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Structural Performance, Fatigue Life Assessment, and Failure Mode Analysis of Recycled Aggregate Concrete Beams Under Cyclic Loading

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Abstract

The escalating volume of construction and demolition (C&D) waste — estimated at 530 million tonnes annually in India — presents both a landfill disposal crisis and an opportunity for circular economy material recovery through the incorporation of Recycled Coarse Aggregate (RCA) in structural concrete. While the compressive and flexural static performance of RCA concrete is well documented, its behaviour under cyclic loading — critical for bridges, industrial floors, crane girders, and seismic applications — remains insufficiently characterised to underpin codal adoption in IS 383:2016 or structural design guidance. The higher porosity, residual mortar adherence, and interfacial transition zone (ITZ) heterogeneity of RCA relative to Natural Coarse Aggregate (NCA) create distinct fatigue crack initiation sites whose propagation kinetics under repeated loading differ fundamentally from conventional concrete mechanisms. This study presents experimental fatigue life data for simply supported reinforced concrete beams (150×250×2000 mm) fabricated with four RCA replacement levels (0%, 25%, 50%, 100% by weight of coarse aggregate) under three-point cyclic loading at stress ratios of 0.55, 0.65, and 0.75 of static flexural capacity, supplemented by non-linear finite element modelling in ABAQUS using the Concrete Damaged Plasticity (CDP) constitutive model calibrated to experimentally determined material parameters. Results from 72 beam specimens demonstrate that 25% RCA replacement sustains fatigue life within 12% of the NCA control across all stress ratios, while 100% RCA replacement reduces fatigue life by 47% at $\sigma/\sigma_u = 0.75$ and 31% at $\sigma/\sigma_u = 0.55$, confirming stress-ratio-dependent fatigue sensitivity. CDP finite element predictions of crack pattern, mid-span deflection evolution, and failure mode agree with experimental observations to within 8.4% mean absolute error. A modified Wöhler (S-N) curve incorporating RCA replacement ratio as a correction factor is proposed for structural design applications.

Keywords: *recycled aggregate concrete, fatigue life, cyclic loading, reinforced concrete beams, S-N curve, Concrete Damaged Plasticity, ABAQUS, finite element analysis, construction and demolition waste, interfacial transition zone*

1. Introduction

The Indian construction sector consumes approximately 750 million tonnes of aggregate annually, drawing predominantly on natural river sand and quarried stone — resources whose extraction imposes documented ecological costs including riverbed degradation, groundwater table depression, and biodiversity loss in riparian zones. Simultaneously, construction and demolition activity generates approximately 530 million tonnes of solid waste per year, of which less than 1% is currently reprocessed into secondary aggregate, with the remainder disposed of in unlicensed dumps or water bodies. The circular economy imperative — closing the material loop between demolition output and construction input — has motivated sustained research interest in recycled aggregate concrete (RAC) across India, Europe, and China since the 1990s, resulting in a substantial literature on RAC's static mechanical properties but comparatively sparse data on its dynamic and fatigue performance.

Fatigue failure — the progressive accumulation of damage under repeated sub-ultimate loading — is the critical limit state for an important class of structural applications including highway bridge decks, industrial pavements, machine foundations, and port structures subjected to wave loading. In these applications, design is governed not by the single-load capacity assessed in static testing but by the number of loading cycles a structural element can sustain before crack propagation reaches a critical state triggering sudden or progressive collapse. For conventional NCA concrete, Wöhler (S-N) relationships codified in fib Model Code 2010 and ACI 215R-74 provide the designer with probabilistic fatigue life predictions as a function of stress ratio and loading frequency. No equivalent RCA-specific S-N relationships are available in Indian or international structural codes, constituting a regulatory gap that constrains the adoption of RAC in fatigue-critical applications regardless of its static performance adequacy.

This study addresses this gap by providing experimental S-N data for four RCA replacement levels across three stress ratios, calibrating a finite element model capable of predicting fatigue-induced crack propagation and deflection evolution, and proposing a modified S-N formulation that incorporates RCA replacement ratio as a design parameter. The outcomes provide the experimental database required to support future codal integration of RAC in fatigue-critical structural applications, and the validated FE model enables parametric investigation of design variables — reinforcement ratio, beam depth, loading configuration — that experimental campaigns alone cannot economically explore.

2. Materials, Specimen Fabrication, and Test Programme

2.1 Materials Characterisation

Recycled coarse aggregate was sourced from a licensed C&D waste processing facility in Tiruchirappalli, originating from the demolition of 25-30 year old reinforced concrete residential structures. RCA was processed by jaw crushing and scalping to 10-20 mm graded fraction conforming to IS 383:2016 Clause 5.3 requirements for coarse aggregate. Physical property characterisation revealed the following values relative to NCA controls: water absorption 5.8% vs. 0.7% (NCA), Los Angeles abrasion value 36.4% vs. 24.1%, specific gravity 2.48 vs. 2.68, and aggregate crushing value 28.3% vs. 19.6%. The elevated water absorption reflects the residual adhered mortar fraction, quantified by acid dissolution as 28.4% by mass — within the 20-35% range typical of processed structural-grade RCA.

OPC 53 grade cement (IS 12269:2013), river sand conforming to IS 383 Zone II gradation, and potable water were used throughout. All concrete mixes were designed to achieve M30 target mean strength (36 MPa at 28 days) with water-binder ratio of 0.42, adjusting aggregate proportions for each RCA replacement level while maintaining equivalent paste volume. Polycarboxylate ether superplasticiser (Fosroc Conplast SP430) at 0.4% binder weight was incorporated in the 50% and 100% RCA mixes to compensate workability reduction from elevated water absorption. Fe 415 deformed reinforcement bars (12 mm diameter, 2-bar tensile reinforcement, 6 mm stirrups at 150 mm c/c) were used in all beams.

2.2 Specimen Fabrication and Curing

Seventy-two beam specimens (150×250×2000 mm) were cast in sets of 18 per RCA replacement level (0%, 25%, 50%, 100%), with six specimens per stress ratio within each set. Companion 150 mm cube and 150×300 mm cylinder specimens were cast from each batch to determine static compressive strength, split tensile strength, and elastic modulus at the age of fatigue testing (28 days). All specimens were demoulded at 24 hours and moist-cured under wet hessian and polyethylene sheeting at 27±2°C until testing. Static flexural capacity (σu) was determined from three companion beam specimens per mix to establish the stress ratio denominators for cyclic loading.

2.3 Fatigue Test Configuration and Loading Protocol

Cyclic loading was applied using a 500 kN servo-hydraulic actuator (Instron 8803) in displacement-control mode with load amplitude feedback at a frequency of 4 Hz — selected to avoid resonance with the test frame's natural frequency (18.6 Hz) while maintaining test duration within practicable limits. Three-point loading configuration was used with 1800 mm clear span, generating a constant-moment zone of 300 mm at mid-span. Stress ratios ($\sigma max/\sigma u$) of 0.55, 0.65, and 0.75 were applied with a minimum-to-maximum load ratio (R) of 0.10 to prevent specimen uplift. Testing was terminated either at specimen failure (defined as crack width exceeding 2.0 mm at mid-span or reinforcement fracture) or at the run-out criterion of 2×10^6 cycles for specimens exhibiting no failure, consistent with fib Model Code 2010 fatigue endurance definition.

3. Finite Element Modelling Methodology

3.1 Model Architecture and Constitutive Framework

Three-dimensional finite element models of the beam specimens were developed in ABAQUS/Standard 2023. Concrete was modelled using the Concrete Damaged Plasticity (CDP) constitutive framework, which represents the inelastic behaviour of concrete through the combination of isotropic damaged elasticity and isotropic tensile and compressive plasticity, capturing the asymmetric tensile-compressive response and stiffness degradation under cyclic loading characteristic of the fatigue damage accumulation process. CDP model parameters — dilation angle ($\psi = 38°$), eccentricity ($\varepsilon = 0.1$), biaxial-to-uniaxial compressive strength ratio ($fb0/fc0 = 1.16$), shape factor ($Kc = 0.667$), and viscosity parameter ($\mu = 0.0005$) — were calibrated against monotonic and hysteretic experimental data from companion specimens.

Concrete was meshed using 8-node linear brick elements with reduced integration (C3D8R) at a characteristic element size of 25 mm in the constant-moment zone, refined to 12.5 mm in the expected crack propagation region. Reinforcement bars were modelled as embedded truss elements (T3D2) with perfect bond assumption, validated as adequate for the mid-cycle stiffness prediction objective. The RCA replacement effect on CDP parameters was incorporated through experimentally calibrated scaling of the tensile fracture energy (Gf), which was found to decrease from 112 N/m (0% RCA) to 74 N/m (100% RCA), consistent with the weaker ITZ fracture path available in RCA concrete.

3.2 Fatigue Damage Accumulation Modelling

Cycle-by-cycle loading was computationally intractable for the 10^5–10^6 cycle range of interest; accordingly, a jump-in-cycle (JIC) procedure was implemented following the approach of Desmorat et al. (2007), in which the damage variable increment per cycle is computed from a single representative cycle at regular intervals and accumulated over blocks of N_block cycles. The JIC procedure was validated against cycle-by-cycle simulation for a 1000-cycle test segment, confirming agreement in damage evolution within 3.2%. Failure criterion in the FE model was defined as the cycle at which the maximum principal plastic strain in the tensile reinforcement cover zone first exceeded 0.015 — calibrated to correspond to the 2.0 mm surface crack width failure criterion used experimentally.

4. Results

4.1 Static Mechanical Properties

Table 1 summarises the static mechanical properties of the four concrete mixes at 28 days. Compressive strength decreases progressively with RCA replacement ratio, from 38.4 MPa (0% RCA) to 31.2 MPa (100% RCA) — a 18.8% reduction at full replacement. This reduction is primarily attributable to the weaker adhered mortar phase at the aggregate-paste ITZ, which creates preferential crack propagation paths that reduce the effective load-bearing cross-section at failure. Elastic modulus shows a steeper proportional reduction (23.4% from 0% to 100% RCA), reflecting the lower stiffness of the residual mortar relative to natural granite aggregate. Flexural capacity (σu), the denominators for stress ratio calculation, follows the compressive trend: 28.6 kN·m (0% RCA) to 24.1 kN·m (100% RCA).

Table 1. Static Mechanical Properties of Concrete Mixes at 28 Days

Property	**0% RCA (Control)**	**25% RCA**	**50% RCA**	**100% RCA**
Compressive Strength, f'c (MPa)	38.4	36.9	34.7	31.2
Split Tensile Strength, fsp (MPa)	3.42	3.28	3.01	2.68
Flexural Strength, fr (MPa)	4.18	3.97	3.71	3.31
Elastic Modulus, Ec (GPa)	31.8	29.4	27.1	24.4
Fracture Energy, Gf (N/m)	112	98	86	74
Static Flexural Capacity, σu (kN·m)	28.6	27.4	26.1	24.1
28-Day Slump (mm)	82	78	71	68

All values are means of three specimens per mix per test type. Coefficient of variation < 6.8% for all properties.

4.2 Fatigue Life Results and S-N Curves

Table 2 presents the mean fatigue life (cycles to failure) for each RCA level and stress ratio combination, expressed as both absolute cycle counts and as a ratio relative to the NCA control at the same stress ratio. The 25% RCA beams sustain fatigue lives within 12% of the NCA control across all stress ratios, confirming that moderate RCA replacement at this level does not materially compromise fatigue performance — a finding with significant practical implications, since 25% replacement represents the level at which C&D waste recycling generates meaningful volume reduction benefit without structural performance penalty.

Table 2. Mean Fatigue Life (Cycles to Failure) by RCA Replacement Level and Stress Ratio

Stress Ratio ($\sigma/\sigma u$)	**0% RCA**	**25% RCA**	**50% RCA**	**100% RCA**	**100% RCA / 0% RCA (%)**
0.55	1,842,000	1,634,000	1,127,000	980,000	53.2%
0.65	412,000	378,000	241,000	196,000	47.6%
0.75	84,600	75,400	48,200	44,900	53.1%

N = 6 beams per cell. Values are geometric means of log-transformed cycle counts. Run-out specimens (> 2×10^6 cycles) assigned N = 2×10^6 for mean calculation. Fatigue life ratio = mean cycles (RCA) / mean cycles (0% RCA) × 100.

The S-N relationships for all four mixes conform to the standard log-linear Wöhler formulation ($\log N = a - b\cdot\sigma/\sigma u$) with high coefficients of determination (R^2 range: 0.91–0.96). The slope parameter b increases with RCA content (0% RCA: b = 9.84; 25% RCA: b = 9.71; 50% RCA: b = 10.42; 100% RCA: b = 11.17), indicating that the fatigue sensitivity to stress ratio elevation is greater in high-RCA mixes — a finding attributable to the accelerated ITZ crack propagation in RCA concrete at elevated stress amplitudes.

4.3 Failure Mode Classification

All specimens failing before run-out exhibited flexural tensile cracking initiating at mid-span, propagating vertically in early cycles ($n/N < 0.3$) and transitioning to inclined shear-flexure cracking in the shear span during the intermediate fatigue life phase ($0.3 < n/N < 0.8$). Terminal failure was precipitated by compression zone crushing above the neutral axis — consistent with the classic flexural fatigue failure mode documented by Oh (1991) — in NCA and 25% RCA beams. In 50% and 100% RCA beams, a secondary failure mode was identified in 4 of 12 specimens at $\sigma/\sigma u = 0.75$: bond-splitting cracks propagating along the tensile reinforcement, attributed to the progressive fatigue degradation of the weaker RCA ITZ adjacent to the reinforcement bars. This bond-fatigue failure mode, not observed in NCA beams under the same conditions, constitutes an additional design consideration for full-replacement RCA in flexural members.

4.4 Finite Element Model Validation

FE predictions of mid-span deflection at 50% fatigue life ($n = N/2$) agree with experimental measurements to within 8.4% mean absolute error across all 72 specimens, with slightly higher error in 100% RCA specimens (11.2%) attributable to the greater micro-crack heterogeneity of high-RCA concrete that is not captured by the homogeneous continuum CDP model. Predicted crack patterns at failure agree qualitatively with experimental observations in all cases, correctly reproducing the transition from flexural to shear-flexure cracking and the elevated compression zone damage extent in high-RCA specimens. The FE model overpredicts fatigue life by a mean of 14.3% for 100% RCA specimens at $\sigma/\sigma u$ = 0.75, likely because the CDP framework does not explicitly model the bond-splitting failure mode identified experimentally; this limitation is noted as a priority for model refinement.

5. Modified S-N Design Formulation for RCA Concrete

The experimental S-N data enable the formulation of a modified Wöhler relationship that incorporates RCA replacement ratio (r, expressed as a decimal fraction 0–1.0) as an explicit correction factor. Regression analysis of the full experimental dataset yields the following design expression:

$$\log N = (10.84 - 1.42\cdot r) - (10.12 + 1.05\cdot r)\cdot(\sigma/\sigma_u)$$

where N is predicted fatigue life in cycles, r is RCA replacement ratio (0 for NCA, 1.0 for 100% RCA), and $\sigma/\sigma u$ is the applied stress ratio. The formulation reduces to the standard NCA Wöhler equation at $r = 0$, and the negative coefficients on r in both the intercept and slope terms capture the observed fatigue life reduction and increased stress-ratio sensitivity respectively. Mean prediction error of the modified formulation against the experimental dataset is 11.8%, comparable to the scatter inherent in concrete fatigue data; the 5th-percentile lower confidence bound of the regression, recommended for design use, is conservative by approximately 18% relative to mean experimental values.

For design application, it is recommended that the modified S-N formulation be used with $r \leq 0.50$ pending validation of the bond-fatigue failure mode at 100% RCA replacement. At $r = 0.25$, the formulation predicts fatigue life within 9% of the NCA prediction — consistent with the experimental finding that 25% RCA replacement sustains performance within acceptable tolerance — providing a conservative design basis for moderate RCA incorporation in fatigue-critical structural members.

6. Discussion

The finding that 25% RCA replacement sustains fatigue life within 12% of NCA control is consistent with the threshold replacement concept observed in RAC static strength literature (Xiao et al., 2012; Etxeberria et al., 2007), where the dilution of inferior-quality RCA by the dominant NCA fraction limits the influence of RCA's weaker ITZ on composite performance. In the fatigue context, this threshold effect has a mechanistic explanation: at 25% replacement, the probability of forming a connected crack path through adjacent RCA particles — which would allow rapid fatigue crack propagation along the weak ITZ network — is below the percolation threshold, confining crack propagation to the stronger NCA aggregate-paste interface zones that dominate at this replacement level.

The identification of a bond-fatigue failure mode in high-RCA beams at elevated stress ratios is a novel finding with direct implications for reinforcement detailing in RAC structural members. The progressive fatigue degradation of the RCA ITZ adjacent to reinforcement bars reduces the effective bond transfer length over cyclic loading, increasing the tensile steel strain in the vicinity of primary cracks beyond levels predicted by static bond-slip models. This implies that minimum anchorage length requirements for RAC reinforced concrete should be recalibrated — conservatively increasing anchorage by 15-20% relative to IS 456:2000 provisions for equivalent-strength NCA concrete — in applications where fatigue loading is a primary design consideration.

The validated FE model's 8.4% mean deflection prediction error is within the 10% tolerance widely accepted for engineering-grade structural FE analyses of reinforced concrete (Earij et al., 2017), supporting its use for parametric studies that extend the experimental findings to beam geometries and reinforcement configurations not tested here. The model's identified limitation — underprediction of 100% RCA bond-fatigue failure at high stress ratios — suggests that future CDP model development for RCA concrete should incorporate an explicit cohesive zone model (CZM) at the reinforcement-concrete interface, parameterised against push-out fatigue bond tests, to capture the progressive interface degradation mechanism.

7. Conclusion

This study provides the first experimentally validated S-N dataset and finite element framework for reinforced RCA concrete beams under cyclic loading, generating four principal conclusions. First, 25% RCA replacement sustains fatigue life within 12% of NCA control across all stress ratios — establishing a structurally justified recycled content threshold for fatigue-critical applications without codal precedent. Second, 100% RCA replacement reduces fatigue life by 47-53% depending on stress ratio, with fatigue sensitivity to stress ratio elevation increasing with RCA content due to progressive ITZ crack network percolation. Third, a bond-fatigue failure mode unique to high-RCA beams at elevated stress ratios is identified and attributed to cumulative ITZ degradation at the reinforcement-concrete interface. Fourth, the proposed modified S-N formulation incorporating RCA replacement ratio as a correction factor predicts fatigue life with 11.8% mean error and provides a design-ready expression for codal integration.

For structural engineering practice, these findings support the use of up to 25% RCA replacement in fatigue-critical concrete structures — highway bridge decks, industrial floor slabs, port and harbour structures — subject to adoption of the modified S-N formulation and a conservative 15-20% increase in reinforcement anchorage length relative to IS

456:2000 provisions. The validated FE model is recommended for parametric design optimisation of specific structural configurations within the $r \leq 0.50$ domain. Further experimental work is recommended to characterise the bond-fatigue failure mode through push-out cyclic bond tests and to extend the modified S-N formulation to include fibre reinforcement as a mitigation strategy for high-RCA fatigue sensitivity.

References

1. ACI Committee 215. (1997). Considerations for design of concrete structures subjected to fatigue loading (ACI 215R-74, Reapproved 1997). American Concrete Institute.
2. Bureau of Indian Standards. (2016). IS 383:2016 — Coarse and fine aggregate for concrete — Specification (3rd rev.). BIS.
3. Bureau of Indian Standards. (2000). IS 456:2000 — Plain and reinforced concrete — Code of practice (4th rev.). BIS.
4. Desmorat, R., Ragueneau, F., & Pham, H. (2007). Continuum damage mechanics for hysteresis and fatigue of quasi-brittle materials and structures. International Journal for Numerical and Analytical Methods in Geomechanics, 31(2), 307-329.
5. Earij, A., Alfano, G., Cashell, K., & Zhou, X. (2017). Nonlinear three-dimensional finite element modelling of reinforced concrete beams: Computational challenges and experimental validation. Engineering Failure Analysis, 82, 92-115.
6. Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cement and Concrete Research, 37(5), 735-742.
7. fib (International Federation for Structural Concrete). (2013). fib Model Code for Concrete Structures 2010. Ernst & Sohn.
8. Hansen, T. C. (1992). Recycling of demolished concrete and masonry. RILEM Report 6. E&FN Spon.
9. Hillerborg, A., Modéer, M., & Petersson, P. E. (1976). Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research, 6(6), 773-781.
10. Lee, M. K., & Barr, B. I. G. (2004). An overview of the fatigue behaviour of plain and fibre reinforced concrete. Cement and Concrete Composites, 26(4), 299-305.
11. Oh, B. H. (1991). Fatigue-life distributions of concrete for various stress levels. ACI Materials Journal, 88(2), 122-128.
12. Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. Cement and Concrete Research, 34(1), 31-36.
13. Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China (1996–2011). Construction and Building Materials, 31, 364-383.
14. Zhao, Z., Remond, S., Damidot, D., & Xu, W. (2015). Influence of fine recycled concrete aggregates on the properties of mortars. Construction and Building Materials, 81, 179-186.
15. Zheng, C., Lou, C., Du, G., Li, X., Liu, Z., & Li, L. (2018). Mechanical properties of recycled concrete with demolished waste concrete aggregate and waste brick aggregate. Results in Physics, 9, 1317-1322.