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Article

Experimental and sustainability-driven engineering assessment of recycled concrete aggregates: mechanical performance, durability, environmental and economic implications

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ABSTRACT

With the increased demand for concrete in modern infrastructure, coupled with the depletion of natural aggregates and the rising volume of construction and demolition waste, there has been a growing need for sustainable construction materials. This study evaluates the mechanical performance, durability, environmental impacts, and economic feasibility of concrete incorporating recycled concrete aggregates (RCA) as a partial or total replacement for natural coarse aggregates. Five concrete mixtures were prepared with RCA replacement levels of 0%, 25%, 50%, 75%, and 100%, aiming for a compressive strength of 30 MPa. Experimental investigations were conducted on compressive and flexural strength, workability, water absorption, and rapid chloride permeability, while environmental and economic performance were assessed through life cycle assessment and cost analysis. Results showed that concrete with 50% RCA achieved compressive strengths of 29.3 MPa and 4.1 MPa and flexural strength of 4.1 MPa at 28 days, which can be considered acceptable structural performance. Workability decreased with increasing RCA content due to increased porosity and water absorption, but improved significantly with the addition of a superplasticizer and aggregate pre-treatment, increasing the slump from 83mm to 120mm. Full RCA replacement resulted in a reduction of CO_2 emissions by 32%, embodied energy by 33%, and concrete production cost by USD 12.3/m^3. Overall, RCA shows a good potential for sustainable and circular infrastructure development.

1. Introduction

Decade after decade, concrete has been the material of choice for infrastructure development because of its strength, durability, and versatility. However, the rapid rate of global urbanization has led to a significant increase in demand for concrete, a corresponding large-scale extraction of natural aggregates, and a simultaneous increase in construction and demolition waste (CDW) [1]. Unsustainable exploitation of raw materials, coupled with inadequate CDW waste management, has caused serious environmental impacts, including the depletion of natural resources and increased pressure on landfills. In this context, recycled concrete aggregates (RCA) have been identified as a potential solution to enhance the environmental sustainability of concrete production [2]. RCA is produced by crushing and processing waste concrete obtained from demolished structures. The addition of RCA to new concrete mixtures has the potential to contribute to a sustainable approach to construction while addressing material scarcity and waste management [3]. When used as a partial and/or total substitute for natural coarse aggregates, RCA can reduce environmental impacts associated with aggregate extraction and demolition waste disposal [4]. Despite these environmental advantages, RCA has certain challenges, such as high porosity, variable composition, and the presence of adhered mortar, which can affect the structural and durability performance of concrete [5].

The basic microstructural behavior of concrete materials and its effects on durability and mechanical performance have been well described in the classical research literature on concrete. These studies show the importance of balancing material performance with the sustainable use of material resources in concrete production [6]. In addition, water absorption and permeability are particularly relevant parameters when assessing recycled aggregate concrete, as increased absorption may affect durability and long-term performance [7]. The scientific understanding of recycled aggregate concrete was first developed through extensive investigations that focused on feasibility studies of using recycled aggregates in structural concrete and on identifying the key factors influencing performance [8]. More recently, global sustainability efforts such as the United Nations Sustainable Development Goals (SDGs) have emphasized sustainable production and consumption of materials, as well as the reuse and recycling of construction materials in the built environment [9]. Sustainability-oriented studies have further emphasized the role of environmentally responsible construction materials in green building development and life-cycle-based decision-making. Research on sustainable building materials has focused on the importance of resource-efficient practices and environmentally responsible material selection [10]. Recent investigations have also examined approaches to using recycled aggregates in combination with alternative low-carbon binders, such as geopolymer materials, to support sustainable building and circular economy measures [11]. Guidance for environmentally responsible building materials selection continues to recognize the importance of recycled aggregates as an important part of sustainable construction systems [12].

At the broader scale of infrastructure, sustainable construction materials make a direct contribution to environmentally responsible building development and to enhanced environmental performance of the built environment [13]. Recent studies have also explored other types of construction materials derived from agricultural residues and other waste resources, which help strengthen the concept of material circularity in the construction industry [14]. Further increases in attention to the analysis of the life-cycle environmental impact of construction materials are evident in institutional initiatives, such as the Building Materials Embodied Greenhouse Gas Assessment System (BEGAS) [15]. In addition, governance frameworks for transforming the building materials industry toward environmentally friendly practices emphasize the importance of the sustainable use of materials such as recycled aggregates [16]. Reviews of sustainable building components also emphasize the importance of proper material selections to reduce the International environmental footprint of buildings [17]. In this study, both the tests, namely the detailed procedure as per the ASTM and the Indian Standard (IS) procedure, are used. ASTM standards are internationally recognized testing methods widely used in scientific research, whereas IS standards represent testing procedures commonly used in regional construction practice. The combination of these standards, therefore, contributes to the comparability of the results with international research findings and ensures practical relevance for on-the-spot engineering use. To assess the engineering feasibility of RCA utilization, this research examines the effects of varying RCA replacement levels (0%, 25%, 50%, 75%, and 100%) on concrete performance. The experimental program tests mechanical properties, durability, workability, environmental impacts, including CO_2 emissions, and the economic implications of RCA incorporation.

The use of recycled concrete aggregates is not only a material substitution but also an engineering design challenge that requires balancing structural performance, durability, environmental sustainability, and economic feasibility. From an engineering systems perspective, RCA-based concrete can therefore be termed a multi-criteria material system in which these parameters must be evaluated concurrently. This study uses an integrated engineering assessment approach that combines experimental testing with environmental and economic assessments. The results are relevant to interdisciplinary engineering applications in infrastructure and construction engineering, as well as sustainable material selection. By integrating RCA utilization into the performance-based engineering framework, this research aims to provide practical knowledge to support circular construction systems and create low-carbon infrastructure. The specific objectives of the research are:

- To identify through laboratory evaluation the effects of RCA replacement levels on the mechanical properties, durability, and workability of the concrete.
- To assess the environmental performance of RCA-based concrete in terms of estimating reductions in CO_2 emissions and embodied energy.
- To establish the economic workability of using RCA in concrete and determine an optimal replacement level considering the balance between performance and sustainability factors.
- To develop an engineering-oriented framework of decision-making for determining the appropriate recycled aggregate replacement levels in infrastructure materials.

2. Research methodology

2.1 Materials selection and characterization

The materials used in this investigation were chosen in accordance with the Indian Standard (IS) standards and ASTM specifications to ensure the reliability of the experimental program and compatibility with engineering practice. Ordinary Portland Cement (OPC 53 Grade) as per the IS 12269 was adopted as the primary binder. The fine aggregate was clean and well-graded natural river sand, which conformed to the Zone II grading requirements of IS 383. Natural coarse aggregate (NCA) used in the control mixture comprised of crushed granite of nominal maximum size 20 mm. The recycled concrete aggregates (RCA) were recovered from demolished reinforced concrete building components collected from local construction and demolition sites. The parent concrete was about 20-25 years old and represented normal-strength structural concrete with an estimated compressive strength class of 25-30 MPa. It had been exposed primarily to normal atmospheric conditions, with no indication of severe chemical exposure. This description has been added to explain the probable origin and service history of the source material used to produce recycled aggregate.

After its collection, the demolished concrete was mechanically crushed to produce RCA. The crushed material was washed with clean water, and the adhered dust, loose mortar particles, and foreign matter were removed. The processed aggregate was then screened in sieves of 20 mm, 10 mm, and 4.75 mm, as per (IS 383). Aggregates contained in a range of 10-20 mm size were used in the concrete mixtures so that the particle size distribution is kept broadly similar to that of the natural coarse aggregate. Because RCA typically absorbs more water due to adhered mortar, the recycled aggregate was pre-soaked in water for about 24 h before mixing. After soaking, the aggregates were drained and dried to a saturated surface dry (SSD) condition prior to batching. SSD condition was visually confirmed by ensuring the aggregate surface was moist and free of visible free water. This step was adopted to decrease uncontrolled absorption of mixing water and improve from mix to mix. The physical properties of both NCA and RCA were measured in accordance with IS 2386 and ASTM C127. The characterization program consisted of a determination of specific gravity, bulk density, absorption, and aggregate crushing value. A polycarboxylate-based high-range water-reducing admixture (superplasticizer) was used to enhance the workability of mixtures with higher proportions of RCA.

2.2 Concrete mix design

Concrete mixtures were prepared with 0%, 25%, 50%, 75%, and 100% replacement of natural coarse aggregate with recycled concrete aggregate (RCA) by weight. The mixtures were designed in accordance with the ACI 211.1 method to achieve a 28-day compressive strength of 30 MPa. To maintain consistency across mixtures and minimize the impact of other variables, the water-to-cement ratio (w/c) was kept constant at 0.45 for all mixes. Cement content was constant for the experimental program at 380kg/m^3. Trial batches were used to assess the workability and volumetric consistency before casting. Since RCA has a higher water absorption 1 capacity than natural aggregate, recycled aggregates are used in the SSD condition before mixing (pre-soaked). This procedure limited excessive, uncontrolled absorption of mixing water and maintained a constant w/c ratio without requiring further water correction during batching. A superplasticizer dosage was determined through trial batching to maintain slump values within the target range of 75 to 100 mm, representative of cast-in-place structural concrete practice. Only the mix parameters that are explicitly reported in the manuscript are presented in Table 1.

Table 1. Reported mix design parameters for RCA concrete mixtures

Mix ID	RCA (%)	Cement (kg/m^3)	Water (kg/m^3)	w/c ratio	Target Strength (MPa)
M0	0	380	171	0.45	30
M25	25	380	171	0.45	30
M50	50	380	171	0.45	30
M75	75	380	171	0.45	30
M100	100	380	171	0.45	30

2.3 Specimen preparation and curing

Concrete samples were prepared in accordance with IS 516 and ASTM C192 to ensure reproducible, uniform specimens. Specimens for compressive strength were cast using a cube mould measuring 150mm by 150mm by 150mm. Flexural strength specimens were 100 mm × 100 mm × 500 mm prismatic beams prepared for 3-point loading. Cylindrical specimens of 150 mm diameter by 300 mm height were cast for the durability-related testing, and slicing, resulting in the Rapid Chloride Permeability Test (RCPT). Fresh concrete was poured into molds in three equal layers, and each layer was tamped with a vibrating table to remove entrapped air, ensuring uniform density. Adequate consolidation was achieved to avoid honeycomb and surface voids, which can affect mechanical and durability properties. After casting, the first setting of the specimens was kept in molds at laboratory ambient temperature conditions for 24h. The specimens were then demoulded and placed in a curing tank at 27 ± 2 °C (the curing water temperature throughout the test). All specimens were fully immersed until testing at ages 7, 14, and 28 days.

2.4 Testing procedures

A series of laboratory tests was conducted to determine the mechanical properties, workability, permeability, and durability characteristics of the used concrete mixtures containing RCA. All procedures were based on appropriate ASTM and IS test methods. For every test condition, three replicate specimens were tested, and the mean values were reported. Because this study reports summarized mean values from replicate tests, more detailed statistical descriptions of the data, such as standard deviation, coefficient of variation, and formal inferential analyses (e.g., analysis of variance), are not presented in the present manuscript. The trends in the reports are thus interpreted using average performance values. Future studies should include comprehensive statistical analyses of larger experimental datasets to further enhance the reliability of comparative RCA performance evaluations.

Compressive strength was measured using a calibrated 2000 kN compression testing machine (CTM) in accordance with ASTM C39. So, Cube specimens of 150mm x 150mm x 150mm were tested for 7, 14, and 28 days. Each specimen was placed centrally in the testing machine, and the test was gradually loaded to failure. The maximum load at failure was noted, and the compressive strength was determined from the loaded area. For each mixture, three specimens were tested at each curing age.

Flexural strength was measured following the third-point loading procedure as per the procedure of ASTM C78. Beam specimens of 100 mm * 100 mm * 500 mm were subjected to a universal testing machine (UTM) after curing. The beam span and loading arrangement have been adopted in accordance with the requirements of the third-point loading configuration, and the modulus of rupture was determined at the maximum applied load. For every mix, three beam specimens were tested.

Water absorption was measured following the procedure in ASTM C642 to determine permeability behavior. After 28 days of curing, they were oven-dried at 105 °C to a constant mass, then cooled and weighed to obtain the mass. The specimens were then immersed in water for 48 h, removed, wiped SSD, and reweighed. Water absorption was determined as the percent increase in mass over oven-dry mass.

Fresh concrete workability was measured using the slump cone method in accordance with ASTM C143. Three slump measurements were taken for each mixture, and the mean slump was reported. The target slump range of 75~100mm was chosen as a representative value of workability requirements at structural concrete placement. Because only mean values are available in the manuscript, the mean values of standard deviations are not reported numerically in the present version.

Resistance-to-chloride-ion penetration measurements were carried out using the Rapid Chloride Permeability Test (RCPT) according to the recommendations of the American Society for Testing and Materials C1202. Concrete cylinders of 150 mm diameter and 300 mm height were cast and left for curing for 28 days, after which 50 mm-thick slices were made from the cylinders for testing. The slices prior to testing were vacuum saturated. A potential difference of 60V was applied for 6 h, and the total charge that flowed through each specimen was measured in coulombs. According to ASTM C1202, chloride penetrability may be interpreted as very low (<1000 coulombs), low (1000-2000 coulombs), moderate (2000-4000 coulombs), or high (>4000 coulombs of chloride).

The static modulus of elasticity was determined in accordance with ASTM C469 using cylindrical concrete specimens with a diameter of 150 mm and a height of 300 mm. The modulus was obtained from the stress-strain response collected during controlled compression loading of the sample. This test was included to measure the effect of RCA content on concrete stiffness.

2.5 Environmental and cost evaluation

A simplified Life Cycle Assessment (LCA) was performed to estimate the embodied CO_2 emissions of each concrete mixture. The system boundary used for the assessment was cradle-to-gate and included raw material extraction, aggregate processing, transportation, and concrete production during the batching stage. Emission factors were taken from published life cycle inventory sources and standardized industry as well as databases commonly used in construction LCA studies, such as Ecoinvent and GaBi. RCA-related emissions were assumed to be lower due to less virgin aggregate processing and shorter transport distances from local aggregate processing. For the economic assessment, a cost-benefit comparison was made between NCA- and RCA-based mixtures. Aggregate procurement, RCA crushing, washing, screening, and transportation costs were included in the analysis. Cement, admixture, labor, and curing costs were considered to be constant for all mixes so that the economic impact of aggregate substitution could be isolated. Cost values were expressed in USD/m^3 under typical Indian market conditions to ensure comparability.

3. Results and discussion

3.1 Workability behavior and RCA content

The slump results for concrete mixes with various percentages of RCA are summarized in Table 2. The results show a clear reduction in workability as the recycled aggregate content increases from 0% to 100%. Slump decreased from 98mm for the control mixture to 70mm at full RCA replacement, representing a total reduction of approximately 28.6%. This reduction in workability is thought to be mainly due to the coarseness of the surface texture, increased water absorption, and tackiness of the mortar on RCA particles. These features will result in less free water for lubrication and increased interparticle friction in the fresh mix. The trend is therefore in line with the expected rheological response of a concrete with recycled coarse aggregate. To improve workability without increasing the water-cement ratio, a superplasticizer was evaluated for a 50% RCA mixture. As illustrated in Table 3, for admixture dosages of 0.0% to 2.0%, the slump increased from 83mm to 120mm, confirming that workability losses associated with RCA can be substantially mitigated through the use of chemical admixture.

Similarly, aggregate processing enhanced the performance of fresh concrete. Unprocessed RCA produced a slump of 72 mm, while the slumps of washed, pre-soaked, crushed, and sieved RCA were better at 80 mm, 86 mm, and 88 mm, respectively. These results show that removing loose mortar and controlling aggregate moisture conditions reduce water demand and enhance the rheological stability of RCA concrete (Table 4). Because the mean values in this study are from replicate tests, it is not possible to provide more detailed statistical descriptions of the study results, such as standard deviation, coefficient of variation, and formal inferential analyses (e.g., anionogram) as numerical values in the present data set.

Table 2. Slump test results for different RCA content

RCA Content (%)	Slump (mm)
0	98
25	90
50	83
75	76
100	70

Table 3. Effect of superplasticizer dosage on the slump of 50% RCA concrete

Superplasticizer Dosage (%)	Slump for 50% RCA (mm)
0.0	83.0
0.5	95.0
1.0	108.0
1.5	115.0
2.0	120.0

Table 4. Effect of RCA processing on workability

Processing Method	Slump (mm)
Unprocessed RCA	72
Washed RCA	80
Pre-soaked RCA	86
Crushed and Sieved RCA	88

3.2 Mechanical strength performance

Mechanical performance was evaluated using compressive strength, flexural strength, elastic modulus, and density. At 28 days, the compressive strength of the control concrete was 34.1 MPa, while that of the concrete samples with 100% RCA APC was 24.5 MPa. This translates to a reduction of 9.6 MPa, or approximately 28.2%, compared to the control. The value of this writing has been elaborated here for the separation purpose, specifically to make the difference between the absolute strength value and the magnitude of reduction clear.

It is also reported, as shown in Figure 1, that concrete with 50% RCA achieved a compressive strength of 29.3 MPa and a flexural strength of 4.1 MPa at 28 days, close to the design target strength of 30 MPa. As per the commonly used provisions for structural design, such as IS 456 and ACI 318, the compressive strength of normal reinforced concrete elements typically ranges from 20 to 30 MPa. Therefore, the strength achieved by the 50% RCA mixture (29.3 MPa) remains within the range generally considered suitable for normal structural concrete under moderate exposure conditions. This suggests that up to 50% RCA may be suitable for normal structural applications where compressive strengths in the 25-30 MPa range are acceptable, whereas higher replacement levels should be used with caution, depending on structural demand and exposure conditions. The observed reduction in compressive strength appears to be directly related to the presence of adhered mortar, increased void content, and a weaker interfacial transition zone (ITZ) between the recycled aggregate and the fresh cement paste.

The old mortar, which is bound between RCA particles, may contain microcracks and pores that can reduce the efficiency of stress transfer under compressive loading. The decrease in elastic modulus from 31.2 GPa in the control mix to 24.9 GPa at full RCA replacement proves a corresponding decrease in stiffness in Figure 2. This behavior is consistent with the increased deformability of adhered mortar and the lower stiffness of porous recycled aggregate particles. Concrete density also decreased slightly with increasing RCA content, owing to the lower specific gravity of RCA compared to natural crushed granite, due to the presence of internal pores and residual mortar in Figure 3.

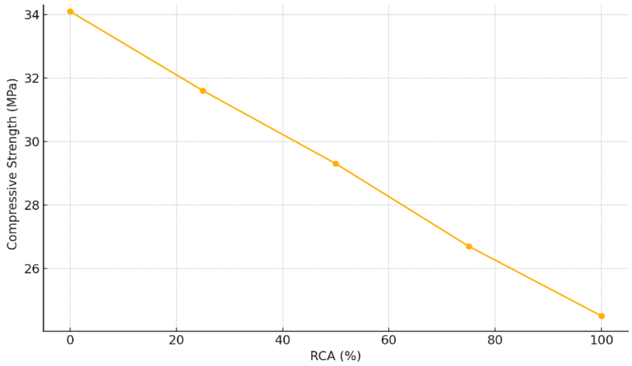

Figure 1. Variation of compressive strength with RCA replacement level

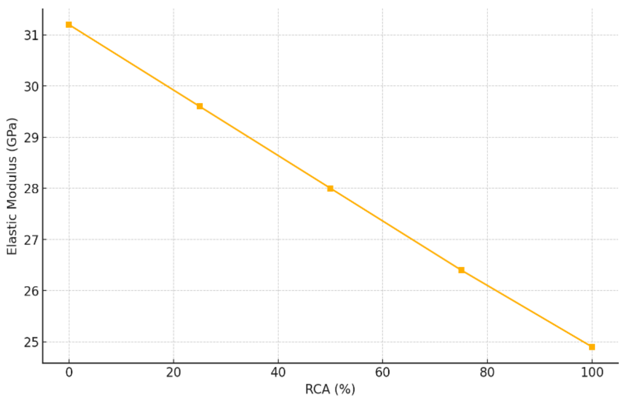

Figure 2. Variation of elastic modulus with RCA replacement level

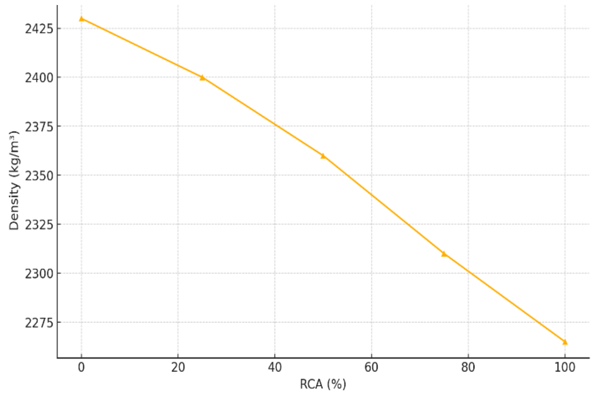

Figure 3. Concrete density vs. RCA replacement

3.3 Durability parameters

Durability check was carried out by the results of water absorption and Rapid Chloride Permeability Test (RCPT) shown in Figure 4 and Figure 5. Water absorption increased from 2.1% in control concrete to 4.5% at 100% RCA, indicating that the concrete's porosity increased significantly with increasing RCA content. RCPT values increased from 2150 coulombs to 4150 coulombs, indicating reduced resistance to chloride-ion penetration with increasing RCA replacement. These two durability indicators are closely related. The increase in water absorption indicates a more open pore structure, and the higher RCPT values confirm that the more porous microstructure is responsible for ionic transport. The overall trends of decreasing strength, increasing water absorption, and higher chloride permeability reinforce the interpretation that increasing RCA content leads to a less dense matrix, the introduction of adhered mortar, pre-existing microcracks, and a weaker ITZ. In other words, the same microstructural features that reduce strength also contribute to reduced durability.

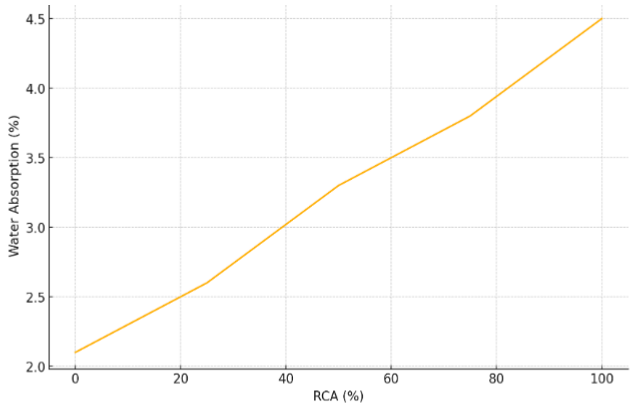

Figure 4. Variation of water absorption with RCA replacement level

Based on an interpretation of the results according to ASTM C1202, the control mix falls within the moderate permeability range, while the 100% RCA mix falls within the high permeability range. Mixtures with up to 50% RCA were kept within the moderate range and may therefore be suitable for moderate exposure conditions, whereas higher replacement levels may warrant supplementary cementitious materials or other durability-enhancing measures in aggressive environments. No direct microstructural characterization was performed in the present study (e.g., SEM or ITZ imaging). Therefore, the microstructural interpretation given here is based on trends in mechanical and durability properties, together with established behavior reported in the literature. This should be admitted as a limitation and a future research opportunity.

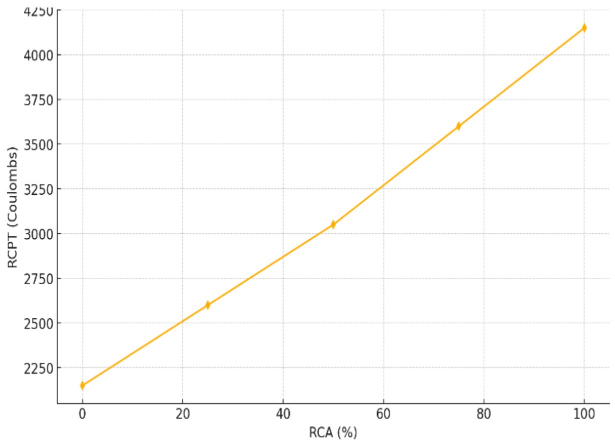

Figure 5. Chloride ion penetrability vs. RCA replacement

3.4 Environmental impact analysis

Environmental performance was assessed by means of embodied CO_2 emissions and embodied energy as key indicators as shown in Table 5 and Table 6. CO_2 reductions were evident, with a steady decrease from 370 kg/m³ for the control mix to 250 kg/m³ for the concrete with 100% RCA. Similarly, embodied energy consumption was reduced from 1340 MJ/ton to 900 MJ/ton, a 33% reduction, as shown in Table 6 for a complete RCA replacement. The primary cause for this reduction is the decreased need for virgin aggregate extraction, crushing, and long-distance transportation. Because this assessment is based on a simplified cradle-to-gate approach, the absolute values are also sensitive to assumptions about transport distance, local electricity mix, processing energy, and the source of recycled aggregate. Nevertheless, the general trend of decreased carbon and energy burdens with increasing RCA content is expected to hold under similar local-sourcing conditions.

Table 5. Co_2 emissions of RCA-based concrete

RCA Content (%)	CO_2 Emissions (kg/m³)
0	370
25	325
50	295
75	270
100	250

Table 6. Energy Consumption in RCA-Based Concrete Production

RCA Content (%)	Energy Use (MJ/ton)
0	1340
25	1190
50	1080
75	980
100	900

3.5 Economic analysis

The results from economic analyses show progressive cost savings along with RCA replacement. As shown in Table 7, cost savings increased from USD 0/m³ for the control mix to USD 12.3/m³ with 100% RCA replacement. These savings have taken the form of reduced coarse aggregate costs, especially when RCA is sourced locally. The cost includes aggregate procurement, RCA crushing, washing, screening, and transportation in this study. By contrast, the costs of cement, admixtures, labor, and curing were assumed to be constant. This clarification makes the basis for the reported savings transparent and consistent with the methodology.

Table 7. Cost savings in RCA-Based concrete

RCA Content (%)	Cost Saving (USD/m³)
0	0
25	3.5
50	6.8
75	9.7
100	12.3

3.6 Sustainability assessment

Table 8 provides a qualitative summary of the broader sustainability benefits of RCA concrete, including resource use, carbon reduction, cost, circular economy integration, and landfill avoidance. The results suggest that RCA offers significant advantages in natural resource conservation and waste diversion, as well as substantial reductions in carbon emissions and embodied energy. However, the results also indicate that these results must be balanced with the loss in durability at higher RCA contents. For this reason, moderate levels of replacement, especially around 50% RCA, offer the most balanced compromise between engineering performance, sustainability benefit, and economic feasibility.

Table 8. Sustainability benefits of RCA concrete

Benefit Category	Impact of RCA Use
Natural Resource Conservation	High
Carbon Emission Reduction	Moderate to High
Cost Efficiency	Moderate
Circular Economy Integration	High
Reduced Landfill Waste	Very High

3.7 Engineering design and decision-making implications

The results show significant engineering trade-offs of RCA incorporation. Replacement levels of up to 50% RCA offer a balanced solution of compressive strength, durability, environmental benefit, and economic performance. Higher replacement levels may be more appropriate for non-structural elements. These mixes may be more appropriate for non-structural elements, pavements, or applications with lower exposure severity, as shown in Table 9. The replacement levels of 75 to 100%, which offer greater environmental and economic benefits, should also be adopted more cautiously due to their higher permeability and lower mechanical performance. These mixes may be capable of use in non-structural elements, pavements, or applications where the level of exposure is less severe. This framework is designed to translate the experimental results into a design orientation and to address the reviewers' request for a clearer, more practical engineering interpretation grounded in performance considerations.

4. Conclusion

This study assessed the mechanical performance, durability, environmental impact, and economic viability of concrete using recycled concrete aggregates (RCA) as a partial or full replacement for natural coarse aggregates. The experimental results indicated that, with increasing RCA content, the workability, compressive strength, flexural strength, elastic modulus, and density decreased, while water absorption and chloride-ion penetrability increased. These changes are primarily related to increased porosity, adhered mortar, and a weaker interfacial transition zone of the recycled aggregates. Nevertheless, concrete containing up to 50% RCA was found to perform close to the target design strength and to be suitable for many normal structural applications under moderate exposure conditions. In particular, the 50% RCA mixture exhibited a compressive strength of 29.3 MPa and a flexural strength of 4.1 MPa at 28 days, indicating that a moderate RCA incorporation ratio can be achieved without significant loss of engineering performance. The other significant finding of the study was that the workability reduction caused by RCA incorporation can be successfully overcome by proper aggregate processing and the use of superplasticizers. Washed, pre-soaked, and properly graded RCA exhibited improved fresh concrete behavior compared with unprocessed recycled aggregates, thereby confirming the importance of aggregate conditioning in mix preparation. From a durability standpoint, the higher the RCA content, the greater the water absorption and the higher the RCPT value, indicating a gradual decrease in resistance to moisture and chloride penetration. Thereupon, under aggressive exposure conditions, moderate replacement rates remain viable, although higher replacement rates must be applied and extra precautionary steps based on matrix densification need to be considered. From an engineering standpoint, the environmental assessment demonstrated that incorporating RCA offers clear sustainability benefits. At full replacement level, embodied carbon emissions were reduced by approximately 32%, while embodied energy consumption decreased by approximately 33% compared with the control mix. These findings show that RCA can play a significant role in low-carbon and resource-efficient construction practices. The economic analysis further showed that RCA use can reduce the cost of concrete production, with savings of about USD 12.3/m^3 for a 100% replacement. Overall, the results suggest the potential benefits of RCA from technical and environmental perspectives as a material for concrete production, especially at moderate replacement levels (up to 50%), where a balanced combination of strength, durability, sustainability, and cost efficiency was achieved. The study thus advocates the use of RCA as a viable material for circular construction and sustainable infrastructural development. Based on the present findings, the following recommendations are made:

- RCA replacement rates of up to 50% might be adopted in conventional concrete applications in which structural performance and moderate durability are required.
- Pre-soaking, washing, and grading of RCA should be adopted prior to mixing, and this should be implemented to ensure better moisture control and workability of the fresh concrete.
- Superplasticizers should be added where required to offset slump loss, especially at medium and high levels of RCA replacement.
- RCA replacement should be limited or combined with the use of supplementary cementitious materials in durability-critical applications where corrosion and/or other durability issues are of most concern, such as in coastal, marine, or water-retaining structures.
- The use of life cycle assessment (LCA) should be integrated into project-level material selection in order to quantify carbon and energy benefits associated with RCA use.
- Localized sourcing and processing of RCA should be encouraged in order to achieve maximum economic savings and minimum emissions from transportation.
- RCA adoption may further be supported through green building frameworks, sustainability certification systems, and public procurement policies that provide for the recognition of recycled construction materials.

This research was limited to evaluating workability, mechanical properties, water absorption, chloride penetrability, environmental effects, and economic feasibility under controlled laboratory conditions. Long-term durability aspects like freeze-thaw resistance, carbonation, drying shrinkage, creep, and field behavior under actual exposure conditions were not studied. In addition, no direct microstructural characterization was performed to assess the behavior of the interface transition zone. Future studies should thus focus on:

- Long-term durability performance with exposure in the field,
- The impact of supplementary cementitious materials on high-RCA mixes,
- Carbonation resistance, shrinkage, and freeze/ thaw durability,
- Microstructural study of RCA concrete,
- Applying high-grade eco-friendly mix technologies, such as RCA-based geopolymer concrete or hybrid low-carbon concrete.

Ethical issue
The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement
The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

Conflict of interest
The authors declare no potential conflict of interest.

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