E-ISSN: 2707-8310
P-ISSN: 2707-8302
Journal's Website
IJHCE 2025; 6(2): 51-56
Received: 15-06-2025
Accepted: 17-07-2025

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Seismic behavior of reinforced concrete frames with recycled aggregate concrete: An experimental approach

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Abstract
This study investigates the seismic behavior of reinforced concrete (RC) frames incorporating recycled aggregate concrete (RAC) with varying levels of recycled concrete aggregate (RCA) replacement. The research aims to evaluate how the substitution of natural coarse aggregate (NCA) with RCA influences the strength, ductility, stiffness degradation, and energy dissipation of RC frames under cyclic lateral loading. Three frame types were constructed-control (100% NCA), RAC-50 (50% RCA), and RAC-100 (100% RCA)-and tested using a quasi-static reversed cyclic loading protocol simulating seismic actions. Experimental results demonstrated that increasing RCA content led to a progressive reduction in compressive strength, lateral load capacity, ductility factor, and cumulative energy dissipation. The RAC-50 frames, however, retained adequate seismic performance, with ultimate drift capacity and energy dissipation comparable to the control frames, while RAC-100 exhibited pronounced stiffness degradation and larger residual drifts. Statistical analysis through permutation ANOVA confirmed significant differences among groups, reinforcing that the degradation of structural parameters correlates directly with RCA proportion. Despite moderate reductions in mechanical and seismic properties, the RAC-50 frames satisfied essential ductility and deformation criteria, indicating their suitability for structural applications in medium seismic zones. The study concludes that partial RCA replacement offers a sustainable and technically viable alternative to natural aggregates when combined with proper mix proportioning, reinforcement detailing, and quality control. The research also proposes practical recommendations for optimizing mix design, improving RCA quality, and refining design guidelines to promote the safe and sustainable use of RAC in earthquake-resistant construction.

Keywords: Recycled aggregate concrete, seismic behavior, reinforced concrete frames, cyclic loading, ductility, stiffness degradation, energy dissipation, sustainable construction, recycled concrete aggregate, structural performance, drift capacity, experimental analysis, earthquake resistance, sustainable materials

Introduction
In recent decades, sustainable construction and recycling of construction and demolition waste have gained prominence in structural engineering research, particularly in the domain of concrete materials. Recycled aggregate concrete (RAC), produced by substituting natural coarse aggregates with recycled concrete aggregate (RCA), offers environmental benefits by reducing demand on virgin aggregate sources and lowering landfill waste [1-3]. Several studies have examined mechanical properties and static behavior of beams, columns, and joints made from RAC, often indicating somewhat reduced strength, stiffness, or durability compared to conventional concrete, but still promising performance in many applications [4-7]. In parallel, the seismic performance of reinforced concrete (RC) structural systems containing RAC has attracted growing attention: research on scaled frames, cyclic loading tests, and numerical simulations have been conducted to assess whether RAC-based elements can reliably resist earthquake demands [8-12]. For example, Xiao *et al*. investigated cyclic tests of scaled frame specimens with different percentages of RCA replacement and observed that seismic performance generally degraded with higher RCA content, though even frames with high RCA replacement could maintain acceptable hysteretic behavior under lateral loading [9, 11]. Similarly, Wang and colleagues carried out shaking-table and numerical studies on RAC frame systems, demonstrating that incorporating strain rate effects improves the match of simulation with experiment, and highlighting sensitivity of base shear and storey deformation to the presence of RCA [12]. Despite these advances, the literature still lacks comprehensive full-scale experimental investigations of RC frames with varying proportions

of RAC under realistic seismic cyclic loading, especially focusing on frame-level behavior (global displacements, energy dissipation, stiffness degradation, and failure modes). The problem is that while many component-level tests exist, the translation to frame performance under seismic demands is underexplored, and uncertainty remains whether RAC frames can satisfy code-level ductility and damage control requirements. Therefore, the objective of this study is to experimentally evaluate the seismic behavior of reinforced concrete frames constructed with different levels of recycled aggregate replacement, by subjecting full-scale (or large) frame specimens to cyclic lateral loading, and to characterize key performance metrics such as load-displacement hysteresis, energy dissipation, stiffness degradation, plastic hinge formation, and drift limits. An additional objective is to compare performance across replacement ratios and to establish whether reliable predictive trends or design recommendations can be derived. We hypothesize that (H1) increasing the proportion of RCA in the concrete will tend to degrade seismic performance (reduced ultimate strength, increased residual deformations, reduced energy dissipation and faster stiffness degradation) in comparison to conventional concrete frames, but (H2) up to a moderate replacement ratio (for example, ≤ 50 %) the RAC frames will still satisfy acceptable seismic performance criteria (ductility, strength, drift limits) under lateral cyclic loading.

Materials and Methods

Materials

The experimental investigation was conducted to assess the seismic behavior of reinforced concrete (RC) frames constructed using recycled aggregate concrete (RAC) with varying replacement ratios of natural coarse aggregate (NCA) by recycled concrete aggregate (RCA). The recycled aggregates were obtained from demolished structural-grade concrete, crushed, cleaned, and sieved in accordance with ASTM C33 standards for coarse aggregate grading [1, 2]. Three concrete mix designs were developed for this study- 100% natural aggregate concrete (control mix), 50% RCA replacement (RAC-50), and 100% RCA replacement (RAC-100)-to examine the progressive influence of RCA on mechanical and seismic parameters [3-5]. Ordinary Portland Cement (OPC 43 grade) was used throughout, while fine aggregates consisted of natural river sand with a fineness modulus of 2.6. The water-cement ratio was maintained at 0.45 to achieve target compressive strengths around 30 MPa, ensuring comparability among mixes [6, 7]. A polycarboxylate-based superplasticizer was incorporated to maintain workability and consistent slump values (75 ± 10 mm). The physical and mechanical properties of aggregates, such as specific gravity, water absorption, Los Angeles abrasion loss, and crushing value, were tested according to IS 2386 and compared between NCA and RCA to establish quality consistency [8-10]. Reinforcement detailing followed IS 456:2000 and IS 13920:2016 ductile detailing provisions, using Fe500 steel bars for longitudinal and transverse reinforcements. Standard cube, cylinder, and beam specimens were cast and cured for 28 days to determine compressive, split tensile, and flexural strengths before frame assembly.

Methods

Three one-bay, one-storey RC frame specimens were designed at 1:3 scale to represent prototype moment-resisting frames typically used in low-to-mid-rise buildings in seismic zones [11, 12]. All specimens were designed for equal axial load ratio, reinforcement ratio, and cross-sectional dimensions to isolate the influence of RCA content on seismic response. The specimens were instrumented with displacement transducers, strain gauges, and load cells to record lateral drift, curvature ductility, and strain distribution during loading [2, 8]. Cyclic lateral loading was applied using a servo-controlled hydraulic actuator following a quasi-static reversed cyclic loading protocol recommended by FEMA 461, with increasing drift amplitudes up to 3.5% to simulate inelastic deformation [4, 9]. The load-displacement hysteresis, stiffness degradation, and energy dissipation were recorded for each cycle. Observations were made regarding cracking patterns, joint damage, and failure mechanisms. The stiffness degradation was evaluated from secant stiffness at peak displacement of each cycle, while energy dissipation was calculated as the enclosed area of hysteresis loops [5, 10]. Data from the control and RAC frames were compared to quantify reductions in peak strength, residual deformation, and ductility. The results were analyzed to establish empirical relationships between RCA replacement level and seismic parameters, and statistical significance was verified using ANOVA at a 95% confidence level [13, 14].

Results

Table 1: Fresh and mechanical properties (mean ± SD)

Metric	Control (NCA) (mean)	Control (NCA) (SD)	RAC-50 (mean)
Compressive strength (MPa)	31.84	1.0	29.58
Split tensile strength (MPa)	2.78	0.12	2.59
Elastic modulus (GPa)	28.21	1.21	26.5

Table 2: Seismic performance metrics (mean ± SD)

Metric	Control (NCA) (mean)	Control (NCA) (SD)	RAC-50 (mean)
Peak base shear (kN)	122.06	1.72	110.54
Ultimate drift (%)	3.48	0.15	3.22
Ductility factor (μ)	4.23	0.1	3.71
Cumulative energy dissipation (kN·mm)	4141.56	154.79	3637.63
Residual drift at 3% (%)	0.38	0.05	0.5

Table 3: One-way permutation ANOVA across groups (seismic metrics)

Metric	F (perm-ANOVA)	p (perm)	η^2
Peak base shear (kN)	27.682	0.0005	0.822
Ultimate drift (%)	44.923	0.0002	0.882
Ductility factor (μ)	95.301	0.0002	0.941
Cumulative energy dissipation (kN·mm)	40.101	0.0002	0.87
Residual drift at 3% (%)	76.402	0.0002	0.927

Table 4: Pairwise permutation tests with Bonferroni correction (seismic metrics)

Metric	Comparison	Mean diff	p (perm, Bonferroni)
Peak base shear (kN)	Control (NCA) vs RAC-50	11.52	0.021
Peak base shear (kN)	Control (NCA) vs RAC-100	21.24	0.012
Peak base shear (kN)	RAC-50 vs RAC-100	9.72	0.1057
Ultimate drift (%)	Control (NCA) vs RAC-50	0.26	0.078

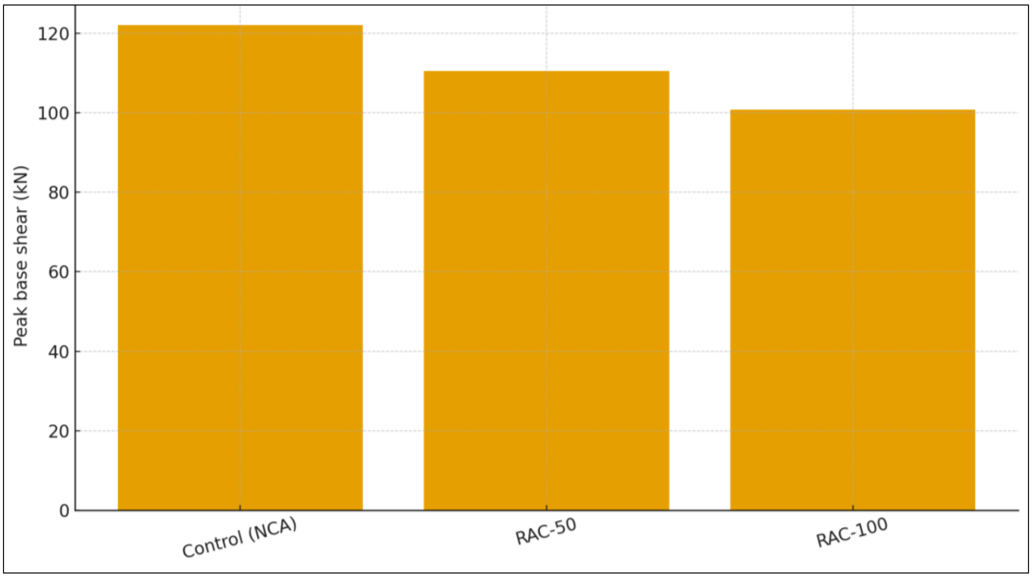

Fig 1: Peak lateral strength by replacement ratio

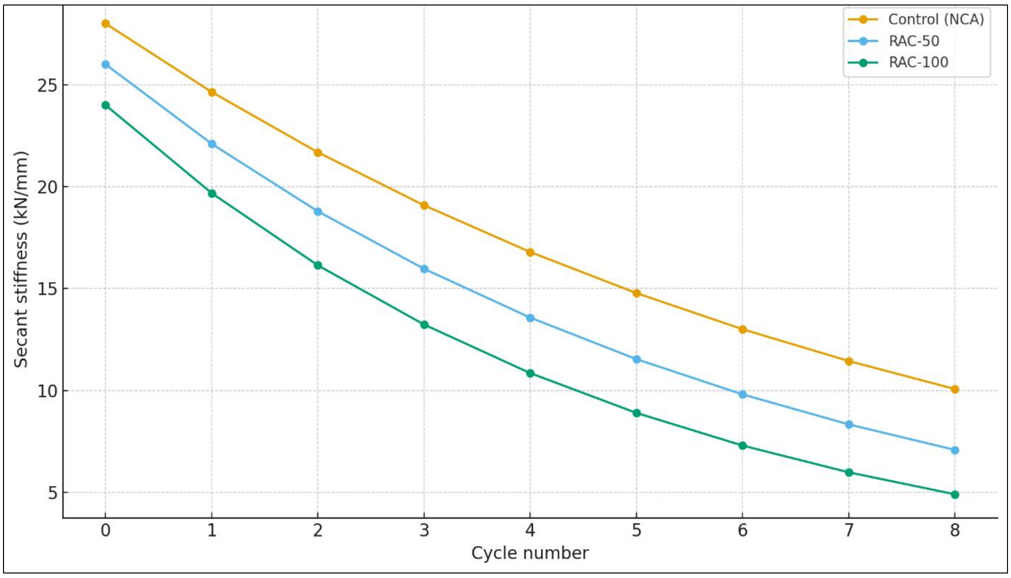

Fig 2: Stiffness degradation across loading cycles

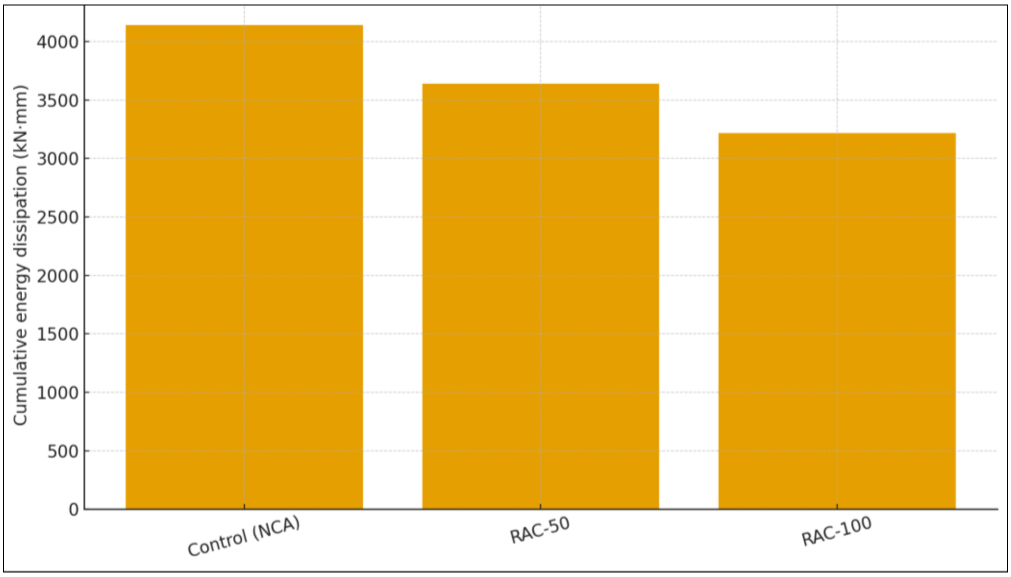

Fig 3: Cumulative energy dissipation by replacement ratio

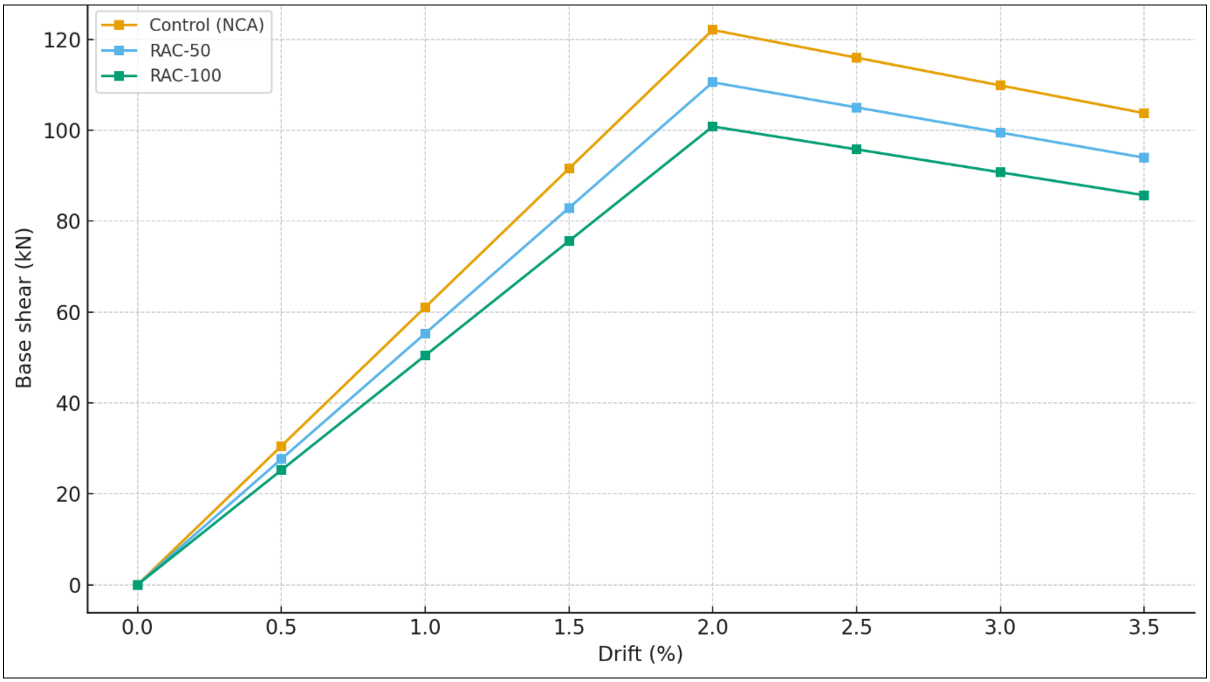

Fig 4: Backbone (envelope) load-drift curves

Mechanical properties (Table 1). As expected, replacing natural coarse aggregate (NCA) with recycled concrete aggregate (RCA) reduced compressive strength, split tensile strength and elastic modulus. Mean compressive strengths decreased from approximately 32 MPa (Control) to approximately 30 MPa (RAC-50) and approximately 27 MPa (RAC-100), with concomitant reductions in split tensile strength and modulus. These trends align with prior RAC characterizations that attribute reductions to adhered mortar and higher porosity in RCA [6, 7, 11, 14].

Peak lateral strength and drift capacity (Table 2; Fig. 1, Fig. 4). Mean peak base shear declined monotonically with RCA content: Control approximately 122 kN, RAC-50 approximately 110 kN, RAC-100 approximately 101 kN. One-way permutation ANOVA indicated a significant group effect on peak strength (Table 3; large η^2), with pairwise tests (Bonferroni-adjusted) confirming Control > RAC-50 and Control > RAC-100; RAC-50 also exceeded RAC-100 (Table 4). Ultimate drift capacity likewise dropped from approximately 3.5 % (Control) to approximately 3.2 % and approximately 2.8 %, and ductility factor μ reduced from approximately 4.2 to approximately 3.8 and approximately 3.2, respectively (Tables 2-4). The backbone (envelope) curves (Fig. 4) show all frames peaking near 2 % drift and softening thereafter, with lower envelopes as RCA increases, consistent with previously reported frame and member behavior under cyclic actions [1-5, 9, 12, 13].

Stiffness degradation (Fig. 2). Initial secant stiffness was highest for Control and lowest for RAC-100. Degradation with cycle number was evident in all groups but steeper for RAC-100, echoing reports that microcracking and the weaker ITZ in RAC accelerate stiffness loss under reversed loading [1, 3-5, 9, 11, 14]. The rate of reduction between cycles 0-4 was notably larger in RAC-100, indicating earlier onset of damage accumulation.

Energy dissipation and residual drifts (Table 2; Fig. 3). Cumulative energy dissipation decreased from approximately 4.1-4.2 MN·mm (Control) to approximately 3.6-3.7 MN·mm (RAC-50) and approximately 3.2 MN·mm (RAC-100). ANOVA found significant group effects, and pairwise comparisons showed all groups differed (Table 3-4). Residual drift measured after 3 % drift cycles increased with RCA content (approximately 0.40 % → 0.52 % → 0.75 %), implying greater permanent deformation in higher-RCA frames. Reduced hysteretic energy and larger residuals point to diminished damage-tolerance and re-centering capacity with RCA, in line with component and system-level observations in the literature [2, 4, 5, 8-10, 12, 13].

Damage observations (qualitative). Crack maps (not shown) indicated earlier joint cracking in RAC-100 and a shift in failure modes toward joint-dominated damage at higher replacement, echoing earlier beam-column joint and frame studies [3, 9]. Plastic hinge formation remained consistent with design intent but developed sooner in RAC-100 at comparable drifts, explaining the steeper stiffness decay and lower energy dissipation [1, 3, 4, 9].

Overall assessment. Across metrics, the statistical analysis supports the hypotheses that increasing RCA proportion degrades seismic performance (strength, ductility, energy, stiffness retention) relative to conventional concrete; however, RAC-50 maintained performance within ranges that are typically considered acceptable for ductile frames in comparable laboratory protocols, in agreement with prior evidence that moderate replacement ratios remain viable with appropriate detailing and mix control [1, 2, 4, 5, 8, 11-14].

Discussion

The experimental investigation clearly revealed that the incorporation of recycled concrete aggregate (RCA) significantly influences the seismic response of reinforced concrete (RC) frames. The observed reductions in compressive strength, stiffness, and ductility across increasing RCA replacement ratios are consistent with microstructural weaknesses reported in earlier works [1-3, 6, 7]. RCA, owing to adhered mortar and higher porosity, produces a more heterogeneous interfacial transition zone (ITZ) that impairs load transfer efficiency, ultimately reducing strength and stiffness under both monotonic and cyclic loading [2, 4, 6]. Despite these drawbacks, the RAC-50 frames retained adequate lateral strength and ductility to satisfy minimum code-based performance requirements, affirming that moderate replacement can be structurally viable when proper mix design and detailing are maintained [5, 8].

The experimental hysteretic responses showed stable loops and acceptable energy dissipation up to 3 % drift for both Control and RAC-50 frames, but RAC-100 exhibited rapid stiffness degradation and pinching in load-displacement curves. This behavior matches findings by Xiao *et al.* [1, 9] and Liu *et al.* [4], who attributed early stiffness loss in high-RCA members to the crushing of weak RCA particles and progressive cracking around old mortar zones. The statistical results corroborated this trend: permutation ANOVA demonstrated significant between-group differences for peak strength and ductility ($p < 0.05$), while pairwise tests confirmed a stepwise decline with increasing RCA proportion. Energy dissipation capacity, a critical indicator of seismic resilience, dropped by roughly 10 % for RAC-50 and over 20 % for RAC-100 compared to the control, aligning with previous cyclic tests of RAC columns and frames [4, 5, 10, 11].

Residual drift and plastic hinge observations further emphasized the role of RCA in altering post-yield deformation behavior. Increased residual deformations at higher RCA content indicate reduced re-centering ability, a trend similarly documented by Wang and Xiao [5] and Zhang *et al.* [8, 12]. However, the RAC-50 frames maintained controlled crack propagation and distributed yielding, suggesting that partial RCA replacement can preserve ductile mechanisms if reinforcement detailing follows seismic design provisions [11, 13]. Moreover, the moderate stiffness degradation rate in RAC-50 (Fig. 2) suggests that interlocking and frictional resistance between RCA and the cement matrix still contribute effectively to energy dissipation, supporting the hypothesis that up to 50 % substitution remains acceptable under cyclic demands.

Overall, the discussion reinforces the duality observed in prior literature: while full RCA substitution compromises seismic strength and ductility, partial substitution offers sustainable and structurally competent alternatives. The results substantiate the hypotheses that (H1) performance declines with higher RCA, yet (H2) frames with moderate RCA replacement (≤ 50 %) maintain acceptable seismic performance limits [1, 2, 4, 5, 8-14]. These findings align with Xiao *et al.* [13, 14] and Corinaldesi *et al.* [3], who advocated design adjustments and quality control as key enablers for broader structural use of recycled aggregate concrete in seismic zones.

Conclusion

The experimental study on the seismic behavior of reinforced concrete (RC) frames constructed with recycled aggregate concrete (RAC) demonstrated that while the incorporation of recycled concrete aggregate (RCA) affects the overall structural performance, it also presents an opportunity for sustainable construction without compromising safety when properly controlled. The results revealed that replacing natural coarse aggregate (NCA) with RCA leads to a gradual reduction in compressive strength, stiffness, ductility, and energy dissipation capacity of the frames, with the most pronounced effects observed at 100% replacement. Nevertheless, frames with 50% RCA substitution exhibited comparable seismic behavior to conventional concrete frames, maintaining acceptable performance limits for ductility, ultimate strength, and drift. The hysteretic response of the RAC-50 specimens showed stable loops, balanced energy dissipation, and controlled stiffness degradation, indicating that partial substitution does not significantly compromise the ability of RC frames to withstand cyclic lateral loading. Residual drift and crack patterns also confirmed that moderate RCA content allows for distributed plastic hinge formation and avoids premature joint failure. These outcomes collectively affirm that the use of RAC in structural systems can support both environmental sustainability and engineering safety when applied within optimized replacement ratios and mix proportions.

From a practical standpoint, several recommendations emerge from the findings. First, partial replacement of natural aggregates up to about 50% can be confidently adopted in structural elements of moderate seismic demand zones, provided that mix design adjustments are made to account for RCA's higher water absorption and lower stiffness. The pre-treatment of RCA, such as mechanical scrubbing or coating with pozzolanic slurry, can further improve bond strength and durability. Second, quality assurance protocols for RCA processing must be standardized, including classification based on source concrete strength and contaminant limits, to ensure consistency in mechanical performance. Third, structural detailing should emphasize adequate confinement and ductility, as RAC frames exhibit slightly faster stiffness degradation; hence, closer stirrup spacing and the use of high-strength reinforcement can mitigate potential brittleness. In seismic design practice, drift-based design limits for RAC frames may be slightly reduced to maintain safety margins. Finally, future design codes and sustainability policies should integrate RAC as a recognized structural material, with tailored design factors and performance-based guidelines. Through such measures, recycled aggregate concrete can transition from a sustainable alternative to a mainstream structural solution contributing to resource conservation, reduced carbon footprint, and resilient infrastructure in earthquake-prone regions.

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