International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 11 | Nov 2026 www.irjet.net p-ISSN: 2395-0072

EVALUATION OF COMPRESSIVE, SPLIT TENSILE, FLEXURAL AND RESIDUAL STRENGTH OF HYBRID FIBER CONCRETE INCORPORATING NANOSILICA AND METAKAOLIN

Dr Sachin Patil[1], Mr Basavaprabhu M S[2], Dilip S[3]

[1]Associate Professor, Dept. of Structural Engineering, RYM ENGINEERING COLLEGE, Ballari, Karnataka, India
[2]Assistant Professor, Dept. of Structural Engineering, RYM ENGINEERING COLLEGE, Ballari, Karnataka, India
[3]P.G. Student, Dept. of Structural Engineering, RYM ENGINEERING COLLEGE, Ballari, Karnataka, India

---

Abstract - *This study experimentally investigates the mechanical performance and sulfuric acid resistance of high-performance concrete incorporating metakaolin (MK), nano-silica (NS) and hybrid alkali-resistant glass (GF) and polypropylene (PPF) fibre reinforcement. Twenty-four mixtures were prepared with MK contents of 15% and 20%, NS contents of 1.5%, 3.0% and 4.5%, GF dosages of 0%, 0.5%, 0.75% and 1.0%, and a constant PPF dosage of 0.25% in the fibre-reinforced mixes, at a water-to-binder ratio of 0.40 and an aggregate-to-binder ratio of 1.8. Compressive, split-tensile and flexural strengths were determined at 28 days using cube, cylinder and beam specimens. Durability was assessed by immersing water-cured cubes in 5% H_2SO_4 for 30, 60 and 90 days and measuring the residual compressive strength. Mix 24 (20% MK, 4.5% NS, 1.0% GF, 0.25% PPF) gave the highest 28-day strengths of 68.5 MPa in compression, 5.72 MPa in split tension and 9.30 MPa in flexure, which are 48.9%, 54.6% and 51.9% higher, respectively, than the fibre-free reference mix (Mix 1). Acid exposure reduced strength progressively with immersion time; Mix 24 retained 90.4%, 85.3% and 80.7% of its 28-day strength after 30, 60 and 90 days, compared with 87.2%, 81.1% and 75.7% for Mix 1. The findings indicate that combining binder modification with hybrid fibre reinforcement can improve the mechanical response of concrete and its resistance to acid-induced deterioration.*

Key Words: High-performance concrete, Metakaolin, Nano-silica, Glass fibre, Polypropylene fibre, Compressive strength, Split tensile strength, Flexural strength, Sulfuric acid resistance.

1. INTRODUCTION

Concrete is the most widely used construction material because of its strength, reliability and versatility. However, Portland cement production is responsible for roughly 7–8% of global carbon dioxide emissions, and conventional concrete is weak in tension, cracks easily and does not perform well in chemically aggressive environments. High-performance concrete (HPC) addresses these limitations through careful mix design, a low water-to-binder ratio, superplasticizers and supplementary cementitious materials (SCMs) that partly replace cement while improving strength and durability [1], [8].

Metakaolin (MK), obtained by calcining kaolin clay, is a highly reactive pozzolan. It reacts with the calcium hydroxide released during cement hydration to form additional C–S–H gel, which refines the pore structure and reduces permeability [8]. Nano-silica (NS) is an ultrafine amorphous silica that acts as a filler of the fine pores in the paste and as a highly reactive pozzolan, accelerating hydration and producing a denser matrix [2], [3]. Mineral additions alone, however, do not remove the brittleness of concrete. Fibres bridge cracks, transfer stress across them and improve post-cracking behaviour. Stiff alkali-resistant glass fibre mainly improves tensile and flexural performance, whereas flexible polypropylene fibre controls shrinkage cracking and crack opening, so a hybrid glass–polypropylene system can provide crack control at different scales [5], [6], [9].

Sulfuric acid attack is particularly relevant to concrete exposed to wastewater, sewage and industrial environments. The acid reacts with the alkaline hydration products, causing surface softening, scaling, cracking and loss of load-bearing capacity. A dense binder matrix slows the ingress of the aggressive solution, while fibres restrict crack widening and help maintain specimen integrity. The present work combines MK and NS as binder modifiers with glass and polypropylene fibres and evaluates the 28-day compressive, split tensile and flexural strengths together with the residual compressive strength after immersion in 5% sulfuric acid.

1.1 Literature Review

Siddique and Klaus [8] showed that metakaolin takes part in the pozzolanic reaction and improves the properties of mortar and concrete, with the effect depending on the replacement level; too much MK raises water demand and lowers workability. Soleimanzadeh et al. [2] reported that concrete containing 10% metakaolin and 1% nano-silica reached 103 MPa at 28 days because of the combined pozzolanic and filler effects, and Sua-Iam et al. [3] found that a suitable MK–NS combination improved the mechanical properties, sulfate resistance and microstructure of concrete. Related work on ternary pastes containing MK and NS [12] and on the synergistic

effect of the two materials [13] supports their combined use.

El-Din et al. [7] observed that hybrid fibres combined with metakaolin produced high-strength concrete with better mechanical properties than fibre-free concrete, and Patil et al. [6] reported improved properties for a mix with 5% metakaolin, 5% silica fume, 1% glass fibre and 0.25% polypropylene fibre. Fallah and Nematzadeh [5] cautioned that fibre and nano-silica contents must be optimised because excessive amounts reduce workability. Polypropylene fibre helps control shrinkage and crack initiation [9], and the behaviour of hybrid polypropylene–glass fibre concrete has also been studied in [14], [15]. For acid exposure, Sriram and Sidhaarth [1] and Patil et al. [10], [11] reported that metakaolin-based hybrid fibre concrete resisted deterioration better than reference concrete, and durability of hybrid fibre concrete in acidic and sulfated environments has been examined in [16], [17].

Most of these studies combined only two or three of the constituents. The combined effect of MK, NS, glass fibre and polypropylene fibre on strength and on residual strength after sulfuric acid exposure therefore needs further experimental evaluation, which is the gap addressed here.

1.2 Objectives of the Study

1) To modify concrete mixtures by partially replacing cement with metakaolin and nano-silica.
2) To evaluate the compressive, split tensile and flexural strengths of the resulting concretes.
3) To investigate the effect of glass and polypropylene fibres, alone and in hybrid form, on strength and crack resistance.
4) To assess the residual compressive strength after 30, 60 and 90 days of immersion in 5% sulfuric acid.
5) To identify the combination of binder and fibre contents giving the best balance of strength and acid resistance.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1 Materials Used

The experimental programme used 53-grade Ordinary Portland Cement (specific gravity 3.10), amorphous nano-silica powder (specific gravity 2.40), high-reactivity metakaolin (specific gravity 2.60), Zone II river sand as fine aggregate and crushed granite of 20 mm down-size grading as coarse aggregate (specific gravity 2.60 for both), and potable water. A polycarboxylate-ether-based superplasticizer was used at 0.8% of the binder mass. Alkali-resistant glass fibre of 12 mm length was used at volume fractions of 0% to 1.0%, and monofilament polypropylene fibre of 12 mm length at a fixed 0.25% in the fibre-reinforced mixes. A 5% H_2SO_4 solution was used for the chemical exposure programme.

Table -1: Properties of Metakaolin, Nano-silica and Fibres

Material	Reported property / function
Metakaolin	Amorphous alumino-silicate; calcined at 650–800 °C; angular, irregular particles; high pozzolanic activity
Nano-silica	Amorphous SiO_2 powder; particle size < 100 nm; very high pozzolanic activity; accelerates C–S–H formation; reduces porosity and permeability
AR glass fibre	SiO_2 + ZrO_2; high alkali resistance, tensile strength and elastic modulus; improves flexural performance and crack resistance
Polypropylene fibre	Low density, hydrophobic; dosage range 0.1–1.0% by volume; high shrinkage control and chemical stability; minimal effect on workability at low dosages

2.2 Mix Proportions

The mixes were proportioned by the absolute volume method with a constant water-to-binder ratio (W/B) of 0.40, an aggregate-to-binder ratio (A/B) of 1.8 and 0.8% superplasticizer. MK replaced cement at 15% (Mixes 1–12) and 20% (Mixes 13–24) and NS at 1.5%, 3.0% and 4.5%. Within each MK–NS combination, four fibre levels were cast: no fibre, and 0.5%, 0.75% and 1.0% GF each with 0.25% PPF, giving 24 mixes in total. The fibres were added as volumetric additions independent of the binder and aggregate. The quantities of materials are given in Table -2.

Table -2: Mix Design Quantities per m^3 of Concrete (W/B = 0.40, A/B = 1.8)

MK (%)	NS (%)	Cement (kg)	NS (kg)	MK (kg)	Water (L)	C.A (kg)	F.A (kg)
15	1.5	592.11	10.64	106.37	283.64	765.84	510.56
15	3	580.89	21.25	106.26	283.36	765.07	510.05
15	4.5	569.69	31.85	106.15	283.08	764.31	509.54
20	1.5	555.43	10.61	141.51	283.02	764.16	509.44
20	3	544.27	21.21	141.37	282.74	763.39	508.93
20	4.5	533.14	31.78	141.23	282.46	762.63	508.42

2.3 Specimen Preparation and Curing

Concrete was mixed in a 40 L pan mixer. The dry materials (cement, NS, MK, fine and coarse aggregate) were mixed for two minutes, water and superplasticizer were added gradually, and the glass and polypropylene fibres were added last to promote uniform distribution and prevent balling. The concrete was placed in three layers and compacted with a table vibrator. Cubes of 100 × 100 × 100 mm were cast for compressive strength and residual compressive strength, cylinders of 100 mm diameter × 200 mm height for split tensile strength, and beams of 100 × 100 × 500 mm for flexural strength. The moulds were covered with damp hessian for 24 hours; the specimens were then demoulded and cured in potable water at 27 ± 2 °C until the test age of 28 days.



Fig -1: Batching of materials.



(a) Casting of cylinders (b) Curing of cylinders (c) Curing of beams

Fig -2: Casting and water curing of specimens.

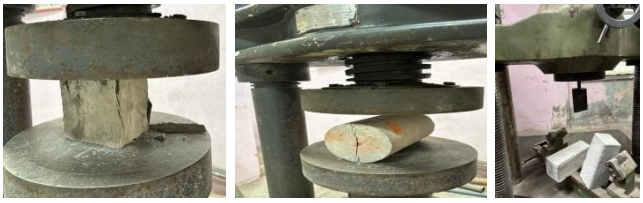
2.4 Testing Programme

Compressive strength was determined on cubes in a 2000 kN compression testing machine in accordance with IS 516–2018, using three specimens per mix at 28 days and a uniform loading rate of 140 kg/cm^2/min; the strength was calculated as f_c = P/A, where P is the peak load (N) and A the loaded area (mm^2). Split tensile strength was determined on cylinders as per IS 5816–1999, and flexural strength (modulus of rupture) on beams in accordance with IS 516–2018.



(a) Compression test under UTM (b) Split tensile test under UTM (c) Flexural test under CTM

Fig -3: Testing of cube, cylinder and beam specimens.



(a) Cube (b) Cylinder (c) Beam

Fig -4: Specimen failure in compression, split tension and flexure.

For the durability assessment, cubes were water-cured for 28 days and then immersed in 5% sulfuric acid for 30, 60 and 90 days. At each age the cubes were removed, loose surface deposits were cleaned off, the specimens were examined, and the residual compressive strength was determined. The residual strength was expressed as a percentage of the corresponding unexposed (28-day) strength: Residual strength (%) = (f_{acid} / $f_{control}$) × 100.



(a) Acid curing (b) Acid-cured cubes

Fig -5: Sulfuric acid curing of cube specimens.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

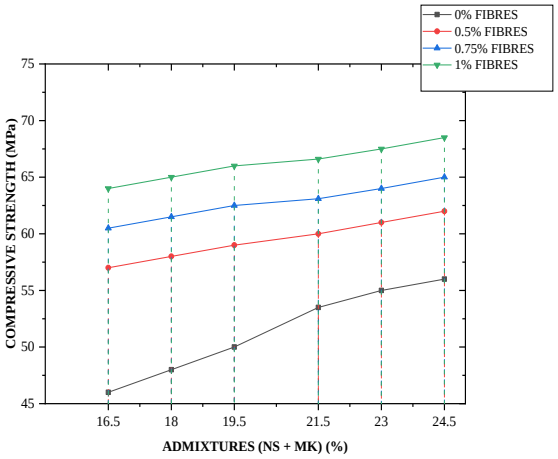
The 28-day cube strengths are given in Table -3 and Graphs 1–2. The compressive strength increased from 46 MPa for Mix 1 (15% MK, 1.5% NS, no fibre) to 68.5 MPa for Mix 24 (20% MK, 4.5% NS, 1.0% GF, 0.25% PPF), an increase of 48.9%. Among the fibre-free mixes, strength

rose with both MK and NS content, from 46 MPa (Mix 1) to 56 MPa (Mix 21: 20% MK, 4.5% NS), showing the effect of the denser MK–NS matrix. Adding hybrid fibres raised the strength of every binder combination; for 20% MK and 4.5% NS it increased from 56 MPa to 68.5 MPa (22.3%). Graphs 1 and 2 show the same data plotted against the binder and fibre contents, respectively, and the legends denote the total MK + NS replacement (%).

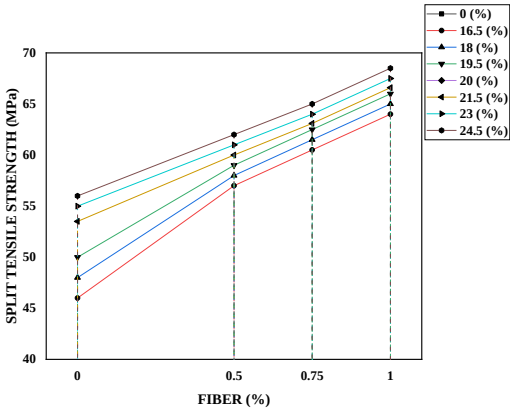
The strength increases with fibre content because fibres delay crack growth, and the improved matrix transfers stress more effectively, so the ratio of mineral admixtures to fibres, rather than the quantity of either alone, governs the response.

Table -3: 28-day Cube Compressive Strength for 0.4 W/B Ratio

Mix	C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
1	83.5	1.5	15	0	0	46
2	82.75	1.5	15	0.5	0.25	57
3	82.5	1.5	15	0.75	0.25	60.5
4	82.25	1.5	15	1	0.25	64
5	82	3	15	0	0	48
6	81.25	3	15	0.5	0.25	58
7	81	3	15	0.75	0.25	61.5
8	80.75	3	15	1	0.25	65
9	80.5	4.5	15	0	0	50
10	79.75	4.5	15	0.5	0.25	59
11	79.5	4.5	15	0.75	0.25	62.5
12	79.25	4.5	15	1	0.25	66
13	78.5	1.5	20	0	0	53.5
14	77.75	1.5	20	0.5	0.25	60
15	77.5	1.5	20	0.75	0.25	63.1
16	77.25	1.5	20	1	0.25	66.6
17	77	3	20	0	0	55
18	76.25	3	20	0.5	0.25	61
19	76	3	20	0.75	0.25	64
20	75.75	3	20	1	0.25	67.5
21	75.5	4.5	20	0	0	56
22	74.75	4.5	20	0.5	0.25	62
23	74.5	4.5	20	0.75	0.25	65
24	74.25	4.5	20	1	0.25	68.5



Graph-1: 28-day cube compressive strength in relation to percentages of metakaolin and nano silica with different glass and polypropylene fibre volumes.



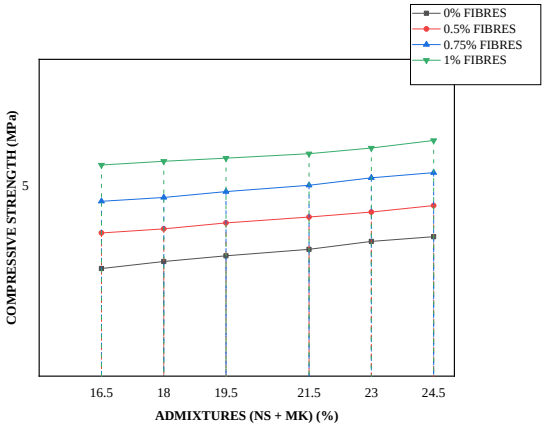
Graph-2: 28-day cube compressive strengths in relation to glass and polypropylene fibre volume percentages for different amounts of metakaolin and nano silica.

3.2 Split Tensile Strength

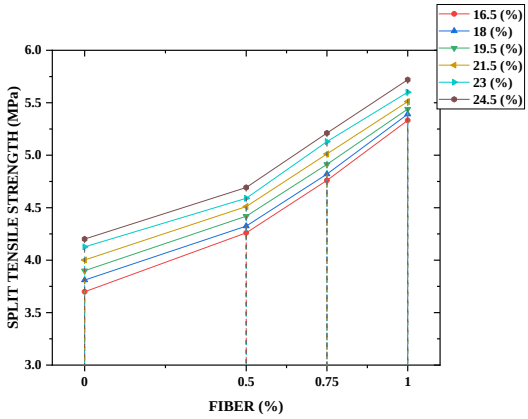
The split tensile strengths are given in Table -4 and Graphs 3–4. The strength increased from 3.70 MPa for Mix 1 to 5.72 MPa for Mix 24, an increase of 54.6%. For the 15% MK and 3% NS series, the strength increased from 3.81 MPa without fibres to 5.39 MPa with 1% glass fibre and 0.25% polypropylene fibre. The lower values occur in the mixes without fibres because plain concrete has limited resistance to tensile cracking, whereas the higher values are obtained with fibres because of the crack-bridging action of glass and polypropylene fibres. The variation between the curves is due to the different MK–NS combinations: suitable proportions produce a denser matrix that allows the fibres to transfer tensile stress more effectively.

Table -4: 28-day Split Tensile Strength for 0.4 W/B Ratio

Mix	C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
1	83.5	1.5	15	0	0	3.699
2	82.75	1.5	15	0.5	0.25	4.26
3	82.5	1.5	15	0.75	0.25	4.76
4	82.25	1.5	15	1	0.25	5.3325
5	82	3	15	0	0	3.81
6	81.25	3	15	0.5	0.25	4.3245
7	81	3	15	0.75	0.25	4.8199
8	80.75	3	15	1	0.25	5.3916
9	80.5	4.5	15	0	0	3.899
10	79.75	4.5	15	0.5	0.25	4.41926
11	79.5	4.5	15	0.75	0.25	4.91252
12	79.25	4.5	15	1	0.25	5.43999
13	78.5	1.5	20	0	0	4.0012
14	77.75	1.5	20	0.5	0.25	4.511
15	77.5	1.5	20	0.75	0.25	5.01245
16	77.25	1.5	20	1	0.25	5.5111
17	77	3	20	0	0	4.1266
18	76.25	3	20	0.5	0.25	4.59001
19	76	3	20	0.75	0.25	5.1299
20	75.75	3	20	1	0.25	5.6001
21	75.5	4.5	20	0	0	4.2011
22	74.75	4.5	20	0.5	0.25	4.69258
23	74.5	4.5	20	0.75	0.25	5.21105
24	74.25	4.5	20	1	0.25	5.71999



Graph-3: 28-day split tensile strength with different volumes of glass and polypropylene fibres in relation to percentages of metakaolin and nano silica.



Graph-4: 28-day split tensile strength in relation to glass and polypropylene fibre volume percentages for different amounts of metakaolin and nano silica.

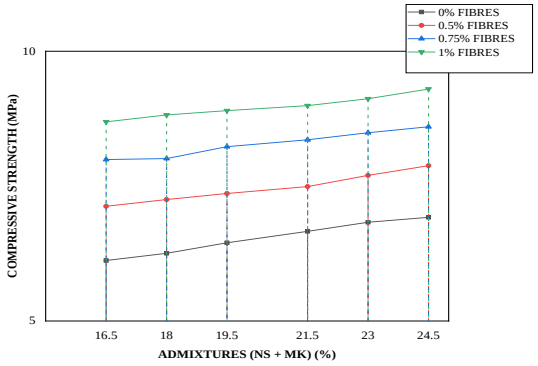
3.3 Flexural Strength

The beam flexural strengths (modulus of rupture) are given in Table -5 and Graphs 5–6. The flexural strength increased from 6.12 MPa for Mix 1 to 9.30 MPa for Mix 24, an increase of 51.9%. For the 15% MK and 3% NS mix with 0.25% polypropylene fibre, the flexural strength increased from about 6.25 MPa to 8.82 MPa as the glass fibre increased from 0% to 1%. The fibres crossing the cracks on the tension face allow the beam to withstand a greater bending stress, so the hybrid fibres have a pronounced effect on flexural resistance, and the flexural strength depends strongly on the fibre content in each binder combination.

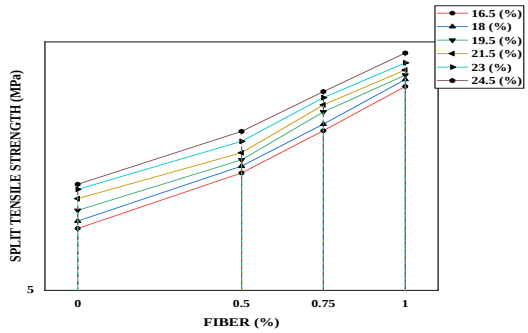
Table -5: 28-day Beam Flexural Strength (MOR) for 0.4 W/B Ratio

Mix	C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
1	83.5	1.5	15	0	0	6.122
2	82.75	1.5	15	0.5	0.25	7.126
3	82.5	1.5	15	0.75	0.25	7.992
4	82.25	1.5	15	1	0.25	8.6923
5	82	3	15	0	0	6.255
6	81.25	3	15	0.5	0.25	7.251
7	81	3	15	0.75	0.25	8.0112
8	80.75	3	15	1	0.25	8.82
9	80.5	4.5	15	0	0	6.45
10	79.75	4.5	15	0.5	0.25	7.364
11	79.5	4.5	15	0.75	0.25	8.2314
12	79.25	4.5	15	1	0.25	8.8996
13	78.5	1.5	20	0	0	6.662
14	77.75	1.5	20	0.5	0.25	7.492
15	77.5	1.5	20	0.75	0.25	8.359
16	77.25	1.5	20	1	0.25	8.9922

Mix	C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
17	77	3	20	0	0	6.83
18	76.25	3	20	0.5	0.25	7.7
19	76	3	20	0.75	0.25	8.49
20	75.75	3	20	1	0.25	9.12
21	75.5	4.5	20	0	0	6.921
22	74.75	4.5	20	0.5	0.25	7.879
23	74.5	4.5	20	0.75	0.25	8.6
24	74.25	4.5	20	1	0.25	9.3



Graph-5: 28-day beam flexural strength (MOR) in relation to percentages of metakaolin and nano silica with various volumes of glass and polypropylene fibres.



Graph-6: 28-day beam flexural strength (MOR) in relation to glass and polypropylene fibre volume percentages for different metakaolin and nano silica percentages.

3.4 Sulfuric Acid Resistance

The residual compressive strengths after immersion in 5% H_2SO_4 for 30, 60 and 90 days are given in Table -6, and the corresponding retention of the 28-day strength in Table -7. The residual strength decreased progressively with immersion time for all mixes, which indicates gradual deterioration of the cement matrix in the acid. Mix 1 retained 87.2%, 81.1% and 75.7% of its 28-day strength after 30, 60 and 90 days, whereas Mix 24 retained 90.4%, 85.3% and 80.7% and recorded the highest residual strengths of 61.9, 58.4 and 55.3 MPa. The highest retention at all three ages (90.7%, 85.6% and 81.0%) was shown by Mix 20 (20% MK, 3% NS, 1% GF, 0.25% PPF). Within every MK–NS group the retention rose with fibre content, and the 20% MK mixes retained more strength than their 15% MK counterparts. For the 20% MK, 3% NS series, adding 1% glass fibre raised the 30-day residual strength from 48.8 to 61.2 MPa and the 90-day residual strength from 42.8 to 54.7 MPa. The dense MK–NS matrix limits acid penetration, while the fibres restrict crack widening, but the protection decreases with longer exposure, as shown in Graphs 7–9.

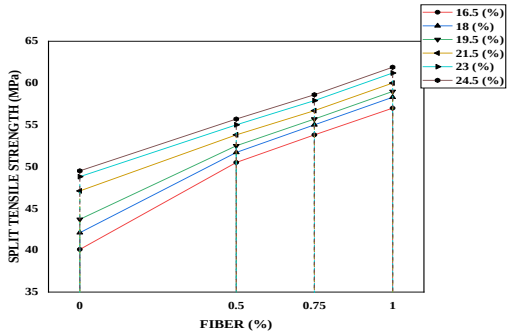
Table -6: H_2SO_4 Immersed Residual Compressive Strength for 30, 60, 90 Days for 0.4 W/B Ratio

Mix	NS (%)	MK (%)	GF+PPF (%)	30D (MPa)	60D (MPa)	90D (MPa)
1	1.5	15	0	40.1	37.3	34.8
2	1.5	15	0.5+0.25	50.5	47.4	44.6
3	1.5	15	0.75+0.25	53.8	50.5	47.5
4	1.5	15	1+0.25	57	53.6	50.5
5	3	15	0	42.1	39.3	36.7
6	3	15	0.5+0.25	51.7	48.6	45.8
7	3	15	0.75+0.25	55	51.7	48.7
8	3	15	1+0.25	58.3	54.9	51.7
9	4.5	15	0	43.7	40.7	38
10	4.5	15	0.5+0.25	52.5	49.3	46.3
11	4.5	15	0.75+0.25	55.7	52.4	49.3
12	4.5	15	1+0.25	59	55.5	52.3
13	1.5	20	0	47.1	44.1	41.3
14	1.5	20	0.5+0.25	53.8	50.6	47.8
15	1.5	20	0.75+0.25	56.7	53.4	50.5
16	1.5	20	1+0.25	60	56.6	53.5
17	3	20	0	48.8	45.7	42.8
18	3	20	0.5+0.25	55	51.9	49
19	3	20	0.75+0.25	57.9	54.6	51.7
20	3	20	1+0.25	61.2	57.8	54.7
21	4.5	20	0	49.5	46.3	43.4
22	4.5	20	0.5+0.25	55.7	52.5	49.6
23	4.5	20	0.75+0.25	58.6	55.2	52.3
24	4.5	20	1+0.25	61.9	58.4	55.3

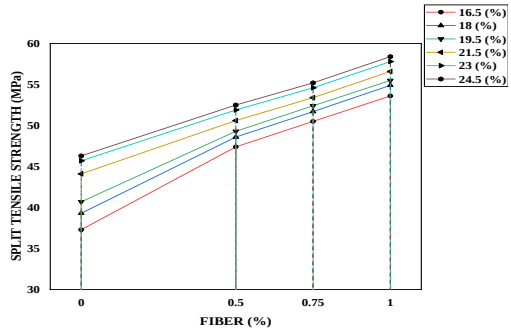
Table -7: Retention of Compressive Strength (%) of Mixes Immersed in H_2SO_4

Mix	NS (%)	MK (%)	GF+PPF (%)	30D (%)	60D (%)	90D (%)
1	1.5	15	0	87.2	81.1	75.7
2	1.5	15	0.5+0.25	88.6	83.2	78.2
3	1.5	15	0.75+0.25	88.9	83.5	78.5
4	1.5	15	1+0.25	89.1	83.8	78.9
5	3	15	0	87.7	81.9	76.5
6	3	15	0.5+0.25	89.1	83.8	79

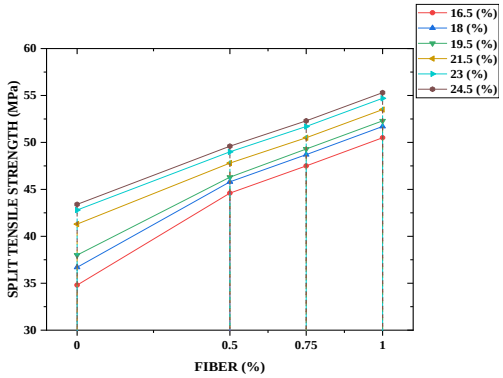
Mix	NS (%)	MK (%)	GF+PPF (%)	30D (%)	60D (%)	90D (%)
7	3	15	0.75+0.25	89.4	84.1	79.2
8	3	15	1+0.25	89.7	84.5	79.5
9	4.5	15	0	87.4	81.4	76
10	4.5	15	0.5+0.25	89	83.6	78.5
11	4.5	15	0.75+0.25	89.1	83.8	78.9
12	4.5	15	1+0.25	89.4	84.1	79.2
13	1.5	20	0	88	82.4	77.2
14	1.5	20	0.5+0.25	89.7	84.3	79.7
15	1.5	20	0.75+0.25	89.9	84.6	80
16	1.5	20	1+0.25	90.1	85	80.3
17	3	20	0	88.7	83.1	77.8
18	3	20	0.5+0.25	90.2	85.1	80.3
19	3	20	0.75+0.25	90.5	85.3	80.8
20	3	20	1+0.25	90.7	85.6	81
21	4.5	20	0	88.4	82.7	77.5
22	4.5	20	0.5+0.25	89.8	84.7	80
23	4.5	20	0.75+0.25	90.2	84.9	80.5
24	4.5	20	1+0.25	90.4	85.3	80.7



Graph-7: 30D residual compressive strength in relation to glass and polypropylene fibre volume percentages for various metakaolin and nano silica percentages of mixes immersed in H_2SO_4.

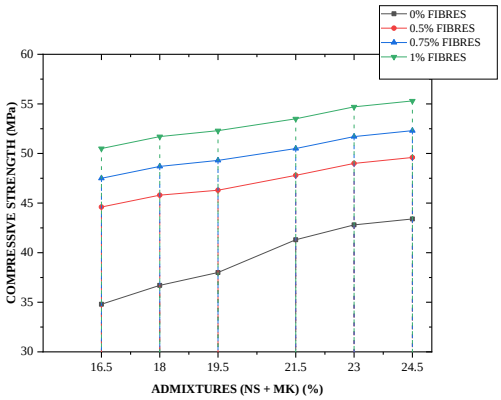


Graph-8: 60D residual compressive strength in relation to glass and polypropylene fibre volume percentages for various metakaolin and nano silica percentages of mixes immersed in H_2SO_4.

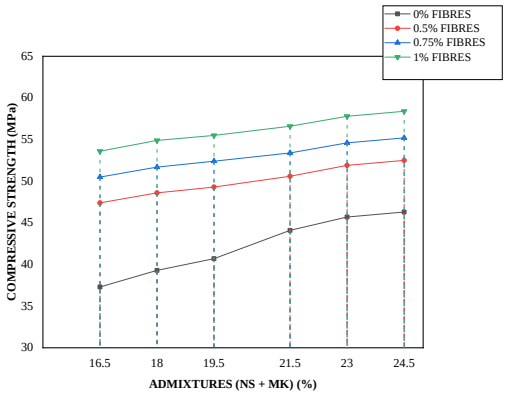


Graph-9: 90D residual compressive strength in relation to glass and polypropylene fibre volume percentages for various metakaolin and nano silica percentages of mixes immersed in H_2SO_4.

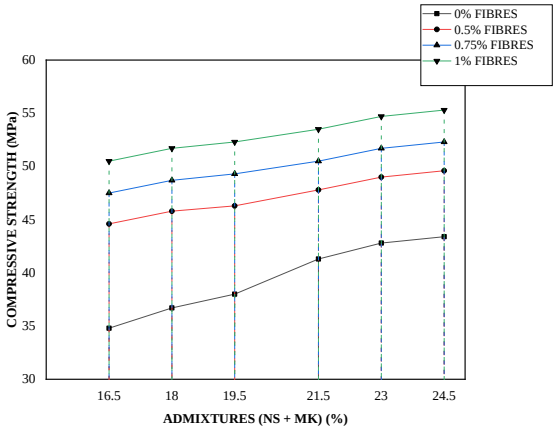
The residual strength also depends on the MK–NS combination (Graphs 10–12). The higher points correspond to the optimum amounts of MK and NS, which give a stronger and denser cement matrix that resists the acid attack better, and the residual strength is much lower at 60 and 90 days than at 30 days, showing the gradual deterioration of the matrix with exposure time. Mix 20, for example, kept 90.7% of its strength at 30 days, 85.6% at 60 days and 81.0% at 90 days. An optimum proportion of MK and NS can therefore counteract the aggressive effect of H_2SO_4 to an extent, although the residual strength diminishes in the longer run.



Graph-10: 30D residual compressive strength in relation to metakaolin and nano silica with various volumes of glass and polypropylene fibres of mixes immersed in H_2SO_4.



Graph-11: 60D residual compressive strength in relation to metakaolin and nano silica with various volumes of glass and polypropylene fibres of mixes immersed in H_2SO_4.



Graph-12: 90D residual compressive strength in relation to metakaolin and nano silica with various volumes of glass and polypropylene fibres of mixes immersed in H_2SO_4.

4. CONCLUSIONS

The experimental study supports the following conclusions:

1) The combined use of metakaolin and nano-silica improved the strength of the concrete; among the fibre-free mixes the 28-day compressive strength increased from 46 MPa (15% MK, 1.5% NS) to 56 MPa (20% MK, 4.5% NS), because the ultrafine particles act as fillers and pozzolans that densify the binder matrix.

2) Hybrid glass–polypropylene fibre reinforcement further increased the strength; for the 20% MK and 4.5% NS binder, 1.0% glass fibre with 0.25% polypropylene fibre raised the compressive, split tensile and flexural strengths by 22.3%, 36.2% and 34.4%, respectively.

3) Mix 24 (20% MK, 4.5% NS, 1.0% GF, 0.25% PPF) gave the highest 28-day strengths: 68.5 MPa in compression, 5.72 MPa in split tension and 9.30 MPa in flexure, which are 48.9%, 54.6% and 51.9% higher than Mix 1.

4) The gain from the fibres was larger in split tensile and flexural strength than in compressive strength, which confirms the crack-bridging role of the hybrid fibres; however, an excessive fibre content can reduce workability and cause fibre balling, so the dosage should be kept within the tested range.

5) Exposure to 5% sulfuric acid caused a progressive loss of strength with increasing exposure time; the retained strength of the mixes ranged from 87.2–90.7% at 30 days, 81.1–85.6% at 60 days and 75.7–81.0% at 90 days.

6) The metakaolin–nano-silica binder with hybrid fibres showed better acid resistance than the fibre-free mixes: Mix 24 had the highest residual strengths (61.9, 58.4 and 55.3 MPa) and Mix 20 the highest retention (90.7%, 85.6% and 81.0%), while the retention of Mix 1 was 87.2%, 81.1% and 75.7%.

7) Overall, the combination of 20% MK, 3–4.5% NS, 1.0% GF and 0.25% PPF is promising for structures that require high strength and crack control in aggressive environments; further work on microstructure, other acid concentrations and structural-scale members is recommended.

ACKNOWLEDGEMENT

I am thankful to my guide, Dr. Sachin Patil, Assoc. Professor, Department of Civil Engineering, RYMEC, Ballari, for his keen interest, constant encouragement and able guidance. I also thank Dr. M. S. Shobha, HOD, Department of Civil Engineering, Dr. H. Mahabaleshwara, Principal, the teaching and non-teaching staff, my parents and friends for their continuous support in making this work complete.

REFERENCES

[1] M. Sriram and K. R. A. Sidhaarth, “Influence of silica fume and metakaolin on durability properties of hybrid fibers reinforced high strength concrete,” Journal of Building Pathology and Rehabilitation, Springer, Feb. 2023, doi: 10.1007/s41024-023-00266-6.

[2] S. Soleimanzadeh, M. F. Nuruddin, N. Shafiq and A. Kusbiantoro, “Effects of modified metakaolin using nano-silica on the mechanical properties and durability of concrete,” Materials, vol. 12, no. 14, p. 2291, Jul. 2019, doi: 10.3390/ma12142291.

[3] G. Sua-Iam et al., "Engineering performance and environmental assessment of sustainable concrete incorporating nano silica and metakaolin as cementitious materials," Scientific Reports, Nature Publishing Group, Jan. 2025, doi: 10.1038/s41598-025-85358-8.

[4] P. Zhang, D. Hu, Q. Li and Z. Ling, "Long-term mechanical performance of high fluidity fiber reinforced concrete modified by metakaolin," Frontiers in Materials, vol. 10, Sep. 2023, doi: 10.3389/fmats.2023.1162053.

[5] S. Fallah and M. Nematzadeh, "Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume," Construction and Building Materials, vol. 132, pp. 170–187, Feb. 2017, doi: 10.1016/j.conbuildmat.2016.11.100.

[6] S. Patil, H. Sudarsana Rao and V. G. Ghorpade, "The influence of metakaolin, silica fume, glass fiber, and polypropylene fiber on the strength characteristics of high performance concrete," Materials Today: Proceedings, vol. 80, pp. 577–586, 2023, doi: 10.1016/j.matpr.2022.10.291.

[7] H. K. S. El-Din, A. S. Eisa, B. H. A. Aziz and A. Ibrahim, "Mechanical performance of high strength concrete made from high volume of metakaolin and hybrid fibers," Construction and Building Materials, vol. 140, pp. 203–209, Jun. 2017, doi: 10.1016/j.conbuildmat.2017.02.118.

[8] R. Siddique and J. Klaus, "Influence of metakaolin on the properties of mortar and concrete: A review," Applied Clay Science, vol. 43, nos. 3–4, pp. 392–400, 2009, doi: 10.1016/j.clay.2008.08.004.

[9] Y. Yin, S. Zhang and L. Wang, "Effect of polypropylene fiber on shrinkage and mechanical properties of concrete," Construction and Building Materials, vol. 93, pp. 121–128, 2015.

[10] S. Patil, H. M. Somasekharaiah, H. S. Rao and V. G. Ghorpade, "Behaviour of fly ash and metakaolin based composite fiber (glass and polypropylene) reinforced high performance concrete under acid attack," Civil Engineering and Architecture, vol. 9, no. 4, pp. 1026–1047, 2021, doi: 10.13189/cea.2021.090406.

[11] S. Patil, H. M. Somasekharaiah and H. S. Rao, "Chloride penetration resistance and behaviour under acid attack of metakaolin and silica fume based composite fiber (glass and polypropylene) reinforced high performance concrete," International Journal of Engineering Trends and Technology, vol. 69, no. 4, pp. 146–161, 2021, doi: 10.14445/22315381/IJETT-V69I4P222.

[12] G. M. M. de Matos, A. M. G. de Oliveira et al., "Chemical and mechanical characterization of ternary cement pastes containing metakaolin and nanosilica," Construction and Building Materials, vol. 159, pp. 18–26, Jan. 2018, doi: 10.1016/j.conbuildmat.2017.10.123.

[13] N. Raveendran and V. K. K. Vasugi, "Synergistic effect of nano silica and metakaolin on mechanical and microstructural properties of concrete: An approach of response surface methodology," Case Studies in Construction Materials, vol. 20, Art. no. e03196, 2024, doi: 10.1016/j.cscm.2024.e03196.

[14] M. H. A. A. Hussein et al., "Effect of using hybrid polypropylene and glass fibre on the mechanical properties and permeability of concrete," Materials, vol. 12, no. 22, Art. no. 3786, 2019.

[15] "An experimental study on mechanical and fracture characteristics of hybrid fibre reinforced concrete," Structures, vol. 68, Art. no. 107053, Oct. 2024, doi: 10.1016/j.istruc.2024.107053.

[16] Shivangi, P. Singh and B. S. Mohammed, "Enhanced durability of hybrid fiber-reinforced concrete in acidic and sulfated environments," Journal of Structural Design and Construction Practice, vol. 31, no. 1, 2026, doi: 10.1061/JSDCCC.SCENG-1885.

[17] A. M. Khan, A. Elahi, R. M. Waqas, M. S. Kirgiz, N. Nagaprasad, K. Ramaswamy et al., "Influence of bentonite, silica fume, and polypropylene fibers on green concrete for pavement and structural durability," Scientific Reports, vol. 15, Art. no. 29567, 2025.

BIOGRAPHIES



Mr. Basavaprabhu M S,

Assistant Professor, Dept. of Structural Engineering, RYM ENGINEERING COLLEGE, Ballari, Karnataka, India

Email:basavaprabhu@gmail.com



Mr. Dilip S,

M Tech Structural Engineering Student ,Dept. of Structural Engineering, RYM ENGINEERING COLLEGE, Ballari, Karnataka, India

Email: s.dilip9110@gmail.com



Dr. Sachin patil,

Associate Professor, Dept. of Structural Engineering, RYM ENGINEERING COLLEGE, Ballari, Karnataka, India

Email:sachinpatil.akruthi@gmail.com