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Experimental Investigation of Mechanical and Durability Behaviour of Sustainable Fibre-Reinforced Geopolymer Concrete Using Fly Ash–GGBS–Metakaolin Ternary Binders

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Abstract

This study experimentally evaluates ambient-cured, steel-fibre-reinforced geopolymer concrete incorporating fly ash, ground-granulated blast-furnace slag (GGBS) and metakaolin. Seven mixtures comprising six geopolymer binder combinations and an ordinary Portland cement (OPC) reference were considered at sodium hydroxide concentrations of 10, 12 and 14 M, a sodium silicate-to-sodium hydroxide mass ratio of 2.5 and an alkaline liquid-to-binder ratio of 0.40. Steel-fibre volume fractions ranged from 0 to 1.5%. The ternary mixture containing 60% fly ash, 25% GGBS and 15% metakaolin (M5) achieved the highest reported compressive strengths: 62.45 MPa at 28 days and 69.26 MPa at 90 days, using 14 M NaOH and 1.5% steel fibres. The same mixture achieved split tensile and flexural strengths of 5.69 and 8.46 MPa, respectively, at 28 days. Water absorption, sulphuric-acid exposure, sodium-sulphate exposure, rapid chloride permeability and ultrasonic pulse velocity were also evaluated. The results indicate favourable mechanical performance for the M5 ternary blend within the investigated matrix. However, inconsistencies in the strength and UPV datasets, durability calculations and supporting statistical information require resolution before the numerical findings can be treated as definitive.

Keywords: Geopolymer concrete, ternary binder, fly ash, GGBS, metakaolin, steel fibres, compressive strength, durability, chloride permeability.

I. INTRODUCTION

Ordinary Portland cement (OPC) production is associated with substantial energy consumption and carbon dioxide emissions. Alkali-activated binders and geopolymer concrete provide an alternative route by using aluminosilicate-rich industrial by-products and supplementary precursor materials. Fly ash contributes reactive silica and alumina, GGBS supplies calcium-bearing phases, and metakaolin provides a relatively fine and reactive aluminosilicate source. Their combined use can modify reaction products, pore structure and strength development.

Geopolymer concrete may nevertheless exhibit limited workability and brittle tensile behaviour. The present investigation therefore combines fly ash, GGBS and metakaolin with sodium-based alkaline activators and crimped steel fibres. The experimental programme compares binary and ternary precursor blends, three NaOH molarities and four fibre-volume levels, and evaluates mechanical and durability-related performance under ambient curing.

This study examines the experimental programme and results for binary and ternary fly ash–GGBS–metakaolin binders reinforced with steel fibres. The discussion retains the stated mixture proportions and measured values while identifying discrepancies that affect interpretation and reproducibility.

II. MATERIALS AND EXPERIMENTAL PROGRAMME

A. Constituent Materials and Activators

The precursor system consisted of fly ash, GGBS and metakaolin. Sodium hydroxide and sodium silicate were used as alkaline activators. The sodium silicate-to-sodium hydroxide mass ratio was maintained at 2.5 and the alkaline liquid-to-binder ratio at 0.40. The NaOH concentrations were 10, 12 and 14 M. A superplasticizer dosage of 1.2% was reported to improve fresh-state flow. OPC concrete was included as the reference mixture.

B. Binder Combinations and Fibre Content

Steel fibres were incorporated at volume fractions of 0, 0.5, 1.0 and 1.5%. The experimental matrix comprised seven mixture categories, three NaOH molarities for the geopolymer mixtures and four fibre-volume levels.

C. Specimen Preparation and Testing

The test specimens comprised 100 mm cubes for compressive-strength testing, 150 mm diameter × 300 mm cylinders for splitting tensile strength and 500 mm × 100 mm × 100 mm prisms for flexural strength. Specimens were demoulded after approximately 24 h and subjected to ambient curing for 28 and 90 days. Slump was measured with reference to IS 1199:2018, while hardened-strength tests were associated with IS 516:1959. Durability investigations included water absorption, exposure to 5% H_2SO_4 and Na_2SO_4 solutions, rapid chloride permeability testing (RCPT) and ultrasonic pulse velocity (UPV).

D. Test Programme at a Glance

Table.1. Test Program Details

Property	Reported method / exposure	Reported age
Workability	Slump cone; IS 1199:2018	Fresh
Compressive strength	100 mm cube; CTM	28 and 90 days
Split tensile strength	150 × 300 mm cylinder	28 and 90 days
Flexural strength	500 × 100 × 100 mm prism	28 and 90 days
Water absorption	Water immersion / oven-dry mass procedure	After 28-day curing
Acid resistance	5% H_2SO_4 immersion	28 and 90 days exposure
Sulphate resistance	Na_2SO_4 immersion	28 and 90 days exposure
Chloride penetrability	RCPT; ASTM C1202 cited	90 days
Concrete quality	UPV; IS 13311:1992 cited	As reported

III. RESULTS AND DISCUSSION

A. Workability

Slump decreased as NaOH molarity and steel-fibre content increased. Across the geopolymer mixtures, the listed slump values generally ranged from approximately 55 to 150 mm, compared with 120–180 mm for the OPC reference. For M1 at 10 M, slump decreased from 150 mm without fibres to 135 mm at 1.5% fibre; at 14 M, the corresponding values were 110 and 82 mm. M6 at 14 M with 1.5% fibres recorded the lowest listed geopolymer slump of 55 mm. The observed trend is consistent with increased activator viscosity, the high specific surface area of metakaolin and the resistance to flow introduced by steel fibres.

Table 2. Selected slump values (0% and 1.5% fibre endpoints).

Mixture	10 M slump (mm), 0→1.5% fibre	12 M slump (mm), 0→1.5%	14 M slump (mm), 0→1.5%
M1	150 → 135	120 → 95	110 → 82
M3	108 → 82	105 → 80	95 → 75
M5	100 → 70	90 → 65	82 → 60

M6	95 → 70	85 → 65	78 → 55
OPC	180 → 120	180 → 120	180 → 120

B. Compressive Strength

Compressive strength increased with NaOH molarity in the M5 mixture. The highest tabulated values were obtained with M5 (60% fly ash, 25% GGBS and 15% metakaolin), 14 M NaOH and 1.5% steel fibres: 62.45 MPa at 28 days and 69.26 MPa at 90 days. At 10 M, the corresponding M5 strengths were 52.80 and 60.08 MPa; at 12 M, they were 59.92 and 62.43 MPa.

Table 3. Compressive strength for different molarities

NaOH molarity	M5, 28-day (MPa)	M5, 90-day (MPa)	M5 fibre volume
10 M	52.80	60.08	1.5%
12 M	59.92	62.43	1.5%
14 M	62.45	69.26	1.5%

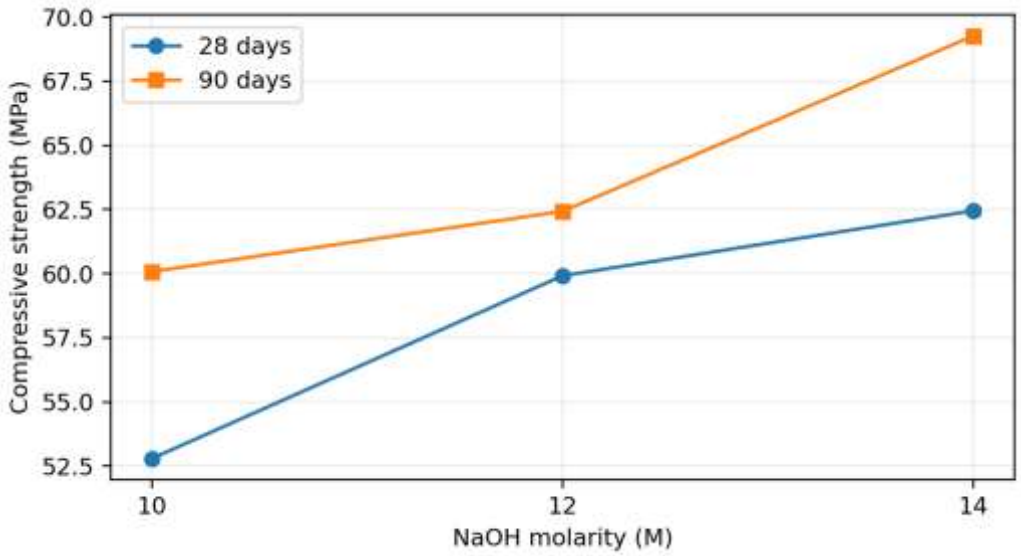


Fig. 1. Compressive strength of M5 at 1.5% steel-fibre volume for the three activator molarities.

At 14 M, M5 exceeded the binary M1–M3 mixtures and the other ternary blends in the tabulated 28-day results. The combined use of fly ash, metakaolin and calcium-bearing GGBS may influence reaction products and matrix development, while steel fibres may contribute to crack bridging. These mechanisms are plausible explanations; direct microstructural evidence is not provided in the results presented here.

C. Split Tensile and Flexural Strength

For M5 with 14 M NaOH and 1.5% fibres, the measured values presented for 28-day split tensile and flexural strengths were 5.69 and 8.46 MPa, respectively; the corresponding 90-day values were 6.56 and 9.62 MPa. These results indicate substantial tensile-related capacity in the selected fibre-reinforced mixture. Crack bridging and delayed crack propagation are possible contributors, although a fibre-free paired comparison is required to quantify the fibre-specific effect.

Table 4. Summary of strengths

Property (M5, 1.5% fibre)	10 M	12 M	14 M
Split tensile, 28 days (MPa)	4.72	5.32	5.69
Split tensile, 90 days (MPa)	5.21	5.78	6.56
Flexural, 28 days (MPa)	6.77	7.24	8.46
Flexural, 90 days (MPa)	7.14	7.81	9.62

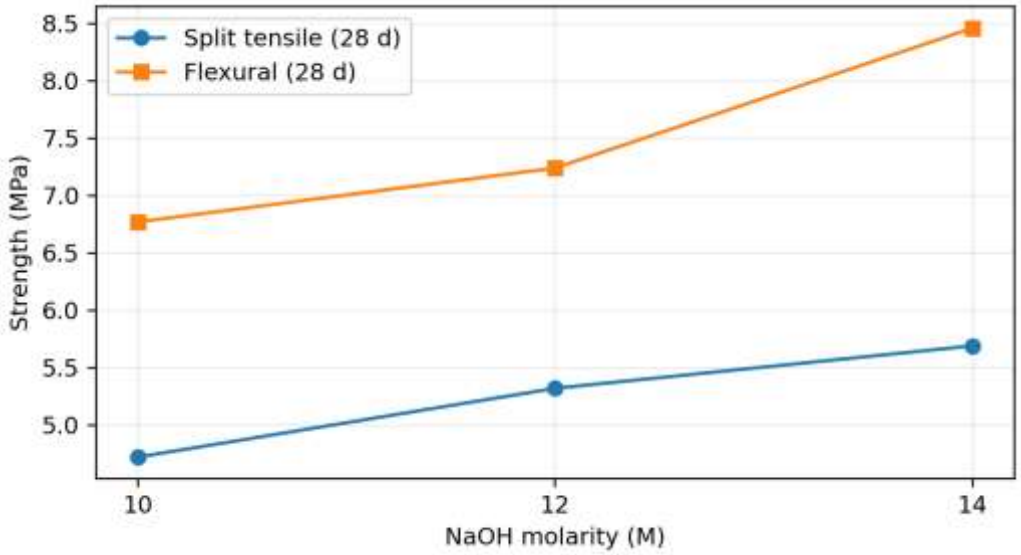


Fig. 2. 28-day split tensile and flexural strengths of M5 at 1.5% fibre.

D. Water Absorption

Average water absorption is given as 6.15% for binary geopolymer mixtures, 3.35% for ternary geopolymer mixtures and 4.46% for OPC. The lowest stated value is 2.9% for M5 at 14 M. These values suggest lower water uptake for the ternary blends within the reported dataset. The mixture-wise values and calculations require confirmation against the original mass records because the tabulated layout and the definitions of the weighing variables are not sufficiently clear.

E. Resistance to Sulphuric Acid and Sodium Sulphate

Specimens were exposed to 5% H_2SO_4 after 28 days of curing, and residual compressive strength was evaluated after 28 and 90 days of exposure. The stated average strength reductions for geopolymer mixtures are 12.35% and 17.77% at 10 M, 11.39% and 17.26% at 12 M, and 10.27% and 17.03% at 14 M, respectively. For OPC, maximum reductions of 22.05% and 45.63% are stated. The M5 mixture at 14 M is described as having reductions of 8.06% and 15.5% after 28 and 90 days, respectively. These percentages should be recalculated from the individual initial and residual strength measurements before comparative conclusions are drawn.

For sodium-sulphate exposure, the listed results indicate lower strength loss for geopolymer mixtures than for OPC. For the 14 M ternary mixtures M4, M5 and M6, the stated reductions are 7.63%, 7.33% and 7.48% after 28 days, and 11.30%, 9.76% and 10.21% after 90 days. The narrative values and the associated tables are not fully consistent; the original measurements should be used to recompute and verify these percentages.

F. Rapid Chloride Permeability and UPV

The RCPT results list charge passed between 2,345 and 2,899 coulombs for the mixtures and fibre contents shown. Most geopolymer entries fall within the moderate chloride-penetrability category using the ASTM C1202

classification reproduced in the study. M5 without fibres recorded 2,415 coulombs, while M5 with 1.5% fibres recorded 2,588 coulombs. Because steel fibres are electrically conductive, their presence may influence measured charge independently of ionic transport through the pore system; RCPT results for fibre-reinforced mixtures therefore require cautious interpretation.

UPV values are listed between 3,641 and 4,674 m/s for geopolymer mixtures and 3,550–3,872 m/s for OPC. A linear relationship between UPV and compressive strength is stated, with $R^2 = 0.9107$.

IV. PRINCIPAL FINDINGS

1. Among the investigated precursor combinations, M5 (60% fly ash, 25% GGBS and 15% metakaolin) produced the highest reported mechanical strengths.
2. The maximum tabulated M5 compressive strength was 62.45 MPa at 28 days and 69.26 MPa at 90 days for 14 M NaOH and 1.5% steel fibres.
3. For the same M5 combination, the reported 28-day split tensile and flexural strengths were 5.69 and 8.46 MPa, increasing to 6.56 and 9.62 MPa at 90 days.
4. Slump decreased as NaOH molarity and fibre volume increased; M6 at 14 M with 1.5% fibres recorded 55 mm.
5. The reported average water absorption was lower for ternary geopolymer mixes (3.35%) than for binary mixes (6.15%) and OPC (4.46%).
6. Acid- and sulphate-exposure results generally indicate lower strength loss for geopolymer mixtures than for OPC, although several tabulated values need verification.
7. RCPT results were mostly classified as moderate penetrability; fibre conductivity is a confounding factor in interpreting charge passed.
8. UPV results indicate higher pulse velocities for several ternary mixes, but the strength values and regression equation require correction and validation.

V. CONCLUSION

The experimental results indicate that fly ash–GGBS–metakaolin ternary binders combined with steel fibres can produce ambient-cured geopolymer concrete with substantial compressive, split tensile and flexural strengths. Among the investigated mixtures, M5 containing 60% fly ash, 25% GGBS and 15% metakaolin achieved the highest stated mechanical strengths at 14 M NaOH and 1.5% steel fibres: 62.45 MPa compressive strength at 28 days and 69.26 MPa at 90 days, together with split tensile and flexural strengths of 5.69 and 8.46 MPa at 28 days.

The reported water-absorption, acid-exposure, sulphate-exposure, RCPT and UPV results suggest potential durability-related benefits for selected ternary geopolymer mixtures. However, inconsistencies in the strength values, regression equation, durability calculations and supporting statistical information limit the certainty of these comparisons. Verification of the original measurements, correction of the affected tables, reporting of replicate statistics and documentation of any microstructural or life-cycle assessment methods are necessary before definitive conclusions are drawn.

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