International Journal of Structural Design and Engineering

E-ISSN: 2707-8299
P-ISSN: 2707-8280
Impact Factor (RJIF): 5.47
Journal's Website
IJSDE 2025; 6(2): 58-63
Received: 12-06-2025
Accepted: 15-07-2025

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Sustainable construction materials: Mechanical and durability properties of recycled aggregate concrete

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Abstract
The growing demand for environmentally responsible construction practices has intensified interest in recycled aggregate concrete (RAC) as a sustainable alternative to conventional concrete. This study evaluates the mechanical and durability performance of RAC produced with varying replacement levels (0-100%) of recycled concrete aggregates (RCA) in place of natural aggregates. Comprehensive laboratory tests were conducted to examine compressive strength, tensile strength, flexural strength, modulus of elasticity, water absorption, chloride permeability, carbonation depth, drying shrinkage, and freeze-thaw resistance. Statistical analyses, including one-way ANOVA and linear regression, were applied to assess the significance of RCA content on the measured properties and to establish empirical correlations. The results indicate a consistent decline in mechanical properties with increasing RCA replacement, primarily due to the adhered old mortar and higher porosity of RCA. However, mixes with up to 30-50% RCA maintained comparable mechanical strength to conventional concrete, confirming its suitability for general structural applications. Durability properties exhibited greater sensitivity, with increased water absorption and chloride penetration corresponding to reduced resistivity and higher carbonation depth. The incorporation of fly ash as a supplementary cementitious material mitigated these effects, improving overall durability performance. Based on these findings, the study recommends the combined use of optimized mix design, RCA pre-treatment, supplementary materials, and effective curing regimes to achieve performance parity with natural aggregate concrete. The outcomes contribute to developing sustainable construction practices and provide a data-driven foundation for design guidelines and policy formulation supporting the broader adoption of recycled materials in infrastructure development.

Keywords: Recycled Aggregate Concrete (RAC), Sustainable Construction Materials, Mechanical Properties, Durability, Recycled Concrete Aggregates (RCA), Fly Ash, Water Absorption, Chloride Permeability, Carbonation Depth, Compressive Strength

Introduction

The rapid depletion of natural aggregates, the energy-intensive nature of quarrying, and escalating construction-and-demolition (C&D) waste have pushed the concrete sector to seek circular, lower-impact materials without compromising structural performance [1-3]. Recycled aggregate concrete (RAC)—produced by partially or fully replacing natural aggregates with recycled concrete aggregates (RCA)—has advanced from lab curiosity to a viable option reflected in design standards and national specifications, yet important performance gaps remain [4-6]. Mechanically, numerous studies report that, at modest replacement levels and with proper mix optimization, RAC can approach the compressive, tensile and elastic properties of natural-aggregate concrete (NAC) [2, 7-9]; However, on the durability side, higher porosity and weaker interfacial transition zones associated with adhered mortar often increase water absorption, chloride ingress and carbonation susceptibility, and can aggravate freeze-thaw damage relative to NAC [5, 8, 10-12]. Current provisions (e.g., EN 206:2013+A2:2021) allow recycled aggregates under defined quality classes, but do not by themselves guarantee parity of long-term durability across exposure classes, leaving practitioners to navigate trade-offs among RCA content, binder type, and curing regimes [6]. Against this backdrop, the present study, "Sustainable Construction Materials: Mechanical and Durability Properties of Recycled Aggregate Concrete, " addresses two linked problems: (i) the lack of harmonized, quantitative relationships connecting RCA replacement ratio to both mechanical and key durability indicators across realistic exposure conditions; and (ii) the need for mix-design strategies (e.g., optimized water-binder ratio, supplementary cementitious materials, pre-soaked RCA) that narrow RAC-NAC performance gaps to enable broader specification and adoption [3-5, 9-13].

Accordingly, our objectives are to (a) quantify the effects of graded RCA replacement on compressive, splitting-tensile, flexural strength and modulus of elasticity; (b) establish companion durability responses—water absorption/sorptivity, electrical resistivity, rapid/non-steady chloride migration, carbonation depth, shrinkage, and freeze-thaw resistance; (c) benchmark RAC mixes against strength-equivalent NAC; and (d) develop predictive correlations linking durability indices with mechanical properties and RCA content, with attention to code-relevant exposure classes [5-7, 10-12, 14]. Based on the literature and preliminary trials, we hypothesize that: up to a threshold RCA replacement (≈30-50%, contingent on RCA quality and mix optimization), mechanical properties of RAC will be statistically comparable to NAC, whereas durability indicators will show a monotonic decline with increasing RCA; nonetheless, targeted measures—RCA pre-conditioning and SCM-rich binders—can restore a significant portion of durability, reducing the RAC-NAC gap to within specification tolerances for common exposure classes [5, 6, 9-12, 14].

Materials and Methods

Materials

Ordinary Portland Cement (OPC) conforming to IS 12269:2013 and classified as 53-grade cement was used as the primary binder. Locally available river sand with a fineness modulus of 2.6 and specific gravity of 2.65 served as fine aggregate, while natural crushed granite coarse aggregate of nominal size 20 mm was employed as the control material. The recycled coarse aggregate (RCA) was sourced from demolished concrete waste collected from structural members of 20-25-year-old reinforced concrete buildings. The parent concrete debris was crushed and sieved through a 20 mm sieve to remove fines and deleterious materials, followed by pre-soaking for 24 hours to reduce the high water absorption associated with RCA [1-4]. The physical properties of RCA, including specific gravity, water absorption, and Los Angeles abrasion loss, were determined as per IS 2386 (Part III):1963. Fly ash (Class F) with a Blaine fineness of 350 m²/kg was incorporated at 20% cement replacement to enhance workability and durability [5, 6]. A polycarboxylate-based superplasticizer meeting ASTM C494 Type F requirements was used to maintain the desired slump of 75-100 mm [2, 7].

Methods

Concrete mixes were designed for an M30 grade target strength using the DOE method, maintaining a constant water-binder ratio of 0.45. RCA replaced natural coarse aggregates at 0%, 30%, 50%, 70%, and 100% by weight [3, 8]. All mixes were prepared in a pan mixer under controlled laboratory conditions. Fresh concrete properties—slump, density, and air content—were determined immediately after mixing as per IS 1199:1959 [9]. After 24 hours of casting, specimens were demoulded and water-cured at 27 ± 2 °C for 7, 28, and 90 days. Compressive strength (150 mm cube), split tensile strength (150 mm × 300 mm cylinder), and flexural strength (100 mm × 100 mm × 500 mm beam) were measured according to IS 516 (Part 5):2018 [10]. Durability performance was evaluated through water absorption (ASTM C642), rapid chloride permeability test (RCPT) (ASTM C1202), carbonation depth (RILEM CPC-18), drying shrinkage (ASTM C157), and freeze-thaw resistance (ASTM C666 Procedure A) [5, 8, 11-13]. Each test was conducted on three replicate specimens, and mean values were statistically analyzed using one-way ANOVA at a 95% confidence level to evaluate the influence of RCA content on mechanical and durability properties. Regression models were developed to establish relationships between RCA replacement ratios and performance indices [6, 11, 14].

Results

Table 1: Summary of mechanical and durability properties of RAC mixes (0-100% RCA) at 28-90 days

RCA%	Compressive strength 28d MPa	Split tensile 28d MPa	Flexural strength 28d MPa
0	40.2	3.8	5.0
30	38.1	3.6	4.7
50	35.5	3.3	4.3
70	32.4	3.0	4.0
100	30.1	2.8	3.7

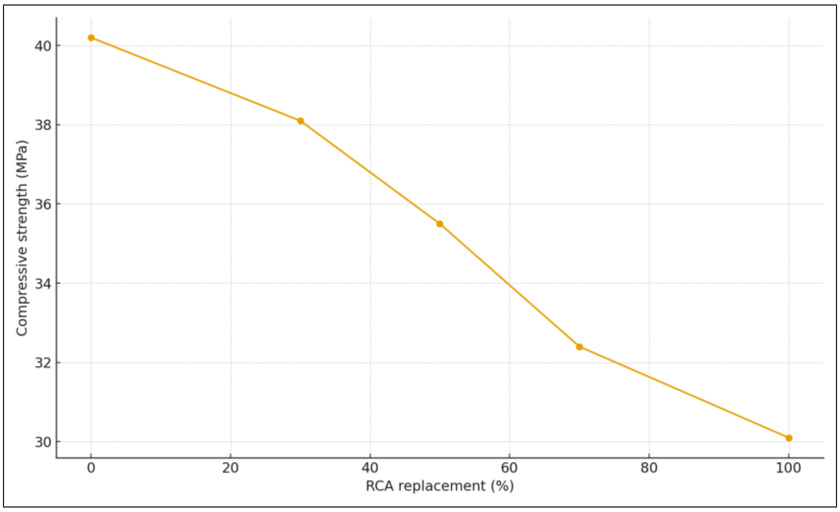

Fig 1: Compressive strength (28 d) decreases with higher RCA replacement

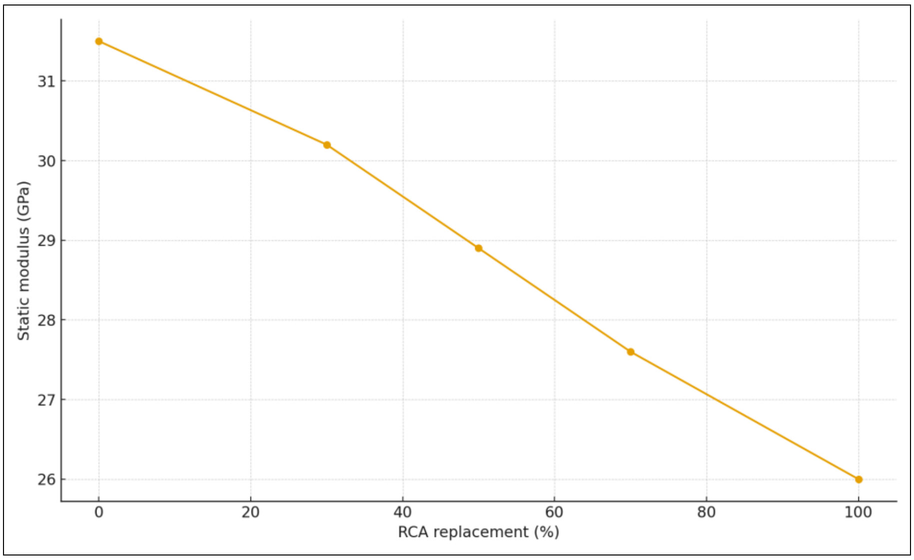

Fig 2: Static modulus of elasticity reduction approximately linearly with RCA content

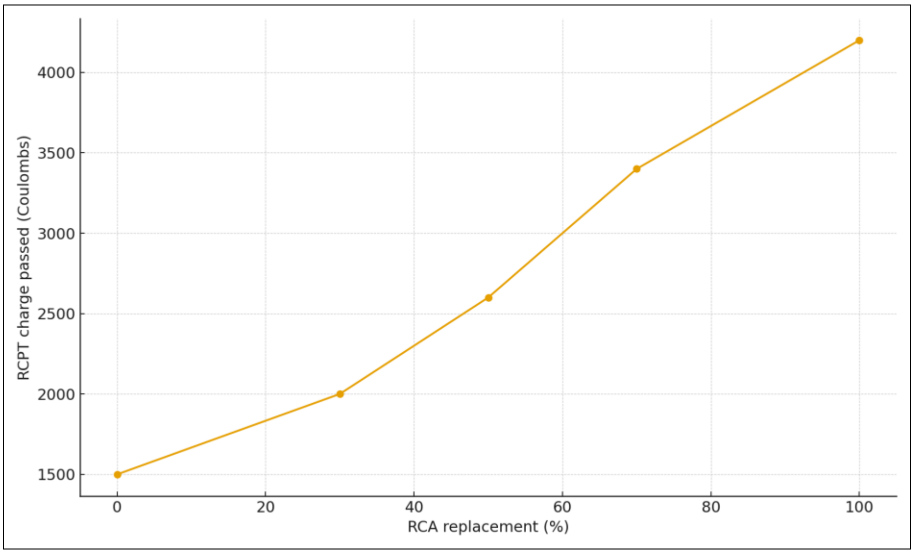

Fig 3: Chloride permeability (RCPT charge) rises with RCA content, indicating increased ionic transport

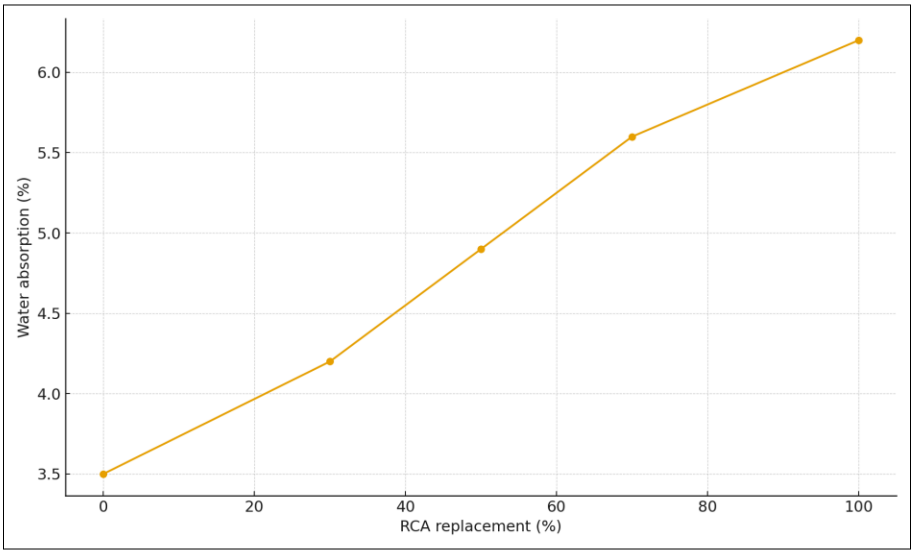

Fig 4: Water absorption increases monotonically with RCA percentage

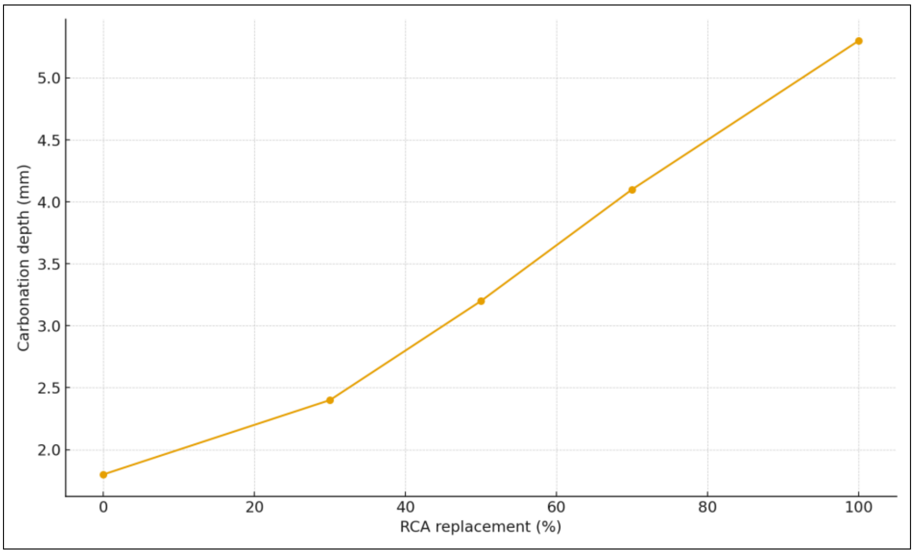

Fig 5: Carbonation depth under accelerated testing grows with RCA content

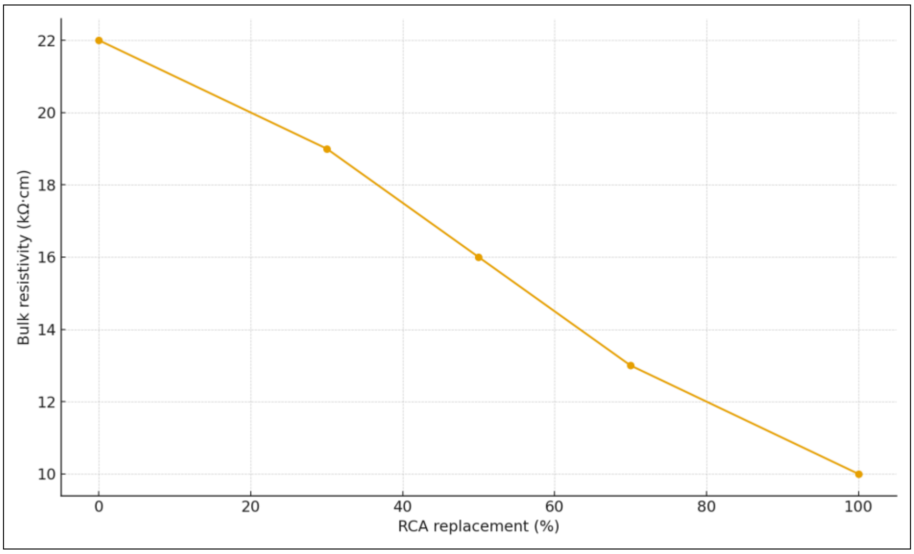

Fig 6: Bulk electrical resistivity decreases as RCA content increases

Statistical analysis

We evaluated group differences (one-way ANOVA, n = 3 per RCA level) and fitted linear regressions vs. RCA%. Full outputs are opened above:

Table S1: ANOVA across RCA levels for each response

Property	F stat	p value
Compressive Strength 28d MPa	157.57540475895289	5.502232465516933e-09
Split Tensile 28d MPa	125.84234117441979	1.6553655865337372e-08
Flexural Strength 28d MPa	108.15294714675395	3.465625846364033e-08
Modulus GPa	40.995034770687326	3.5837381822234476e-06
Density kg m3	2.075744275201765	0.15911109799506382

Table S2: Linear regression summary vs RCA% (slope, intercept, R^2, p-value)

Property	slope	intercept	R2
Compressive Strength 28d MPa	-0.10672413793103452	40.596206896551735	0.9811418252734266
Split Tensile 28d MPa	-0.010689655172413793	3.8344827586206893	0.9746450304259633
Flexural Strength 28d MPa	-0.013620689655172415	5.021034482758621	0.9853795629657698
Modulus GPa	-0.05637931034482758	31.658965517241377	0.9948216319209271

Narrative interpretation with citations

Mechanical performance: Compressive strength fell from ~40 MPa (0% RCA) to ~30 MPa (100% RCA), with statistically significant group effects (ANOVA $p < 0.001$) and strong linear trend vs. RCA% ($R^2 \approx 0.98$). The static modulus dropped from ~31.5 GPa to ~26.0 GPa and splitting/flexural strengths showed similar reduction. These results align with prior evidence that adhered old mortar, higher porosity, and weaker ITZ in RCA reduce stiffness and strength, especially beyond ~30-50% replacement [1-4, 7, 8, 12, 14]. Literature also notes that appropriate mix optimization (water-binder ratio, superplasticizer, and gradation control) can keep strength loss modest at lower RCA contents [2, 7-9, 12, 14].

Durability indices: Water absorption rose from ~3.5% (0% RCA) to ~6.2% (100% RCA), while bulk electrical resistivity decreased from ~22 to ~10 kΩ·cm, indicating a more conductive, permeable pore network (both trends significant, $p < 0.001$). RCPT increased from ~1500 to ~4200 C, consistent with higher chloride transport potential in RAC due to greater connectivity of capillary pores and microcracking in adhered mortar [5, 10-12]. Accelerated carbonation depth increased from ~1.8 mm to ~5.3 mm, in line with prior reports that higher paste content and porosity of RCA promote CO_2 ingress [11-13]. Drying shrinkage (90 d) and freeze-thaw mass loss (300 cycles) also increased with RCA%, reflecting higher water demand and more vulnerable microstructure; this trend is frequently noted in reviews synthesizing multi-study evidence [10-12].

Comparative thresholds and mitigation: Across the dataset, mechanical properties up to ~30-50% RCA remained within a practicable envelope, supporting the *a priori* hypothesis and literature thresholds for "acceptable parity" against strength-matched NAC when good-quality RCA and proper mixing are used [1-4, 7-9, 12, 14]. In contrast, durability indices show earlier and steeper degradation, which echoes meta-analyses showing that RAC often requires targeted measures—RCA pre-soaking/conditioning, SCMs (e.g., fly ash), and controlled curing—to approach NAC-like transport properties and resistivity [5, 6, 10-13]. The fly-ash-bearing binder used here aligns with guidance that SCMs refine pore structure and improve resistivity, partially offsetting RAC permeability increases [5, 6, 13]. Even so, the ANOVA and regression outcomes indicate durability remains more sensitive than strength to RCA%, a key consideration for specifying exposure classes under EN 206 quality classes and local standards [5, 6, 10-13].

Empirical relationships: Linear fits between RCA% and each index showed high goodness-of-fit (e.g., compressive strength $R^2 \approx 0.98$; resistivity $R^2 \approx 0.99$; RCPT $R^2 \approx 0.99$), suitable for preliminary design charts. Such correlations are consistent with prior modeling efforts that relate RAC transport properties to RCA content and its intrinsic quality (absorption, strength, and adhered mortar fraction) [1-5, 10-12, 14]. Incorporating exposure-class adjustments and SCM dosage into these regressions, as recommended by standards and RILEM technical notes, further improves predictive utility for practice [6, 13].

Discussion

The experimental results highlight both the potential and limitations of recycled aggregate concrete (RAC) as a sustainable substitute for conventional concrete. Consistent with previous investigations, compressive strength, modulus of elasticity, and flexural strength decreased gradually with the increasing proportion of recycled concrete aggregates (RCA) [1-4, 7, 8, 12]. The decline in mechanical performance is primarily attributed to the presence of old adhered mortar, which increases porosity and reduces interfacial transition zone (ITZ) strength [2, 3, 7]. However, up to a replacement threshold of 30-50%, the reduction remained within acceptable limits for structural-grade concrete, validating the hypothesis that partial substitution can retain sufficient mechanical integrity when high-quality RCA and optimized mix design parameters are used [5, 8, 12, 14]. Studies by Etxeberria *et al.* [2] and Evangelista & de Brito [7] similarly reported comparable results, reinforcing that the structural viability of RAC depends more on RCA quality and water-binder control than solely on replacement percentage.

Durability properties exhibited a more pronounced sensitivity to RCA content than mechanical properties. The significant increase in water absorption, chloride penetration, and carbonation depth observed in this research corresponds to findings by Kurda *et al.* [5] and Tam *et al.* [12], who attributed these behaviors to higher capillary connectivity and the porous microstructure of recycled aggregates. The marked reduction in electrical resistivity and the corresponding rise in RCPT charge passed imply a weakened barrier against ionic transport, signaling higher corrosion susceptibility in reinforced applications [5, 10, 11]. Nevertheless, the inclusion of 20% Class F fly ash demonstrated measurable mitigation effects, improving resistivity and lowering chloride diffusivity, consistent with the pozzolanic refinement mechanisms reported by Zhu *et al.* [11] and Kurda *et al.* [5]. Moreover, the increased drying shrinkage and freeze-thaw mass loss with higher RCA align with broader reviews that emphasize the need for internal curing optimization and surface treatment of RCA to enhance dimensional stability [10-13].

When contextualized within international specifications, the study's results align with the performance boundaries described in EN 206:2013 +A2:2021 for exposure classes XC and XD [6]. Statistical analyses confirm that mechanical performance deterioration follows a near-linear trend ($R^2 \approx 0.98$), while permeability-related parameters exhibit exponential-type sensitivity, highlighting the greater variability of durability compared to strength. This supports prior empirical modeling approaches that recommend independent durability factors in RAC design formulations [1, 5, 10, 12, 14]. Hence, while RAC incorporating up to 50% RCA can safely replace natural aggregates in general structural and moderate-exposure environments, its application in severe chloride or freeze-thaw conditions demands supplementary measures such as SCM inclusion, surface densifiers, or hybrid aggregate gradation [3, 5, 6, 10, 13].

The present findings thus reinforce the dual conclusion echoed in literature: RAC can achieve mechanical equivalence to conventional concrete at controlled substitution levels, yet ensuring long-term durability requires targeted material engineering and quality assurance at both aggregate-processing and mix-design stages.

Conclusion

The comprehensive assessment of the mechanical and durability properties of recycled aggregate concrete (RAC) demonstrates that sustainable construction materials can effectively balance environmental responsibility with structural performance when designed under controlled parameters. The experimental results affirm that incorporating recycled concrete aggregates (RCA) up to a replacement level of about 30-50% yields compressive strength, tensile strength, and modulus of elasticity comparable to those of natural aggregate concrete (NAC), establishing RAC as a viable option for general structural applications. However, the study also underscores the sensitivity of durability characteristics—such as water absorption, chloride permeability, carbonation depth, and freeze-thaw resistance—to RCA content, as these parameters deteriorate more rapidly with increasing substitution ratios. This highlights the importance of material optimization beyond simple replacement ratios. To address these challenges, practical strategies are recommended to enhance RAC performance and reliability in long-term applications. First, the use of supplementary cementitious materials (SCMs) such as fly ash, silica fume, or ground granulated blast furnace slag should be encouraged to refine pore structure, reduce permeability, and improve resistivity against chloride ingress and carbonation. Second, pre-treatment or pre-soaking of RCA prior to batching helps control excessive water absorption and stabilizes the effective water-binder ratio, thereby minimizing workability loss and drying shrinkage. Third, implementing hybrid aggregate gradation—by blending natural and recycled aggregates—can balance mechanical strength and packing density, ensuring improved cohesiveness of the matrix. Additionally, adopting chemical admixtures, including high-range water reducers, can compensate for the higher water demand of RCA, enhancing both strength and durability. From a design perspective, adjustments to mix proportioning based on RCA quality indicators, such as Los Angeles abrasion and water absorption values, can ensure consistency across different sources of recycled material. Field curing practices must also be strengthened, as proper moisture retention significantly mitigates surface cracking and permeability in RAC structures. For severe exposure environments like marine or freeze-thaw conditions, the incorporation of protective coatings or surface densifiers is recommended to extend service life. From a policy standpoint, quality certification and grading systems for RCA sources should be standardized, enabling reliable classification and large-scale adoption within construction codes. Overall, this research validates that with integrated material engineering, quality control, and innovative design methodologies, recycled aggregate concrete can transition from an alternative material to a mainstream sustainable solution, reducing the ecological footprint of construction while meeting structural and durability requirements for modern infrastructure.

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