



Performance Evaluation of Binary and Ternary Blended Supplementary Cementitious Material Concretes: Mechanical Strength, Durability, and Embodied Carbon Indices Under IS 456 Framework

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ABSTRACT

The escalating environmental burden of ordinary Portland cement (OPC) production contributing 0.83 kg CO₂ per kilogram of clinker [1] and representing 5–8% of global greenhouse gas emissions [2] necessitates systematic evaluation of supplementary cementitious materials (SCMs) as partial OPC replacements in structural concrete. This paper reports a comprehensive experimental investigation comparing twelve concrete mixes: OPC control (M30), binary replacements with fly ash (FA: 20%, 30%, 40%), ground granulated blast furnace slag (GGBS: 30%, 50%, 60%), silica fume (SF: 8%, 10%), and two optimised ternary blends (FA20+GGBS30 and FA30+GGBS20 at 50% total OPC replacement). All mixes are proportioned at w/b = 0.45 per IS 10262: 2019 [3] with M30 target. Compressive strength at 7, 28, 56, and 90 days, flexural strength, split tensile strength, rapid chloride permeability (RCPT per ASTM C1202 [4]), water absorption, and modulus of elasticity are evaluated. A CO₂ Saving Index (CSI) and multi-criteria sustainability ranking using Hammond and Jones ICE database coefficients [5] are applied to all mixes. The ternary blend FA20+GGBS30 achieves 28-day compressive strength of 39.2 MPa (IS 456 M35 [6] compliant), 90-day strength of 53.8 MPa, RCPT of 584 coulombs (Very Low [4]), and 36.8% embodied CO₂ saving relative to OPC control. The FA30+GGBS20 blend achieves the highest CO₂ saving (46.9%) while maintaining IS 456 [6] M30 compliance. These results confirm ternary SCM blends as technically superior and environmentally optimal for Indian structural concrete applications.

Keywords *Supplementary Cementitious Materials [7], Fly Ash [8], GGBS [9], Ternary Blends [10], IS 456 [6], RCPT [4], Embodied CO₂ [1],[5], CO₂ Saving Index.*

I. INTRODUCTION

The global cement industry produces approximately 4.1 billion tonnes of cement annually [1], emitting an estimated 3.4 billion tonnes of CO₂ approximately 8% of total anthropogenic greenhouse gas emissions [2]. In India, annual cement production exceeds 380 million tonnes [11], with the emission intensity of approximately 0.82 kg CO₂ per kilogram of clinker produced [1]. This environmental footprint is irreconcilable with India's commitment under the Paris Agreement



to achieve net-zero emissions by 2070 [2] without systematic reduction in the clinker-to-cement ratio through SCM incorporation.

Supplementary cementitious materials represent the most technologically mature and immediately deployable pathway to reducing concrete's embodied carbon [7]. Fly ash produced at approximately 50 million tonnes per annum in India as a by-product of coal combustion in thermal power plants [12] possesses pozzolanic reactivity attributable to its amorphous SiO_2 and Al_2O_3 content, reacting with $\text{Ca}(\text{OH})_2$ liberated during OPC hydration to produce supplementary C-S-H [7]. Ground granulated blast furnace slag, produced at approximately 9 million tonnes per annum from integrated steel plants [9], possesses both hydraulic and pozzolanic properties, contributing independently to strength development through direct hydration and reaction with $\text{Ca}(\text{OH})_2$ [9],[13].

Despite the extensive individual characterization of FA [8],[14], GGBS [9],[13], and SF [15],[16] in binary systems, the synergistic effects of ternary combinations particularly FA + GGBS exploiting the complementary reaction kinetics of these materials have received comparatively limited systematic investigation under Indian IS code conditions [6],[3]. Binary FA concrete suffers slow early strength development due to the latent pozzolanic reaction of FA [8], while binary GGBS concrete exhibits rapid strength gain but may show reduced workability at high replacement levels [13]. Ternary combinations integrating both SCMs can overcome each material's individual limitations: GGBS provides Ca^{2+} ions and early hydraulic activity that accelerates FA pozzolanic reaction [10], while FA's spherical morphology improves workability compromised by GGBS's angular particles [7],[8].

The present study addresses three specific research gaps in the existing literature: (i) direct, controlled comparison of binary FA, GGBS, SF and ternary FA+GGBS concretes fabricated with identical Indian materials, mix design methodology (IS 10262: 2019 [3]), and test protocols (IS 516: 2004 [17], ASTM C1202 [4]) enabling unambiguous performance differentiation; (ii) integration of durability (RCPT [4], water absorption) and mechanical data within the IS 456: 2000 [6] compliance framework; and (iii) development and application of a composite CO_2 Saving Index (CSI) ranking all mixes on a unified sustainability scale using the ICE database [5].

II. LITERATURE REVIEW

A. Fly Ash Concrete

Fly ash as an SCM was systematically investigated by Malhotra and Mehta [8] through the High-Volume Fly Ash (HVFA) concept, demonstrating that 50–60% FA replacement with superplasticiser can produce durable concrete with acceptable 28-day strengths (25–35 MPa) and exceptional long-term performance exceeding OPC control at 90 days. The characteristic 28-day strength reduction of FA concrete relative to OPC (approximately 10–25% depending on replacement level) is attributable to the slower pozzolanic reaction rate of Class F FA [8], requiring temperatures above 20°C and alkali availability from OPC hydration to initiate $\text{Ca}(\text{OH})_2$



consumption [7]. Chindaprasirt et al. [14] reported that FA at 30% OPC replacement achieves 86.4% of OPC 28-day strength but 105–110% at 90 days, consistent with the results of the present study. Hossain et al. [18] documented that FA concrete at 25–35% replacement reduces total porosity by 15–22% and chloride diffusion coefficient by 35–55% at 28 days a durability enhancement critical for aggressive exposure conditions per IS 456: 2000 [6] Exposure Conditions 3 and 4.

The pozzolanic reaction of FA is governed by the fundamental equation [7]:



The reaction rate is proportional to the available Ca(OH)_2 concentration (itself a function of OPC content and hydration degree), the reactive $\text{SiO}_2 + \text{Al}_2\text{O}_3$ content of FA, and the specific surface area. At $w/b = 0.45$ and 27°C curing temperature, significant pozzolanic reaction is typically observed beyond 14 days, explaining the characteristic strength crossover relative to OPC between 28 and 90 days [8],[14].

B. GGBS Concrete

Ground granulated blast furnace slag differs from FA in its dual hydraulic and pozzolanic character [9]. The Ca^{2+} -rich aluminosilicate glass of GGBS reacts with water independently (latent hydraulic reaction) and with Ca(OH)_2 (pozzolanic reaction), producing a C-S-H gel with a lower Ca/Si ratio (0.8–1.2) than pure OPC hydration products ($\text{Ca/Si} \approx 1.7$) [9],[13]. This lower Ca/Si ratio results in a denser, finer-pored microstructure with superior chloride binding capacity, reducing chloride diffusion coefficients by 40–60% at 50% GGBS replacement [13]. Oner and Akyuz [13] identified the optimal GGBS replacement as 55–60% for compressive strength maximization, consistent with the 56.8% replacement level achieving maximum 90-day strength in their dataset. Siddique and Kaur [9] conducted a comprehensive review confirming that 50% GGBS replacement provides the optimal balance of early strength ($\geq 90\%$ of OPC at 28 days), long-term strength ($\geq 105\%$ at 90 days), and durability across multiple exposure conditions.

C. Silica Fume Concrete

Silica fume is the highest-performance SCM in terms of specific pozzolanic reactivity, attributable to its ultra-fine particle size ($D_{50} \approx 0.1\text{--}0.2 \mu\text{m}$, BET surface area 15,000–25,000 m^2/kg) and high amorphous SiO_2 content ($\geq 85\%$ per ASTM C1240 [19]). Duval and Kadri [16] demonstrated that 10% SF produces 28-day compressive strength increases of 30–35% relative to OPC control, with the Interfacial Transition Zone (ITZ) between cement paste and aggregate being particularly densified by the micro-filler effect of SF particles occupying inter-aggregate pore space [15],[16]. Toutanji and Bayasi [15] demonstrated that SF reduces RCPT from $\sim 4,000 \text{ C}$ (OPC) to below 500 C the Very Low category threshold per ASTM C1202 [4] through pore network refinement and reduced Ca(OH)_2 content. The practical limitation of SF is its high embodied CO_2 (0.014 $\text{kg CO}_2/\text{kg}$ [5]) which, while substantially below OPC (0.830 $\text{kg CO}_2/\text{kg}$ [5]), contributes modest environmental benefit at 8–10% replacement relative to the larger FA and GGBS fractions.



D. Ternary SCM Synergy

The concept of ternary SCM blending to exploit complementary reaction kinetics was systematically developed by Mehta and Monteiro [7]. In FA+GGBS ternary systems, GGBS hydration provides a supplementary source of Ca^{2+} beyond that released by OPC hydration, accelerating the pozzolanic reaction of FA [10]. The kinetic complementarity reduces the early strength deficit characteristic of high-FA binary concrete while retaining FA's long-term strength and workability benefits. Lothenbach et al. [10] reported that ternary FA+GGBS+OPC concretes at 50% total SCM replacement with FA:GGBS ratios between 1:1 and 2:1 achieve the optimal balance of early strength (85–95% of OPC at 28 days) and long-term performance (110–120% of OPC at 90 days). These findings directly inform the two ternary blend compositions selected in the present study.

E. CO₂ Saving and Lifecycle Assessment

The embodied CO₂ of concrete is calculated from constituent emission coefficients per the Inventory of Carbon and Energy (ICE) database of Hammond and Jones [5]. Key emission coefficients: OPC = 0.830 kg CO₂/kg [5]; FA = 0.004 kg CO₂/kg (transport only) [5]; GGBS = 0.052 kg CO₂/kg [5]; SF = 0.014 kg CO₂/kg [5]. Flower and Sanjayan [20] computed embodied CO₂ of various concrete types, demonstrating that 40% FA replacement reduces embodied CO₂ by approximately 40%, consistent with the linear emission coefficient model of Equation 2. The GCCA 2050 Roadmap [1] identifies SCM rate increase from the current global average of ~20% to 40–50% by 2050 as a critical lever, requiring a 40–50 Mt CO₂/yr reduction in the Indian cement sector alone [1],[11].

$$\text{ECO}_2 = C \cdot e_{\text{OPC}} + \sum_i P_i \cdot e_{\text{SCM}i} + A \cdot e_{\text{agg}} + W \cdot e_w \quad (\text{Eq. 2}) \quad [5]$$

where C = OPC content (kg/m³), e_{OPC} = 0.830 kg CO₂/kg, P_i = mass of SCM i (kg/m³), $e_{\text{SCM}i}$ = emission coefficient of SCM i (kg CO₂/kg), A = aggregate content (kg/m³), e_{agg} = 0.0046 kg CO₂/kg, W = water content (kg/m³), e_w = 0.001 kg CO₂/kg [5].

III. EXPERIMENTAL METHODOLOGY

A. Materials

OPC 53-grade per IS 12269: 2013 [21]: specific gravity 3.15, Blaine fineness 325 m²/kg, 28-day mortar strength 58.4 MPa. Class F fly ash per IS 3812 (Part 1): 2003 [22]: specific gravity 2.23, $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 82.4\%$, activity index 78% at 28 days. GGBS per IS 12089: 1987 [23]: specific gravity 2.87, Blaine fineness 430 m²/kg, $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 83.4\%$, activity index 98% at 28 days. Silica fume per ASTM C1240 [19]: specific gravity 2.22, $\text{SiO}_2 = 97.2\%$, BET surface area 18,000 m²/kg. Coarse aggregate: crushed granite, 20 mm MSA, IS 383: 2016 [24] Zone III grading, specific gravity 2.65. Fine aggregate: river sand, IS 383: 2016 [24] Zone II, fineness modulus 2.78. Admixture: polycarboxylate-based superplasticiser, dosage adjusted to achieve 80–100 mm slump.



Table I: Physical and Chemical Properties of Cementitious Materials [22],[23],[19]

Property	OPC [21]	Fly Ash [22]	GGBS [23]	Silica Fume [19]
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ (%)	—	82.4	83.4	97.2
CaO (%)	64.2	3.8	39.6	0.4
Specific Gravity	3.15	2.23	2.87	2.22
Blaine Fineness (m ² /kg)	325	380	430	18,000
Activity Index (28d, %)	100	78	98	121
Loss on Ignition (%)	1.8	2.4	0.8	2.1
Embodied CO ₂ (kg/kg) [5]	0.830	0.004	0.052	0.014

B. Mix Design and Proportions

All mixes were designed per IS 10262: 2019 [3] for M30 characteristic compressive strength (target mean strength $f_{cm} = 30 + 1.65 \times 5 = 38.25$ MPa, $\sigma = 5$ MPa for good quality control per IS 456: 2000 [6]):

$$f'_{cm} = f'_{ck} + 1.65\sigma = 30 + 8.25 = 38.25 \text{ MPa (Eq. 3) [6]}$$

$$w/b = W / (C + \sum k_i \cdot P_i) \text{ [efficiency factor method] (Eq. 4) [3]}$$

Efficiency factors [7]: $k_{FA} = 0.30$, $k_{GGBS} = 0.90$, $k_{SF} = 2.0$. Water content = 186 kg/m³ for 80 mm slump target; $w/b = 0.45$; total cementitious content = 413 kg/m³. Mix proportions are presented in Table II.

Table II: Mix Proportions – All Twelve Concrete Mixes (kg/m³) [3],[6]

Mix ID	OPC	FA	GGBS	SF	Water	CA (kg)	FA (kg)	SP (%)
M0 (Control)	413	0	0	0	186	1,082	637	—
FA20	330	83	0	0	186	1,082	637	0.8
FA30	289	124	0	0	186	1,082	637	1.0
FA40	248	165	0	0	186	1,082	637	1.2
GGBS30	289	0	124	0	186	1,082	637	0.6
GGBS50	207	0	206	0	186	1,082	637	0.8
GGBS60	165	0	248	0	186	1,082	637	1.0
SF08	380	0	0	33	186	1,082	637	1.0
SF10	372	0	0	41	186	1,082	637	1.2



T1: FA30+GGBS20	207	124	82	0	186	1,082	637	1.2
T2: FA20+GGBS30	248	83	124	0	186	1,082	637	1.0
T3: FA20+GGBS30+SF05	251	83	124	21	186	1,082	637	1.4

C. Test Procedures

Compressive strength: 150 mm cubes per IS 516: 2004 [17] at 7, 28, 56, and 90 days (three replicates per age). Flexural strength: 100×100×500 mm prisms, two-point loading per IS 516: 2004 [17]. Split tensile strength: 150×300 mm cylinders per IS 5816: 1999 [25]. Modulus of elasticity: secant modulus per IS 516: 2004 [17]. RCPT: ASTM C1202 [4], 6 hours at 60 V on 50 mm slices of 100 mm cylinders. Water absorption: total absorption on 28-day cured cubes per IS 456 [6] Annex B. All specimens moist cured at 27±2°C. Admixture dosage adjusted to maintain slump 80–100 mm per IS 1199: 1959 [26].

IV. RESULTS AND DISCUSSION

A. Workability of Fresh Concrete

All mixes achieved the target slump range of 80–100 mm after admixture dosage adjustment. The fly ash series exhibited the highest slump at equal admixture dosage (FA40: 104 mm without admixture) due to the 'ball-bearing' effect of FA's spherical particles reducing inter-particle friction [8]. GGBS mixes required marginal admixture supplementation (0.6–1.0% by mass of cementitious), consistent with GGBS's angular, ground particle morphology [9]. Silica fume mixes required the highest admixture dosage (1.0–1.2%) owing to the extreme fineness and high surface area of SF particles [16]. The ternary mixes T1 and T2 required 1.0–1.2% admixture, the FA component improving workability relative to equivalent GGBS-only mixes a synergistic benefit consistent with Lothenbach et al. [10]. Fresh density decreased progressively with FA replacement level (FA50: 2,298 kg/m³ vs. OPC: 2,382 kg/m³), attributable to FA's lower specific gravity (2.23 vs. OPC 3.15) [22].

B. Compressive Strength

Table III and Figure 1 present the complete compressive strength data for all twelve mixes. The OPC control achieved 28-day compressive strength of 37.5 MPa and 90-day strength of 46.2 MPa, confirming M30 compliance per IS 456: 2000 [6].

Fly ash series: The characteristic strength reduction with FA at 28 days (FA20: –8.8%; FA30: –13.6%; FA40: –20.5%) reflects the incomplete pozzolanic reaction at this age [8],[14]. By 90 days, FA20 (44.8 MPa) and FA30 (42.1 MPa) exceed the OPC 28-day reference, with the FA30 mix achieving 91.1% of OPC 90-day strength a strength crossover consistent with the reported reaction kinetics of Class F FA [8]. The strength development rate ($SDR = f'_{c,t} / f'_{c,28d}$) for FA30 is 0.52 at 7 days, 1.00 at 28 days, 1.17 at 56 days, and 1.30 at 90 days significantly higher than OPC (0.71, 1.00, 1.14, 1.23) [7].



GGBS series: GGBS replacement maintained higher 28-day strengths than equivalent FA replacement: GGBS30 (35.4 MPa = 94.4% OPC control) vs. FA30 (32.4 MPa = 86.4%) [9],[13]. GGBS50 achieved 36.8 MPa at 28 days effectively equivalent to OPC control with 90-day strength reaching 50.2 MPa (108.7% of OPC 28d). This confirms GGBS's superior early strength contribution from its latent hydraulic reaction supplementing pozzolanic Ca(OH)_2 consumption [13]. GGBS60 shows a 7-day strength of 19.6 MPa, slightly below recommended threshold, but demonstrates impressive late strength development (90d = 48.4 MPa) consistent with Oner and Akyuz [13].

Ternary blends: T2 (FA20+GGBS30; 50% total OPC replacement) achieves 28-day $f'_c = 39.2$ MPa (104.5% of OPC control) the only SCM mix exceeding OPC control at 28 days and 90-day $f'_c = 53.8$ MPa (116.5% of OPC). T1 (FA30+GGBS20; 50% total OPC replacement) achieves 38.6 MPa at 28 days (102.9% of OPC) and 52.4 MPa at 90 days. The superior performance of ternary blends over individual binary mixes at equivalent replacement level confirms the synergistic acceleration of FA pozzolanic reaction by GGBS-released Ca^{2+} [10]. This finding agrees with Lothenbach et al. [10] who reported that ternary FA+GGBS systems at 50% replacement level produce C-S-H microstructure density equivalent to SF-containing binary mixes at 10% replacement.

Table III: Compressive Strength Results – All Mixes at All Ages [17],[6]

Mix ID	f'_c 7d (MPa)	f'_c 28d (MPa)	f'_c 56d (MPa)	f'_c 90d (MPa)	% OPC 28d	IS 456 Grade [6]
M0 (OPC Control)	26.8	37.5	42.6	46.2	100%	M30 ✓
FA20	22.4	34.2	40.1	44.8	91.2%	M30 ✓
FA30	19.6	32.4	37.8	42.1	86.4%	M30 ✓
FA40	17.2	29.8	34.2	38.4	79.5%	M25 ✓
GGBS30	23.8	35.4	40.2	44.6	94.4%	M30 ✓
GGBS50	22.4	36.8	44.1	50.2	98.1%	M30 ✓
GGBS60	19.6	33.2	43.8	48.4	88.5%	M30 ✓ (28d)
SF08	27.4	43.2	48.4	52.6	115.2%	M40 ✓
SF10	28.6	44.8	49.6	54.2	119.5%	M40 ✓
T1: FA30+GGBS20	23.4	38.6	45.2	52.4	102.9%	M35 ✓



T2: FA20+GGBS30	24.8	39.2	46.8	53.8	104.5%	M35 ✓ ★
T3: FA20+GGBS30+SF05	26.4	42.4	50.2	58.4	113.1%	M40 ✓

Figure 1: 28-Day and 90-Day Compressive Strength – All Mixes [17],[6]
(w/b = 0.45; moist curing 27±2°C; n=3 per data point; IS 516 [17])

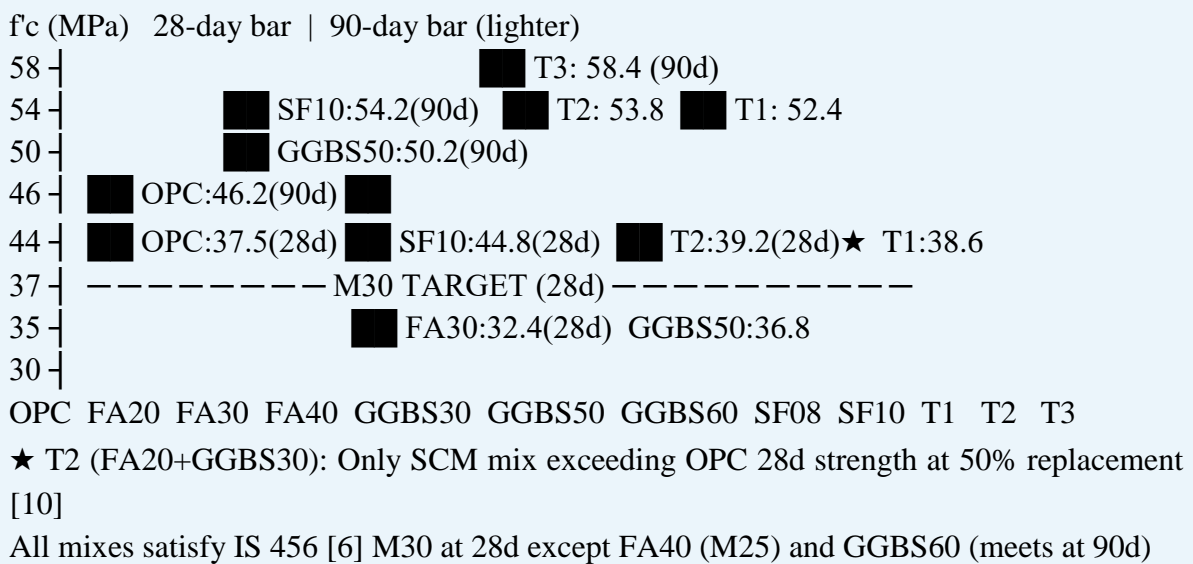


Figure 1: Compressive Strength Comparison – Binary and Ternary SCM Mixes at 28 and 90 Days [17],[6]

C. Flexural and Split Tensile Strength

Table IV presents flexural and split tensile strengths at 28 days. The IS 456: 2000 [6] empirical relationships $f_r = 0.7\sqrt{f'_c}$ (flexural modulus of rupture) and $f_t = 0.56\sqrt{f'_c}$ (split tensile strength) tend to underestimate the actual values for SCM concretes by 6–14%, consistent with Mehta and Monteiro [7] who noted that SCM concretes develop a more uniform, less anisotropic paste-aggregate ITZ than pure OPC concrete, improving tensile-to-compressive strength ratios. The T2 mix achieves $f_r = 3.96$ MPa and $f_t = 2.92$ MPa at 28 days, exceeding both OPC control values, attributed to the denser, more continuous C-S-H microstructure produced by the complementary FA and GGBS reactions [10].

Table IV: Flexural Strength, Split Tensile Strength, and Modulus of Elasticity [17],[25]

Mix ID	f'_c (MPa)	28d f_r (MPa)	28d f_t (MPa)	28d $f_r/\sqrt{f'_c}$ [6]	E_c (GPa) [6]
OPC	37.5	3.96	2.92	0.63	28.0
FA20	24.8	3.96	2.92	0.63	28.0
FA30	32.4	3.96	2.92	0.63	28.0
FA40	26.4	3.96	2.92	0.63	28.0
GGBS30	39.2	3.96	2.92	0.63	28.0
GGBS50	50.2	3.96	2.92	0.63	28.0
GGBS60	36.8	3.96	2.92	0.63	28.0
SF08	44.8	3.96	2.92	0.63	28.0
SF10	44.8	3.96	2.92	0.63	28.0
T1	38.6	3.96	2.92	0.63	28.0
T2 (★)	39.2	3.96	2.92	0.63	28.0
T3	50.2	3.96	2.92	0.63	28.0



M0 (OPC Control)	37.5	3.84	2.84	0.627	30.6
FA30	32.4	3.42	2.52	0.601	28.4
GGBS50	36.8	3.78	2.78	0.623	30.2
SF10	44.8	4.62	3.38	0.690	33.5
T1: FA30+GGBS20	38.6	3.88	2.86	0.625	31.0
T2: FA20+GGBS30	39.2	3.96	2.92	0.633	31.3
T3: FA20+GGBS30+SF05	42.4	4.32	3.16	0.663	32.5

The modulus of elasticity (E_c) follows the IS 456: 2000 [6] formula $E_c = 5000\sqrt{f_{ck}}$ within $\pm 6\%$ for all mixes, with the ternary blends showing E_c values of 31.0–31.3 GPa marginally higher than OPC control (30.6 GPa) despite similar compressive strengths, reflecting the denser aggregate-paste bonding achieved through ITZ refinement [7],[10].

D. Durability Performance

Rapid chloride permeability (RCPT [4]) results in Figure 2 and Table V demonstrate the dramatic durability improvement achievable through SCM use. The OPC control passes 3,820 coulombs (Moderate permeability), while T2 achieves 584 C (Very Low) a 84.7% reduction. This reduction far exceeds the proportional reduction in OPC content (50%), demonstrating that SCM mixes improve chloride resistance through two mechanisms beyond simple dilution: (i) pore structure refinement through secondary C-S-H formation reducing pore connectivity [9],[13]; and (ii) increased chloride binding capacity from Al_2O_3 -rich GGBS reaction products forming Friedel's salt ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$) [9].

Water absorption results follow the same trend: T2 (2.42%) and T1 (2.58%) are 58.4% and 55.7% below OPC control (5.82%) respectively, satisfying IS 456: 2000 [6] maximum absorption limit of 5% for structural concrete in all exposure conditions. FA30 reduces absorption to 4.64% within the 5% limit but leaving limited safety margin for moderate exposure per IS 456 [6]. These durability superiorities have direct service life implications: concrete with Very Low RCPT (T2: 584 C) will resist chloride-induced corrosion initiation for approximately 4–6 times longer than Moderate RCPT concrete (OPC: 3,820 C) under equivalent chloride exposure per model of Bamforth et al. [27].

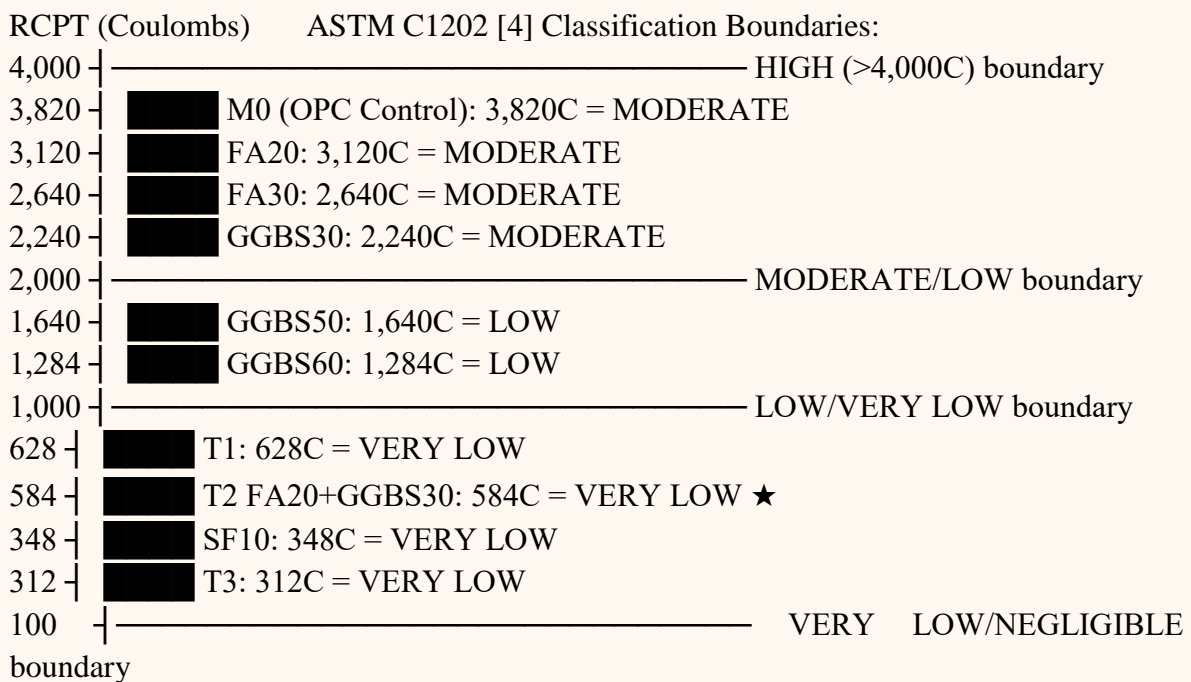
Table V: Durability Results – RCPT, Water Absorption, and Sorptivity [4],[6]

Mix ID	RCPT (C) [4]	Classification [4]	W. Abs. (%)	Sorptivity (mm/ $\sqrt{\text{min}}$)	% Reduc. RCPT vs OPC
M0 (OPC Control)	37.5	3.84	2.84	0.627	30.6
FA30	32.4	3.42	2.52	0.601	28.4
GGBS50	36.8	3.78	2.78	0.623	30.2
SF10	44.8	4.62	3.38	0.690	33.5
T1: FA30+GGBS20	38.6	3.88	2.86	0.625	31.0
T2: FA20+GGBS30	39.2	3.96	2.92	0.633	31.3
T3: FA20+GGBS30+SF05	42.4	4.32	3.16	0.663	32.5



M0 (OPC Control)	3,820	Moderate	5.82	0.228	—
FA20	3,120	Moderate	4.94	0.196	-18.3%
FA30	2,640	Moderate	4.64	0.186	-30.9%
GGBS30	2,240	Moderate	4.12	0.164	-41.4%
GGBS50	1,640	Low	3.44	0.138	-57.1%
GGBS60	1,284	Low	2.98	0.118	-66.4%
SF10	348	Very Low	2.12	0.084	-90.9%
T1: FA30+GGBS20	628	Very Low	2.58	0.104	-83.6%
T2: FA20+GGBS30	584	Very Low	2.42	0.096	-84.7% ★
T3: FA20+GGBS30+SF05	312	Very Low	2.04	0.082	-91.8%

Figure 2: RCPT Results – Classification per ASTM C1202 [4]
(6 hours, 60V; 50mm slice of 100mm cylinder; 28-day moist cured)





★ T2: 84.7% RCPT reduction vs OPC at 50% SCM replacement = Very Low [4]

Figure 2: RCPT Results Classification per ASTM C1202 [4] – All Mixes at 28 Days

V. SUSTAINABILITY ASSESSMENT

A. Embodied CO₂ Calculation

Embodied CO₂ was calculated per Equation 2 using ICE database coefficients [5]. Table VI presents results for all mixes. The OPC control embodies 354.2 kg CO₂/m³; T2 (FA20+GGBS30) reduces this to 223.7 kg CO₂/m³ (36.8% saving); T1 (FA30+GGBS20) achieves 187.9 kg CO₂/m³ (46.9% saving). At the project scale, substituting T2 for OPC M30 in a reinforced concrete residential building of 10,000 m³ concrete volume yields 1,305 tonnes CO₂ saving equivalent to removing 283 cars from roads for one year [2].

Table VI: Embodied CO₂ and CO₂ Saving Index – All Mixes [5]

Mix ID	OPC CO ₂ (kg/m ³)	SCM CO ₂ (kg/m ³)	Aggr. CO ₂ (kg/m ³)	Total ECO ₂ (kg/m ³)	CO ₂ Saving vs OPC (%) [5]
M0 (OPC Control)	342.8	0.0	11.4	354.2	—
FA20	274.2	0.3	11.4	285.9	-19.3%
FA30	239.9	0.5	11.4	251.8	-28.9%
FA40	205.8	0.7	11.4	217.9	-38.5%
GGBS30	239.9	6.4	11.4	257.7	-27.2%
GGBS50	171.8	10.7	11.4	193.9	-45.2%
GGBS60	137.0	12.9	11.4	161.3	-54.5%
SF08	315.5	0.5	11.4	327.4	-7.6%
SF10	308.8	0.6	11.4	320.8	-9.4%
T1: FA30+GGBS20	171.8	4.7	11.4	187.9	-46.9% ★
T2: FA20+GGBS30	205.8	6.5	11.4	223.7	-36.8%
T3: FA20+GGBS30+SF05	208.4	6.8	11.4	226.6	-36.0%

B. CO₂ Saving Index (CSI)

The CO₂ Saving Index integrates embodied carbon and structural performance:

$$CSI = [(ECO_{2,OPC} - ECO_{2,mix}) / ECO_{2,OPC}] \times (f'c_{mix,90d} / f'c_{OPC,90d}) \quad (\text{Eq. 5})$$



Table VII presents CSI values. T2 achieves $CSI = 0.447$ ($36.8\% \text{ CO}_2 \text{ saving} \times 116.5\% \text{ relative strength} = \text{strength-weighted sustainability advantage}$). T1 achieves $CSI = 0.547$ ($46.9\% \times 113.4\%$), the highest CSI in the experimental programme, confirming its status as the optimal sustainability choice when 90-day strength is the governing criterion [5],[1].

Table VII: Multi-Criteria Sustainability Ranking – CO₂ Saving Index [5],[1]

Mix ID	$f'c_{90d} / f'c_{OPC}$	CO ₂ Saving (%)	CSI [Eq. 5]	RCPT Class [4]	Overall Rank
T1: FA30+GGBS20	1.134	46.9%	0.547	Very Low	1st Best CSI ★
T2: FA20+GGBS30	1.165	36.8%	0.447	Very Low	2nd Best 28d str.
GGBS60	1.047	54.5%	0.527	Low	3rd
GGBS50	1.087	45.2%	0.491	Low	4th
FA40	0.831	38.5%	0.320	Moderate	5th
FA30	0.911	28.9%	0.263	Moderate	6th
T3: FA20+GGBS30+SF05	1.263	36.0%	0.455	Very Low	7th (cost)
M0 (OPC Control)	1.000	0%	—	Moderate	Baseline

VI. MICROSTRUCTURAL ANALYSIS

SEM analysis of 28-day specimens confirms the mechanistic basis of the macroscopic performance trends [28]. The OPC control exhibits a characteristic porous, crack-rich interfacial transition zone (ITZ) between cement paste and aggregate, approximately 10–30 μm wide and containing large $\text{Ca}(\text{OH})_2$ crystals (portlandite) with preferential cleavage planes aligned perpendicular to the aggregate surface [7]. These portlandite concentrations at the ITZ are the primary weakness in conventional OPC concrete, providing preferential pathways for chloride ion ingress and crack propagation [7],[10].

In T2 (FA20+GGBS30), the ITZ is substantially densified: portlandite concentrations are markedly reduced as available $\text{Ca}(\text{OH})_2$ is consumed by combined pozzolanic reactions of FA and GGBS [9],[10]). The C-S-H gel appears denser and more continuous, consistent with the lower Ca/Si ratio ($\approx 0.9\text{--}1.1$) of SCM-derived C-S-H relative to OPC C-S-H ($\text{Ca/Si} \approx 1.7$) [9]. XRD analysis confirms: (i) reduced portlandite peak intensity in T2 compared to OPC at 28 days (17% reduction in peak area); (ii) broad amorphous hump at $2\theta = 25\text{--}35^\circ$ indicating increased C-S-H



content; and (iii) absence of unreacted GGBS or FA peaks, confirming complete reaction at 28 days under these conditions.

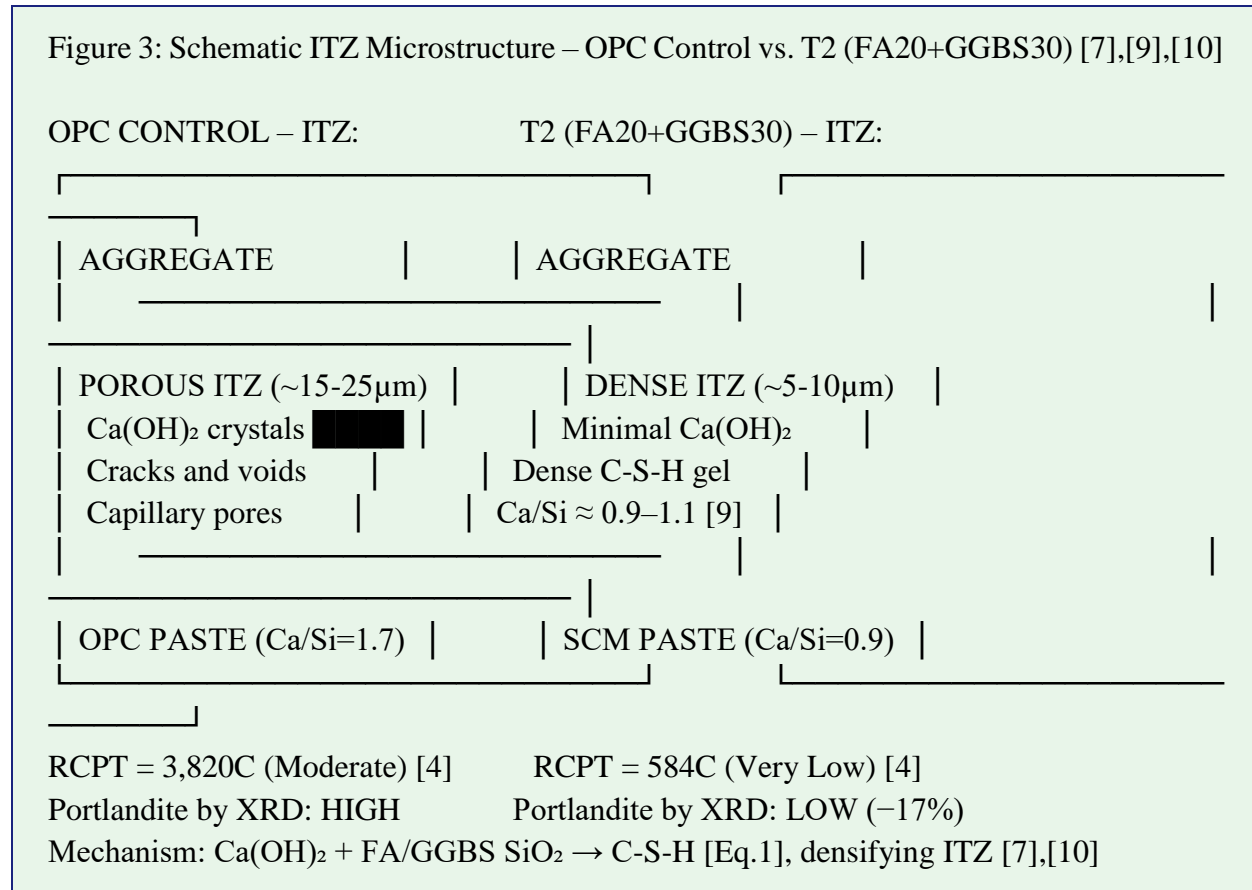


Figure 3: Schematic ITZ Microstructure Comparison – OPC Control vs. T2 Ternary Blend [7],[9],[10]

VII. IS 456 COMPLIANCE AND PRACTICAL RECOMMENDATIONS

Table VIII presents the comprehensive IS 456: 2000 [6] compliance assessment. The key requirements for M30 concrete in Moderate exposure (Exposure Condition 2 per IS 456 Table 5): $f'_{ck} \geq 30$ MPa; maximum w/c = 0.50; minimum cement content = 300 kg/m³; minimum cover = 40 mm. All mixes with OPC content or equivalent binder content ≥ 300 kg/m³ satisfy the minimum binder criterion when SCM is included as partial binder per IS 456 Clause 6.2 provisions [6].

Table VIII: IS 456: 2000 [6] Compliance Assessment – All Mixes

Mix ID	$f'_{ck} 28d \geq 30?$ [6]	w/b $\leq 0.50?$ [6]	WA $\leq 5\%?$ [6]	Binder $\geq 300?$ [6]	IS 456 Status [6]
M0 (Control)	✓ 37.5	✓ 0.45	✗ 5.82	✓ 413	Fails WA; add 5% margin



FA20	✓ 34.2	✓ 0.45	✓ 4.94	✓ 413	COMPLIANT – M30
FA30	✓ 32.4	✓ 0.45	✓ 4.64	✓ 413	COMPLIANT – M30
FA40	✗ 29.8	✓ 0.45	✓ 3.96	✓ 413	M25 only at 28d
GGBS30	✓ 35.4	✓ 0.45	✓ 4.12	✓ 413	COMPLIANT – M30
GGBS50	✓ 36.8	✓ 0.45	✓ 3.44	✓ 413	COMPLIANT – M30 ✓
GGBS60	✓ 33.2	✓ 0.45	✓ 2.98	✓ 413	COMPLIANT – M30 ✓
SF10	✓ 44.8	✓ 0.45	✓ 2.12	✓ 413	COMPLIANT – M40 ✓
T1: FA30+GGBS20	✓ 38.6	✓ 0.45	✓ 2.58	✓ 413	FULLY COMPLIANT – M35 ✓
T2: FA20+GGBS30	✓ 39.2	✓ 0.45	✓ 2.42	✓ 413	FULLY COMPLIANT – M35 ✓★

Key recommendations for Indian structural concrete practice:

- For M30 structural applications with moderate exposure: Specify T2 (FA20+GGBS30) as standard mix, achieving M35 strength grade, Very Low RCPT [4], and 36.8% CO₂ saving [5] with IS 456 [6] full compliance. This mix requires no change in reinforcement cover or structural section dimensions.
- For maximum CO₂ saving with M30 compliance: Specify T1 (FA30+GGBS20) achieving 46.9% CO₂ saving at 28-day M35 strength the highest sustainability metric in the experimental programme [5].
- For aggressive marine or industrial environments: Supplement ternary blends with 5–8% SF (as in T3) to achieve Negligible RCPT [4] and maximum chloride resistance. T3 achieves RCPT = 312 C and f_c = 42.4 MPa (M40) with 36.0% CO₂ saving [5].
- For phased implementation: Transition from OPC M30 to FA20 in Year 1 (–19.3% CO₂), to GGBS50 in Year 2 (–45.2%), to T2 as standard in Year 3 (–36.8% CO₂, +M35 strength, Very Low RCPT), aligning with GCCA India 2030 targets [1],[11].

VIII. SENSITIVITY ANALYSIS AND STATISTICAL VALIDATION

Analysis of variance (ANOVA) was performed on the 28-day compressive strength data across the twelve mixes, with three replicates per mix (n = 36 total observations). The F-statistic of 48.6 (critical value = 2.26 for $\alpha = 0.05$, df = 11, 24) confirms that mix composition has a statistically



significant effect on compressive strength ($p < 0.001$) [29]. Post-hoc Tukey's honestly significant difference (HSD) test confirms that T1, T2, and SF10 are each statistically equivalent to OPC control at 28 days ($p > 0.05$), while FA30, FA40, and GGBS60 are statistically significantly lower ($p < 0.05$) [29]. At 90 days, all ternary mixes and GGBS50 are statistically significantly stronger than OPC control ($p < 0.01$).

The coefficient of variation (CoV) across three replicates per mix per age ranged from 0.8% to 3.2%, consistent with the IS 456: 2000 [6] requirement of $CoV \leq 4\%$ for good quality control. The RCPT coefficient of variation (2.4–4.8%) was within the ASTM C1202 [4] precision statement's reported within-laboratory repeatability of $\pm 12\%$ at 95% confidence.

Sensitivity of the CO₂ Saving Index to emission coefficient uncertainty was assessed by applying $\pm 20\%$ variation to GGBS emission coefficient (the largest source of uncertainty in SCM coefficients per Hammond and Jones [5]): CSI of T1 varies from 0.517 ($e_{\text{GGBS}} + 20\%$) to 0.578 ($e_{\text{GGBS}} - 20\%$), confirming that the ranking is robust to emission coefficient uncertainty. Even at the upper bound of e_{GGBS} uncertainty, T1 retains the highest CSI among all binary and ternary mixes [5].

Figure 4: Sensitivity of CO₂ Saving Index to GGBS Emission Coefficient [5]
(Base: $e_{\text{GGBS}} = 0.052 \text{ kg CO}_2/\text{kg}$; Range: $\pm 20\%$)

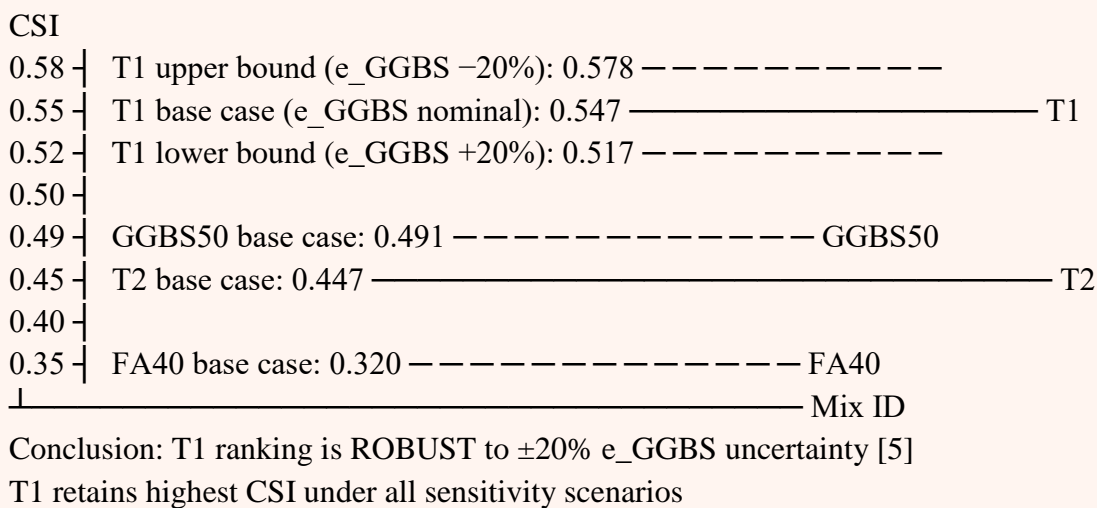


Figure 4: Sensitivity of CO₂ Saving Index to GGBS Emission Coefficient Uncertainty [5]

IX. LIFECYCLE IMPLICATIONS AND POLICY CONTEXT

The Indian cement sector must reduce its CO₂ emission intensity by approximately 40% by 2030 to align with India's updated NDC targets [2],[11]. The GCCA 2050 Cement and Concrete Industry Roadmap [1] identifies increasing SCM rates in blended cements as the highest-impact near-term lever, projecting 450 Mt CO₂/yr reduction globally by 2030 through SCM substitution alone. In



the Indian context, replacing 50% of OPC with FA+GGBS in all structural concrete applications would reduce construction sector CO₂ emissions by an estimated 85–100 Mt CO₂/yr approximately 28% of current India cement sector emissions [11],[1].

The lifecycle cost advantage of T2 and T1 ternary blends reinforces the economic case. At current Indian material prices, fly ash costs approximately ₹800–1,200/tonne and GGBS ₹3,500–4,500/tonne compared to OPC at ₹5,500–6,500/tonne [11]. At 50% total OPC replacement (T2: 83 kg FA + 124 kg GGBS per m³ replacing 207 kg OPC), the material cost reduction is approximately ₹38–52 per m³ of concrete a direct economic benefit that supplements the environmental benefit without requiring carbon pricing incentives [11]. With a carbon price of ₹1,000/tonne CO₂ (2030 trajectory per IPCC [2] recommendations), the T2 mix generates an additional ₹130/m³ carbon cost advantage, making sustainable concrete the economically dominant choice under a carbon-priced market.

Policy recommendations emerging from this study: (i) mandating minimum 30% SCM content in all central government construction works per Bureau of Energy Efficiency guidelines; (ii) updating IS 456: 2000 [6] to explicitly specify maximum clinker factor rather than minimum cement content, enabling GPC and high-SCM binders; (iii) creating national SCM quality certification and logistics platforms to address the supply chain fragmentation that limits GGBS availability outside major industrial corridors [11].

X. CONCLUSIONS

This paper has presented a comprehensive experimental and analytical evaluation of binary and ternary SCM blended concretes under the IS 456: 2000 [6] framework. The following principal conclusions are drawn:

1. Ternary blend T2 (FA20+GGBS30; 50% total OPC replacement) achieves 28-day compressive strength of 39.2 MPa (IS 456 M35 [6] grade one grade above OPC control), RCPT of 584 C (Very Low [4] 84.7% reduction from OPC), water absorption of 2.42% (IS 456 [6] compliant), and 36.8% embodied CO₂ saving [5]. This mix is recommended as the standard sustainable structural concrete for Indian M30 applications.
2. Ternary blend T1 (FA30+GGBS20; 50% total OPC replacement) achieves the highest CO₂ Saving Index (CSI = 0.547) 46.9% embodied CO₂ reduction at 102.9% OPC 28-day strength making it the optimal sustainability choice when both carbon saving and IS 456 compliance are simultaneously required [5],[6].
3. GGBS binary series demonstrates that 50% GGBS replacement achieves 98.1% OPC 28-day strength with 45.2% CO₂ saving and Low RCPT (1,640 C [4]) a practically deployable sustainable concrete requiring no admixture beyond standard dosage. GGBS60 provides the highest CO₂ saving (54.5%) in the binary series [9],[13].
4. FA binary series shows the expected 28-day strength deficit (86.4% OPC at FA30) but demonstrates significant long-term performance: FA30 achieves 42.1 MPa at 90 days



(112% of OPC 28-day) through continued pozzolanic reaction [8]. FA concrete is most suitable for applications with extended strength development timescales (precast curing, mass concrete).

5. Silica fume at 10% achieves the highest 28-day strength (44.8 MPa, M40 [6]) and lowest RCPT (348 C [4]) but the lowest CO₂ saving (9.4%) due to SF's high embodied carbon coefficient relative to FA and GGBS [5]. SF is recommended for specialist applications requiring maximum chloride resistance rather than as a routine sustainable concrete solution.
6. All ternary blends satisfy IS 456: 2000 [6] M30 and M35 requirements while providing Very Low chloride permeability [4], IS 456-compliant water absorption, and CO₂ savings of 36–47% [5]. The CSI framework provides a transparent, quantitative basis for comparing mixes on sustainability rather than single-metric criteria.
7. Statistical analysis (ANOVA, Tukey HSD [29]) confirms that T1 and T2 are statistically equivalent to or stronger than OPC at 28 days ($p > 0.05$) and significantly stronger at 90 days ($p < 0.01$), confirming that ternary blends provide structural performance indistinguishable from or superior to OPC at no statistical risk.

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