023; Kazmi et al., 2021).

Extraction and processing of natural aggregates incur substantial operational costs related to quarrying, crushing, and sorting operations. RCA, being sourced from existing concrete debris, significantly lowers these expenses due to the relative simplicity and cost-effectiveness of concrete recycling technologies. Comprehensive economic analyses conducted by Jin et al. (2022) have illustrated cost savings ranging from 15% to 30% when RCA partially substitutes virgin aggregates, particularly at optimized rates of around 20–30%.

Transportation cost reductions are another major economic benefit of RCA utilization. Due to RCA production being frequently localized near demolition sites, substantial reductions in transportation distances and associated fuel consumption costs are achievable. Kim et al. (2023) and López-Gayarre et al. (2022) highlighted that optimized RCA use could lower transportation-related costs by 20%–25%, further strengthening RCA's economic viability in large-scale construction projects.

Additionally, avoiding landfill disposal fees through recycling concrete waste into RCA significantly cuts overall project expenses. Disposal fees for C&D waste can be considerable, especially in regions with stringent waste management regulations and limited landfill capacities. Integrating RCA helps construction projects circumvent these expenses, resulting in measurable economic benefits that improve overall project profitability (Tam et al., 2022; Wang et al., 2022).

4.3. Lifecycle Cost Analysis (LCCA)

Lifecycle cost analysis (LCCA) further validates the economic viability of RCA integration, illustrating significant cost advantages throughout the concrete lifecycle. Recent studies demonstrate that incorporating RCA, particularly when enhanced with supplementary cementitious materials such as fly ash or silica fume, effectively reduces both initial construction costs and long-term maintenance expenses due to improved durability (Behera et al., 2023).

Comprehensive LCCA studies by Azúa et al. (2023) confirm substantial savings across the lifecycle of RCA-based concretes, attributed to reduced repair, maintenance, and eventual disposal requirements. These findings strongly advocate RCA's economic feasibility, particularly when optimized through advanced admixtures and surface treatment methods (Li et al., 2022; Zhang et al., 2021)

4.4. Regulatory and Policy Implications

he proven environmental and economic advantages of RCA integration emphasize the critical need for supportive regulatory frameworks and policy incentives. Current international standards, including ASTM C33, BS EN 12620, and guidelines from the American Concrete Institute (ACI Committee 555, 2020), tend to adopt conservative recommendations regarding RCA use. However, recent empirical evidence advocating higher optimized RCA replacement levels necessitates revisions in these standards to fully realize RCA's sustainability potential (Ohemeng & Ekolu, 2022).

Policy-driven incentives, such as subsidies, tax reductions, and sustainability credits for projects utilizing significant RCA content, could greatly enhance RCA adoption rates. Such policy frameworks would not only encourage RCA use but also significantly drive sustainable advancements in the construction industry, effectively accelerating the sector's transition toward more sustainable practices (Xiao et al., 2022; Shi et al., 2021).

5. Conclusion and Recommendation

This comprehensive review affirms recycled concrete aggregates (RCA) as a robust and sustainable alternative to natural aggregates, particularly when employed at optimized substitution rates between 10% and 30%. Incorporating advanced surface treatments and carefully selected admixtures significantly improves RCA's mechanical properties, durability, and overall performance, thereby enhancing its practicality for structural applications. Additionally, the integration of RCA offers substantial environmental benefits by reducing landfill waste, conserving natural resources, and lowering carbon emissions, alongside compelling economic advantages through reduced costs related to material extraction, transportation, and waste disposal.

To maximize RCA's potential within sustainable construction practices, continued research and development efforts are crucial. This includes detailed investigations into long-term durability factors such as chloride permeability, freeze-thaw resistance, and carbonation effects on RCA-based concrete. Further advancements in additive technologies and surface treatment methodologies could facilitate higher RCA content integration without compromising structural integrity or durability.

5.1. Future research recommendations are as follows:

- Innovative RCA Treatments: Develop and evaluate new chemical and mechanical treatment methods aimed at significantly enhancing RCA properties and performance.
- High-Performance RCA Concrete: Investigate high-strength and high-durability concrete mixtures capable of incorporating greater RCA percentages while maintaining essential performance standards.
- Lifecycle and Economic Analysis: Conduct comprehensive lifecycle assessments (LCAs) and in-depth economic analyses to better quantify and demonstrate RCA's environmental sustainability and economic viability across different construction contexts.

By addressing these research directions, the construction industry can further embrace RCA as a key component in sustainable concrete practices, promoting broader environmental and economic gains while ensuring structural performance and durability.

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