International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 10 | Oct 2026 www.irjet.net p-ISSN: 2395-0072

NANO-SILICA AND METAKAOLIN-BASED HYBRID FIBRE REINFORCED CONCRETE UNDER MECHANICAL LOADING AND SULFURIC ACID EXPOSURE

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Abstract - *This study experimentally investigates the mechanical performance and sulfuric acid resistance of concrete incorporating nano-silica (NS), metakaolin (MK), and hybrid glass–polypropylene fibre reinforcement. The programme examined concrete mixtures with different NS and MK replacement levels and fibre dosages while maintaining a water-to-binder ratio of 0.30 and an aggregate-to-binder ratio of 1.8. Compressive, split-tensile and flexural behaviour were evaluated using cube, cylinder and beam specimens. In addition, cube specimens were exposed to a 5% sulfuric acid solution for 30, 60 and 90 days following water curing. Deterioration was assessed through visual observations, mass variation and residual compressive strength. The report identifies Mix 26, containing 4.5% NS, 20% MK, 1.0% alkali-resistant glass fibre and 0.25% polypropylene fibre, as the best-performing combination in the reported mechanical results. Its 28-day split-tensile strength was 7.16 MPa compared with 3.82 MPa for the control mixture, an increase of 87.4%. The report also records a compressive strength of approximately 71 MPa for this mixture. Acid exposure reduced strength with increasing duration; however, the modified mixtures retained performance better than conventional concrete. The findings indicate that combining binder modification with hybrid fibre reinforcement can improve mechanical response and resistance to acid-induced deterioration.*

Key Words: Nano-silica, Metakaolin, Hybrid fibre reinforced concrete, Glass fibre, Polypropylene fibre, Split tensile strength, Sulfuric acid resistance.

1. INTRODUCTION

Concrete is widely used in construction because of its availability, versatility and high compressive strength. Its relatively low tensile capacity and brittle response, however, make it susceptible to cracking under tensile and flexural actions. Cracks can provide pathways for water and aggressive chemicals, accelerating deterioration and reducing service life. Improving concrete therefore requires attention not only to strength but also to crack control and durability. Supplementary cementitious materials can modify the cementitious matrix. Metakaolin contributes through pozzolanic reactions, while the fine particles of nano-silica can fill voids and promote additional reaction products. These effects may produce a denser matrix. Fibre reinforcement provides a complementary mechanism: fibres bridge cracks and help control their initiation and propagation. The present work combines NS and MK with alkali-resistant (AR) glass and polypropylene (PP) fibres and evaluates the resulting concrete under mechanical loading and sulfuric acid exposure.

1.1 Research Problem and Motivation

Sulfuric acid attack is a concern for concrete exposed to aggressive environments, including wastewater and sewage-related infrastructure. Acid reactions can soften and erode the cementitious matrix, causing surface scaling, mass loss and strength reduction. A stronger matrix alone does not eliminate brittle cracking; conversely, fibres alone do not necessarily improve the chemical stability of the binder. The study addresses the need to evaluate these strategies together by examining compression, split tension and flexure, as well as residual compressive behaviour after exposure to 5% H_2SO_4.

1.2 Objectives of the Study

The objectives were to: (i) investigate concrete mixtures with varying NS and MK contents; (ii) assess the influence of hybrid glass and polypropylene fibre

reinforcement; (iii) determine compressive, split-tensile and flexural strengths; (iv) examine deterioration during 30-, 60- and 90-day exposure to 5% sulfuric acid; and (v) compare residual compressive strength and mass changes with the corresponding reference concrete.

2. MATERIALS AND EXPERIMENTAL METHODOLOGY

2.1 Materials Used

The experimental programme used 53-grade ordinary Portland cement, nano-silica, metakaolin, Zone II river sand, 10 mm nominal-size crushed granite coarse aggregate, alkali-resistant glass fibres, polypropylene fibres, a polycarboxylate-ether-based superplasticizer and potable water. A 5% H_2SO_4 solution was used for the chemical exposure programme. The report considers NS replacement levels of 1.5%, 3.0% and 4.5% and MK replacement levels of 15% and 20% by binder mass.



Fig -1: Mixing of cement, sand, aggregates, NS, MK and Fibres with super plasticizers water solution.

2.2 Mix Proportions

The water-to-binder ratio was maintained at 0.30 and the aggregate-to-binder mass ratio at 1.8. The fibre system included AR glass fibre and polypropylene fibre. The reported optimum mixture, Mix 26, contained 75.5% cement, 4.5% nano-silica and 20% metakaolin, together with 1.0% glass fibre and 0.25% polypropylene fibre. The thesis contains an inconsistent later conclusion referring to 0.5% polypropylene fibre; the split-tensile discussion identify 0.25%.

2.3 Specimen Preparation and Curing

Cube specimens of 100 × 100 × 100 mm were prepared for compressive strength and residual compressive strength. Cylinders of 100 mm diameter × 200 mm height were used for split-tensile testing, and beams of 100 × 100 × 500 mm were used for flexural testing. Specimens were cast, demoulded after approximately 24 hours and water-cured. The report describes a 28-day water-curing period before acid immersion; mechanical test ages are stated as 28 days in the main programme.

2.4 Testing Programme

Compressive strength was determined using a compression testing machine in accordance with IS 516:2021 as stated in the report. Split-tensile testing was conducted on cylindrical specimens and flexural testing on beam specimens under third-point (four-point bending) loading. For the durability assessment, water-cured cubes were immersed in 5% sulfuric acid for 30, 60 and 90 days. Specimens were examined for surface deterioration and weighed; residual compressive strength was then determined and compared with the corresponding water-cured reference specimens.

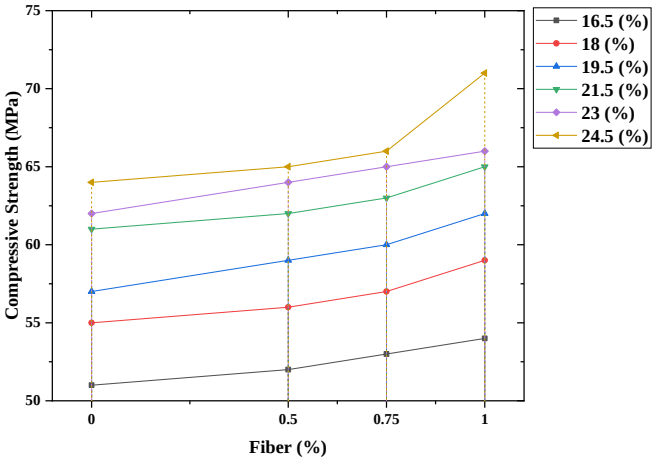
3. RESULTS AND DISCUSSION

3.1 Compressive Strength

The report identifies Mix 26 as the highest-performing mixture in the 28-day cube compressive-strength programme. The reported value is approximately 71 MPa, stated to be about 48% higher than the control mixture. The improvement is attributed in the thesis to the combined action of NS and MK in refining the cementitious matrix and the contribution of hybrid fibres to crack control.

Table -1: 28-day Cube Compressive Strength for 0.3W/B Ratio

C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
100	0	0	0	0	48
83.5	1.5	15	0	0	51
83.5	1.5	15	0.5	0.25	52
83.5	1.5	15	0.75	0.25	53
83.5	1.5	15	1	0.25	54
82	3	15	0	0	55
82	3	15	0.5	0.25	56
82	3	15	0.75	0.25	57
82	3	15	1	0.25	59
80.5	4.5	15	0	0	57
80.5	4.5	15	0.5	0.25	59
80.5	4.5	15	0.75	0.25	60
80.5	4.5	15	1	0.25	62
80	0	20	0	0	58
78.5	1.5	20	0	0	61
78.5	1.5	20	0.5	0.25	62
78.5	1.5	20	0.75	0.25	63
78.5	1.5	20	1	0.25	65
77	3	20	0	0	62
77	3	20	0.5	0.25	64
77	3	20	0.75	0.25	65
77	3	20	1	0.25	66
75.5	4.5	20	0	0	64
75.5	4.5	20	0.5	0.25	65
75.5	4.5	20	0.75	0.25	66
75.5	4.5	20	1	0.25	71



Graph-1: 28 days cube compressive strength versus volume percentages of glass & polypropolene fibres for various metakaolin and nano silica percentages.

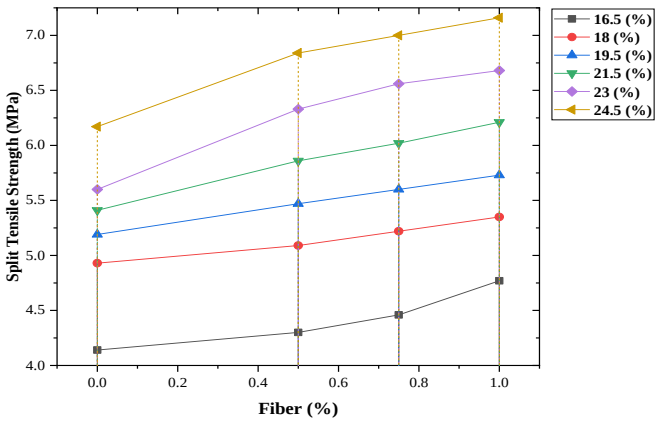
3.2 Split-Tensile Strength

The split-tensile results show an increase from 3.82 MPa for the control mixture to 7.16 MPa for Mix 26. This corresponds to an increase of approximately 87.4%. The thesis reports that the combination of 1.0% glass fibre and 0.25% polypropylene fibre produced the highest split-tensile value among the investigated combinations. The improvement is consistent with crack bridging by the fibres, while the NS–MK binder system contributes to matrix densification.

Table -2: 28-day Split Tensile Strength for 0.3W/B Ratio

C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
100	0	0	0	0	3.82
83.5	1.5	15	0	0	4.14
83.5	1.5	15	0.5	0.25	4.30
83.5	1.5	15	0.75	0.25	4.46
83.5	1.5	15	1	0.25	4.77
82	3	15	0	0	4.93
82	3	15	0.5	0.25	5.09
82	3	15	0.75	0.25	5.22
82	3	15	1	0.25	5.35

80.5	4.5	15	0	0	5.19
80.5	4.5	15	0.5	0.25	5.47
80.5	4.5	15	0.75	0.25	5.60
80.5	4.5	15	1	0.25	5.73
80	0	20	0	0	5.35
78.5	1.5	20	0	0	5.41
78.5	1.5	20	0.5	0.25	5.86
78.5	1.5	20	0.75	0.25	6.02
78.5	1.5	20	1	0.25	6.21
77	3	20	0	0	5.60
77	3	20	0.5	0.25	6.33
77	3	20	0.75	0.25	6.56
77	3	20	1	0.25	6.68
75.5	4.5	20	0	0	6.17
75.5	4.5	20	0.5	0.25	6.84
75.5	4.5	20	0.75	0.25	7.00
75.5	4.5	20	1	0.25	7.16



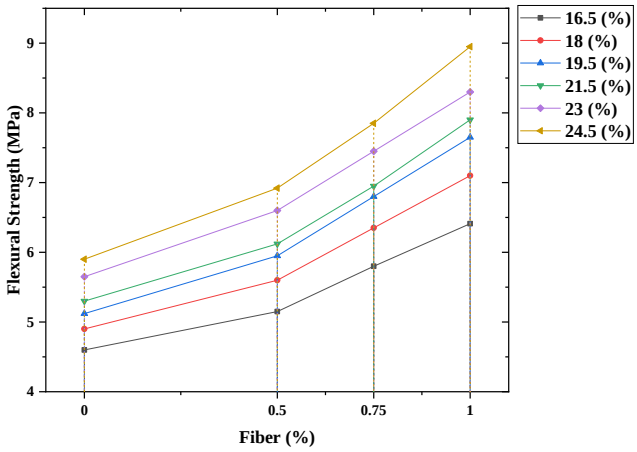
Graph-2: 28 – day's split-tensile strength versus the volume percentage's of glass & polypropolene fibres for the variou's metakaolin & nano silica percentage's.

3.3 Flexural Strength

Beam specimens were tested under third-point loading, and the modulus of rupture was calculated from the failure load. The thesis reports that hybrid fibre reinforcement had a pronounced influence on beam behaviour and that fibre-containing mixtures showed improved post-cracking response and a less brittle failure pattern.

Table -3: 28-day Beam Flexural Strength (MOR) for 0.3W/B Ratio

C (%)	NS (%)	MK (%)	GF (%)	PPF (%)	28D (MPa)
100	0	0	0	0	4.25
83.5	1.5	15	0	0	4.6
83.5	1.5	15	0.5	0.25	5.15
83.5	1.5	15	0.75	0.25	5.8
83.5	1.5	15	1	0.25	6.42
82	3	15	0	0	4.95
82	3	15	0.5	0.25	5.6
82	3	15	0.75	0.25	6.35
82	3	15	1	0.25	7.1
80.5	4.5	15	0	0	5.12
80.5	4.5	15	0.5	0.25	5.95
80.5	4.5	15	0.75	0.25	6.8
80.5	4.5	15	1	0.25	7.65
80	0	20	0	0	4.85
78.5	1.5	20	0	0	5.3
78.5	1.5	20	0.5	0.25	6.12
78.5	1.5	20	0.75	0.25	6.95
78.5	1.5	20	1	0.25	7.9
77	3	20	0	0	5.65
77	3	20	0.5	0.25	6.6
77	3	20	0.75	0.25	7.45
77	3	20	1	0.25	8.3
75.5	4.5	20	0	0	5.9
75.5	4.5	20	0.5	0.25	6.92
75.5	4.5	20	0.75	0.25	7.85
75.5	4.5	20	1	0.25	8.95



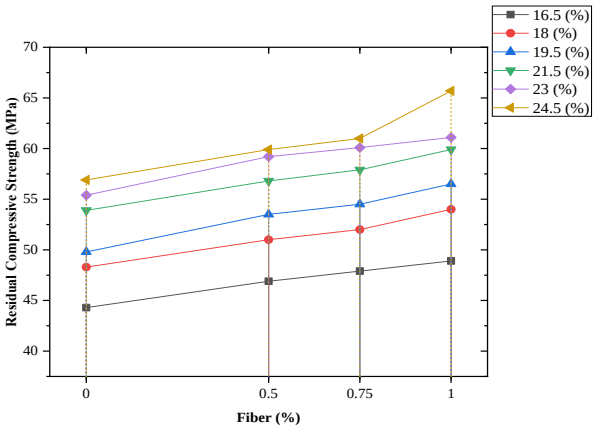
Graph-3: 28 day's flexural strength versus volume percentages of glass & poly-propylene fibres for various metakaolin and nano silica percentages.

3.4 Sulfuric Acid Resistance

The acid durability programme involved immersion in 5% H_2SO_4 for 30, 60 and 90 days after an initial water-curing period. The report describes progressive deterioration with longer exposure, including surface softening and loss of material, accompanied by a reduction in residual compressive strength. It also reports that the modified NS–MK hybrid-fibre mixtures retained a greater proportion of their strength than the conventional reference concrete. The proposed explanation is that the denser binder matrix limits acid penetration, while fibres restrict crack widening and help maintain specimen integrity.

Table -4: H_2SO_4 Immersed Residual Compressive Strength for 30,60,90 Days for 0.3W/B Ratio.

C (%)	NS (%)	MK (%)	GF+PPF (%)	30D MPa	60D MPa	90D MPa
100	0	0	0	41.3	38.6	36
83.5	1.5	15	0	44.3	41.7	39
83.5	1.5	15	0.5+0.25	46.9	44.4	41.9
83.5	1.5	15	0.75+0.25	47.9	45.4	42.9
83.5	1.5	15	1+0.25	48.9	46.4	43.8
82	3	15	0	48.3	45.6	42.9
82	3	15	0.5+0.25	51	48.4	45.9
82	3	15	0.75+0.25	52	49.5	46.9
82	3	15	1+0.25	54	51.4	48.8
80.5	4.5	15	0	49.8	46.9	44
80.5	4.5	15	0.5+0.25	53.5	50.7	47.9
80.5	4.5	15	0.75+0.25	54.5	51.7	48.9
80.5	4.5	15	1+0.25	56.5	53.6	50.8
80	0	20	0	50.8	47.8	44.7
78.5	1.5	20	0	53.9	51.1	47.9
78.5	1.5	20	0.5+0.25	56.8	54.1	51.2
78.5	1.5	20	0.75+0.25	57.9	55.2	52.2
78.5	1.5	20	1+0.25	59.9	57.1	54.1
77	3	20	0	55.4	52.6	49.6
77	3	20	0.5+0.25	59.2	56.6	53.8
77	3	20	0.75+0.25	60.1	57.7	54.8
77	3	20	1+0.25	61.1	58.7	55.9
75.5	4.5	20	0	56.9	54	50.7
75.5	4.5	20	0.5+0.25	59.9	57.1	54.1
75.5	4.5	20	0.75+0.25	61	58.2	55.1
75.5	4.5	20	1+0.25	65.7	62.8	59.6



Graph-4: Residual compressive strength versus volume percentages of glass & poly-propylene fibres for various metakaolin and nano silica percentages mixes immersed in H_2SO_4.

4. CONCLUSIONS

The experimental study supports the following conclusions:

1) The combined use of nano-silica and metakaolin improved the reported mechanical performance of the concrete mixtures, with the 20% MK and 4.5% NS combination identified as the strongest binder modification in the study.

2) Mix 26 was reported to achieve approximately 71 MPa compressive strength at 28 days, about 48% above the control value.

3) The split-tensile strength increased from 3.82 MPa for the control mixture to 7.16 MPa for Mix 26, representing an improvement of approximately 87.4%.

4) Hybrid glass and polypropylene fibre reinforcement improved the reported tensile and flexural response and helped control crack propagation.

5) Exposure to 5% sulfuric acid caused deterioration with increasing exposure duration. Nevertheless, the modified mixtures showed better residual performance than the conventional control, according to the report.

6) The report identifies 1.0% glass fibre and 0.25% polypropylene fibre as the optimum hybrid-fibre combination in the split-tensile results.

ACKNOWLEDGEMENT

I am thankful to my guide, Mr. Basavaprabhu M S, Asst. Professor, Department Civil Engineering and Dr. Sachin Patil, Assoc. Professor, Department Civil Engineering for their constant encouragement and able guidance. Also I thank my parents, friends and others for their continuous support in making this work complete.

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