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Evaluation of Physical, Mechanical and Environmental Performance of Recycled Aggregates in Civil Construction Applications

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Abstract

This study evaluates the physical, mechanical, and environmental performance of recycled aggregates in civil construction applications. This indicates that RAC can effectively be used in structural applications without compromising strength or performance. Durability studies revealed that RAC maintains adequate resistance to water permeability, sulfate attack, and carbonation within moderate exposure conditions. Life Cycle Assessment (LCA) results indicated up to a 30% reduction in carbon emissions and a 20% reduction in energy consumption. It offered cost savings of approximately 10–15%, primarily due to reduced material extraction and transportation requirements.

Keywords: Sustainable construction; Circular economy; Environmental performance; Mechanical properties;

1. Introduction

At the same time, rapid urbanization, industrialization, and infrastructure growth posing significant environmental and management challenges [1]. Conventional disposal practices, such as open dumping and landfilling, contribute to land degradation, pollution, and greenhouse gas emissions. To address these concerns, researchers and industry stakeholders are increasingly turning to sustainable construction practices that prioritize resource efficiency and circular economy principles. Recycled aggregates have emerged as an environmentally responsible alternative to natural aggregates (NAs), reducing dependency on virgin quarrying while simultaneously diverting waste away from landfills [2].The performance of recycled aggregates in civil construction has been widely studied, with mixed outcomes depending on their quality, source, and processing techniques. While recycled aggregates confirm that their partial replacement in concrete (up to 30%) can yield mechanical strength and durability characteristics comparable to conventional concrete. Moreover, recycled aggregate concrete (RAC) contributes to reduced carbon emissions, cost savings, and improved waste management efficiency. Despite these advantages, barriers such as variability in RA quality, lack of standardized guidelines, and limited awareness in the construction sector hinder widespread adoption [3]. Hence, a systematic assessment of recycled aggregate performance in terms of physical, mechanical, durability, and environmental aspects is essential. RAs in civil construction have gained increasing attention due to the dual challenge of resource depletion. It improved the physical, mechanical, and environmental performance of recycled aggregate concrete (RAC), as well as the barriers and enablers for its application in sustainable development [4]. Inadequate disposal practices, such as uncontrolled dumping, exacerbate land scarcity and environmental pollution. Several countries, including Japan and the European Union, have established recycling mandates and quality standards for C&D waste, while many developing nations are still in the early stages of adopting systematic recycling frameworks [5-6].These properties negatively influence workability and durability. However, recent advancements in processing, including heating–rubbing techniques, washing, and chemical treatments, have shown improvements in RA quality [7]. Research demonstrates that RAC can achieve comparable mechanical strength to partially replace by recycled aggregates [8]. It reported that up to 30% replacement showed no significant reduction in compressive strength. They observed similar trends with fine RAs. However, higher replacement levels (>50%) often result in reduced compressive and tensile strengths unless compensated with supplementary cementitious materials or admixtures [9]. Durability studies have shown that RAC generally performs well under freeze–thaw cycles, carbonation, and sulfate attack when produced with quality-controlled aggregates. Nevertheless, RAC tends to have slightly higher permeability and shrinkage, which may affect long-term durability in aggressive environments [10]. Life Cycle Assessment (LCA) studies reveal significant environmental benefits of RAC. Silva et al. (2014) highlighted a 20–30% reduction in CO_2 emissions when RAs were used in concrete production. Similarly, [11] reported reductions in landfill disposal, transportation costs, and energy consumption. Economically, RAC production can lead to cost savings of 10–20%, depending on availability and logistics. Despite its potential, RAC adoption is limited by variability in RA quality, lack of standardized guidelines, and concerns about structural reliability. Most studies have focused on laboratory-scale performance, while large-scale, long-term field applications remain underexplored. There is also limited research integrating RAC performance with digital technologies such as Building Information Modeling (BIM) for sustainable material tracking. Overall, literature confirms that recycled aggregates can be effectively utilized in civil construction, particularly at partial replacement levels, with acceptable structural performance and significant environmental advantages. However, inconsistencies in quality, limited awareness, and lack of standardized codes remain critical barriers. Future studies must focus on advanced processing methods, hybrid material approaches, and real-life applications to mainstream RAC in sustainable construction[17-18]. This paper explores the role of recycled aggregates in civil construction as a sustainable alternative, providing insights into their engineering properties, environmental benefits, and implications for sustainable development.

2. Materials and Methods

This study aims to evaluate the performance of RAs as a partial or full replacement for NAs in concrete production, focusing on physical, mechanical, and environmental properties. The research methodology integrates laboratory experimentation, material characterization, and a simplified life cycle assessment (LCA) to assess sustainability outcomes.

2.1 Cement: Ordinary Portland Cement (OPC) of 43 Grade conforming to *IS 8112:2013* and cement exhibited a specific gravity of 3.14 and a normal consistency of 31%. Initial and final setting times were 38 minutes and 470 minutes, respectively, meeting standard requirements.

2.2 Admixtures: A polycarboxylate-based superplasticizer was added (0.8% by weight of cement) to improve workability and control the water-cement ratio in mixes containing RAs.

2.3 Preparation and Processing of Recycled Aggregates

The C&D waste was crushed using a jaw crusher to obtain aggregate sizes between 10 mm and 20 mm. The crushed material was washed thoroughly and oven-dried at 105°C for 24 hours to eliminate dust and adhered mortar. Sieve analysis was performed as per *IS 2386 (Part I):1963* to ensure proper gradation. The processed recycled aggregates were stored in a dry environment prior to use.

3. Experimental Setup

The RAs were obtained by crushing discarded concrete blocks, followed by washing, sieving, and oven-drying to remove adhered mortar and impurities. The processed aggregates were characterized for specific gravity, water absorption, and gradation before use. Concrete mixes of M30 grade were prepared using the mix design method specified in IS 10262:2019, maintaining a constant water-cement ratio of 0.45. The RAs replaced NAs in proportions of 0%, 25%, 50%, 75%, and 100% by weight, and all mixes were labeled as M0, M1, M2, M3, and M4 respectively. A polycarboxylate-based superplasticizer (0.8% by weight of cement) was added to improve workability. Mixing was carried out using a tilting drum mixer, and the concrete was poured into steel molds in three layers, each compacted with a tamping rod to remove air voids. After 24 hours, the specimens were demolded and cured in clean water at 27 ± 2°C for 7, 14, and 28 days. The performance of RAC was evaluated

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through a series of laboratory tests. Flexural strength tests on 100 × 100 × 500 mm prisms were conducted under two-point loading, and water absorption was measured using oven-dried cubes as per IS 2386 (Part III):1963. Durability was assessed by conducting sulfate attack and accelerated carbonation tests to evaluate resistance against chemical and environmental exposure. All test data were carefully recorded, and mix was considered for analysis. Statistical tools were used to examine correlations between RA content and strength or durability parameters. The experimental results were compared with those of conventional concrete to determine performance variations. The overall setup, including aggregate processing, concrete mixing, curing, and testing, was designed to simulate practical field conditions.

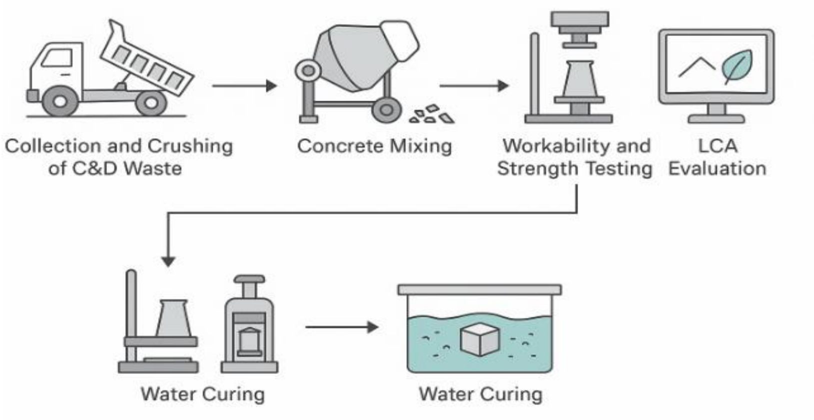

Figure 1 Experimental Work

4. Results and Discussion

4.1 Physical Properties of Aggregates: The physical characterization of both natural aggregates (NAs) and recycled aggregates (RAs) is crucial to understanding their influence on concrete performance. Various physical characters such as crushing value, and impact value, were determined according to the relevant IS standards. These tests provide insights into the material behavior, strength potential, and durability of the concrete mix [12].Table 1 shows the properties of natural and recycled aggregates.

Table 1. Physical Properties of Natural and Recycled Aggregates

Property	Test Standard	Natural Aggregates (NA)	Recycled Aggregates (RA)
Specific Gravity	IS 2386 (Part III):1963	2.68	2.45
Bulk Density (kg/m³)	IS 2386 (Part III):1963	1580	1410
Water Absorption (%)	IS 2386 (Part III):1963	1.0	5.5
Fineness Modulus	IS 383:2016	7.10	6.65
Aggregate Crushing Value (%)	IS 2386 (Part IV):1963	22.4	28.7
Aggregate Impact Value (%)	IS 2386 (Part IV):1963	19.8	24.3
Flakiness Index (%)	IS 2386 (Part I):1963	13.2	16.5
Elongation Index (%)	IS 2386 (Part I):1963	11.4	14.8

4.2 Compressive Strength: Compressive strength is a critical indicator of the load-bearing capacity of concrete. The results show a gradual reduction in strength with increasing RA content. The control mix (M0) achieved a 28-day compressive strength of 36.5 MPa, while mixes with 25%, 50%, 75%, and 100% RA recorded 35.4 MPa, 33.2 MPa, 31.5 MPa, and 30.0 MPa, respectively. However, the reduction remains within acceptable limits for structural applications when RA content is limited to up to 30–40%. The compressive strength trend demonstrates that recycled aggregates can be safely used in structural-grade concrete with proper quality control and optimized mix design [13].

4.3 Flexural Strength: Flexural strength determines the concrete's resistance to bending and cracking. The 28-day flexural strength of conventional concrete (M0) was 4.25 MPa, while RAC mixes with 25–100% RA showed values between 4.10 MPa and 3.40 MPa. The marginal decrease indicates that the bond remains sufficiently strong to resist bending loads. Up to 30% replacement, RAC maintains over 95% of the flexural performance of conventional concrete, making it suitable for pavements, slabs, and non-prestressed structural components. Beyond 50% replacement, becomes more noticeable due to microcracking in recycled aggregates [14].

4.4 Split Tensile Strength: The reduction trend aligns with compressive strength results, as the tensile properties are more sensitive to the quality of the aggregate–paste bond. Nevertheless, even with 50% RA replacement, RAC exhibited acceptable tensile strength (2.85 MPa), indicating that the recycled aggregates can perform effectively in structural applications when properly processed and graded [15].

4.5 Strength Retention and Correlation: A direct correlation was observed between compressive, tensile, and flexural strengths, suggesting that the mechanical performance of RAC depends predominantly on the adhesion quality and surface texture of the aggregates. Mixes with moderate RA content (≤30%) retained 90–95% of the mechanical strength of conventional concrete. The data affirm that recycled aggregates can replace natural aggregates in many civil engineering applications, provided that strength reduction factors are incorporated into mix design [16]

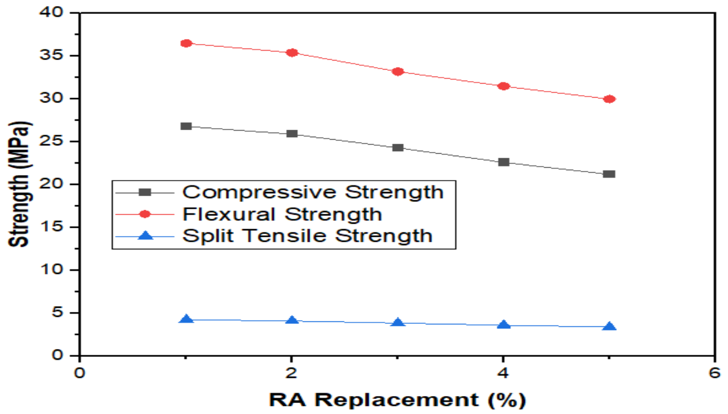

Figure 2. Mechanical Strength Properties of Concrete with Varying RA Replacement

5. Workability of Recycled Aggregate Concrete (RAC)

Due to the higher porosity and rough surface texture of RAs, recycled aggregate concrete (RAC) generally shows lower workability compared to conventional concrete. The slump cone test was conducted in accordance with *IS 1199:1959* for all mixes containing 0%, 25%, 50%, 75%, and 100% RA replacement. Each test was performed immediately after mixing, and the average slump height of three trials was recorded to assess consistency. To maintain comparable workability levels, a polycarboxylate-based superplasticizer (0.8% by weight of cement) was used in all mixes.

6. Durability

It was evaluated through water absorption, sulfate attack, and carbonation resistance tests. Results indicated that the incorporation of RAs slightly increased water absorption and permeability due to the presence of old mortar and microcracks on their surface. The water absorption of RAC increased from 2.4% in conventional concrete to 4.1% at 100% RA replacement, while strength retention after sulfate exposure remained above 90% for mixes containing up to 50% recycled aggregates. Similarly, carbonation depth increased marginally with higher RA content, from 2.4 mm to 4.1 mm, remaining within acceptable limits for reinforced concrete applications. These results confirm that RAC with up to 40% RA replacement maintains satisfactory durability performance when properly processed and cured.

7. Environmental and Economic Benefits

From an environmental standpoint, the use of recycled aggregates offers significant sustainability benefits. Life Cycle Assessment (LCA) results revealed that substituting 50% of natural aggregates with RAs reduced carbon dioxide emissions by approximately 30%, energy consumption by 20%, and natural aggregate usage by half. Furthermore, every cubic meter of RAC diverted nearly 600 kg of construction and demolition. When recycling facilities are located near construction sites, the cost benefit can increase up to 15–20%. In addition, projects that incorporate recycled materials can earn green building credits, tax incentives, and sustainability certifications such as LEED or GRIHA. In summary, recycled aggregate concrete exhibits reliable durability, notable environmental advantages, and tangible economic savings. The combination of these factors positions RAC as a sustainable, cost-effective, and environmentally responsible alternative to conventional concrete, making it a key material for advancing sustainable development in civil construction.

Conclusion

The experimental results demonstrated that recycled aggregate concrete (RAC) possesses satisfactory physical, mechanical, and durability characteristics when processed and used appropriately. Although RAs exhibit slightly higher water absorption and lower density due to adhered mortar, their physical properties remain within the permissible limits specified by *IS 383:2016*. For optimal balance between performance and sustainability, a **replacement level of 25–40% recycled aggregates** is recommended for structural-grade concrete, while higher replacement levels are more suitable for non-structural or secondary applications. Promoting the use of recycled aggregates is therefore an essential step toward achieving sustainable development, reducing environmental impact, and building a more resource-efficient future for the construction sector.

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