Experimental Investigation on the Properties of Hybrid Fiber Reinforced High-Performance Concrete

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Abstract

This study investigates high-performance concrete (HPC) of M60 target grade containing metakaolin (MK) and nano-silica (NS) as supplementary cementitious materials (SCM), reinforced with glass fibre (GF) and polypropylene (PP) fibre individually and in hybrid form, at water–binder (w/b) ratios of 0.30 and 0.45. Cement was replaced by 0–30% MK and 0–3% NS, and the optimum levels of 10% MK and 2% NS were used in eighteen optimised mixes with 1% GF and 0.3% PP fibre. Workability, compressive, split tensile and flexural strength at 7, 14, 28 and 90 days, and resistance to 2% HCl and magnesium sulphate were evaluated. The blend of 10% MK and 2% NS raised the 28-day compressive strength by 31.5% at 0.30 w/b. Adding GF to the blended mix gave the highest strengths: 102 MPa in compression, 7.1 MPa in split tension and 9.8 MPa in flexure at 28 days, and 127 MPa in compression at 90 days. Hybrid GF + PP reinforcement gave smaller strength gains than the single fibres, because the fibres bundled and dispersed unevenly. It did, however, give the best durability: the hybrid mix at 0.30 w/b lost only 4.2% of its strength after 90 days in acid and 6.3% in sulphate, against 12.9% and 16.2% for the control. Fibres reduced workability, with compaction factors falling from 0.85–0.90 to 0.71–0.79.

Keywords: High-performance concrete; Hybrid fibre; Metakaolin; Nano-silica; Glass fibre; Polypropylene fibre; Acid attack; Sulphate attack

1. Introduction

High-performance concrete (HPC) combines high strength with high durability and is increasingly used in tall buildings, bridges and structures exposed to aggressive environments. Its low water–binder ratio and dense matrix are typically achieved with superplasticisers and supplementary cementitious materials. Metakaolin, a highly reactive calcined kaolin with particles of about 2 µm, reacts with calcium hydroxide to form additional C–S–H and refines the pore structure. Nano-silica, with particles of 15–200 nm and over 99% SiO_2, acts as both a pozzolan and a nano-filler. Replacing part of the cement with these materials also lowers the carbon footprint of concrete.

HPC is, however, brittle, and its tensile and flexural capacities rise less than its compressive strength. Fibres bridge cracks and improve post-cracking behaviour. Combining fibres of different stiffness, such as stiff glass fibres and flexible polypropylene fibres, can control cracking at more than one scale. Excess fibre, however, bundles and reduces workability. The objectives of this study are to (i) optimise the MK and NS contents in HPC at w/b ratios of 0.30 and 0.45, (ii) evaluate the effect of GF, PP and hybrid GF + PP fibres on the workability and strength of the optimised HPC, and (iii) assess its resistance to acid and sulphate attack.

2. Literature Review

Combining metakaolin with fibre reinforcement improves the strength of HPC, as shown both experimentally and through AI-based strength prediction [1], [6]. Nano-silica and metakaolin used together improve engineering performance while reducing cement content and environmental impact [4]. Reviews of hybrid fibre-reinforced concrete explain that microfibres control early crack formation while stiffer or longer fibres bridge larger cracks, so fibres of different geometry and stiffness act at different loading stages [5], [10]. Vadivel et al. found that suitable combinations of steel, glass and PP fibres improved compressive, tensile and flexural strength and elastic modulus [3]. Smarzewski and Błaszczyk showed that polymeric and mineral fibres together affect both fresh-state performance and fracture behaviour of high-performance self-compacting concrete [2].

On durability, Patil et al. studied fly ash- and metakaolin-based HPC reinforced with glass and PP fibres, reporting strength gains [8] and better resistance to acid attack [7]. They also studied metakaolin–silica fume HPC with the same fibres for chloride and acid resistance [9]. Nano-silica with ultrafine fly ash improved the durability of composite-fibre HPC [11], and hybrid fibres reduced the drying shrinkage and creep of HPC [12]. Few studies, however, examine MK and NS together with glass and PP fibres at two w/b ratios under both acid and sulphate exposure, which this study addresses.

3. Materials and Methodology

3.1 Materials

OPC 53 grade cement conforming to ASTM C150 was used (Table 1). Zone II river sand (1.18–2.36 mm) and angular river gravel (10–20 mm) were used as fine and coarse aggregate (Table 3). Metakaolin (particle size about 2 µm) and nano-silica (20 nm, surface area 220 m²/g) are described in Table 2. Glass fibres were chopped to 7 mm, with a tensile strength of 1700 N/mm² and elastic modulus of 72 GPa. PP fibres were chopped to 12 mm, with a tensile strength of 550 N/mm² and specific gravity of 0.91. Conplast SP 430 superplasticiser (specific gravity 1.2, chloride-free) was dosed at 1% by weight of binder. The materials are shown in Fig. 1.



Fig. 1. Materials used: (a) metakaolin, (b) nano-silica, (c) glass fibre, (d) polypropylene fibre

Table 1. Properties of cement

Property	**Value**	**Limiting values (ASTM C150/C150M–20)**
Initial setting time	28 min	Up to 30 min
Final setting time	540 min	Up to 600 min
Compressive strength	54.2 MPa	53 MPa
Surface area	335 m²/kg	> 225 m²/kg
Loss on ignition	3.40%	Up to 4%
Magnesia	4.16%	1–5%
Insoluble residue	2.14%	1.5–5%
Sulphuric anhydride	3.09%	1.5–3.5%
Chloride content	0.02%	Up to 0.1%

3.2 Mix Design and Optimised Mixes

The control mixes for M60 grade were designed as per IS 10262 with 550 kg/m³ cement, 640 kg/m³ fine aggregate and 1075 kg/m³ coarse aggregate, and water of 165 and 247.5 kg/m³ for w/b ratios of 0.30 and 0.45. In a first stage, 38 mixes were prepared with 5–30% MK (in 5% steps), 0.5–3% NS (in 0.5% steps) and their combinations at both w/b ratios, from which 10% MK and 2% NS were selected as optimum. Eighteen optimised mixes (Table 4) were then prepared: controls (OP1, OP2), 10% MK (OP3, OP4), 2% NS (OP5, OP6) and the blend of both (OP7, OP8). Fibres were added to the control (OP9–OP12) and to the blend (OP13–OP16), with hybrid GF + PP fibres in the blend (OP17, OP18). Odd-numbered mixes are at w/b 0.30 and even-numbered mixes at 0.45.

Table 2. Properties of metakaolin and nano-silica

Property	Metakaolin	Limits (ASTM C618-17)	Nano-silica	Limits (ASTM C1240-20)
Specific gravity	2.59	2.4–2.6	2.4	2.4–2.8
Density (g/cc)	0.35	0.30–0.75	—	—
Particle size	—	—	20 nm	15–200 nm
Surface area (m^2/g)	—	—	220	> 200
Colour	White	Off-white/white/grey	White	White
SiO_2	51.5%	Up to 90%	99.5%	99.8%
Al_2O_3	40.15%	38–45%	0.0050%	0.0010–0.00050%
CaO	1.8%	Up to 2.4%	—	—
Fe_2O_3	1.15%	0.4–4.5%	0.0010%	0.0005–0.0010%
MgO	0.15%	0.07–0.3%	—	—

Table 3. Properties of aggregates (IS 2386-3)

Property	Fine aggregate	Coarse aggregate	BIS limits
Specific gravity	2.57	2.73	2 to 3
Water absorption (%)	0.95	0.85	< 2
Density (kg/m^3)	1547	1709	1200 to 1750
Fineness modulus	3.05	6.30	5.5 to 8

Table 4. Quantities of raw materials for the optimised HPC mixes (FA 640 kg/m^3 and CA 1075 kg/m^3 in all mixes)

Mix	Mix ID	Cement (kg/m^3)	MK (kg/m^3)	NS (kg/m^3)	GF (kg/m^3)	PP (kg/m^3)	Water (kg/m^3)	w/b
OP1	M0NS0WB0.3	550	0	0	—	—	165	0.3
OP2	M0NS0WB0.45	550	0	0	—	—	247.5	0.45
OP3	M10NS0WB0.3	550	55	0	—	—	165	0.3
OP4	M10NS0WB0.45	550	55	0	—	—	247.5	0.45
OP5	M0NS2.0WB0.3	539	0	11	—	—	165	0.3
OP6	M0NS2.0WB0.45	539	0	11	—	—	247.5	0.45
OP7	M10NS2WB0.3	484	55	11	—	—	165	0.3
OP8	M10NS2WB0.45	484	55	11	—	—	247.5	0.45
OP9	M0NS0WB0.3PP0.3	550	0	0	—	7.29	165	0.3
OP10	M0NS0WB0.3GF1.0	550	0	0	24.30	—	165	0.3
OP11	M0NS0WB0.45PP0.3	550	0	0	—	7.53	247.5	0.45
OP12	M0NS0WB0.45GF1.0	550	0	0	25.12	—	247.5	0.45
OP13	M10NS2.0WB0.3PP0.3	484	55	11	—	7.29	165	0.3
OP14	M10NS2.0WB0.3GF1.0	484	55	11	24.30	—	165	0.3
OP15	M10NS2.0WB0.45PP0.3	484	55	11	—	7.53	247.5	0.45
OP16	M10NS2.0WB0.45GF1.0	484	55	11	25.12	—	247.5	0.45
OP17	M10NS2.0WB0.3PP0.3GF1.0	484	55	11	24.30	7.29	165	0.3
OP18	M10NS2.0WB0.45PP0.3GF1.0	484	55	11	25.12	7.53	247.5	0.45

3.3 Testing

The mixes were prepared in a pan mixer, cast in three layers with vibration and cured in water (Fig. 2). Workability was measured by the compaction factor test (IS 5515). Compressive strength was tested on 150 mm cubes (IS 516), split tensile strength on 150 × 300 mm cylinders (IS 5816) and flexural strength on 100 × 100 × 500 mm prisms (IS 516), at 7, 14, 28 and 90 days. For acid resistance (ASTM C1898-20), cubes were immersed in 2% HCl with the pH held at 1.6–1.8. For sulphate resistance (ASTM C1012), cubes were immersed in magnesium sulphate solution. The residual compressive strength was determined after 60 and 90 days of immersion.

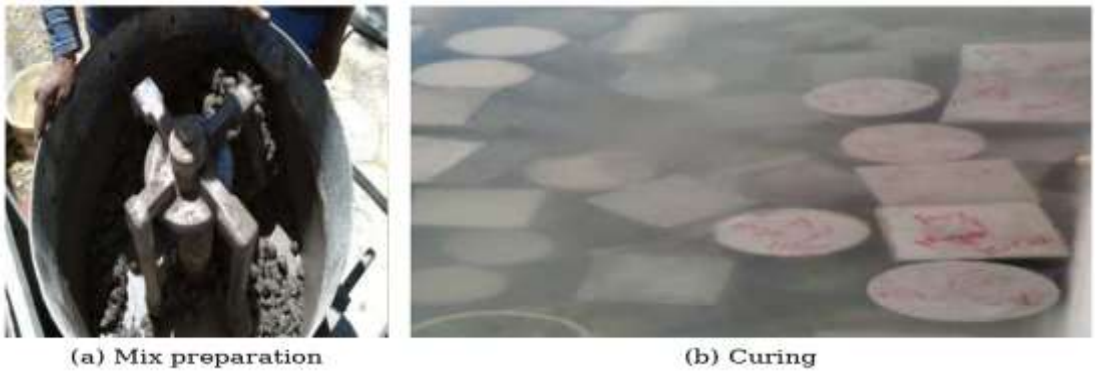


Fig. 2. Preparation of HPC: (a) mix preparation, (b) curing

4. Results and Discussion

4.1 Workability

The compaction factors are shown in Fig. 3. MK reduced workability, owing to its high fineness and water demand. At 0.30 w/b, the compaction factor fell by 1.17% at 5% MK and by 11.76% at 30% MK relative to the control. The control mixes had compaction factors of 0.85 and 0.90 at 0.30 and 0.45 w/b, and the SCM mixes 0.83–0.88. Fibres reduced workability further, to 0.72–0.79. The hybrid mixes were the least workable (0.71 and 0.73), because the non-metallic fibres bundled and raised the viscosity of the mix. The higher w/b ratio consistently gave better workability.



Fig. 3. Workability (compaction factor) of HPC mixes with fibres

4.2 Compressive Strength

The compressive strengths are given in Table 5 and Fig. 4. At 28 days and 0.30 w/b, 10% MK, 2% NS and their blend increased strength by 12.3%, 16.4% and 31.5% over the control (73 MPa), and the blend reached 117 MPa at 90 days. MK and NS react with calcium hydroxide to form additional C–S–H, and NS also fills the finest pores. Fibres alone gave only small gains (77–78 MPa), but fibres in the blended matrix gave the highest strengths. With GF (OP14), the mix reached 102 MPa at 28 days and 127 MPa at 90 days, 39.7% and 54.9% above the control. At 0.45 w/b, OP16 reached 87 MPa at 28 days, 38.1% above its control. The hybrid mixes OP17 and OP18 (90 and 77 MPa) gained less than the single-fibre mixes, because the larger total fibre content bundled and dispersed unevenly, creating voids.

Table 5. Compressive strength (MPa) of the optimised mixes

Mix	7 days	14 days	28 days	90 days
OP1	48	63	73	82
OP2	42	53	63	69
OP3	52	69	82	97
OP4	44	58	69	80
OP5	54	72	85	97
OP6	47	61	73	82
OP7	60	78	96	117
OP8	51	69	82	96
OP9	49	64	77	88
OP10	43	66	78	89
OP11	42	55	65	73
OP12	42	56	66	75
OP13	61	84	100	125
OP14	63	86	102	127
OP15	52	71	86	101
OP16	52	71	87	103
OP17	61	82	90	100
OP18	52	70	77	85

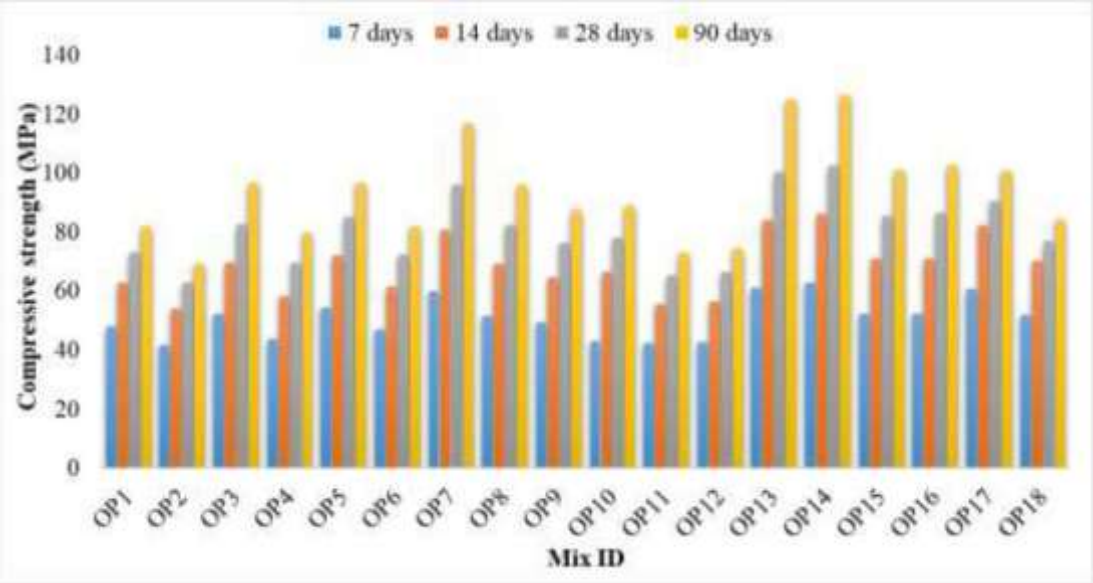


Fig. 4. Compressive strength of the optimised HPC mixes

4.3 Split Tensile and Flexural Strength

The split tensile and flexural strengths are given in Table 6, and the flexural strengths are plotted in Fig. 5. Both followed the compressive trend. The blended SCM matrix with GF again performed best, reaching 7.1 MPa in split tension and 9.8 MPa in flexure at 28 days (OP14), 42% and 53% above the control. At 90 days these rose to 7.9 and 10.9 MPa. At 0.45 w/b, OP16 reached 6.2 MPa and 8.1 MPa, 32% and 59% above its control. The SCMs densify the matrix and the fibres, with their high tensile strength and modulus, bridge cracks and delay their propagation. Fibres added without SCM did not improve flexural strength (6.1–6.3 MPa against 6.4 MPa for OP1), which shows that a dense matrix is needed to anchor the fibres. The hybrid mixes again gained less than the single-fibre blended mixes.

Table 6. Split tensile and flexural strength (MPa) of the optimised mixes

Mix	STS 7 d	STS 14 d	STS 28 d	STS 90 d	FS 7 d	FS 14 d	FS 28 d	FS 90 d
OP1	4.2	4.7	5.0	5.4	5.2	6.0	6.4	6.8
OP2	3.8	4.3	4.7	5.0	4.2	4.8	5.1	5.4
OP3	4.5	5.2	5.6	6.1	6.5	7.5	8.2	8.9
OP4	4.1	4.7	5.1	5.5	5.3	6.1	6.7	7.1
OP5	4.9	5.6	6.1	6.5	6.7	7.6	8.3	8.9
OP6	4.3	5.0	5.5	5.7	5.5	6.3	6.8	7.2
OP7	5.3	6.1	6.7	7.4	7.0	8.2	8.9	9.8
OP8	4.6	5.4	5.9	6.3	5.8	6.7	7.3	7.9
OP9	4.3	4.9	5.4	5.7	4.9	5.6	6.1	6.5
OP10	4.1	5.0	5.5	5.9	4.6	5.7	6.3	6.6
OP11	3.9	4.5	4.9	5.1	4.6	5.2	5.6	6.0
OP12	4.0	4.6	5.0	5.3	4.6	5.0	5.6	6.0
OP13	5.3	6.4	6.9	7.7	7.3	8.6	9.4	10.5
OP14	5.6	6.5	7.1	7.9	7.6	9.0	9.8	10.9
OP15	4.8	5.5	6.0	6.6	6.1	7.1	7.8	8.4
OP16	4.9	5.6	6.2	6.8	6.3	7.3	8.1	8.8
OP17	5.3	6.2	6.5	6.9	7.2	8.2	8.8	9.3
OP18	4.7	5.4	5.8	6.0	6.0	6.9	7.3	7.6

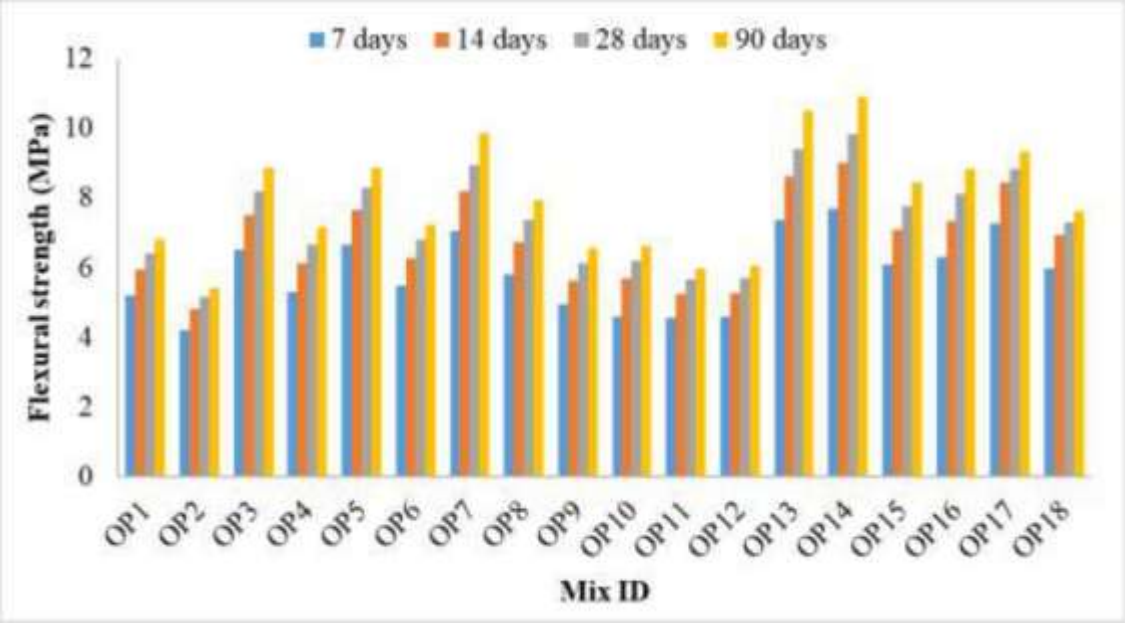


Fig. 5. Flexural strength of the optimised HPC mixes

4.4 Resistance to Acid Attack

The residual compressive strengths after immersion in 2% HCl are given in Table 7 and the percentage losses in Fig. 6. Losses increased with exposure time and w/b ratio: the controls lost 12.9% and 14.5% after 90 days at 0.30 and 0.45 w/b. MK reduced the loss slightly (11.5% at 0.30 w/b). The additional C–S–H from the pozzolanic reaction consumes calcium hydroxide, the phase most readily attacked by acid, and reduces porosity. The hybrid-fibre mix OP17 performed best by a wide margin, losing only 3.0% at 60 days and 4.2% at 90 days. It retained 86 MPa against 63 MPa for the control. The GF mix OP10 lost 7.4%. Fibres restrain the micro-cracking and spalling of the acid-softened surface layer.

Table 7. Residual compressive strength and percentage decrease after acid immersion

Mix	28 days (MPa)	60 days (MPa)	90 days (MPa)	Decrease at 60 days (%)	Decrease at 90 days (%)
OP1	73	67	63	8.2	12.9
OP2	63	56	53	10.5	14.5
OP3	83	77	74	7.8	11.5
OP4	70	63	59	9.8	13.9
OP5	85	77	74	10.1	13.1
OP6	73	67	63	7.8	18.3
OP10	78	75	72	3.8	7.4
OP13	100	91	88	9.7	12.4
OP14	102	93	91	8.9	11.0
OP17	90	87	86	3.0	4.2
OP12	66	—	57	11.0	14.7
OP15	85	79	77	7.0	10.3
OP18	77	70	67	9.5	13.3

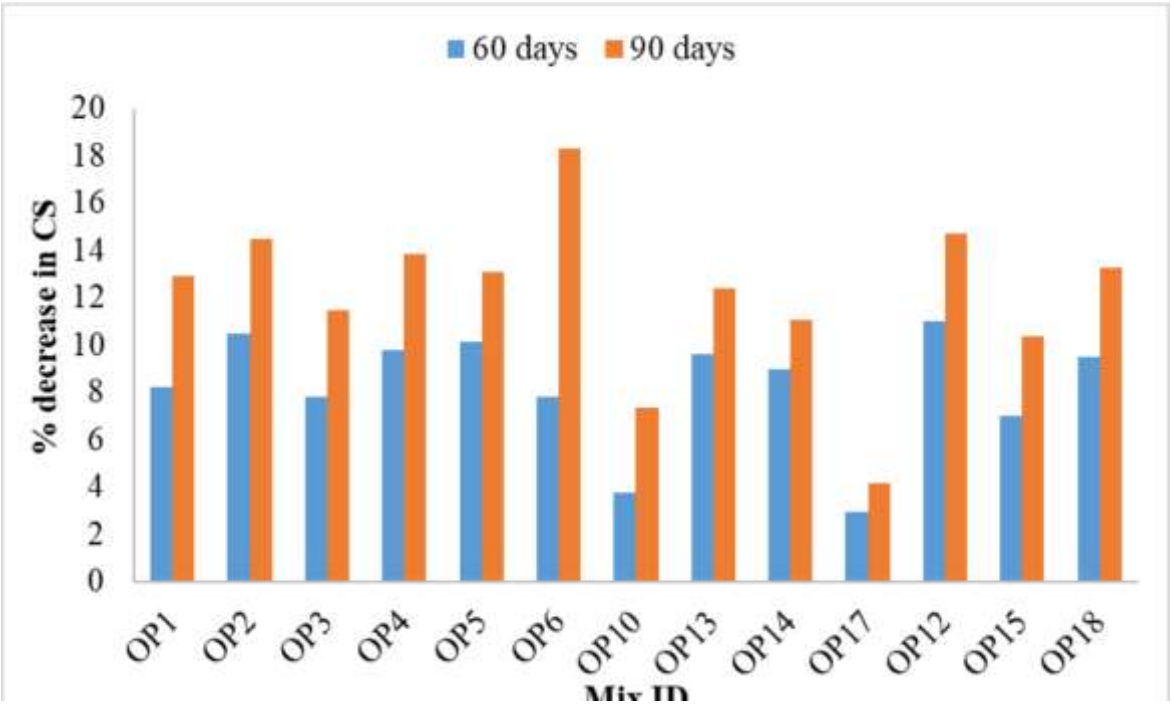


Fig. 6. Percentage decrease in the strength of HPC after immersion in acid

4.5 Resistance to Sulphate Attack

Sulphate exposure caused larger losses than acid (Table 8 and Fig. 7). The controls lost 16.2% and 18.8% after 90 days at 0.30 and 0.45 w/b. Magnesium sulphate reacts with calcium hydroxide to form gypsum, which reacts with the aluminate phases to form expansive ettringite and so weakens the matrix. The 2% NS mix at 0.45 w/b lost the most (21.5%). The hybrid mix OP17 again showed the best resistance, losing only 1.9% at 60 days and 6.3% at 90 days. The GF mix OP10 lost 10.1% and OP14 10.9%. The dense SCM matrix limits sulphate ingress and the hybrid fibres restrain expansion cracking, so the combination gives the most durable HPC.

Table 8. Residual compressive strength and percentage decrease after sulphate immersion

Mix	28 days (MPa)	60 days (MPa)	90 days (MPa)	Decrease at 60 days (%)	Decrease at 90 days (%)
OP1	73	65	60	10.0	16.2
OP2	62	54	50	12.9	18.8
OP3	82	75	71	9.3	14.2
OP4	69	61	57	11.8	17.3
OP5	85	75	72	11.3	15.3
OP6	72	65	56	9.4	21.5
OP10	78	73	70	5.3	10.1
OP13	100	89	85	10.5	14.2
OP14	102	90	90	10.9	10.9
OP17	90	88	84	1.9	6.3
OP12	66	57	54	12.8	18.2
OP15	85	78	74	8.2	12.8
OP18	77	68	64	10.9	16.0

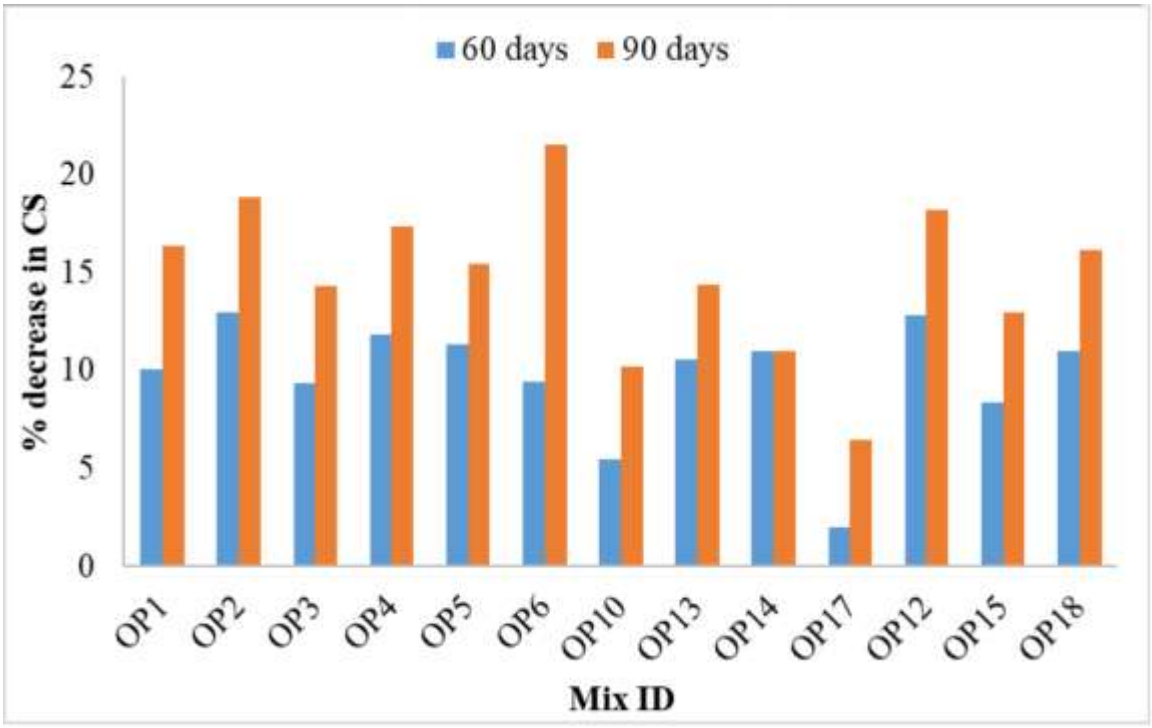


Fig. 7. Percentage decrease in the strength of HPC after immersion in sulphate

5. Conclusions

1. The optimum SCM levels were 10% metakaolin and 2% nano-silica. Their blend increased the 28-day compressive strength of HPC by 31.5% at 0.30 w/b, and the blended mix reached 117 MPa at 90 days.
2. Adding 1% glass fibre to the blended mix gave the highest strengths: 102 MPa in compression, 7.1 MPa in split tension and 9.8 MPa in flexure at 28 days (39.7%, 42% and 53% above the control), and 127 MPa in compression at 90 days.
3. Fibres were effective only in the dense SCM matrix; added to plain HPC they gave small compressive gains and no gain in flexure.

4. Hybrid GF + PP fibres gave smaller strength gains than single fibres, as excess fibre bundled and dispersed unevenly, and they reduced the compaction factor to 0.71–0.73.
5. The hybrid mix at 0.30 w/b showed the best durability, losing only 4.2% of its compressive strength after 90 days in 2% HCl and 6.3% in magnesium sulphate, against 12.9% and 16.2% for the control. Sulphate attack was more severe than acid attack, and losses increased with w/b ratio.
6. For maximum strength, HPC with 10% MK, 2% NS and 1% glass fibre is recommended; for aggressive chemical environments, the hybrid GF + PP mix at 0.30 w/b is preferable.

Future work should examine metallic and other non-metallic fibres, fibre geometry, long-term durability such as freeze–thaw and carbonation, elevated-temperature behaviour and fracture properties.

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