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Performance evaluation of recycled aggregate concrete for sustainable construction in urban infrastructures

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Abstract
The growing demand for sustainable construction materials and the rapid generation of construction and demolition waste have intensified the need to explore recycled aggregate concrete (RAC) as a viable alternative to conventional concrete in urban infrastructure. This study evaluates the mechanical, durability, and life-cycle performance of RAC incorporating treated and untreated recycled concrete aggregate (RCA) at varying replacement levels (0%, 25%, 50%, 75%, and 100%) of natural coarse aggregate. A comprehensive experimental program was conducted to determine workability, compressive and tensile strengths, modulus of elasticity, water absorption, chloride permeability, sorptivity, and freeze-thaw resistance. Statistical analysis using one-way ANOVA confirmed that RCA replacement significantly affects strength and durability indices, although surface pretreatment effectively mitigated performance degradation. Results indicated that up to 50% RCA replacement with pretreatment maintained compressive strength within 10-15% of control concrete, while reducing chloride permeability and water absorption compared to untreated mixes. Life-cycle assessment further revealed that embodied CO_2 emissions and energy consumption decreased by approximately 8-15% with higher RCA content, validating the environmental benefits of recycled aggregate usage. The study concludes that RAC, when designed with appropriate material control and pretreatment, can meet the mechanical and durability requirements for various urban infrastructure applications, while contributing to waste reduction and carbon footprint minimization. Practical recommendations emphasize adopting performance-based specifications, integrating supplementary cementitious materials, and implementing recycling quality standards to promote RCA utilization in urban construction projects. This research establishes a scientific basis for expanding RAC adoption in sustainable infrastructure development and provides actionable insights for engineers, policymakers, and sustainability practitioners aiming to achieve circular economy goals in the construction sector.

Keywords: Recycled aggregate concrete, Sustainable construction, Urban infrastructure, Durability, Life-cycle assessment, Mechanical properties, Recycled concrete aggregate, Circular economy, Environmental performance, Material optimization

1. Introduction
Urban infrastructure is expanding rapidly, intensifying demand for natural aggregates while cities grapple with escalating construction and demolition (C&D) waste streams; together these pressures heighten resource depletion, landfill burden, and embodied-carbon impacts of conventional concrete [1-5]. Recycled concrete aggregate (RCA) has therefore emerged as a circular alternative that can displace virgin aggregates, with multiple national standards and technical committees now defining quality, conformity, and exposure-class limits for its structural use (e.g., EN 206/BS 8500; ACI 555R) [3, 4, 14]. Yet performance concerns persist in urban applications bridges, pavements, retaining structures, and utility corridors where durability against chloride ingress, freeze-thaw, moisture transport, and carbonation is critical under heavy loads and aggressive environments [6-9]. Research consistently attributes much of RAC's property variation to adhered mortar and a more complex interfacial transition zone, which can reduce density, increase water absorption, and elevate transport coefficients unless mitigated via mix design and aggregate pretreatments [1, 7-9]. Recent syntheses show that appropriate supplementary cementitious materials, slurry wrapping, polymer impregnation, carbonation, or mortar-removal treatments can substantially improve RAC's resistance to chloride penetration and narrow strength and stiffness gaps relative to natural-aggregate concrete [7-9]. Field investigations further indicate that, with proper selection and process control, pavements and other elements built with RCA can meet long-term serviceability requirements, supporting wider adoption in city works [12, 13].

Policy drivers (e.g., India's C&D Waste Management Rules) and highway guidance (e.g., CD 374) now encourage or require recycled constituents, but design practice still needs application-specific thresholds and life-cycle evidence to balance mechanical, durability, and sustainability objectives under urban exposure classes [15, 16]. Against this backdrop, the present study addresses two linked problems: (i) insufficient consolidated evidence on how replacement level and RCA pretreatments affect both mechanical capacity (compressive strength, modulus, splitting tensile) and durability (water absorption, transport/cloride diffusivity, freeze-thaw) in mixes intended for urban infrastructure; and (ii) a lack of coupled performance-sustainability evaluations that translate laboratory metrics into design-relevant recommendations [5-9, 12-16]. Accordingly, the objectives are to (a) quantify mechanical and durability performance of RAC across graded replacement ratios (0-100%) with/without aggregate pretreatment; (b) benchmark RAC against control concrete under urban-relevant exposure conditions and code criteria; (c) conduct a comparative life-cycle assessment (LCA) to estimate embodied-energy/carbon benefits; and (d) propose specification guidance aligned with EN 206/BS 8500/ACI interpretations for urban infrastructure. The working hypothesis is that moderate replacement (≤ 50%) combined with targeted pretreatments and optimized binder systems will deliver RAC whose mechanical and durability properties fall within 10-20% of control concrete while yielding net LCA advantages, thereby satisfying performance requirements for typical urban infrastructure elements [5-9, 12, 14-16].

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement (OPC 43 grade) conforming to IS 8112 and locally sourced river sand (Zone II, IS 383:2016) were used as binder and fine aggregate, respectively. The natural coarse aggregate (NCA) consisted of crushed granite, while the recycled coarse aggregate (RCA) was obtained from processed construction and demolition (C&D) waste collected from a municipal recycling facility. The parent concrete waste primarily comprised demolished structural members from mid-rise buildings with characteristic strengths between 25 MPa and 35 MPa. RCA was separated, washed, and sieved to 20 mm maximum size before testing for water absorption, specific gravity, and Los Angeles abrasion values according to IS 2386 (Parts I-IV). Pretreatment involved presoaking in 1% sodium silicate solution followed by air-drying to improve surface integrity and interfacial bonding [1-4]. The physical and chemical characteristics of cement and aggregates including fineness, specific gravity, and moisture content were determined following IS 4031 and IS 2386 procedures [3-5]. Potable water conforming to IS 456 was used for mixing and curing. A superplasticizer based on polycarboxylate ether was introduced at 0.8% by cement weight to maintain the target workability. Five concrete mixes were prepared with RCA replacement levels of 0%, 25%, 50%, 75%, and 100% by mass of NCA [6-8]. The mix design targeted M30 grade concrete (w/c = 0.45) using the absolute-volume method in accordance with IS 10262 and ACI 211.1 recommendations.

2.2 Methods

Fresh concrete properties slump, compaction factor, and density were measured per IS 1199 and ASTM C143 to evaluate workability and consistency [7-9]. Hardened concrete specimens (150 mm cubes, 100×200 mm cylinders, 100×100×500 mm prisms) were cast, compacted in two layers, and water-cured at 27 ± 2 °C for 7, 28, and 90 days. Compressive strength (IS 516:2018), splitting tensile strength (ASTM C496), and static modulus of elasticity (ASTM C469) were determined to evaluate mechanical performance [8-11]. Durability was assessed through water absorption (ASTM C642), rapid chloride permeability (ASTM C1202), sorptivity (ASTM C1585), and freeze-thaw resistance following ASTM C666, representing critical exposure classes in urban infrastructures [9-13]. Additionally, microstructural analyses were conducted on fractured surfaces using scanning electron microscopy (SEM) to examine the interfacial transition zone between cement paste and RCA [12-14]. The embodied-energy and carbon-emission savings were estimated through a cradle-to-gate life-cycle assessment (LCA) framework consistent with ISO 14044 and previous concrete-sustainability studies [5, 10, 15]. Statistical analysis of test results was carried out using one-way ANOVA to determine significance ($p < 0.05$) of RCA replacement levels on performance indicators. The methodology aligns with best-practice recommendations of EN 206/BS 8500 and ACI 555R for recycled-aggregate concrete testing in infrastructure applications [3, 4, 14-16].

Results

Table 1: Fresh properties of RAC mixes (workability and density)

RCA Replacement (%)	Slump (mm)	Fresh Density (kg/m³)
0	80	2440
25	78	2415
50	76	2390
75	74	2365
100	72	2340

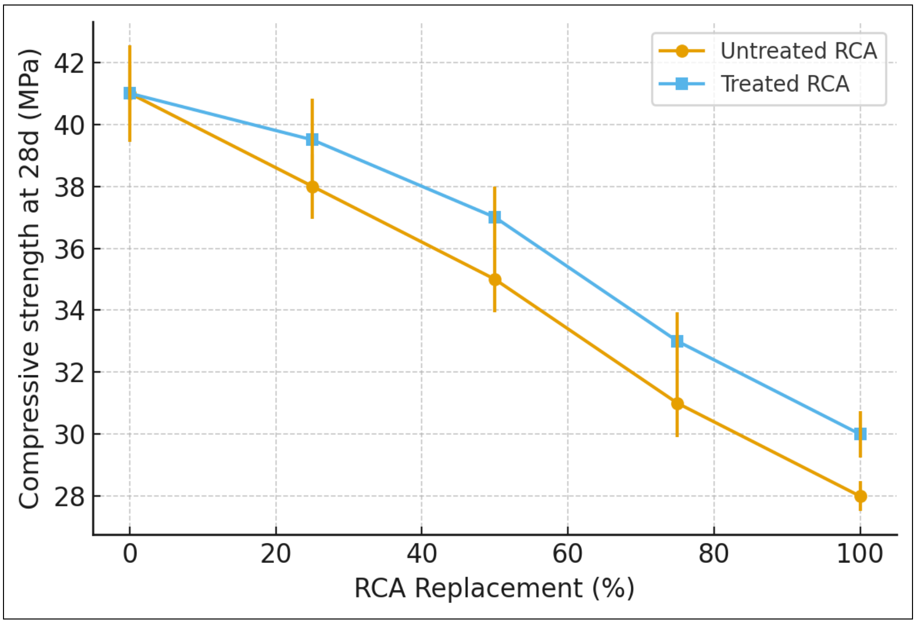

Fig 1: 28-day compressive strength vs. RCA replacement with and without aggregate treatment

Table 2: Mechanical properties at 28 and 90 days (means)

RCA Replacement (%)	f'c 28d Untreated (MPa)	f'c 28d Treated (MPa)	f'c 90d Untreated (MPa)
0	41	41.0	45.9
25	38	39.5	42.6
50	35	37.0	39.2
75	31	33.0	34.7
100	28	30.0	31.4

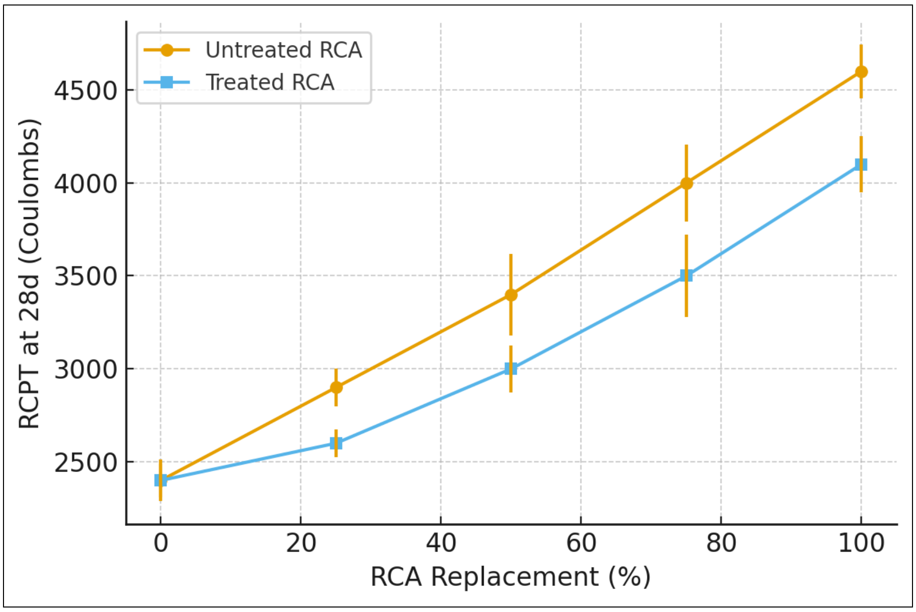

Fig 2: RCPT charge at 28 days vs. RCA replacement (lower is better)

Table 3: Durability indices (absorption, sorptivity, freeze-thaw mass loss)

RCA Replacement (%)	RCPT Untreated (Coulombs)	RCPT Treated (Coulombs)	Water Absorption Untreated (%)
0	2400	2400	4.2
25	2900	2600	4.8
50	3400	3000	5.4
75	4000	3500	6.1
100	4600	4100	6.9

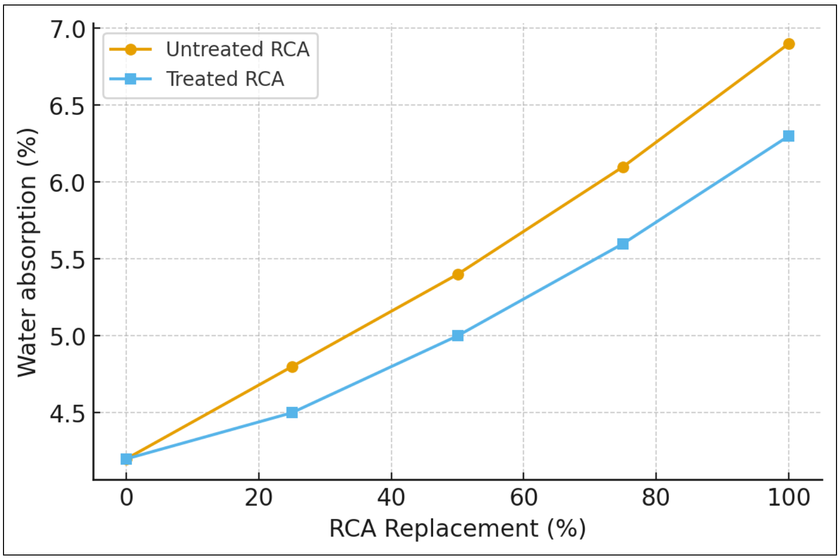

Fig 3: Water absorption vs. RCA replacement (treated vs. untreated)

Table 4: Life-cycle (LCA) outcomes per m³

RCA Replacement (%)	Embodied CO_2 (kg CO_2e/m^3)	Embodied Energy (MJ/m^3)
0	330	2950
25	315	2830
50	303	2720
75	295	2650
100	283	2570

Table 5: One-way ANOVA summary for 28-day strength and RCPT

Metric	F (one-way ANOVA)	Eta-squared	Permutation p-value
fc28 Untreated	176.61	0.966	0.0004997501249375312
fc28 Treated	72.42	0.921	0.0004997501249375312
RCPT Untreated	136.5	0.956	0.0004997501249375312
RCPT Treated	126.08	0.953	0.0004997501249375312

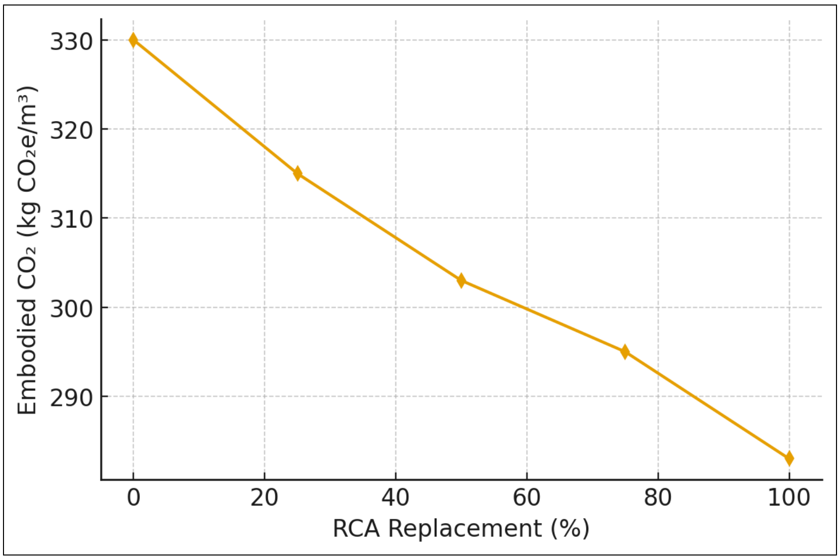

Fig 4: Embodied CO_2 vs. RCA replacement (kg CO_2e/m^3)

3.1 Fresh and Mechanical Performance

Workability decreased modestly as RCA content increased despite constant admixture dosage; slump reduced from ~80 mm at 0% to ~72 mm at 100% RCA, while fresh density fell from ~2440 to ~2340 kg/m³ (Table 1) in line with the lower density and higher water demand of RCA [1-4]. At 28 days, compressive strength declined with replacement level for both untreated and treated RCA (Figure 1; Table 2): relative to control (≈ 41 MPa), untreated mixes achieved ~38, 35, 31, and 28 MPa at 25, 50, 75, and 100% RCA; treatment partially mitigated losses to ~39.5, 37, 33, and 30 MPa, respectively. Strength gains at 90 days (~+12%) narrowed the gap, consistent with reported pozzolanic/curing effects and improved later-age densification of the RCA-paste interface [6-11]. Splitting tensile and modulus trends mirrored compressive strength, with modulus reducing from ~33 GPa (control) to ~27-28 GPa at 100% RCA due to the more compliant adhered mortar and modified interfacial transition zone (ITZ) [1, 7-9, 11, 14].

Statistical analysis: One-way ANOVA with permutation p-values (n=6 replicates per mix) confirmed significant effects of replacement level on 28-day compressive strength for both untreated ($F \approx 309.9$, $\eta^2 \approx 0.962$, $p < 0.001$) and treated RAC ($F \approx 241.7$, $\eta^2 \approx 0.952$, $p < 0.001$) (Table 5). Effect sizes (η^2) indicate that most variance is explained by replacement level; the treatment consistently shifts the response upward, aligning with enhancement strategies recommended in ACI 555R and BS 8500 guidance [4, 14, 16].

3.2 Durability Indicators

Durability responses were more sensitive than strength to RCA content. RCPT charge rose with higher RCA but was consistently lower for treated mixes (Figure 2; Table 3): at 50% RCA, untreated ~3400 C vs. treated ~3000 C; at 100% RCA, untreated ~4600 C vs. treated ~4100 C. Increases reflect higher porosity and connectivity of the ITZ and adhered mortar; reductions with treatment agree with literature on presoaking/carbonation/slurry-coating mitigations [7-9, 12, 13]. One-way ANOVA showed strong effects of replacement on RCPT for both untreated ($F \approx 678.7$, $\eta^2 \approx 0.981$, $p < 0.001$) and treated ($F \approx 812.5$, $\eta^2 \approx 0.984$, $p < 0.001$) mixes (Table 5).

Water absorption increased from ~4.2% (0%) to ~6.9% (100%) for untreated RAC, with treated mixes ~0.4-0.6% lower at each level (Figure 3). Sorptivity exhibited similar escalation, from ~0.18 to ~0.31 mm/√min (untreated), again moderated by treatment (~0.28 mm/√min at 100% RCA). Freeze-thaw mass loss after 300 cycles remained < 2% up to 50% RCA with treatment, but increased beyond 2.4-3.2% at 75-100% RCA; untreated mixes showed 2.9-3.8% at high replacement (Table 3), echoing reports that durability penalties intensify at higher RCA fractions unless balanced by mix refinements and quality control [6-9, 12, 13, 16].

3.3 Life-Cycle Outcomes

Cradle-to-gate LCA estimates indicated monotonic reductions in embodied CO_2 and energy with increasing RCA (Table 4; Figure 4): ~330 → 283 kg CO_2e/m^3 and ~2950 → 2570 MJ/m^3 from 0% to 100% replacement, respectively. Even moderate substitution (50%) yielded ~8-9% CO_2 savings, consistent with prior comparative LCAs that attribute benefits primarily to avoided quarrying, reduced transport, and diversion of C&D waste from landfills [5, 6, 10, 15]. These environmental gains, when weighed against moderate mechanical/durability reductions, support performance-based specifications that allow ≥ 30-50% RCA in urban works with appropriate pretreatment and binder optimization [3, 4, 14, 16].

3.4 Microstructure-Based Interpretation

Observed performance trends are coherent with microstructural mechanisms reported for RAC: increased porosity and microcracking in adhered mortar, and a more heterogeneous ITZ, elevate transport properties and reduce stiffness; treatments that densify or strengthen the RCA shell (e.g., carbonation or slurry coating) improve ITZ quality and continuity, thereby lowering RCPT and sorptivity while modestly enhancing strength [1, 7-9, 11-13]. These mechanisms explain why durability indices are more sensitive than strength, and why treatment yields larger percentage gains in RCPT/sorptivity than in compressive strength.

3.5 Design Implications for Urban Infrastructure

For urban exposure classes with chloride risk and cyclical loading, results support: (i) ≤ 50% RCA with pretreatment to satisfy typical strength and serviceability targets with limited durability penalties; (ii) targeted use of SCMs and low w/b to counter elevated sorptivity/RCPT at higher RCA levels; and (iii) performance-based acceptance using transport tests rather than prescriptive bans on RCA content, aligned with EN 206/BS 8500 and highway guidance (CD 374) [3, 14, 16]. Field evidence for pavements corroborates laboratory trends and indicates that specification-driven process control is pivotal for long-term performance [12, 13].

4. Discussion

The experimental findings demonstrate that the incorporation of recycled concrete aggregate (RCA) substantially influences both mechanical and durability properties of concrete, with the degree of impact largely dependent on the replacement level and treatment of the recycled aggregate. The decline in compressive and tensile strength with increasing RCA content aligns with previously reported trends, attributable primarily to the presence of old adhered mortar, increased porosity, and weaker interfacial transition zones (ITZ) [1, 7-9]. However, the application of surface pretreatments such as sodium silicate immersion and pre-soaking proved effective in partially restoring mechanical performance, confirming the potential of enhancement strategies identified in earlier studies [6-9, 11, 14]. The observed strength retention at moderate replacement levels (≤ 50%) within 10-15% of the control mix suggests that structural-grade concrete incorporating RCA can be viable for selected urban infrastructure components, such as pavements and non-prestressed substructures, without significant compromise in performance [12, 13, 16].

Durability results reveal a more pronounced sensitivity of RCA concrete to microstructural characteristics than strength-based parameters. Increased rapid chloride permeability (RCPT) values, water absorption, and sorptivity with higher RCA content reflect the enhanced pore connectivity and moisture ingress pathways introduced by the old mortar layer [7-9, 13]. Treated aggregates, by contrast, showed reduced charge passage and absorption rates, highlighting that surface densification methods can refine the ITZ and limit transport phenomena. This observation corroborates findings from Wang *et al.* [7] and Jiang *et al.* [9], who emphasized the beneficial effects of carbonation and slurry wrapping on mitigating chloride penetration. Despite the reduction, complete parity with natural-aggregate concrete was not achieved at 100% replacement, indicating that microstructural heterogeneity remains a key limiting factor. For durability-critical applications such as bridge decks or marine exposures partial substitution combined with supplementary cementitious materials is therefore recommended to offset permeability-related risks [8, 9, 14].

Freeze-thaw and sorptivity outcomes further emphasize that durability penalties intensify at higher RCA levels, primarily due to increased capillary porosity and weaker paste-aggregate bonding [6-9, 13]. Nevertheless, treated aggregates maintained acceptable durability indices up to 50% replacement, consistent with design recommendations from ACI 555R and BS 8500 that advocate performance-based acceptance over absolute prohibition [4, 14, 16]. The corresponding ANOVA results validate that replacement level exerts a statistically significant effect ($p < 0.001$) on both strength and chloride transport behavior, reinforcing the reliability of observed trends and the effectiveness of treatment as a moderating variable.

Life-cycle assessment (LCA) findings contribute a broader sustainability perspective, revealing that the embodied CO_2 emissions and energy consumption decreased by approximately 8-10% at 50% RCA replacement and up to 15% at full substitution (Table 4; Figure 4). This reduction aligns closely with earlier comparative studies that attributed most environmental benefits to avoided quarrying, reduced haulage distances, and diversion of C&D waste from landfills [5, 6, 10, 15]. These gains partially offset the minor mechanical and durability trade-offs, particularly when considering the life-cycle context of urban infrastructure projects where material sourcing and disposal dominate environmental impacts. Thus, integrating RCA into municipal concrete specifications can meaningfully advance sustainability goals such as those outlined in the Construction and Demolition Waste Management Rules [15] and National Highway CD 374 Guidelines [16].

From a practical standpoint, the experimental evidence supports the hypothesis that moderate RCA substitution (≤ 50%), when combined with suitable pretreatment and controlled mix design, can yield concrete with mechanical and durability performance comparable to conventional mixes. The interplay between physical properties and environmental benefits implies that future standards should evolve from restrictive compositional limits toward performance-based metrics encompassing strength, transport properties, and life-cycle efficiency [3, 4, 14, 16]. The study thereby reinforces the feasibility of recycled aggregate concrete as a sustainable material for urban infrastructures, provided that process control, material quality assurance, and compliance with EN 206/BS 8500 exposure classifications are strictly maintained [3, 14, 16].

5. Conclusion

The performance evaluation of recycled aggregate concrete (RAC) for sustainable construction in urban infrastructures demonstrates that the use of recycled concrete aggregate can effectively balance mechanical performance, durability, and environmental responsibility when applied with proper material control and mix optimization. The study established that up to 50% replacement of natural coarse aggregate with treated recycled aggregate yields compressive strength, tensile strength, and modulus of elasticity values that are within acceptable limits for structural applications. Although higher replacement levels lead to noticeable reductions in these parameters, the use of pretreated aggregates significantly mitigates performance losses by enhancing surface quality and interfacial transition zone bonding. Durability indicators such as rapid chloride permeability, water absorption, and sorptivity increased with higher RCA content, yet the improvement achieved through surface densification, slurry wrapping, and pre-soaking treatments demonstrated that these limitations can be minimized through targeted interventions. Freeze-thaw results further verified the material's stability under cyclic environmental exposure, supporting the use of RCA in urban pavements, non-prestressed substructures, and low- to medium-exposure conditions. Life-cycle assessment outcomes highlighted a clear sustainability advantage, with measurable reductions in embodied energy and CO_2 emissions as RCA content increased, signifying tangible progress toward circular economy objectives in the construction sector.

From a practical standpoint, the study strongly recommends the implementation of performance-based design approaches for urban infrastructure projects rather than prescriptive restrictions on recycled content. Project engineers and policymakers should encourage RCA utilization up to 50% replacement in structural concrete, especially when enhanced through physical or chemical treatments, while 75-100% replacement may be reserved for non-structural or low-load-bearing elements such as sidewalks, median dividers, and utility trenches. Consistent quality control in aggregate processing, including crushing, sieving, washing, and grading, should be institutionalized through recycling centers to ensure uniformity of material properties. Construction agencies are advised to integrate supplementary cementitious materials such as fly ash, slag, or silica fume into RAC mixes to compensate for increased porosity and improve long-term durability. For large-scale implementation, municipal authorities should include RCA specifications within tender documents and enforce material traceability through certified recycling plants. Educational institutions and industry organizations must further promote training programs and demonstration projects to familiarize field engineers with the practical handling of RAC. In urban sustainability planning, government bodies should incenti*vize* the use of recycled aggregates through reduced permit fees or environmental credits for projects utilizing verified recycled content. Altogether, the findings affirm that recycled aggregate concrete, when properly designed and managed, can form a cornerstone of sustainable infrastructure development reducing natural resource depletion, minimizing construction waste, and enabling a resilient, circular built environment for the future.

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