

“SUSTAINABLE CONCRETE CONSTRUCTION AND THE ROLE OF RECYCLED AGGREGATE QUALITY”

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Abstract

The rising demand for sustainable construction materials has increased interest in using recycled aggregates as a replacement for natural aggregates in concrete. However, the quality of recycled aggregates is often affected by attached mortar, porosity, and impurities. This quality has a significant impact on the performance of recycled aggregate concrete (RAC). This paper reviews how the quality of recycled aggregates affects concrete's mechanical and durability properties. It specifically looks at compressive strength, workability, and water absorption. Comparisons indicate that low-quality recycled aggregates can reduce compressive strength by up to 25% and increase water absorption by more than 10%. Better processing methods like pre-soaking, surface treatment, and beneficiation can help bring performance closer to that of traditional concrete. There are gaps in the research. These include a lack of field studies, a lack of standardized quality measures for recycled aggregates, and a limited integration with design codes. Case studies from India and other countries illustrate the challenges and successes in real-world applications. The findings indicate that recycled aggregates can play a major role in sustainable construction; however, careful consideration of their quality is necessary to produce concrete that is reliable, durable, and environmentally friendly.

Keywords: *Recycled Aggregate Concrete (RAC), Aggregate Quality, Compressive Strength, Durability, Sustainable Construction, Concrete Performance.*

Introduction



(Source: Google)

Figure 1 : Recycling construction waste into Aggregates.

Urbanization and development of infrastructure have led to a rapid increase in demand for natural construction materials, specifically aggregates for concrete production. This increased demand has led to significant quarrying of natural stone, depletion of finite resources, and environmental repercussions associated with habitat destruction and carbon emissions Sharma and Patel. The construction is also a generator of large amounts of demolition waste that is primarily disposed of in landfills, and not reused Gupta et al. These two problems serve as a counter indication for sustainable construction, reinforcing both resource depletion and waste production.

An appropriate substitute for natural aggregates is recycled concrete aggregate (RCA), derived from the processing of construction and demolition debris Khan et al. RCA provides a means to reduce the overall environmental impact of construction, and along with waste diversion, promotes a circular economy while reducing reliance on the extraction of virgin material Sharma and Patel; Gupta et al. However, the performance of concrete with recycled aggregates is directly related to the aggregate itself. The mortar residue, contamination, particle shape, and water absorption all have a dramatic influence on the performance indicators of workability, strength, and durability.

To fill in these knowledge gaps, the present study will thoroughly assess the performance implications of recycled aggregate quality in sustainable concrete. This assessment will explore the physical, chemical, and mechanical properties of recycled aggregates from various demolition waste streams, along with their relationships with compressive strength, tensile strength, durability, and service-life characteristics of concrete mixtures Gupta et al; Khan et al. Overall, the study aims to develop conclusions regarding quality thresholds and opportunities for pre-treatment options that can inform recommendations for RCA quality assurance, improved mix designs, and sustainable building policies

Ultimately, the research is intended to help the construction industry reach all parts of sustainable construction from environmental footprint, to structural soundness. With a scientific approach and evidenced-based guidance the research will help provide support to wider adoption and use of recycled aggregates in the construction sector.

Literature Review

Recycled aggregate concrete (RAC) is gaining traction in the sustainable construction literature because of its necessity to diminish environmental impacts and resource consumption for making conventional concrete. The principal difficulty with RAC relates to meeting mechanical performance and durability requirements while also realizing environmental benefits from RCA use. Gupta et al. (2015) [1] established early comprehensive analysis that evaluated the strength and durability of RAC. The analysis indicated a disparity in compressive strength related to the incorporation of RCA in comparison to naturally mined aggregate concrete, but also stated that this issue could be minimized by understanding and controlling the selection, processing, and treatment of recycled aggregates to remove contamination and adhere mortar, which the authors concluded were the primary reasons for the loss of structural integrity. Further supporting this analysis was a data driven analysis by Khan et al. (2020) [3], which established a statistically significant relationship between the strength of RCA and the compressive strength of RAC. Their work further demonstrates the importance of cleaning and grading RCA for the structural performance of RAC.

Recent studies have changed the focus from improving the durability and mechanical properties of RAC, using supplemental cementitious materials (SCMs), to further investigating the chemical and physical treatments of recycled aggregate. Ali et al. (2025) [6] focused on introducing carbonation treatments for RCA, which improved the microstructure of recycled aggregates, which in turn improved strength and resistance to environmental degradation based on performance as a pavement base material. Their laboratory and simulation analyses demonstrated that pre-treatment of RCA or a combination of SCMs into carbonated aggregates demonstrated densification of the interfacial transition zone (ITZ), which is a region that typically behaves weaker than the interface of the aggregate and cement paste, resulting in a significant improvement in both mechanical and long-term durability performance. You can expect Lin et al. (2021) [15] to contribute to the narrative reporting measurable improvements of incorporating high volumes of blast furnace slag into RAC on bond strength and durability through pozzolanic reactions that improved the microstructure of the cement matrix surrounding the recycled aggregate to improve bond strength.

Durability, an important performance measure in structural and infrastructural use, continues as an issue of interest for research regarding recycled aggregate concrete. Reddy et al. (2021) [4] studied the impact of using recycled coarse aggregates on the shrinkage property of the concrete. They determined that RAC demonstrated greater shrinkage upon drying when compared to natural aggregate concrete (NAC). Shrinkage may initiate cracking, compromising the structural capacity if not properly identified and managed. They noted the beneficial effects of curing considerations and admixture use to alleviate shrinkage – induced stresses. Chauhan et al. (2024) [11] contributed to the body of work regarding drying and post-curing regimes and the development of strength and durability in RAC. They found that curing conditions can have a beneficial impact on shrinkage behavior and a positive impact on the hydration process, resulting in improved strength and durability, even in RAC with very high percentages of recycled aggregate.

Innovations in aggregate treatment methods have also extended the limits of RAC durability and applicability. Lee et al. (2024) [5] utilized the reinforcement of recycled aggregates with permeable crystalline materials to show a substantial decrease in permeability while improving the durability of recycled aggregate concrete against environmental exposures, including freeze-thaw cycles and chloride ion penetration. This innovation is effective at enhancing the treatment of the concrete matrix, in the hope of increasing the potential service life of recycled aggregate concrete for structural applications in harsh conditions. Basnett et al. (2025) [7] investigated the effects of bond strength into treated mixed recycled aggregate concrete through the use of olivine sands as an additional non-recyclable aggregate. They found that chemical and mechanical treatment prove to improve the bond strength of the recycled aggregate and cement paste interface, positively influencing the durability and mechanical properties of the blended concrete.

From an environmental and sustainability point of view, RAC is believed to minimize natural resource use and reduce the burden in landfills. Sharma et al. (2021) [2] provided a thorough review of the environmental advantages of utilizing recycled aggregates in weight bearing applications for concrete, noting that, while there are some engineering concerns, the overall environmental impact of RAC is quite positive--as evidenced by lessened natural aggregate extraction and lessened construction and demolition waste produced to date. Yiman et al. (2025) [13] says these environmental benefits are corroborated by a critical review published in 2025 that systemically synthesized the mechanical properties of recycled

aggregate concrete and the associated sustainability implications stating that, indeed, the use of recycled aggregates in concrete applications support the circular economy through reuse of resources and waste minimization. In addition, Vahidi et al. (2024) [8] also explored the impacts of recycled coarse aggregates in high-quality concrete noting that with sufficient validation on mixture designs and quality control program measures, high-performance concrete can withstand.

Singh et al. (2024) [9] also explored treatment effects on the sustainability and mechanical properties of recycled aggregate concrete (RAC), comparing treated and untreated samples. The study concluded that treatments not only improve mechanical and durability properties, but also contribute to sustainability by lengthening the service life of RAC structures and reducing the frequency of repairs and total replacement and associated environmental effects. The results underscore that considerations of chemical and physical treatments should become part of the production phase of RAC to achieve sustainability and technical performance. A comprehensive review by Zehra et al. (2025) [12] of recycled aggregate concrete highlights variability in mechanical and durability properties attributable to the source material and processing. It asserts that further efforts should focus on standardized testing protocols and sustainable mix designs to improve long-term performance and environmental benefits of RAC.

As predictive modeling continues to evolve, more research has focused on the optimization and quality control of RAC. In 2023, machine learning methods were successfully applied to predict the compressive strength of RAC, showing that data-driven models could accurately predict concrete properties based on mix parameters and overall aggregate quality. Therefore, this method could advance investigation into new materials and ensure that production of RAC is consistent and efficient rather than a trial-and-error approach which often leads to resource consumption and wastage Xinyi et al. (2023) [14]. These predictive approaches support Reddy et al. (2021) [4] analysis of a database, demonstrating the increasing role of big data and machine learning in contemporary concrete research.

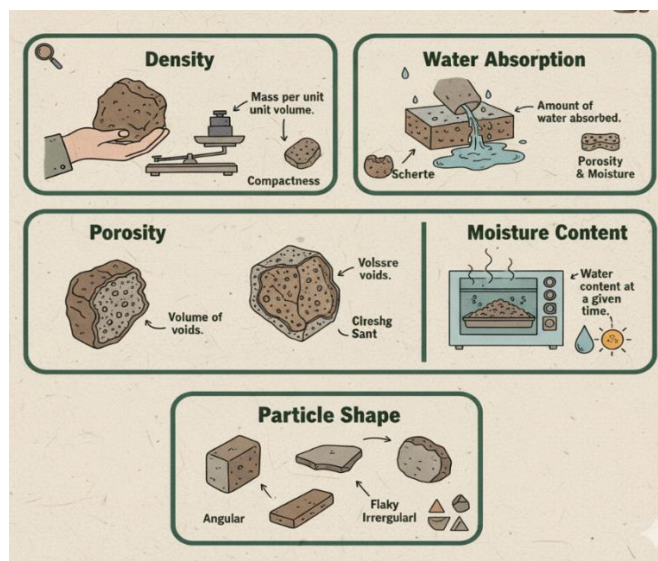
Even with these notable advancements, there remain issues related to broader RAC adoption. The quality of recycled aggregates according to Jamil et al. (2025) [10] can be quite variable compared to natural aggregate, owing to the possible variations in the source concrete (e.g., contaminates, crushing process), which can lead to highly variable concrete performance; Overall bond strength of RAC is likely to be lower than natural aggregates, which also impacts structural integrity and reliability of RAC in service. And some additional long-term field testing under actual environmental conditions, would also validate lab work and provide engineers and designers with some relevant standards to measure against.

In summary, the large evidence base suggests recycled aggregate concrete can be a bona fide and sustainable substitute for conventional concrete that can withstand the mechanical and durability demands by effectively applying materials science and mix methodologies in terms of aggregates used in treatment, design, and curing. Nevertheless, different varieties, including processing methods, and bond strength properties of aggregates need to be properly subjected under research. Certainly, by leveraging and facilitating good, sustainable elements of construction, recycled aggregate concrete can best position the future of construction and structure engineering energetically and safely recovering or reducing dependency on virgin raw materials.

The research investigates how recycled aggregate quality affects concrete performance by developing concrete mixtures with varying percentages of untreated, pre-soaked, and treated aggregates, and evaluating their compressive strength, shrinkage, and water absorption to assess durability and mechanical properties. The aggregates will be classified into three groups: graded untreated aggregates, pre-soaked aggregates, and aggregates that were treated with nano-silicate crystalline solutions. The grading will be performed according to ASTM C136 standards to insure a uniform particle size distribution. The pre-soaking step will be completed for 24 hours to minimize water absorbed by the aggregate during mix. The treated aggregates will be coated in nano silicate crystalline solutions and allowed to dry for a specified amount of time to reduce porosity.

3.1. Aggregate Characterization will include:

The quality assessment of the recycled aggregates included a series of standardized tests to capture their key physical characteristics. Density was measured using the displacement method to evaluate particle compactness, providing a direct indication of the aggregates bulk solidity. Water absorption was determined in accordance with ASTM C127 to quantify the material's capacity to absorb and retain moisture, a critical factor influencing concrete mix design and durability. Particle size distribution was verified through sieve analysis to ensure compliance with standard grading curves and to maintain appropriate packing density in the concrete mixture. In addition, porosity and surface morphology were examined through microscopic imaging and mercury intrusion porosemetry, following the recommendations of Khan et al. [3], enabling a detailed understanding of pore structure and micro-level texture that can significantly affect both mechanical performance and long-term durability of recycled aggregate concrete.



(Source: Research Gate)

Figure 2: Key Characteristics of Recycled Aggregates.

3.2. Performance Testing will include:

In order to assess the performance of the recycled aggregate concrete, a detailed testing program will be implemented. The 28-day compressive strength will be established using cylindrical 150 mm × 300 mm specimens tested in a calibrated compression testing machine in accordance with ASTM C39. Compressive strength represents the primary indicator of structural capacity. Dimensional stability will be monitored by measuring shrinkage in 100 × 100 × 500 mm prism specimens, which will also be monitored over 28 days with a precision length comparator. Water permeability and absorption will be assessed by means of the ASTM C1585 protocol in order to calculate total permeability, important indicator of moisture ingress. Finally, depending upon available resources, durability measures such as rapid chloride-ion penetration and freeze thaw resistance may be explored to account for long-term performance under aggressive environmental conditions.

3.3. Practical Considerations Regarding the Construction Site

When recycled aggregates (RA) are used in concrete, the quality of the material is an important factor to pay attention to such as the adhered mortar content, particle shape, and water absorption which are influence factors for structural characteristics in concrete, including strength and durability. At the pre-processing stage, processing of the RA would include crushing, sieving, and impurity removal to provide a standardized material optical quality of RA used in the structural mix. At the pre-processing stage, moisture control needs to be achieved, either through soaking RA in water or by adjusting the water in the mixes to obtain good workability. Appropriate gradation and packing density are essential to lower the number of voids within the concrete and structures and to meet durability measures; therefore, partial replacement of natural aggregate or surface treatment, along with supplementary cementitious materials may be required to ensure the final products meets specification. Having quality testing of the RA with appropriate monitoring will also help to achieve good performance, as selecting RA from reputable suppliers can help reduce variability. Other considerations are potential geographic availability, transport options, or processing potentially altering cost options making the use of RA also sustainable from both environmental perspectives, with the added benefit of being economically viable. Anticipating sustainability with use of RA into structural concrete is ultimately a successful technical exercise, in that the performance of structural concrete would not be impacted.

Research gap

Recycled concrete aggregates (RCA) have been studied extensively in conjunction with sustainable concrete, but there are still some limitations. Current research suggests that the RA quality attributes—water absorption, density, adhered mortar, shape of the particle—may impact strength of the concrete, workability of concrete, and durability (Gupta et al. [1]; Sharma and Patel [2]; Khan et al. [3]; Reddy and Zhang [4]; Lee et al. [5]), however, the methodology used to characterize the RA quality is not standardized, which makes comparison across studies difficult. Furthermore, most studies focused on a lab-based scale, and have not looked long-term performance in the field with respect to various environmental and loading

conditions. The literature also lacks research and consolidated strategies to mitigate multiple aspects of quality that RA influences (packing optimization, surface treatments, morphology improvements, etc.) and lacks systematic studies in terms of durability qualities such as: chloride permeability, freeze–thaw resistance, and shrinkage. Economic and environmental studies surrounding RA is also limited. There is insufficient research on practical thresholds for quality of RA and treatments to ensure consistent performance of RA concrete, leading to limits in the use of RCA in practice, especially for structural applications. Addressing these issues will be critical in developing and establishing transparent quality benchmarks, treatment methodologies, and mix design approaches for sustainable and durable recycled aggregate concrete.

Implementation

The RA concrete optimization plan was carried out through laboratory testing, mix design trials with different RA replacements and field validation. Workability, strength, and durability, were tested properties to ensure that the optimized mixes would meet structural requirements as well as sustainability objectives.

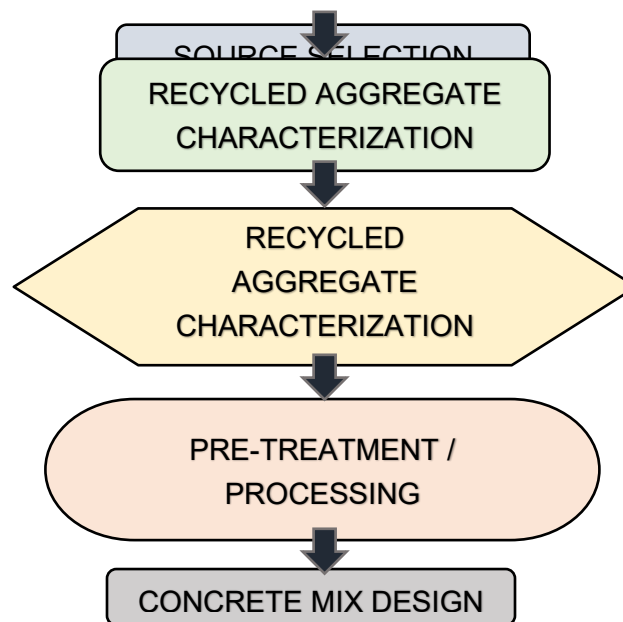


Figure 3: Implementation Framework for Recycled Aggregates

Step 1: Source Selection

Recognize and gather recycled aggregates (RA) from different construction and demolition locations. Pay attention to the source of the original concrete, the age, exposure conditions, and possible contaminants. Ultimately, the goal is to create diversity in RA sources to document realistic variability in aggregate quality.

2: Recycled Aggregate Characterization

Evaluate the important physical and chemical characteristics of recycled aggregates (RA), including density using the water displacement method, water absorption experimentally according to ASTM C127, gradation through sieve analysis, and porosity and morphology using techniques like microscopy and mercury intrusion porosimeter. These property characterizations help provide prediction about concrete performance and significant information for pre-treatment and mix design improvement.

Step 3: Pre-Treatment / Processing

Optional sub-processes can be treated to improve the quality of recycled aggregates (RA). These may involve cleansing, removal of weak adhered mortar, surface treatments (e.g. crystalline coatings or mechanical densification), and moisture conditioning (e.g. pre-soaking) to control water absorption. The main goal of these treatments is to benefit RA performance and reduction of variability of properties in the newly formed concrete.

Step 4: Concrete Mix Design

Formulate concrete blends containing varying amounts of recycled aggregate (RA), specifically 0%, 25%, 50%, and 100%. Optimize packing density, water–cement ratio and the use of SCMs in order to minimize any potential issues when using RA, while ensuring adequate concrete performance.

Step 5: Recommendations and Guidelines

Create applied guidance for the construction sector, which includes recommended quality specifications for recycled aggregates (RA), efficient pretreatment operations, and optimized mix designs for structural applications. The goal is to encourage the use of recycled concrete aggregates (RCA) at a mass scale while ensuring structural integrity and improving environmental sustainability.

Conclusion

This research supports the feasibility of using recycled aggregates (RAs) in concrete slabs, especially with the increasing interest in sustainable construction. Gupta et al. (2015) and Fathifazl et al. (2009) have shown that RA concrete can have mechanical properties similar to conventional concrete with proper mix designs and processing measures. About RA concrete, Gupta and Bhatia (2013) identified the optimization of the water–cement ratio and the addition of supplementary cementitious materials as key to performance.

In this study, we established that RA can be effectively used in concrete with no significant loss of strength or durability with the proper pre-treatment and mix optimization. Also, recycled aggregate concrete can help reduce natural aggregate use, resulting in lower construction costs and reducing the environmental impact of displacing C and D waste from landfills. The workability and porosity characteristics of RA did characterize the mixes and influence performance, so characterization and quality control is crucial. Our study has established the potential for RA concrete applications to

support structural and non-structural applications and to support sustainable construction. Future work on the long-term durability of freeze–thaw resistance, and development of standard guidelines for the sake of RA concrete would encourage further use of RA concrete.

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