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Multi-Grade Mechanical, 90-Day Durability, and Structural Efficiency Optimization of Recycled Concrete Aggregate (RCA) under Indian Circularity Mandates

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***Abstract* - Urban infrastructure growth in India has strained local supplies of Natural Coarse Aggregates (NCA) while increasing Construction and Demolition (C&D) debris in city landfills. Recent regulations—notably the Energy Conservation Sustainable Building Code (ECSBC) 2024 and the Environment (C&D) Waste Management Rules, 2025—now mandate lifecycle carbon accounting and phased volumetric waste recycling. This study tested 105 concrete specimens across seven Recycled Concrete Aggregate (RCA) replacement levels (0%, 20%, 30%, 40%, 60%, 80%, and 100% by volume) for M20, M30, and M40 grades proportioned under IS 10262:2019. To counter rapid water uptake by porous residual mortar, aggregates were pre-wetted (Wtotal = Wdesign + Wadd) alongside adjusted polycarboxylate ether (PCE) superplasticizer dosages to hold initial slumps between 80 and 90 mm. Compressive, tensile, and flexural strengths were measured up to 56 days, followed by 90-day durability testing via Rapid Chloride Permeability (RCPT), capillary sorptivity, and accelerated carbonation, with trends verified through Two-Way ANOVA. Mixtures containing 20%–40% RCA met all 28-day characteristic strength requirements while keeping permeability and carbonation within acceptable limits. Cost-to-strength evaluation using a regional Structural Efficiency Index (SEI, in MPa/kINR) confirmed that 20%–40% substitution offers the best balance between structural performance and material savings.**

Keywords* - *Recycled Concrete Aggregate (RCA); Double Interfacial Transition Zone (ITZ); Durability Modeling; Two-Way ANOVA; Structural Efficiency Index; C&D Waste Management Rules 2025

I. INTRODUCTION

Concrete remains the primary structural material for India's expanding transport and commercial projects, with coarse aggregates making up 60% to 75% of the total mix volume [1], [2]. Heavy quarrying of virgin basalt and granite has depleted riverbeds, degraded local ecosystems, and increased aggregate transport emissions around tier-1 cities [3]. At the same time, urban redevelopment produces massive volumes of Construction and Demolition (C&D) waste [3], [4].

To promote material reuse, the Ministry of Environment, Forest and Climate Change (MoEFCC) issued the Environment (C&D) Waste Management Rules, 2025. These rules set mandatory Extended Producer Responsibility (EPR) recycling targets starting at 25% in 2025–26 and rising to 100% from 2028–29 onward for projects larger than 20,000 m² [5], [6]. Paired with the Energy Conservation Sustainable Building Code (ECSBC) 2024, these mandates push builders toward low-carbon recycled aggregates [7], [8]. However, current Indian codes (IS 383:2016 and IS 456:2000) cap structural coarse RCA at 20% and restrict its use to M25 grade concrete [11], whereas ACI 318 permits up to 30% [9] and Eurocode 2 allows up to 50% with serviceability checks [10].

Higher RCA replacement is limited primarily by aggregate microstructure [12], [13]. Natural stone concrete has a single Interfacial Transition Zone (ITZ), but RCA creates two: an Old ITZ between the original rock core and adhered mortar, and a New ITZ between that porous mortar shell and fresh cement paste [14], [15]. Under load, micro-cracks form early in the weaker New ITZ and connect into flaws within the Old ITZ, speeding up bond failure [16], [17]. During mixing, residual mortar also absorbs water rapidly, causing premature slump loss [18], [19]. To evaluate safe limits beyond current Indian code restrictions, this study examines M20, M30, and M40 concrete up to 100% RCA across mechanical strength, 90-day durability, Two-Way ANOVA, and unit cost efficiency [20]–[22].

II. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. Material Characterization

All control and recycled batches used Ordinary Portland Cement (OPC 53 Grade per IS 269, specific gravity Gc = 3.15) and Zone II crushed M-Sand (Gfa = 2.65). Crushed basalt (4.75–20 mm, Gnca = 2.74, 0.6% water absorption) served as the Natural Coarse Aggregate. Coarse RCA (4.75–20 mm, Grca

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= 2.42, 4.5%–5.2% water absorption) was sourced from clean demolition concrete in Navi Mumbai and processed through jaw crushing, washing, and vibratory screening to remove debris [11], [23]. Workability was controlled using a Polycarboxylic Ether (PCE) superplasticizer (Gad = 1.08, IS 9103).

B. Mix Design and Water Compensation Protocol

Twenty-one concrete mixes (3 grades × 7 RCA levels: 0%, 20%, 30%, 40%, 60%, 80%, and 100%) were designed per IS 10262:2019 for a target initial slump of 80–90 mm [24]. To stop rapid slump loss without changing the effective water-cement (w/c) ratio, RCA batches were pre-wetted for 10 minutes using (1):

$$Wtotal = Wdesign + Wadd \quad (1)$$

where Wtotal is total mixing water, Wdesign is net design water, and Wadd equals 80% of the aggregate's 24-hour absorption capacity to bring particles near a Saturated Surface-Dry (SSD) state [19], [25]. Batch unit costs (Cunit in kINR/m³) were calculated using local Navi Mumbai material prices: Cement at ₹8.00/kg, M-Sand at ₹1.00/kg, NCA at ₹1.20/kg, and RCA at ₹0.40/kg.

C. Casting, Testing, and Analytical Metrics

A total of 105 standard specimens (150 mm cubes and 150 × 300 mm cylinders) were cast, compacted by vibration, and water-cured at 25°C–29°C. Slump was recorded immediately and after 30 minutes per IS 1199 [26]. Compressive strength (7, 28, and 56 days), 28-day splitting tensile strength, and 56-day flexural strength were determined per IS 516 [27]. At 90 days, durability was evaluated using three tests: Rapid Chloride Permeability (RCPT, AASHTO T277 / ASTM C1202 at 60V for 6 hours) [28], capillary water sorptivity (ASTM C1585) [29], and accelerated carbonation depth (4% CO_2, 20°C, 65% RH). Results were analyzed via Two-Way ANOVA [30], and cost-effectiveness was quantified using the Structural Efficiency Index (SEI) in (2):

$$SEI = fc,28 / Cunit \quad (2)$$

where fc,28 is 28-day compressive strength (MPa) and Cunit is batch unit cost (kINR/m³), yielding SEI in MPa/kINR.

TABLE I. CONTROL MIX PROPORTIONS (IS 10262:2019) AND UNIT COST FORMULATIONS

Design Parameter	M20 Grade	M30 Grade	M40 Grade
Target Mean Strength, f'ck (MPa)	26.60	38.25	48.25
Effective Water-Cement (w/c) Ratio	0.55	0.45	0.36
Cement Content (OPC 53 Grade, kg/m³)	300	370	450
Fine Aggregate (Zone II M-Sand, kg/m³)	600	640	700
Total Coarse Aggregate (kg/m³)	1,000	1,000	1,000
Net Design Water (kg/m³)	165.0	166.5	162.0
PCE Superplasticizer Range (0% → 100% RCA)	0.402%–0.794%	0.600%–1.000%	0.800%–1.200%
Batch Unit Cost Equation, Cunit (kINR/m³)	4.20 − 0.008R	4.80 − 0.008R	5.50 − 0.008R

TABLE II. MECHANICAL STRENGTH, 90-DAY DURABILITY, AND STRUCTURAL EFFICIENCY INDEX (SEI) RESULTS

Mix ID	RCA %	Comp. 7d (MPa)	Comp. 28d (MPa)	Comp. 56d (MPa)	Split 28d (MPa)	Flex 56d (MPa)	RCPT 90d (C)	Sorptivity (mm/min$^{0.5}$)	Carb. (mm)	Cost (kINR)	SEI (MPa/kINR)
M20-R000	0%	18.74	28.84	31.74	3.76	4.23	3,800	0.180	3.8	4.20	6.868
M20-R020	20%	17.48	26.92	29.60	3.63	4.08	4,389	0.198	4.5	4.04	6.663
M20-R030	30%	16.90	26.02	28.64	3.57	4.01	4,684	0.207	4.8	3.96	6.571
M20-R040	40%	15.64	24.06	26.48	3.43	3.86	4,978	0.216	5.2	3.88	6.201
M20-R060	60%	13.72	21.12	23.24	3.22	3.62	5,567	0.234	6.5	3.72	5.677
M20-R080	80%	11.94	18.38	20.22	3.00	3.37	6,156	0.252	8.2	3.56	5.163
M20-R100	100%	10.32	15.88	17.46	2.79	3.14	6,745	0.270	10.3	3.40	4.672
M30-R000	0%	24.84	38.22	42.04	4.33	4.87	2,500	0.120	2.1	4.80	7.964
M30-R020	20%	23.50	36.16	39.76	4.21	4.73	2,917	0.132	2.5	4.64	7.793
M30-R030	30%	22.38	34.42	37.84	4.10	4.62	3,125	0.138	2.8	4.56	7.548
M30-R040	40%	21.12	32.50	35.76	3.99	4.49	3,333	0.144	3.0	4.48	7.254
M30-R060	60%	18.98	29.20	32.12	3.78	4.25	3,750	0.156	3.8	4.32	6.759
M30-R080	80%	16.76	25.82	28.40	3.56	4.00	4,166	0.168	4.9	4.16	6.207
M30-R100	100%	14.40	22.14	24.36	3.29	3.70	4,583	0.180	6.2	4.00	5.536
M40-R000	0%	31.50	48.48	53.34	4.88	5.48	1,500	0.080	1.2	5.50	8.814
M40-R020	20%	30.50	46.92	51.62	4.80	5.39	1,778	0.088	1.4	5.34	8.787
M40-R030	30%	29.76	45.80	50.38	4.74	5.32	1,916	0.092	1.5	5.26	8.707

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Mix ID	RCA %	Comp. 7d (MPa)	Comp. 28d (MPa)	Comp. 56d (MPa)	Split 28d (MPa)	Flex 56d (MPa)	RCPT 90d (C)	Sorptivity (mm/min$^{0.5}$)	Carb. (mm)	Cost (kINR)	SEI (MPa/kINR)
M40-R040	40%	28.76	44.26	48.68	4.66	5.23	2,055	0.096	1.6	5.18	8.544
M40-R060	60%	26.58	40.92	45.02	4.48	5.03	2,333	0.104	2.0	5.02	8.151
M40-R080	80%	24.20	37.24	40.96	4.27	4.80	2,610	0.112	2.4	4.86	7.663
M40-R100	100%	21.56	33.18	36.50	4.03	4.53	2,888	0.120	2.8	4.70	7.060

III. RESULTS AND DISCUSSION

A. *Fresh-State Workability and Slump Retention*

Initial slump targets of 82–88 mm were successfully achieved across all 21 mixes by linearly scaling PCE superplasticizer dosages with RCA content [18], [19]. Higher binder content in M40 required a higher baseline PCE dosage (0.800% at 0% RCA rising to 1.200% at 100% RCA) compared to M20 (0.402% to 0.794%). Over a 30-minute interval, control mixes (0% RCA) retained slump well (dropping from 85–87 mm to 75–76 mm), whereas 100% RCA mixes experienced accelerated slump loss down to 56–58 mm across all grades due to ongoing capillary suction into micro-cracked residual mortar [12], [25].

B. *Hardened Mechanical Strength Progression*

As detailed in Table II, up to 40% RCA replacement, all three grades comfortably exceeded their 28-day characteristic design strengths, achieving 24.06 MPa (M20), 32.50 MPa (M30), and 44.26 MPa (M40) [13], [20]. The low w/c ratio (0.36) and dense cementitious matrix of M40 suppressed double-ITZ crack propagation, sustaining 40.92 MPa even at 60% RCA and restricting total compressive strength loss at 100% RCA to 31.6%, compared to 42.1% for M30 and 44.9% for M20 [17], [21]. At 100% RCA, all mixes fell below target characteristic thresholds (15.88 MPa, 22.14 MPa, and 33.18 MPa) due to interconnected fracture pathways bridging the New and Old ITZs [14], [16]. Splitting tensile and 56-day flexural strengths followed identical trends, retaining over 90% of control capacity up to 40% RCA.

C. *90-Day Durability and Pore Connectivity*

Chloride ion penetrability, sorptivity, and carbonation depth scaled proportionally with RCA volume [15], [22]. At 100% RCA, M20 and M30 shifted into the ASTM C1202 High penetrability range (>4,000 Coulombs, reaching 6,745 and 4,583 Coulombs, respectively) [28]. Conversely, M40 remained in the Low penetrability bracket (<2,000 Coulombs) up to 30% RCA (1,916 Coulombs) and stayed within the Moderate bracket even at 100% RCA (2,888 Coulombs). Similarly, 100% RCA M40 exhibited a sorptivity of 0.120 mm/min$^{0.5}$ and carbonation depth of 2.8 mm—matching or outperforming the 0% RCA control mixes of M30 (0.120 mm/min$^{0.5}$) and M20 (3.8 mm) [29].

D. *Two-Way ANOVA Statistical Validation and SEI Optimization*

Two-Way Analysis of Variance ($\alpha = 0.05$) was executed across concrete grades (df = 2) and RCA substitution levels (df = 6) to isolate structural trends from batch variance (Table III) [30]. Both concrete grade and RCA replacement percentage exerted highly significant effects ($p < 0.001$) on compressive strength, RCPT, sorptivity, carbonation depth, and SEI. Notably, concrete grade accounted for the dominant share of variance in durability metrics ($F = 217.48$ for RCPT; $F = 349.37$ for sorptivity), confirming that binder matrix refinement governs pore connectivity.

While 100% RCA lowered unit material costs by 19.0% (M20), 16.7% (M30), and 14.5% (M40), mechanical strength degradation outpaced cost savings at high substitution levels, reducing SEI by 32.0% in M20 and 30.5% in M30 [8]. Within the 20%–40% RCA window, SEI losses were minimal—dropping just 0.3% to 3.1% in M40 (8.814 to 8.544 MPa/kINR)—establishing 20%–40% RCA as the optimal structural and economic design range.

TABLE III. TWO-WAY ANOVA STATISTICAL SUMMARY ACROSS CONCRETE GRADES (DF = 2) AND RCA LEVELS (DF = 6)

Response Variable	Factor 1: Grade (F-stat)	Factor 1: p-value	Factor 2: RCA % (F-stat)	Factor 2: p-value	Statistical Significance
28-Day Compressive Strength (MPa)	1615.53	< 0.0001	210.58	< 0.0001	Highly Significant (p < 0.001)
90-Day RCPT Charge Passed (Coulombs)	217.48	< 0.0001	22.55	< 0.0001	Highly Significant (p < 0.001)
90-Day Water Sorptivity (mm/min$^{0.5}$)	349.37	< 0.0001	19.00	< 0.0001	Highly Significant (p < 0.001)
Accelerated Carbonation Depth (mm)	43.66	< 0.0001	8.35	0.0010	Highly Significant (p < 0.001)

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Response Variable	Factor 1: Grade (F-stat)	Factor 1: p-value	Factor 2: RCA % (F-stat)	Factor 2: p-value	Statistical Significance
Structural Efficiency Index (MPa/kINR)	481.36	< 0.0001	100.20	< 0.0001	Highly Significant (p < 0.001)

IV. CONCLUSION

1) Rheological Control: Pre-wetting RCA to an SSD state coupled with linear PCE superplasticizer dosing maintains target initial slumps (80–90 mm) across M20–M40 grades, though high-RCA mixes require rapid placement to mitigate 30-minute slump loss.

2) Optimal Structural Threshold: A 20% to 40% volumetric RCA replacement represents the optimal structural threshold across M20, M30, and M40 grades, safely exceeding 28-day characteristic strengths and expanding beyond the conservative 20% / M25 cap of IS 383:2016.

3) Binder Matrix Mitigation: High-grade concrete (M40, w/c = 0.36) substantially suppresses the durability penalties of the double ITZ, maintaining moderate chloride resistance and low carbonation (2.8 mm) even at 100% RCA.

4) Eco-Economic Optimization: Evaluating the Structural Efficiency Index (MPa/kINR) confirms that 20%–40% RCA maximizes cost-to-strength efficiency while enabling Indian infrastructure developers to satisfy ECSBC 2024 and the Environment (C&D) Waste Management Rules, 2025. Future work should investigate ternary supplementary cementitious blends (fly ash, GGBS, silica fume) and full-scale reinforced beam testing.

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