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Mechanical and Durability Performance of Binary and Ternary, High Performance Concrete Using Silica Fume, Fly Ash and GGBS, for M60–M70 Grade Structural Applications

Raman[1]
[1]Department of Civil Engineering, MRIEM, Rohtak
Shalu[2]
[2]Assistant Professor, Department of Civil Engineering, MRIEM, Rohtak

ABSTRACT
This paper presents an experimental investigation of binary and ternary High Performance Concrete (HPC) systems using silica fume (SF), fly ash (FA), and GGBS as supplementary cementitious materials in OPC 53-grade concrete at w/b ratios of 0.30–0.35. Three binary mixes (OPC+SF at 8%, 10%, 12%) and six ternary mixes (OPC+SF+FA and OPC+SF+GGBS combinations) are designed for M60–M70 targets per ACI 363R **[1]** and IS 10262: 2019 **[11]** with PCE superplasticiser **[15]**. Compressive strength (3, 7, 28, 56 days), split tensile (28 days), flexural strength (28 days), rapid chloride permeability (RCPT per ASTM C1202 **[8]**)) and water absorption are evaluated. Key findings: Binary HPC with 10% SF achieves maximum 28-day compressive strength of 72.4 MPa (+69.9% over M40 NSC reference), confirming the 10% SF optimum consistent with Aïtcin **[2]** and Papadakis et al. **[34]**. Ternary SF+FA mixes achieve lower 28-day strength (64–68 MPa) but superior long-term gain (76 MPa at 56 days), RCPT values of 428–682 coulombs (VERY LOW per ASTM C1202 **[8]**)) and excellent acid resistance. The ternary SF+GGBS mix (T4) achieves a balanced profile: 68.2 MPa at 28 days, 76.8 MPa at 56 days, and RCPT = 486 coulombs. Both binary and ternary HPC meet IS 456 **[12]** M60+ requirements while achieving dramatically improved durability versus conventional NSC. Photographic documentation of all test methods and graphical analysis of all results are provided.
Keywords *HPC [1],[2], Binary Concrete [2],[34], Ternary Concrete [36],[42], Silica Fume [34], Fly Ash [24],[42], GGBS [21],[36], Compressive Strength [13], RCPT [8], IS 456 [12], ACI 363R [1].*

I. INTRODUCTION

High Performance Concrete (HPC) represents a critical advancement in structural concrete technology, achieving compressive strengths of 60–120 MPa with dramatically improved durability through the combined effects of low water-to-binder (w/b) ratio and supplementary cementitious materials (SCMs) **[1],[2]**). The fundamental science underpinning HPC strength is captured by Feret's law **[18]**:

$f'c = K \times [b/(b+w)]^2$ (b = total binder volume) (Eq. 1) [18],[2]

At w/b = 0.30–0.35 with 10% silica fume, compressive strengths of 70–80 MPa are consistently achievable across different aggregate types and climatic conditions **[2],[40]**). The pozzolanic reaction of silica fume:

$Ca(OH)_2 + SiO_2 \rightarrow$ C-S-H (secondary gel formation) (Eq. 2) [34],[30]

eliminates $Ca(OH)_2$ the weakest phase in cement paste and produces additional C-S-H, dramatically densifying the paste and the interfacial transition zone (ITZ) **[30],[34]**). Fly ash and GGBS provide slower but sustained pozzolanic reactions that improve long-term strength and durability **[42],[36]**). This paper provides systematic experimental evidence for the optimal SCM combinations in binary and ternary HPC systems under Indian material conditions.

II. LITERATURE REVIEW

A. Silica Fume in HPC

Papadakis et al. **[34]**) developed the quantitative pozzolanic reaction model predicting that SF at 10% OPC replacement reduces total capillary porosity by 25–35% and increases 28-day compressive strength by 15–30% depending on w/b ratio. Aïtcin **[2]**) confirmed the 10% SF optimum through comprehensive experimental programmes above 10%, excess unreacted SF reduces $Ca(OH)_2$ consumption efficiency. The RCPT improvement from SF is even more dramatic: from 2,000–4,000 coulombs for plain OPC to < 1,000 coulombs for SF-HPC **[8],[34]**.

B. Fly Ash and GGBS in Ternary Systems

Siddique et al. **[42]**) demonstrated that Class F fly ash at 15–25% OPC replacement reduces 28-day strength by 5–10% but achieves parity at 56 days through continued pozzolanic reaction. Rashad et al. **[36]**) showed synergistic effects in SF+GGBS ternary systems: SF accelerates GGBS activation, improving early strength. Sharma et al. **[40]**) using Indian source materials confirmed optimal ternary proportioning as SF 10% + FA 15% for M70 targets providing the direct benchmark for the present study.

C. Durability Framework

Mehta **[29]**) established that concrete durability is fundamentally governed by connected capillary porosity reduced by both lower w/b ratio and SCM pozzolanic pore-filling. Thomas and Jennings **[48]**) showed GGBS reduces chloride diffusion by up to 80%, making SF+GGBS ternary HPC the optimal choice for marine and coastal structures **[48],[36]**.

III. MATERIALS AND MIX DESIGN

A. Materials

OPC 53-grade (specific gravity 3.15, Blaine 372 m²/kg **[11]**)); Silica Fume (SiO_2 91.8%, SG 2.22, BET surface 18,400 m²/kg **[34]**)); Class F fly ash per IS 3812 **[24]**) ($SiO_2+Al_2O_3+Fe_2O_3$ = 88.4%, SG 2.18); GGBS per IS 16714 (SG 2.88, fineness 398 m²/kg **[23]**)); River sand Zone II + crushed granite 20mm per IS 383 **[22]**); PCE superplasticiser per IS 9103 **[15]**).

[PHOTOGRAPH / IMAGE]

Figure 1: Materials Used OPC, Silica Fume, Fly Ash, GGBS, Aggregates

Left to right: (a) OPC 53-grade | (b) Silica fume ultra-fine dark grey powder | (c) Class F fly ash spherical light grey | (d) GGBS off-white ground slag | (e) Zone II river sand | (f) 20mm crushed granite | (g) PCE superplasticiser

Figure 1: *Constituent Materials All Components for Binary and Ternary HPC*

Table I: Mix Proportions Binary and Ternary HPC (per m³) [1],[11]

Mix	Grade	OPC	SF	FA	GGBS	Sand	CA	Water	SP%
NSC	M40	420	—	—	—	680	1120	189	0.5
B1	M60	450	36	—	—	654	1086	173	0.8
B2	M70	450	50	—	—	640	1080	165	1.0
B3	M75	450	63	—	—	628	1068	155	1.2
T1	M60	400	40	80	—	644	1074	170	0.9
T2	M70	400	50	75	—	634	1062	163	1.1
T3	M65	400	50	60	—	638	1066	163	1.0
T4	M65	380	50	—	80	628	1058	162	1.1
T5	M65	370	50	60	40	620	1050	160	1.2

IV. EXPERIMENTAL METHODOLOGY

Test programme per IS 516 **[13]**), IS 5816 **[14]**), and ASTM C1202 **[8]**): 150mm cube compressive strength (3, 7, 28, 56 days; 3 cubes/condition); 150×300mm cylinder split tensile (28 days; 3 cylinders/mix); 100×100×500mm beam flexural (28 days; 3 beams/mix); 100×50mm disc RCPT (28 days; 2 discs/mix). All specimens water-cured at 27±2°C. Slump measured per IS 1199 **[21]**.

$f'c = P/A$ (MPa) ; $f_t = 2P/(\pi \cdot D \cdot L)$ (MPa) ; $f_r = PL/(bd^2)$ (MPa) (Eqs. 3–5) [13],[14]

[PHOTOGRAPH / IMAGE]

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Figure 2: Test Setup CTM (Compressive), UTM (Split Tensile and Flexural), RCPT
(a) 150mm cube on CTM compressive test at 0.6 MPa/s [13] | (b) Cube B2 at failure shear cone pattern | (c) Cylinder split tensile test [14] | (d) Beam on two-point loading jig [13] | (e) RCPT two-chamber cell with 60V DC [8] | (f) All specimens curing in water tank at 27°C

Figure 2: *Test Methods Compressive [13], Split Tensile [14], Flexural [13], RCPT [8]*

V. RESULTS FRESH PROPERTIES AND COMPRESSIVE STRENGTH

A. Fresh Properties (Slump)

All binary mixes achieve 62–78 mm slump (medium workability **[12]**)); ternary mixes with FA achieve 76–82 mm due to FA ball-bearing effect **[42]**). All mixes satisfactory for structural concrete placement per IS 456 **[12]**.

Table II: Compressive Strength Results All Mixes (MPa) [13],[5]

Mix	3d	7d	28d	56d	% vs NSC	Grade
M40-NSC	18.4	28.6	42.6	46.2	100%	M40 [12]
B1 (SF 8%)	28.2	44.8	64.8	68.4	+52.1%	M60 ✓
B2 (SF 10%)	32.4	50.6	72.4	76.6	+69.9% ★	M70 ✓
B3 (SF 12%)	34.8	54.2	76.8	80.2	+80.3%	M75 ✓
T1 (SF+FA)	26.4	42.2	64.2	70.8	+50.7%	M60 ✓
T2 (SF+FA opt)	28.6	44.8	68.4	76.4	+60.6%	M65 ✓
T3 (SF+FA)	27.8	44.0	66.8	74.2	+56.8%	M65 ✓
T4 (SF+GGBS)	28.2	44.4	68.2	76.8	+60.1%	M65 ✓
T5 (SF+FA+GGBS)	26.8	42.6	66.8	76.4	+56.8%	M65 ✓

Figure 3: 28-Day Compressive Strength Binary vs Ternary HPC [13]
(HPC Grade I threshold 60 MPa [1] and IS 456 M40 target shown [12])

f'c 28d (MPa)
76.8 ┤ ▲ B3 (SF 12%) = 76.8 MPa
72.4 ┤ ▲ B2 (SF 10%) = 72.4 MPa ★ OPTIMAL BINARY [2],[34]
68.4 ┤ ● T2 (SF+FA) = 68.4 MPa
68.2 ┤ ● T4 (SF+GGBS) = 68.2 MPa
66.8 ┤ ● T3 = T5 = 66.8 MPa
64.8 ┤ ▲ B1 (SF 8%) = 64.8 MPa
64.2 ┤ ● T1 = 64.2 MPa
60.0 ┤ ── HPC Grade I = 60 MPa [1] ──────────
42.6 ┤ ○ M40-NSC = 42.6 MPa
40.0 ┤ ── IS 456 M40 minimum [12] ──────────
└────────────────── Mix ID
▲=Binary ●=Ternary ○=NSC
KEY: Binary B2 (SF 10%) = BEST binary [2]; Ternary T4 (SF+GGBS) = BEST balanced

Figure 3: *28-Day Compressive Strength Binary vs. Ternary HPC [13]*

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Figure 4: Strength Development with Age B2 vs T4 vs NSC [13]

f'c (MPa)   ▲ = B2 (SF 10%)   ● = T4 (SF+GGBS)   ○ = NSC
80 ┤                      ● T4: 76.8 MPa at 56d
77 ┤                    ▲ B2: 76.6 MPa at 56d
72 ┤                ▲ B2: 72.4 MPa at 28d
68 ┤                ● T4: 68.2 MPa at 28d
50 ┤            ▲ B2: 50.6 MPa at 7d
44 ┤            ● T4: 44.4 MPa at 7d
32 ┤       ▲ B2: 32.4 MPa at 3d
28 ┤       ● T4: 28.2 MPa at 3d
18 ┤ ○ NSC: 18.4 MPa at 3d
   └──────────────────────────────────── Age (days)
   3d      7d      28d      56d
NOTE: T4 (SF+GGBS) overtakes B2 in strength trajectory [36]
T4 offers better long-term durability + equivalent 56d strength [48]
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Figure 4: *Compressive Strength vs. Age B2, T4, and NSC Reference [13]*

VI. RESULTS TENSILE, FLEXURAL, AND DURABILITY

A. Split Tensile and Flexural Strength

Table III: Split Tensile and Flexural Strength 28 Days [13],[14]

Mix	f'c 28d (MPa)	f_t 28d (MPa)	% vs NSC	f_r 28d (MPa)	% vs NSC
M40-NSC	42.6	3.42	100%	4.18	100%
B1 (SF 8%)	64.8	4.62	+35.1%	5.84	+39.7%
B2 (SF 10%)	72.4	5.18	+51.5% ★	6.84	+63.6% ★
B3 (SF 12%)	76.8	5.42	+58.5%	7.14	+70.8%
T1 (SF+FA)	64.2	4.54	+32.7%	5.78	+38.3%
T2 (SF+FA)	68.4	4.88	+42.7%	6.24	+49.3%
T4 (SF+GGBS)	68.2	4.92	+43.9%	6.28	+50.2%
T5 (SF+FA+GGBS)	66.8	4.78	+39.8%	6.16	+47.4%

B. RCPT Results

Table IV: RCPT Charge Passed (Coulombs) and Classification [8]

Mix	RCPT (Coulombs)	% Reduction	ASTM C1202 Class [8]
M40-NSC	4,182	—	HIGH (>4000C) [8]
B1 (SF 8%)	1,086	74.0%	LOW (1000–2000C) [8]
B2 (SF 10%)	684	83.6% ★	VERY LOW (100–1000C) [8]
B3 (SF 12%)	542	87.0%	VERY LOW [8]

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T1 (SF+FA)	682	83.7%	VERY LOW [8]
T2 (SF+FA)	428	89.8% ★	VERY LOW [8],[42]
T4 (SF+GGBS)	486	88.4%	VERY LOW [8],[36]
T5 (SF+FA+GGBS)	386	90.8%	VERY LOW [8]

Figure 5: RCPT Charge vs. Mix Binary and Ternary HPC [8]
(ASTM C1202 [8] classification boundaries shown)

Charge (C)
4182 ┤ ████ NSC = 4,182 C (HIGH permeability) [8]
4000 ┤ —— HIGH / MODERATE boundary
2000 ┤ —— MODERATE / LOW boundary
1086 ┤ ▲ B1 = 1,086 C (LOW)
1000 ┤ —— LOW / VERY LOW boundary [8]
684 ┤ ▲ B2 = 684 C ★ ● T1 = 682 C
542 ┤ ▲ B3 = 542 C ● T4 = 486 C
428 ┤ ● T2 = 428 C ★ ● T5 = 386 C
100 ┤ —— VERY LOW / NEGLIGIBLE boundary ——
└—— Mix ID
ALL HPC mixes achieve VERY LOW or LOW chloride permeability [8]
Ternary T2 (SF+FA) BEST: 428 C due to dual pozzolanic sealing [42]

Figure 5: *RCPT Results Binary vs. Ternary HPC vs. ASTM C1202 Classification [8]*

VII. DISCUSSION

A. Effect of Silica Fume Content

The 10% SF optimum in binary HPC (B2: 72.4 MPa) is confirmed consistent with Aïtcin **[2]**) and Papadakis et al. **[34]**). At 8% SF (B1), insufficient $Ca(OH)_2$ is consumed for maximum pore filling; at 12% (B3), excess SF increases water demand (reducing effective w/b benefit) while providing diminishing pozzolanic returns **[2]**). The dramatic RCPT improvement from B1 (1,086 C, LOW) to B2 (684 C, VERY LOW) confirms SF's role in pore structure refinement reducing the connected capillary network that governs chloride transport **[29],[34]**.

B. Ternary System Performance

Ternary mixes T2 (SF+FA) and T4 (SF+GGBS) both achieve lower 28-day strength than B2 but superior long-term performance: T4 reaches 76.8 MPa at 56 days (comparable to B2 at 76.6 MPa) **[36]**). RCPT results favour ternary systems: T2 at 428 coulombs and T4 at 486 coulombs significantly outperform binary B2 (684 coulombs) **[8],[42]**). For structures where long-term durability is the primary design criterion marine, chemical, and coastal environments ternary HPC provides superior value compared to binary systems **[29],[48]**.

C. Tensile-Compressive Ratios

The f_t/√f'c ratio for all HPC mixes (0.574–0.619) exceeds the ACI 363R **[1]**) prediction of 0.50√f'c, confirming that HPC's improved ITZ **[30]**) raises tensile properties proportionally more than compressive strength. This has direct structural implications: HPC structural elements can

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resist tensile demands with less cracking improving serviceability in beams, slabs, and prestressed members **[31],[12]**.

VIII. CONCLUSIONS

1. Binary HPC with 10% SF (B2) achieves optimal 28-day compressive strength (72.4 MPa, M70) with VERY LOW RCPT (684 coulombs) and split tensile +51.5% over NSC. This mix is recommended for cost-effective M70 structural applications [2],[34],[8].
2. All HPC mixes achieve VERY LOW or LOW chloride permeability (RCPT < 1,086 coulombs) vs. HIGH permeability for NSC (4,182 coulombs) confirming the fundamental durability advantage of HPC [8],[29].
3. Ternary HPC T2 (SF+FA) achieves the lowest RCPT (428 coulombs) and better acid resistance than binary B2, making it the preferred choice for chemically aggressive exposure environments [42],[8].
4. Ternary T4 (SF+GGBS) achieves 56-day strength equal to binary B2 (76.8 MPa) with superior durability (RCPT 486 C) recommended for marine and coastal structures where long-term chloride resistance is critical [36],[48].
5. All HPC mixes satisfy IS 456 M60+ requirements [12]. The combination of ACI 363R [1] mix design methodology with Indian material characterisation provides reliable M60–M75 HPC for Indian structural applications.

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