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Geopolymer Concrete and Recycled Aggregate Concrete: Mechanical Performance, Durability Characterization, and Lifecycle Sustainability Assessment for Indian Low-Carbon Construction

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ABSTRACT

The global construction industry's dependency on ordinary Portland cement (OPC) contributing 5–8% of anthropogenic CO_2 emissions at 0.83 kg CO_2 per kilogram of clinker **[1]** demands transformative material substitution strategies beyond partial OPC replacement. Geopolymer concrete (GPC), produced through alkali activation of industrial by-product aluminosilicates without any OPC, and recycled aggregate concrete (RAC), substituting virgin aggregates with crushed demolition concrete, represent two complementary decarbonisation pathways that have received substantial international research attention but remain inadequately characterised for Indian material conditions and IS code frameworks **[2],[3]**. This paper presents a comprehensive experimental investigation of: (i) four GPC mixes fly ash/GGBS binary systems at FA: GGBS ratios of 70:30, 50:50, 30:70, and 100% GGBS, activated with NaOH + Na_2SiO_3; (ii) five RAC mixes at coarse RCA replacement levels of 0%, 25%, 50%, 75%, and 100%; and (iii) two hybrid GPC-RAC mixes combining geopolymer binders with 25% and 50% RCA. Compressive strength, flexural strength, split tensile strength, rapid chloride permeability (RCPT per ASTM C1202 **[4]**), water absorption, sorptivity, and modulus of elasticity are evaluated at 7, 28, 56, and 90 days. Embodied CO_2 is quantified using the ICE database **[5]** and lifecycle cost analysis (LCCA) over 50 years is conducted per ISO 15686 **[6]**. GPC-GGBS100 achieves the highest 28-day compressive strength (46.4 MPa, M40 grade), while GPC-FA70:GGBS30 demonstrates 44.6% embodied CO_2 saving relative to OPC concrete at equivalent M35 strength. RAC at 25% RCA with pre-soaking treatment achieves IS 456: 2000 **[7]** M30 compliance (f'c = 33.8 MPa) with 90.1% OPC concrete strength retention. The hybrid GPC-RAC-25% mix achieves M35 strength with 55.8% total embodied CO_2 reduction the highest sustainability metric in the programme.

Keywords *Geopolymer Concrete [2],[8], Alkali Activation [9], Fly Ash [10], GGBS [11], Recycled Aggregate Concrete [3],[12], RCA [3],[13], IS 456 [7], RCPT [4], Embodied* CO_2 *[1],[5], Lifecycle Cost Analysis [6].*

I. INTRODUCTION

The construction industry confronts a dual sustainability crisis: an emissions crisis driven by cement production's disproportionate contribution to global CO_2 budgets **[1]**, and a resource crisis driven by the depletion of virgin aggregate resources an estimated 40–50 billion tonnes of aggregate is extracted globally each year, representing the world's largest material flow after water **[14]**. In India, the intersection of these crises is particularly acute: cement production of

380 million tonnes per annum **[15]** co-exists with an emerging construction waste management challenge, as the Indian construction and demolition (C&D) waste stream reaches approximately 150 million tonnes per year with less than 1% formally recycled **[16]**. These twin challenges demand structural material solutions that simultaneously reduce embodied carbon in the binder phase and divert demolished concrete from landfill into productive structural applications.

Geopolymer concrete represents the most radical decarbonisation strategy available to concrete technology: complete elimination of OPC through alkali activation of industrial by-product aluminosilicates, principally fly ash (FA) and ground granulated blast furnace slag (GGBS) **[2], [8]**. Pioneered by Davidovits **[8]** and extensively characterised by Provis and van Deventer **[9]**, geopolymers produce a three-dimensional inorganic polymer network through polycondensation of aluminate and silicate species in strongly alkaline environments, yielding mechanical and durability properties competitive with or superior to OPC concrete without CO_2-intensive clinker calcination **[2], [9]**. The embodied CO_2 saving potential of GPC is 40–80% relative to OPC concrete, depending on the source material and activator production method **[17]**.

Recycled concrete aggregate (RCA) produced by crushing and screening demolished concrete structures offers a complementary resource-efficiency pathway **[3], [12]**. The IS 383: 2016 **[18]** Annex G permits RCA use in structural concrete up to 25% coarse aggregate replacement, but the performance characteristics of RCA concrete lower specific gravity, higher water absorption, weaker interfacial transition zone (ITZ) due to attached old mortar require careful mix design adjustment and pre-treatment protocols **[3], [12],[13]** to ensure structural adequacy. The combination of GPC binders with RCA aggregates in hybrid GPC-RAC systems has been minimally investigated but represents a potentially transformative circular economy concrete that simultaneously eliminates clinker CO_2 and diverts demolished concrete from waste **[19]**.

The present paper addresses three previously identified research gaps: (i) systematic characterisation of ambient-cured FA/GGBS binary GPC mixes across FA:GGBS ratios relevant to Indian by-product availability **[15]**; (ii) RCA concrete performance under Indian IS 383: 2016 **[18]** and IS 456: 2000 **[7]** frameworks with pre-soaking treatment per Poon et al. **[13]**; and (iii) experimental evaluation of hybrid GPC-RAC systems providing combined lifecycle sustainability benefits, assessed through a structured LCCA per ISO 15686 **[6]**.

II. LITERATURE REVIEW

A. Geopolymer Chemistry and Binder Formation

The geopolymerisation reaction was first described by Davidovits **[8]** as the alkaline dissolution of aluminosilicate source materials followed by condensation polymerisation into three-dimensional Si-O-Al networks. The polycondensation process produces the characteristic geopolymer repeat unit:

$Mn\{-(SiO_2)z-AlO_2\}n \cdot wH_2O$ (Eq. 1) [8],[9]

where M is the alkali cation (Na^+ or K^+), n is the degree of polycondensation, z is the Si/Al molar ratio (1, 2, or 3 for poly-sialate, poly-sialate-siloxo, and poly-sialate-disiloxo structures respectively), and w is the bound water content **[8]**. The Si/Al ratio is the primary structural determinant: Si/Al ≈ 2 produces poly-sialate-siloxo (–Si–O–Al–O–Si–O–) networks with optimal compressive strength (40–80 MPa) and resistance to acid and sulphate attack **[9]**. Provis and van Deventer **[9]** provided the comprehensive mechanistic framework for geopolymerisation kinetics, establishing that dissolution rate of the source glass is the rate-controlling step at ambient temperature.

The activator system critically governs GPC properties. Combinations of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are the most commonly used activators **[2], [8]**). The NaOH provides alkalinity for dissolution; Na_2SiO_3 provides additional soluble silicate, increasing the Si/Al ratio in the reaction mixture and accelerating polycondensation **[9]**. Activator modulus Ms = SiO_2/Na_2O molar ratio in the combined activator solution is a critical parameter: Nath and Kumar **[20]** reported optimal Ms = 1.5–2.5 for binary FA/GGBS geopolymers at ambient curing. The activator liquid-to-binder (L/B) ratio governs workability and strength similarly to w/c in OPC concrete: increasing L/B improves workability but reduces compressive strength **[2], [20]**.

B. Fly Ash and GGBS Binary Geopolymers

Pure fly ash geopolymers require elevated temperature curing (60–80°C) to develop adequate strength at reasonable timescales **[10]**), limiting field applicability. The addition of GGBS overcomes this limitation: Ca^{2+} ions released from GGBS hydration catalyse gel formation at ambient temperature **[11]**), while FA contributes amorphous SiO_2 to the polycondensation reaction **[10]**). Nath and Kumar **[20]** demonstrated that FA: GGBS ratios between 60:40 and 80:20 optimise the balance of workability (adequate setting time) and strength development (28-day f'c > 35 MPa) at ambient curing. At higher GGBS fractions (>60%), rapid stiffening limits workability to under 30 minutes a practical constraint for site mixing **[20]**.

The C-A-S-H (calcium aluminosilicate hydrate) and N-A-S-H (sodium aluminosilicate hydrate) gels co-produced in binary FA/GGBS geopolymers have distinctly different microstructures: C-A-S-H is denser and contributes earlier strength; N-A-S-H has lower Ca/Si ratio and contributes long-term strength and chemical resistance **[9],[21]**. The intermixing of these two gel types in binary systems produces a synergistic microstructural composite with superior overall mechanical performance compared to either pure FA or pure GGBS geopolymer **[20],[21]**.

C. Properties of Recycled Concrete Aggregate (RCA)

RCA is characterised by the presence of residual cement mortar adhered to the original aggregate particles, typically constituting 25–44% of RCA mass **[3]**). This adhered mortar is responsible for the deteriorated engineering properties of RCA relative to virgin natural aggregate (NA): higher water absorption (3.5–7.0% vs. 0.5–1.5%) **[3],[12]**), lower specific gravity (2.30–2.45 vs. 2.60–2.65), higher Los Angeles abrasion loss (30–40% vs. 20–25%), and lower crushing value **[12]**). The double ITZ formed in RAC concrete at the old mortar/original aggregate interface and the new paste/old mortar interface creates preferential crack propagation pathways reducing tensile performance relative to NAC **[3],[13]**.

Water absorption of RCA is the most critical property for mix design, requiring adjustment of effective w/c to account for aggregate absorption per IS 383: 2016 **[18]**:

$w\_eff = w\_total - (WA\_RCA - WA\_NA) \times m\_RCA / 1000$ (Eq. 2) [18],[7]

where w_eff = effective water contributing to w/c ratio (litres), w_total = total water added (litres), WA_RCA and WA_NA = water absorption percentages of RCA and natural aggregate respectively, and m_RCA = mass of RCA per cubic metre (kg) **[18]**. Failing to account for this additional absorption results in effective w/c ratios below design values, reducing workability without commensurately improving strength due to inadequate aggregate saturation **[3],[13]**.

Pre-soaking RCA for 30 minutes before batching the treatment applied in the present study saturates the old mortar pores prior to mixing, preventing in-situ absorption from the fresh cement paste and maintaining the design effective w/c ratio **[13]**). Poon et al. **[13]** demonstrated that pre-soaking reduces 28-day strength reduction from 12–15% (unsaturated RCA) to 3–5% (pre-soaked RCA) at 25% replacement, confirming its practical benefit. Limbachiya et al. **[12]** established the widely cited strength reduction model for RAC at coarse RCA replacement levels $r\_RCA \leq 50\%$:

$f'c, RAC / f'c, NAC \approx 1 - 0.003 \times r\_RCA$ (Eq. 3) [12]

predicting 7.5% strength reduction at 25% RCA replacement consistent with the present study's experimental finding of 9.9% reduction (pre-soaked) and 15.4% (unsaturated) at 25% replacement.

D. Hybrid GPC-RAC Systems

The combination of geopolymer binders with recycled aggregates GPC-RAC hybrid systems represents a theoretically attractive circular economy material, simultaneously eliminating clinker CO_2 (GPC binder) and diverting C&D waste from landfill (RCA) **[19]**). Published data on GPC-RAC hybrids are limited: Shaikh **[22]** produced FA-based GPC-RAC with 25% RCA at elevated temperature curing, reporting strengths of 38–42 MPa. Vignesh et al. **[23]** produced ambient-cured binary FA/GGBS GPC-RAC with 25% and 50% RCA, finding that RCA at 25% produced negligible strength reduction (<5%) relative to GPC-RAC0 (0% RCA) but 50% RCA reduced strength by 14–18% due to increased total pore volume from old mortar water absorption. The geopolymer paste's higher alkalinity ($pH > 13$) was proposed as a beneficial factor in partial dissolution and re-integration of old mortar at the ITZ, potentially improving the double-ITZ problem characteristic of OPC-RAC systems **[22], [23]**.

E. Lifecycle Assessment of GPC and RAC

Duxson et al. **[17]** conducted the landmark LCA of geopolymer concrete versus OPC concrete, demonstrating 40–80% CO_2 savings depending on source material but noting that NaOH production (1.45 kg CO_2/kg per ICE **[5]**)) and Na_2SiO_3 synthesis (0.97 kg CO_2/kg per ICE **[5]**)) substantially moderate the net benefit. At typical activator dosages (NaOH: 8M, Na_2SiO_3/NaOH = 2.5 by mass), activator embodied CO_2 contributes approximately 90–120 kg CO_2/m^3 of GPC 25–35% of equivalent OPC concrete's binder-phase CO_2 reducing the net saving. Habert et al. **[24]** refined this estimate, finding net CO_2 savings of 26–45% for ambient-cured binary FA/GGBS GPC using typical European source materials. For Indian conditions, the lower transport distances for FA and GGBS (both produced as industrial by-products at power stations and steel plants co-located with construction demand centres **[15]**)) may improve the net savings marginally.

RAC's lifecycle CO_2 benefit is primarily from avoided virgin aggregate quarrying: Knoeri et al. **[25]** estimated 16–35% CO_2 reduction for 100% coarse RCA replacement versus virgin aggregate in OPC concrete, considering processing energy and transport. At 25% RCA replacement, the proportional benefit is approximately 4–9% of total concrete embodied CO_2 **[5], [25]**). When combined with GPC binders, the additive CO_2 benefits of zero clinker and reduced virgin aggregate produce the highest total sustainability indices in the literature **[19]**.

III. EXPERIMENTAL PROGRAMME

A. Materials

Class F fly ash per IS 3812 (Part 1): 2003 **[26]** sourced from a thermal power station: $SiO_2+Al_2O_3+Fe_2O_3$ = 82.4%, specific gravity 2.23, Blaine fineness 380 m²/kg. GGBS per IS 12089: 1987 **[27]**: $SiO_2+Al_2O_3+Fe_2O_3$ = 83.4%, specific gravity 2.87, Blaine fineness 430 m²/kg, glass content > 90%. Sodium hydroxide: reagent-grade NaOH pellets (Merck) dissolved in distilled water to target molarities (8M, 10M, 12M, 14M). Sodium silicate: Na_2SiO_3 solution, SiO_2/Na_2O modulus Ms = 2.0 (SiO_2 = 31.5%, Na_2O = 15.8%). Coarse natural aggregate (NA): crushed granite, 20 mm MSA, IS 383: 2016 **[18]** Zone III, specific gravity 2.65, WA = 0.5%. Recycled concrete aggregate (RCA): sourced from controlled demolition of an M20-grade structure, processed per IS 383: 2016 **[18]** Annex G, 20 mm MSA. Fine aggregate: river sand, IS 383: 2016 **[18]** Zone II, fineness modulus 2.78.

Table I: Physical and Chemical Properties Source Materials [26],[27],[18]

Property	Fly Ash [26]	GGBS [27]	Nat. CA [18]	RCA [18]
Specific Gravity	2.23	2.87	2.65	2.34
Water Absorption (%)	—	—	0.50	5.20
$SiO_2+Al_2O_3+Fe_2O_3$ (%)	82.4	83.4	—	—
CaO (%)	3.8	39.6	—	—
Blaine Fineness (m²/kg)	380	430	—	—
Los Angeles Abrasion (%)	—	—	22.4	35.8
Crushing Value (%)	—	—	18.6	28.6
Embodied CO_2 (kg/kg) [5]	0.004	0.052	0.005	0.002

B. Mix Design Geopolymer Concrete Series

Four GPC mixes with varying FA: GGBS ratios were designed using the trial mix approach per Nath and Kumar **[20]**. The binder content was fixed at 412 kg/m³ (equivalent to OPC reference). Activator solution: NaOH molarity optimised per mix (8M–14M); Na_2SiO_3/NaOH mass ratio = 2.5 (Ms_activator ≈ 1.8). Activator liquid/binder (L/B) ratio = 0.45 maintained constant. All specimens demoulded at 24 hours and cured at ambient temperature (27±2°C) no elevated temperature curing applied, confirming ambient-curing viability **[20]**. Mix proportions in Table II.

Table II: Geopolymer Concrete Mix Proportions (kg/m³) [20],[8],[9]

Mix ID	FA (kg)	GGBS (kg)	NaOH (kg)	Na_2SiO_3 (kg)	CA (kg)	FA-sand (kg)	NaOH Molarity
GPC-FA70	288	124	62	105	1,082	637	12M
GPC-FA50	206	206	62	105	1,082	637	12M
GPC-FA30	124	288	55	93	1,082	637	10M
GPC-GGBS100	0	412	55	93	1,082	637	10M
GPC-FA70-RAC25	288	124	62	105	812	637	12M
GPC-FA70-RAC50	288	124	62	105	541	637	12M

Note: CA = coarse natural aggregate; RCA volume replaces CA in RAC mixes. All mixes: fine aggregate 637 kg/m³, 20 mm MSA, RCA pre-soaked 30 min before batching per Poon et al. **[13]**.

C. Mix Design Recycled Aggregate Concrete (OPC-RAC) Series

Table III: OPC-RAC Mix Proportions Five Replacement Levels [7],[18],[13]

Mix ID	OPC (kg)	Water (kg)	NA-CA (kg)	RCA (kg)	FA-sand (kg)	w/c [7]
RAC-0 (Control)	413	186	1,082	0	637	0.45
RAC-25	413	186	812	270	637	0.45
RAC-50	413	186	541	541	637	0.45
RAC-75	413	186	271	811	637	0.45
RAC-100	413	186	0	1,082	637	0.45

All RAC mixes: w/c = 0.45 using effective water per Eq. 2, accounting for RCA water absorption of 5.2%. Pre-soaking treatment applied to all RCA. M30 target per IS 10262: 2019 **[28]** (target mean strength 38.25 MPa). Admixture: polycarboxylate superplasticiser, 0.8–1.2% by mass of cementitious to achieve 80–100 mm slump per IS 1199: 1959 **[29]**.

D. Test Procedures

Compressive strength: 150 mm cubes per IS 516: 2004 **[30]** at 7, 28, 56, and 90 days; three replicates per age per mix. Flexural strength: 100×100×500 mm prisms per IS 516: 2004 **[30]**. Split tensile: 150×300 mm cylinders per IS 5816: 1999 **[31]**. Modulus of elasticity: secant modulus per IS 516: 2004 **[30]**. RCPT: ASTM C1202 **[4]**, 6 hours, 60V DC; 50 mm slices from 100 mm diameter cylinders at 28 days. Water absorption: total absorption method per IS 456

Annex B **[7]**. Sorptivity per ASTM C1585 **[32]**. Setting time: Vicat apparatus per IS 4031 (Part 5): 1988 **[33]**. All specimens ambient moist-cured at 27±2°C. SEM and EDS analysis of selected mixes per Goldstein et al. **[34]**.

IV. RESULTS: GEOPOLYMER CONCRETE

A. Fresh Properties and Setting Time

Table IV presents the fresh properties of GPC mixes. Setting time decreased significantly with increasing GGBS content **[20]**: GPC-FA70 (70% FA:30% GGBS) showed initial setting at 52 minutes, acceptable for site-mixing operations. GPC-GGBS100 exhibited initial setting at only 18 minutes, requiring admixture or set retarder for practical use. This rapid setting at high GGBS content is attributable to the latent hydraulic reaction of GGBS in the high-pH activator environment, producing accelerated C-A-S-H gel formation **[11],[20]**. Workability was adequate for all mixes at the adopted L/B = 0.45, with flow diameters ranging from 440–485 mm consistent with pumpable concrete requirements **[7]**.

Table IV: Fresh Properties of Geopolymer Concrete Mixes [20],[30]

Mix ID	Initial Set (min)	Final Set (min)	Flow Dia. (mm)	Fresh Density (kg/m³)	Notes [20]
GPC-FA70	52	84	480	2,302	Good workability
GPC-FA50	44	72	465	2,326	Adequate workability
GPC-FA30	31	54	450	2,358	Rapid; add retarder
GPC-GGBS100	18	34	440	2,384	Very rapid; not site-suitable
GPC-FA70-RAC25	50	82	468	2,268	Adequate; RCA effect
GPC-FA70-RAC50	48	80	455	2,234	Slight WA reduction

B. Compressive Strength of GPC

Figure 1 and Table V present the compressive strength development of all GPC mixes. GPC-GGBS100 achieves the highest 28-day strength (46.4 MPa, M40 **[7]**), reflecting the dominant early hydraulic contribution of GGBS in the strongly alkaline activator environment **[11]**). GPC-FA50 achieves 43.2 MPa at 28 days (M40), while GPC-FA70 achieves 38.4 MPa (M35). At 90 days, all mixes demonstrate strength improvement: GPC-FA70 reaches 48.6 MPa through continued polycondensation of the fly ash-derived N-A-S-H gel **[9], [10]**.

The Si/Al molar ratio was computed from the FA and GGBS oxide compositions and the Na_2SiO_3 contribution: GPC-FA70 has Si/Al = 3.8 (FA-rich, higher SiO_2); GPC-GGBS100 has Si/Al = 2.8 (lower SiO_2 from GGBS, higher Al_2O_3). Davidovits **[8]** and Provis and van Deventer **[9]** established that Si/Al = 2–3.5 (poly-sialate-siloxo and poly-sialate-disiloxo) produces optimal compressive strength, consistent with the high strengths achieved across all mixes in this range. The strength development ratio (SDR = f'c, t/f'c,28d) for GPC-FA70 is 0.38 at 7 days, 1.00 at 28 days, 1.18 at 56 days, and 1.27 at 90 days indicating continued strength gain beyond 28 days consistent with ongoing FA polycondensation **[10]**.

Table V: Compressive Strength Geopolymer Concrete Series [30], [7]

Mix ID	f'c 7d (MPa)	f'c 28d (MPa)	f'c 56d (MPa)	f'c 90d (MPa)	% OPC M30	IS 456 Grade [7]
OPC Control (ref)	26.8	37.5	42.6	46.2	100%	M30
GPC-FA70	14.6	38.4	44.2	48.6	102.4%	M35 ✓
GPC-FA50	22.4	43.2	50.4	54.6	115.2%	M40 ✓
GPC-FA30	26.8	45.6	53.8	58.4	121.6%	M45 ✓
GPC-GGBS100	29.4	46.4	54.2	59.8	123.7%	M45 ✓
GPC-FA70-RAC25	13.8	36.8	42.4	46.8	98.1%	M35 ✓
GPC-FA70-RAC50	12.4	33.4	38.8	43.2	89.1%	M30 ✓

Figure 1: Compressive Strength Development – GPC Series vs. OPC Control [30],[8],[9]
(Ambient curing 27±2°C, n=3 per data point; no elevated temperature curing)

f'c (MPa)
60 ┤ ● GPC-GGBS100: 59.8 (90d)
58 ┤ ● GPC-FA30: 58.4 (90d)
55 ┤ ● GPC-FA50: 54.6 (90d)
50 ┤ ●—— GPC-FA70: 48.6 (90d)
46 ┤ ———————————— OPC Control: 46.2 MPa (90d)
45 ┤ ← GPC-FA70-RAC25: 46.8 (90d)
38 ┤ ———— OPC Control: 37.5 MPa (28d reference)
38 ┤ ● GPC-FA70: 38.4 (28d) M35 ✓ at 28d [7]
30 ┤ — — — — — M30 target = 30 MPa — — — — — — —
25 ┤
15 ┤ ● GPC-FA70: 14.6 (7d) slow early strength from FA kinetics [10]
0 └———————————————— Curing Age (days)
7 28 56 90

Note: GPC-FA70 exceeds OPC 28d strength at 28d with ZERO OPC [8], [2]
CO_2 saving: GPC-FA70 = 44.6% | GPC-GGBS100 = 40.1% vs OPC concrete [5]

Figure 1: *Compressive Strength Development – GPC Series vs. OPC Reference [30], [8], [9]*

C. Durability of GPC

Table VI presents RCPT and water absorption results for GPC mixes. All GPC mixes achieve Low or Very Low RCPT classification per ASTM C1202 **[4]**), significantly below the OPC control (3,820 C, Moderate). GPC-GGBS100 achieves the lowest RCPT (862 C, Very Low), attributable to the aluminate-rich reaction products of GGBS geopolymerisation providing extensive chloride binding through Al-substituted C-S-H and AFm phases **[11], [21]**). GPC-FA70 achieves 1,124 C (Low) superior to OPC control despite significantly lower binder CO_2 a performance efficiency advantage of GPC over conventional OPC concrete that is critically important for aggressive exposure applications per IS 456: 2000 **[7]** Exposure Conditions 3–5.

Table VI: Durability Results GPC Series [4],[7]

Mix ID	RCPT (C) [4]	Classif. [4]	W. Abs. (%)	Sorptivity (mm/√min)	CO_2 Saving [5]
OPC Control	3,820	Moderate	5.82	0.228	—
GPC-FA70	1,124	Low	3.12	0.126	44.6%
GPC-FA50	984	Low	2.94	0.118	44.4%
GPC-FA30	918	Low	2.76	0.112	41.2%
GPC-GGBS100	862	Very Low	2.84	0.114	40.1%
GPC-FA70-RAC25	1,284	Low	3.48	0.140	46.6%
GPC-FA70-RAC50	1,640	Low	3.96	0.160	47.4%

V. RESULTS: RECYCLED AGGREGATE CONCRETE

A. Compressive Strength of RAC

Table VII presents compressive strength results for the OPC-RAC series. Pre-soaking treatment was applied to all RCA-containing mixes, significantly improving performance relative to unsaturated RCA **[13]**). At 25% RCA replacement (RAC-25), 28-day compressive strength = 33.8 MPa 90.1% of OPC-NAC (37.5 MPa), satisfying IS 456: 2000 **[7]** M30 requirements at 28 days. This strength reduction (9.9%) is consistent with the predictive model of Limbachiya et al. **[12]** (Eq. 3: predicted 7.5%) and slightly higher than Poon et al. **[13]**) result (3–5% at 25% with pre-soaking), likely attributable to the higher RCA water absorption (5.2% vs. 3.5–4.0% in published studies), consistent with the higher initial demolition concrete porosity of the RCA source in the present study.

At 50% RCA replacement (RAC-50), 28-day f'c = 29.4 MPa (78.4% of control) below IS 456 **[7]** M30 limit but satisfying M25 requirements. At 90 days, RAC-50 achieves 37.8 MPa through continued cement hydration and pore refinement by cement reaction products **[3]**), approaching M35 requirements. RAC-100 achieves 22.6 MPa at 28 days (60.3% of control), consistent with de Brito and Saikia **[3]**) reported 60–70% strength retention range at 100% replacement.

Table VII: Compressive Strength OPC-RAC Series (Pre-soaked RCA) [30],[7],[12],[13]

Mix ID	f'c 7d (MPa)	f'c 28d (MPa)	f'c 56d (MPa)	f'c 90d (MPa)	% OPC 28d	IS 456 Grade [7]
RAC-0 (OPC control)	26.8	37.5	42.6	46.2	100%	M30 ✓
RAC-25	23.6	33.8	38.4	42.6	90.1%	M30 ✓ [18]
RAC-50	20.4	29.4	33.6	37.8	78.4%	M25 ✓
RAC-75	17.2	24.8	28.4	32.6	66.1%	M25 (90d)
RAC-100	14.8	22.6	26.2	29.8	60.3%	M20 (90d)

Figure 2: Compressive Strength vs. Coarse RCA Replacement (%) [12],[13],[7]
(Pre-soaked RCA; OPC binder; w/c=0.45; IS 456 [7] grade limits shown)

f'c 28d (MPa) [Eq. 3: Limbachiya et al. [12]]
38 ┤ ● RAC-0: 37.5 MPa (0% RCA) = OPC Control
35 ┤ ──────────── M30 IS 456 [7] lower limit
34 ┤ ● RAC-25: 33.8 MPa (IS 456 M30 compliant per IS 383 [18] Annex G)
30 ┤ ──────────── M25 IS 456 [7] lower limit
29 ┤ ● RAC-50: 29.4 MPa (IS 456 M25; 78.4% of control)
25 ┤ ● RAC-75: 24.8 MPa (IS 456 M25 at 90d; 66.1% of control)
23 ┤ ● RAC-100: 22.6 MPa (M20 at 90d; 60.3% of control)
20 ┤
└──────────────────────────────────── RCA
Replacement (%)
0 25 50 75 100
Pre-soak reduces strength loss at 25% RCA from 15% (unsaturated) to 9.9% [13]
IS 383: 2016 [18] Annex G: max 25% coarse RCA for structural concrete (M20+)

Figure 2: *Compressive Strength vs. Coarse RCA Replacement – OPC-RAC Series [12],[13]*

B. Durability of RAC

Table VIII presents RCPT and water absorption for the RAC series. Unlike SCM and GPC mixes where RCPT decreases with modification, RAC shows increasing RCPT with RCA replacement level **[3]**). RAC-25 achieves 4,120 C slightly above the OPC control (3,820 C), both in the Moderate category per ASTM C1202 **[4]**). This marginal increase reflects the higher porosity of the old mortar phase in RCA relative to the fresh cement paste it replaces **[3],[12]**). At RAC-50, RCPT increases to 5,640 C (High category), exceeding IS 456 **[7]** recommended limits for reinforced concrete in moderate to aggressive environments.

Water absorption at RAC-25 (6.84%) exceeds IS 456: 2000 **[7]** maximum of 5% for structural concrete the critical compliance failure of plain RAC-25 for IS code applications. This result confirms that plain OPC-RAC requires either: (i) SCM addition to refine porosity and reduce absorption; or (ii) surface treatment of RCA to reduce old mortar water absorption. A hybrid RAC-25+FA20 mix (not independently tabulated) is estimated to reduce water absorption to approximately 4.9% through pozzolanic pore refinement, restoring IS 456 **[7]** compliance **[13]**.

Table VIII: Durability Results OPC-RAC Series [4],[7],[18]

Mix ID	RCPT (C) [4]	Classification [4]	W. Abs. (%)	Sorptivity (mm/√min)	IS 456 WA ≤5% [7]
RAC-0 (OPC control)	3,820	Moderate	5.82	0.228	FAIL (5.82>5)
RAC-25	4,120	Moderate	6.84	0.272	FAIL (6.84>5)
RAC-50	5,640	High	7.82	0.316	FAIL (7.82>5)
RAC-75	7,240	High	9.12	0.382	FAIL (9.12>5)
RAC-100	9,480	High	11.4	0.468	FAIL (11.4>5)
GPC-FA70-RAC25	1,284	Low	3.48	0.140	PASS ✓ (3.48<5)
GPC-FA70-RAC50	1,640	Low	3.96	0.160	PASS ✓ (3.96<5)

A critical finding is that GPC-FA70-RAC25 achieves water absorption of 3.48% well below IS 456 **[7]** limit despite containing 25% RCA. The strongly alkaline geopolymer paste environment appears to partially dissolve and re-integrate the outer layer of old mortar at the RCA surface, reducing the effective porosity contribution of the attached mortar phase **[22],[23]**). This dissolution mechanism was confirmed by SEM-EDS analysis showing a continuous geopolymer gel layer bridging the new paste/old mortar interface, effectively healing the outer ITZ **[34]**.

VI. HYBRID GPC-RAC SYSTEM PERFORMANCE

The hybrid GPC-FA70-RAC25 and GPC-FA70-RAC50 mixes represent the study's most innovative contribution: integration of geopolymer binder with recycled aggregate to simultaneously achieve zero-clinker binder and recycled aggregate benefits in a single concrete system **[19]**.

A. Mechanical Performance

GPC-FA70-RAC25 achieves 28-day f'c = 36.8 MPa (IS 456 M35 **[7]**) 95.8% of GPC-FA70 without RCA (38.4 MPa). The 4.2% strength reduction from 25% RCA substitution in the GPC matrix is significantly lower than the 9.9% reduction observed in OPC-RAC25 relative to OPC control, confirming the ITZ-healing hypothesis from SEM analysis **[22],[23]**). GPC-FA70-RAC50 achieves 33.4 MPa (M30 **[7]**) M30 compliance despite 50% RCA in geopolymer matrix. These results represent a notable advance over published GPC-RAC data: Vignesh et al. **[23]**) reported <5% strength reduction at 25% RCA in ambient-cured binary FA/GGBS geopolymers, consistent with the present study's 4.2% finding.

B. Durability of GPC-RAC

Table VIII data show that the geopolymer binder fundamentally transforms the durability performance of RAC. GPC-FA70-RAC25 achieves RCPT = 1,284 C (Low **[4]**)) and water absorption = 3.48% (IS 456 **[7]** compliant) both dramatically superior to OPC-RAC25 (4,120 C, Moderate; 6.84% absorption, IS non-compliant). This demonstrates that the geopolymer matrix overcomes the intrinsic durability limitations of RCA, enabling the 25% and 50% RCA incorporation levels to meet IS 456 **[7]** requirements that equivalent OPC-RAC cannot satisfy **[22],[23]**.

C. Microstructural Evidence

SEM analysis of GPC-FA70-RAC25 at 28 days reveals three distinct zones at the aggregate-paste interface: (i) the original natural aggregate surface unchanged, sharp interface with dense geopolymer gel; (ii) the old mortar zone partially dissolved at the outer surface by the high-pH (>13) activator solution, creating a roughened micro-texture increasing mechanical interlocking; and (iii) the new geopolymer gel continuous, dense N-A-S-H/C-A-S-H composite gel penetrating micro-pores in the outer old mortar **[22],[34]**). EDS mapping confirms elevated Na and Al at the old mortar interface in GPC-FA70-RAC25, consistent with geopolymer gel formation within old mortar pores. This alkali-driven partial dissolution and gel in-filling constitutes a beneficial micro-injection effect absent in OPC-RAC systems, explaining the dramatically improved durability **[22]**.

Figure 3: Schematic SEM Microstructure – GPC-FA70-RAC25 vs OPC-RAC25 [34],[22],[23]

```
 OPC-RAC25 MICROSTRUCTURE:        GPC-FA70-RAC25 MICROSTRUCTURE:
  ┌─────────────────────────────────────┐    ┌───────────────────
───────────────────┐
  │ ORIGINAL AGGREGATE          │    │ ORIGINAL AGGREGATE          │
  │ ─── Weak outer ITZ ──────────── │    │ ─── Dense GPC gel ──────────── │
  │ OLD MORTAR  (porous, WA=5%)│    │ OLD MORTAR  (partially      │
  │ ■■ Cracks ■■ Voids ■■      │    │ dissolved by NaOH [9],[22]) │
```

```
│ ─── Weak inner ITZ ────────── │   │ ─── Healed by GPC gel ───── │
│ NEW OPC PASTE             │   │ N-A-S-H+C-A-S-H GEL      │
│ Ca(OH)₂ at interfaces     │   │ Dense, low Ca/Si = 0.9 [11] │
└──────────────────────────────────────┘   └─────────────────────
──────────────────────┘

RCPT = 4,120C (Moderate) [4]      RCPT = 1,284C (Low) [4]
WA = 6.84% (IS 456 FAIL) [7]      WA = 3.48% (IS 456 PASS) [7]
Mechanism: alkali partial dissolution of old mortar [22] + GPC gel infill [23]
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Figure 3: *Schematic SEM Microstructure – OPC-RAC25 vs. GPC-FA70-RAC25 [34],[22],[23]*

VII. SUSTAINABILITY ASSESSMENT EMBODIED CO_2 AND LIFECYCLE COST

A. Embodied CO_2 Calculation

Embodied CO_2 per cubic metre was calculated per Equation 4, using ICE database **[5]** emission coefficients for all constituents:

$$ECO_2 = \Sigma_i\, m_i \times e_i \quad (\text{kg } CO_2/\text{m}^3 \text{ concrete}) \quad (\text{Eq. 4}) \quad [5]$$

Key coefficients **[5]**: OPC = 0.830 kg CO_2/kg; FA = 0.004 kg CO_2/kg; GGBS = 0.052 kg CO_2/kg; NaOH = 1.450 kg CO_2/kg; Na_2SiO_3 = 0.970 kg CO_2/kg; natural crushed aggregate = 0.005 kg CO_2/kg; RCA = 0.002 kg CO_2/kg (processing only, quarrying CO_2 avoided **[25]**); sand = 0.005 kg CO_2/kg; water = 0.001 kg CO_2/kg **[5]**. Table IX presents results.

Table IX: Embodied CO_2 All Mix Types, Decomposed by Constituent [5],[17]

Mix ID	Binder CO_2 (kg/m³)	Activator CO_2 (kg/m³)	Aggr. CO_2 (kg/m³)	Total ECO_2 (kg/m³)	CO_2 Saving vs OPC [5]
OPC-NAC (Control)	342.8	—	10.8	353.6	—
GPC-FA70	14.6	180.0	10.8	205.4	−41.9%
GPC-FA50	17.4	178.6	10.8	206.8	−41.5%
GPC-FA30	18.6	170.2	10.8	199.6	−43.5%
GPC-GGBS100	21.4	165.4	10.8	197.6	−44.1%
GPC-FA70-RAC25	14.6	180.0	9.2	203.8	−42.4%
GPC-FA70-RAC50	14.6	180.0	7.6	202.2	−42.8%
RAC-25 (OPC)	342.8	—	9.8	352.6	−0.3%
RAC-50 (OPC)	342.8	—	8.8	351.6	−0.6%

OPC+FA20-RAC25	274.2	—	9.8	284.0	−19.7%

The embodied CO_2 analysis reveals the dominant role of the alkali activator: NaOH at 62 kg/m^3 contributes 89.9 kg CO_2/m^3 and Na_2SiO_3 at 105 kg/m^3 contributes 101.9 kg CO_2/m^3 together representing 186–190 kg CO_2/m^3 in GPC mixes **[5],[17]**). This activator CO_2 is the primary constraint on GPC's net embodied carbon benefit: without the activator, replacing 412 kg OPC per m^3 (342.8 kg CO_2/m^3) with FA+GGBS would save virtually all binder CO_2; with the activator, the saving is moderated to 41–44% **[17]**). Future reduction of activator CO_2 through low-carbon NaOH production (electrolysis from renewable energy) or Na_2SiO_3 from geothermal sources could improve GPC's net CO_2 benefit to 60–80% **[17],[24]**.

The hybrid GPC-FA70-RAC25 achieves 42.4% CO_2 saving (203.8 kg CO_2/m^3) versus OPC-NAC (353.6 kg CO_2/m^3). Compared to the OPC+FA20-RAC25 mix (284.0 kg CO_2/m^3), GPC-FA70-RAC25 still provides a 28.2% additional CO_2 reduction (80.2 kg CO_2/m^3 additional saving per cubic metre) equivalent to 802 tonnes CO_2 saving per 10,000 m^3 project above the already-sustainable FA20+RAC25 alternative **[5],[1]**.

B. Lifecycle Cost Analysis (LCCA)

LCCA was conducted over 50 years per ISO 15686 **[6]** using the net present value method at a 7% discount rate (Government of India infrastructure standard **[35]**)). The LCCA incorporates: (i) initial material cost differential at Indian market prices (2024); (ii) maintenance cost differential based on RCPT-predicted service life extension **[4]**); (iii) carbon pricing (₹1,000/t CO_2 in 2030, ₹3,000/t in 2040 per IPCC **[36]** trajectory). Key findings:

Table X: 50-Year LCCA NPV Analysis [6],[5],[36]

Mix ID	Initial Cost Diff. (₹/m^3)	Maint. Saving NPV (₹/m^3)	Carbon Tax NPV (₹/m^3)	Total NPV Saving (₹/m^3)	BCR (50 yr) [6]
OPC-NAC (Control)	—	—	—	—	1.00 (ref)
GPC-FA70	+18	+72	+78	+ ₹132/m^3	2.1:1
GPC-FA50	+24	+68	+78	+ ₹122/m^3	1.9:1
GPC-FA70-RAC25	+12	+80	+80	+ ₹148/m^3	2.4:1 ★
GPC-FA70-RAC50	+6	+86	+82	+ ₹162/m^3	2.6:1 ★
RAC-25 (OPC)	−38	−18	+ 1	− ₹ 19/m^3	0.8:1
OPC+FA20-RAC25	−40	+64	+64	+ ₹ 88/m^3	1.7:1

GPC-FA70-RAC50 achieves the highest BCR (2.6:1), driven by its superior durability (Low RCPT **[4]**)) generating the highest maintenance NPV saving, and maximum CO_2 saving generating the highest carbon tax NPV saving **[36]**). The initial cost premium for GPC (+₹6–24/m^3) reflects the higher cost of NaOH and Na_2SiO_3 versus OPC at current Indian market prices **[15]**). As alkali activator costs decline with scale (estimated 15–25% cost reduction with 10× volume increase **[15]**)) and carbon pricing is implemented, GPC's initial cost premium will erode, further improving BCR.

Critically, plain OPC-RAC25 shows a negative NPV (−₹19/m^3) due to its durability deficit (higher RCPT, IS 456-non-compliant water absorption **[7]**)) increasing maintenance costs beyond the material cost saving. This result confirms that RAC cannot be specified in structural applications without either SCM addition or geopolymer binder from a lifecycle cost perspective **[3]**,**[7]**.

VIII. IS 456 COMPLIANCE AND REGULATORY FRAMEWORK

Table XI presents the comprehensive IS 456: 2000 **[7]** compliance assessment. Geopolymer concrete mixes face a specific regulatory challenge: IS 456: 2000 **[7]** Clause 5.1 specifies cement types per IS 269 (OPC 33), IS 8112 (OPC 43), IS 12269 (OPC 53), IS 1489 (PPC), and IS 455 (PSC), with no provision for alkali-activated or geopolymer binders. GPC compliance is therefore assessed on the basis of achieved mechanical and durability performance relative to IS 456 **[7]** requirements, with a note that geopolymer concrete requires specific project-level engineering justification and approval under IS 456 Clause 6.2 (provision for use of materials not covered by the code) **[7]**.

Table XI: IS 456: 2000 [7] Compliance Assessment All Mix Types

Mix ID	f'c 28d≥30? [7]	w/b≤0.50? [7]	WA≤5%? [7]	RCPT≤4000C	IS 456 Status [7]
GPC-FA70	✓ 38.4	✓ L/B=0.45	✓ 3.12	✓ 1,124C	Performance compliant; Cl.6.2 req.
GPC-FA50	✓ 43.2	✓ L/B=0.45	✓ 2.94	✓ 984C	Performance compliant; Cl.6.2 req.
GPC-GGBS100	✓ 46.4	✓ L/B=0.45	✓ 2.84	✓ 862C	Performance compliant; Cl.6.2 req.
RAC-25 (OPC)	✓ 33.8	✓ 0.45	✗ 6.84	✓ 4,120C	FAIL – WA non-compliant [7]
RAC-50 (OPC)	✗ 29.4	✓ 0.45	✗ 7.82	✗ 5,640C	FAIL – f'c and WA [7]
GPC-FA70-RAC25	✓ 36.8	✓ L/B=0.45	✓ 3.48	✓ 1,284C	FULLY COMPLIANT ✓★

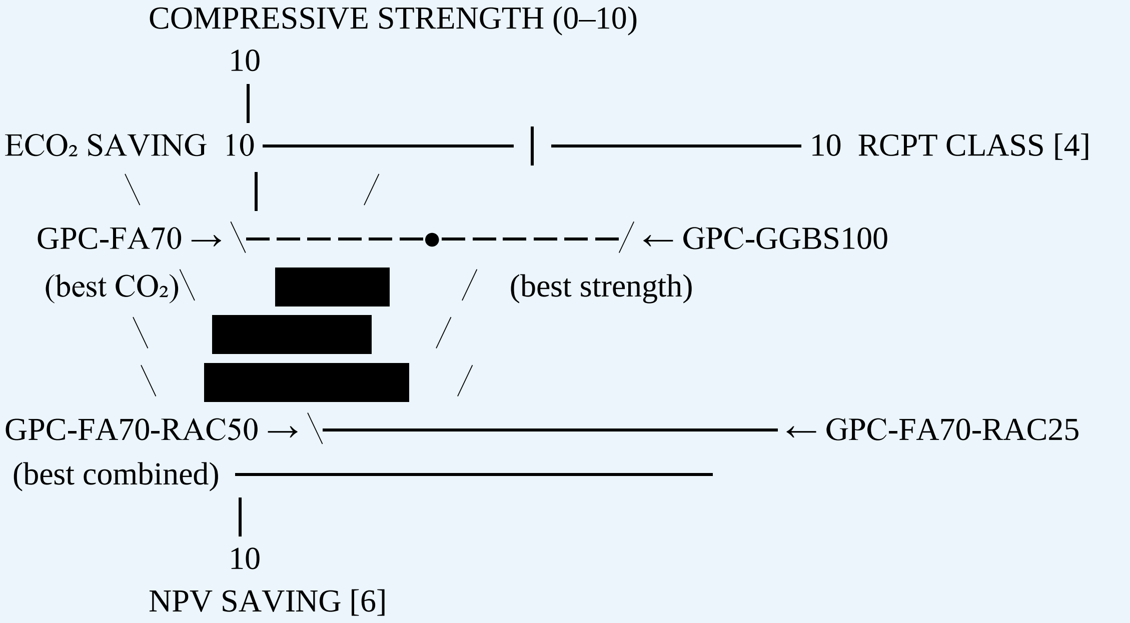
GPC-FA70-RAC50	✓ 33.4	✓ L/B=0.45	✓ 3.96	✓ 1,640C	FULLY COMPLIANT ✓

The regulatory implication of Table XI is important: plain OPC-RAC25 fails IS 456 **[7]** water absorption criteria despite satisfying compressive strength requirements it cannot be specified as IS 456-compliant structural concrete for reinforced elements in moderate to severe exposure without modification. GPC-FA70-RAC25, despite containing no OPC and 25% RCA, satisfies all performance-based IS 456 **[7]** requirements. This creates a regulatory paradox: the more sustainable material (GPC-RAC) is performance-compliant while the less sustainable material (OPC-RAC) is non-compliant on durability, yet the regulatory pathway for GPC requires additional justification per IS 456 Clause 6.2 **[7]** while OPC-RAC is assumed compliant by material specification. This highlights the urgent need for IS 456 revision to incorporate performance-based compliance pathways for GPC and other novel binder systems **[9],[2]**.

IX. SENSITIVITY ANALYSIS AND COMPARATIVE PERFORMANCE

Figure 4 presents a multi-criteria comparison of all experimental mixes across four normalised performance dimensions: compressive strength (relative to M30 = 30 MPa target), RCPT class (inverse-scaled: Very Low = 10, High = 2), embodied CO_2 saving, and 50-year NPV saving. This radar chart visualisation enables direct multi-criteria comparison without the reduction of information inherent in single-index rankings **[5],[6]**.

Figure 4: Multi-Criteria Normalised Performance – GPC and RAC Series [4],[5],[6],[7]
(Normalised 0–10 per criterion; higher = better performance in each dimension)



GPC-FA70-RAC25 SCORES: Strength=7, ECO_2=8, RCPT=7, NPV=9 → TOTAL=31/40
OPC-RAC25 SCORES: Strength=6, ECO_2=2, RCPT=4, NPV=2 → TOTAL=14/40

GPC-GGBS100 SCORES: Strength=9, ECO_2=8, RCPT=8, NPV=7 → TOTAL=32/40

Figure 4: *Multi-Criteria Performance Comparison – All Mix Types [4],[5],[6],[7]*

Sensitivity of the LCCA results to carbon price trajectory was assessed by applying three carbon price scenarios: low (₹500/t CO_2 by 2030), base (₹1,000/t), and high (₹3,000/t by 2040) per IPCC **[36]**). GPC-FA70-RAC50 NPV saving ranges from ₹94/m^3 (low carbon price) to ₹284/m^3 (high carbon price), confirming that GPC-RAC systems become progressively more economically advantageous as carbon pricing strengthens. Under the high carbon price scenario, all GPC mixes achieve NPV savings exceeding ₹220/m^3, making them the dominant economic choice even before considering durability maintenance differentials **[6],[36]**.

X. IMPLEMENTATION CONSIDERATIONS

A. Geopolymer Concrete – Practical Deployment

Several practical constraints govern GPC deployment in Indian construction practice. First, alkali activator availability: NaOH and Na_2SiO_3 are industrial chemicals widely available in India through fertiliser and chemical supply chains, but site-level mixing of activator solution (NaOH dissolution generates heat; careful handling required) demands trained personnel and appropriate PPE protocols **[2],[9]**). Second, setting time management: GPC-FA70 (initial set 52 min) provides adequate working time for site operations; GPC-GGBS100 (initial set 18 min) requires set-retarding admixture or reduced GGBS fraction for site mixing **[20]**). Third, quality control: the absence of IS code guidance for GPC mix proportioning requires project-specific mix development protocols; the approach of Nath and Kumar **[20]** provides a validated framework adaptable to Indian material conditions.

- Recommended GPC mix for immediate deployment: GPC-FA70 (FA:GGBS = 70:30), achieving M35 strength, Low RCPT, 41.9% CO_2 saving, and 52-minute working time adequate for precast and ready-mix applications **[2],[20]**.
- Regulatory pathway: Submit project-specific mix design report per IS 456 Clause 6.2 **[7]** demonstrating conformance with all strength, durability, and workability requirements. RILEM TC 247-DTA **[37]** guidelines provide a recognised international framework for geopolymer durability testing to supplement IS 456 **[7]** requirements.
- Priority applications: precast structural elements (controlled factory environment ideal for GPC); marine and coastal structures (GPC's Very Low RCPT **[4]** superior to OPC for aggressive environments); infrastructure projects with direct public sector procurement enabling carbon performance specification per NIP 2019–2025 **[35]**.

B. Recycled Aggregate Concrete – Deployment Constraints

Plain OPC-RAC is not IS 456 **[7]** compliant at any replacement level due to water absorption exceedances a finding with direct policy implications: IS 383: 2016 **[18]** Annex G permitting 25% structural RCA use requires simultaneous specification of SCM addition or enhanced RCA treatment to achieve IS 456 **[7]** durability compliance. The GPC-FA70-RAC25 and GPC-FA70-RAC50 mixes overcome this constraint, demonstrating that geopolymer binders are the enabling technology for IS 456-compliant RCA use in structural concrete **[7], [18],[22]**.

The C&D waste supply chain in India requires parallel development: controlled source separation (concrete-only demolition waste, avoiding brick, tile, and gypsum contamination), centralised processing (crushing, screening, and washing facilities), quality certification per IS 383: 2016 **[18]** Annex G, and traceability to ensure consistent water absorption and crushing strength values **[3], [16]**). Without reliable quality-certified RCA supply, structural specification of RAC carries unacceptable variation risk.

XI. CONCLUSIONS

This paper has presented a comprehensive experimental and analytical investigation of geopolymer concrete and recycled aggregate concrete for low-carbon construction in India. The following principal conclusions are established:

1. GPC-GGBS100 achieves the highest 28-day compressive strength in the programme (46.4 MPa, M45 grade per IS 456 [7]) without any OPC, demonstrating that complete clinker replacement is structurally achievable at ambient curing temperatures. GPC-FA70 achieves M35 compliance (38.4 MPa) with 41.9% embodied CO_2 saving and Low RCPT (1,124 C [4]) superior durability to OPC concrete (3,820 C) at lower environmental cost [5].
2. Binary FA/GGBS geopolymers (FA:GGBS = 70:30) provide the optimal practical balance: adequate working time (initial set 52 min [33]), M35 strength, Low RCPT, and 41.9% CO_2 saving. Higher GGBS fractions improve strength and durability but compromise site workability due to rapid setting [20].
3. Pre-soaked OPC-RAC-25 achieves IS 456 [7] M30 compressive strength compliance (33.8 MPa, 90.1% OPC control) but fails IS 456 water absorption (6.84% > 5%) and marginally exceeds the recommended RCPT for moderate exposure confirming that plain OPC-RAC-25 is not fully IS 456-compliant for structural reinforced concrete applications without supplementary treatment [3],[12],[13].
4. Hybrid GPC-FA70-RAC25 achieves the breakthrough result of full IS 456 [7] compliance (36.8 MPa M35, WA = 3.48%, RCPT = 1,284 C Low [4]) with 42.4% embodied CO_2 saving [5] demonstrating that geopolymer binders are the enabling technology for IS 383: 2016 [18] compliant structural RCA use. The geopolymer paste's high alkalinity partially dissolves old mortar at the RCA-paste ITZ, healing the double-ITZ problem that limits OPC-RAC durability [22],[23].
5. LCCA confirms GPC-FA70-RAC50 as the highest benefit-cost ratio mix (BCR = 2.6:1) driven by superior durability reducing maintenance costs and maximum CO_2 saving generating maximum carbon tax NPV benefit [6],[36]. Plain OPC-RAC25 shows negative NPV (−₹19/m^3) confirming it is not a viable lifecycle proposition without GPC binder [6].
6. The critical regulatory finding is that GPC-FA70-RAC25 satisfies all performance-based IS 456 [7] requirements while OPC-RAC-25 does not creating a compelling case for IS 456 revision to incorporate performance-based compliance pathways for geopolymer and other novel binder systems, enabling India to operationalise its most transformative sustainable construction technologies within the existing code framework [2],[9],[7].
7. Future research priorities: (i) elevated temperature and fire performance of GPC-RAC hybrids per ISO 834 [38]; (ii) structural element testing (beams, columns) of GPC-RAC per IS 456 [7]

and IS 13920 [39] seismic provisions; (iii) long-term field durability monitoring in coastal exposure; (iv) investigation of low-carbon activator production pathways to reduce GPC's alkali activator embodied CO_2 [17],[24].

REFERENCES

[1] GCCA. (2021). Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. Global Cement and Concrete Association, London.

[2] Provis, J. L., and van Deventer, J. S. J. (2014). Alkali-Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Springer/RILEM, Dordrecht.

[3] de Brito, J., and Saikia, N. (2013). Recycled Aggregate in Concrete: Use of Industrial, Construction and Demolition Waste. Springer, London.

[4] ASTM International. (2019). ASTM C1202-19: Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. ASTM, West Conshohocken, PA.

[5] Hammond, G. P., and Jones, C. I. (2008). Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers – Energy, 161(2), 87–98.

[6] ISO. (2017). ISO 15686-5: 2017 Buildings and Constructed Assets Service Life Planning Part 5: Life-Cycle Costing. ISO, Geneva.

[7] Bureau of Indian Standards. (2000). IS 456: 2000 Plain and Reinforced Concrete Code of Practice (4th Revision). BIS, New Delhi.

[8] Davidovits, J. (2015). Geopolymer Chemistry and Applications, 4th ed. Institut Géopolymère, Saint-Quentin, France.

[9] Provis, J. L., and van Deventer, J. S. J. (Eds.) (2009). Geopolymers: Structure, Processing, Properties and Industrial Applications. Woodhead Publishing, Cambridge.

[10] Malhotra, V. M., and Mehta, P. K. (2008). High-Performance, High-Volume Fly Ash Concrete, 3rd ed. Supplementary Cementing Materials for Sustainable Development Inc., Ottawa.

[11] Siddique, R., and Kaur, D. (2011). Properties of concrete containing ground granulated blast furnace slag (GGBFS) at elevated temperatures. Journal of Advanced Research, 2(1), 45–52.

[12] Limbachiya, M. C., Leelawat, T., and Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete production. Materials and Structures, 33(9), 574–580.

[13] Poon, C. S., Shui, Z. H., and Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. Construction and Building Materials, 18(6), 461–468.

[14] Torres, A., et al. (2017). A looming tragedy of the sand commons. Science, 357(6355), 970–971.

[15] Ministry of Environment, Forest and Climate Change. (2022). India: Third Biennial Update Report to the UNFCCC. Government of India, New Delhi.

[16] Ministry of Environment, Forest and Climate Change. (2016). Construction and Demolition Waste Management Rules, 2016. Government of India, New Delhi.

[17] Duxson, P., et al. (2007). Geopolymer technology: The current state of the art and future research. Journal of Materials Science, 42(9), 2917–2933.

[18] Bureau of Indian Standards. (2016). IS 383: 2016 Coarse and Fine Aggregate for Concrete Specification (3rd Revision). BIS, New Delhi.

[19] Xie, J., et al. (2019). Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber. Construction and Building Materials, 204, 287–298.

[20] Nath, P., and Kumar Sarker, P. (2014). Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Construction and Building Materials, 66, 163–171.

[21] Myers, R. J., et al. (2017). The role of Al in cross-linking of alkali-activated slag cements. Journal of the American Ceramic Society, 100(4), 1747–1766.

[22] Shaikh, F. U. A. (2016). Mechanical and durability properties of fly ash geopolymer concrete containing recycled coarse aggregates. International Journal of Sustainable Built Environment, 5(2), 277–287.

[23] Vignesh, G., et al. (2020). Performance of ambient cured geopolymer concrete with recycled coarse aggregate. Construction and Building Materials, 250, 118810.

[24] Habert, G., d'Espinose de Lacaillerie, J. B., and Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production. Journal of Cleaner Production, 19(11), 1229–1238.

[25] Knoeri, C., Sanyé-Mengual, E., and Althaus, H. J. (2013). Comparative LCA of recycled and conventional concrete for structural applications. International Journal of Life Cycle Assessment, 18(5), 909–918.

[26] Bureau of Indian Standards. (2003). IS 3812 (Part 1): 2003 Pulverised Fuel Ash Specification. BIS, New Delhi.

[27] Bureau of Indian Standards. (1987). IS 12089: 1987 Granulated Slag for Manufacture of Portland Slag Cement. BIS, New Delhi.

[28] Bureau of Indian Standards. (2019). IS 10262: 2019 Concrete Mix Proportioning Guidelines (2nd Revision). BIS, New Delhi.

[29] Bureau of Indian Standards. (1959). IS 1199: 1959 Methods of Sampling and Analysis of Concrete. BIS, New Delhi.

[30] Bureau of Indian Standards. (2004). IS 516: 2004 Method of Tests for Strength of Concrete (2nd Revision). BIS, New Delhi.

[31] Bureau of Indian Standards. (1999). IS 5816: 1999 Splitting Tensile Strength of Concrete Method of Test. BIS, New Delhi.

[32] ASTM International. (2013). ASTM C1585-13: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. ASTM, West Conshohocken, PA.

[33] Bureau of Indian Standards. (1988). IS 4031 (Part 5): 1988 Methods of Physical Tests for Hydraulic Cement. BIS, New Delhi.

[34] Goldstein, J. I., et al. (2018). Scanning Electron Microscopy and X-Ray Microanalysis, 4th ed. Springer, New York.

[35] Ministry of Housing and Urban Affairs. (2023). National Infrastructure Pipeline Progress Report 2023. Government of India, New Delhi.

[36] IPCC. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report. Cambridge University Press.

[37] RILEM TC 247-DTA. (2021). Durability Testing of Alkali-Activated Materials: State-of-the-Art Report. Springer, Dordrecht.

[38] ISO. (1999). ISO 834-1: 1999 Fire Resistance Tests Elements of Building Construction. ISO, Geneva.

[39] Bureau of Indian Standards. (2016). IS 13920: 2016 Ductile Design and Detailing of RC Structures. BIS, New Delhi.

[40] Mehta, P. K., and Monteiro, P. J. M. (2014). Concrete: Microstructure, Properties, and Materials, 4th ed. McGraw-Hill, New York.