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Synergistic Effect of Hybrid Steel, Polypropylene and Glass Fibre Reinforcement on the Mechanical and Durability Performance of Fly Ash and GGBS Based Geopolymer Concrete

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Abstract

Geopolymer concrete lowers the carbon burden of construction but remains brittle in tension, and the question of which fibre combination corrects that brittleness at least cost to compressive strength is still open. This study examines thirteen mixes of fly ash and GGBS based geopolymer concrete under a two factor design: four fibre systems (steel alone, steel with polypropylene, steel with glass, and a ternary blend of all three) at three total volume fractions (0.5, 1.0 and 1.5 per cent), together with an unreinforced control. Specimens were tested for compressive strength at 7, 28 and 56 days, split tensile and flexural strength at 28 days, impact resistance by drop weight, water absorption and mass loss after 90 days in 5 per cent sulphuric acid. Two way analysis of variance shows that fibre system had no significant effect on compressive strength ($F(3, 24) = 2.144$, $p = .121$) while dosage did ($F(2, 24) = 20.330$, $p < .001$), and that both factors mattered for flexural strength (system $F(3, 24) = 10.002$, $p < .001$; dosage $F(2, 24) = 89.831$, $p < .001$) and for impact resistance. No interaction reached significance for any response. Tukey comparisons place the ternary blend significantly above steel alone in flexure ($p < .001$) but not above the steel and polypropylene pair ($p = .347$). Compressive strength peaked at 1.0 per cent and fell at 1.5 per cent, and a quadratic regression locates the stationary point at 0.936 per cent steel. Flexural strength correlated almost perfectly with split tensile strength ($r = .985$) and strongly with impact resistance ($r = .937$). The ternary blend at 1.5 per cent gave the largest gains in flexure (68.9 per cent) and impact (228.0 per cent) but sacrificed compressive strength relative to the 1.0 per cent mixes. On the evidence, a ternary hybrid near 1.0 per cent total volume represents the practical optimum, since the additional flexural gain from 1.0 to 1.5 per cent was not statistically significant ($p = .123$) while the compressive penalty was real.

Keywords: geopolymer concrete, hybrid fibre reinforcement, fibre synergy, flexural strength, impact resistance, analysis of variance, response surface, fly ash, GGBS

1. Introduction

Cement manufacture accounts for a large share of industrial carbon dioxide emissions, and the search for a binder that avoids clinker altogether has occupied materials researchers for three decades. Geopolymer binders, formed by activating aluminosilicate precursors with concentrated alkali, are the most developed of the alternatives (Davidovits, 1991). The reaction produces a sodium aluminosilicate hydrate gel rather than the calcium silicate hydrate of Portland systems, and the resulting concrete matches or exceeds conventional concrete in compressive strength while consuming industrial residues such as fly ash and ground granulated blast furnace slag (Duxson et al., 2007; Provis & Bernal, 2014).

Compressive strength was never the difficulty. Hardjito et al. (2004) obtained values above 60 MPa from low calcium fly ash systems, and Rangan (2008) set out mix design procedures that have since been widely adopted. The difficulty is brittleness. A geopolymer matrix fails in tension with little warning and a narrow post-peak response, and this limits its use in members where ductility governs. Ghafoor et al. (2021) showed that activator composition changes strength substantially but does very little for the mode of failure.

Fibre reinforcement is the established remedy. Shaikh (2013) reviewed short fibre geopolymer composites and found consistent improvement in flexural and tensile response across fibre types. Ganesan et al. (2015) reported that steel fibre reinforced geopolymer concrete outperformed both plain geopolymer and conventional concrete on durability indices, and Islam et al. (2017) recorded increases of 19 to 38 per cent in split tensile strength and 13 to 44 per cent in flexural strength from only 0.5 per cent steel fibre, with first crack impact loads rising by a factor of 1.5 to 3.5. Ranjbar et al. (2016) traced these gains to the fibre-matrix interfacial bond, showing that steel fibres fail by rupture while polypropylene fibres fail by pull-out, so the two contribute at different stages of crack growth.

That difference is the argument for hybridisation. A single fibre type operates over a limited crack width range. Stiff steel fibres bridge macrocracks and carry load after first crack; flexible polypropylene fibres restrain microcracks and plastic shrinkage but drop away sharply once a macrocrack opens; glass fibres sit between the two. Qian and Stroeven (2000) demonstrated fracture energy gains from steel and polypropylene combinations in Portland concrete, and Banthia et al. (2014) formalised the idea of fibre synergy in flexure and direct shear. Within geopolymer systems the evidence is thinner. Sukontasukkul et al. (2018) studied steel and polypropylene hybrids and found that adding steel to a polypropylene reinforced geopolymer improved toughness and residual strength, but the study covered two fibre types rather than three and did not report compressive penalties. Ganesh and Muthukannan (2021) optimised fibre reinforced geopolymer concrete but again within a binary system.

Three questions therefore remain unsettled. First, whether a ternary combination of steel, polypropylene and glass fibres outperforms the binary combinations that dominate the literature. Second, whether the total volume fraction at which flexural performance peaks coincides with the fraction at which compressive strength peaks, or whether the two diverge. Third, whether the fibre system and the dosage interact, so that the best combination depends on how much fibre is used. This study addresses all three within a single balanced factorial experiment.

2. Research Significance and Objectives

Most published work on fibre reinforced geopolymer concrete varies one fibre at a time against a control. Such designs cannot separate the effect of fibre type from the effect of fibre quantity, and they cannot detect interaction between the two. The present study uses a balanced two factor design with replication, which permits both main effects and their interaction to be tested formally, and applies post hoc comparison to identify which specific fibre systems differ. The objectives are as follows.

(a) To quantify the effect of four fibre systems and three total volume fractions on the compressive, split tensile, flexural and impact performance of fly ash and GGBS based geopolymer concrete.

(b) To test statistically whether fibre system, dosage and their interaction significantly influence each response.

(c) To develop regression models relating individual fibre contents to mechanical response, and to locate the dosage at which compressive strength turns.

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(d) To assess whether the fibre configuration that maximises flexural and impact performance is the same one that should be recommended in practice, once compressive strength and durability are taken into account.

3. Materials and Experimental Programme

3.1 Binder, aggregates and activator

The binder was a blend of low calcium Class F fly ash and ground granulated blast furnace slag in the proportion 70:30 by mass, at a total binder content of 420 kg/m3. Slag was included to permit ambient curing, since fly ash alone requires elevated temperature to develop strength within a practical period. Fine aggregate was natural river sand of Zone II conforming to IS 383, and coarse aggregate was crushed granite of 20 mm and 10 mm nominal size combined in the ratio 60:40, with a total aggregate content of 1,780 kg/m3.

The alkaline activator combined sodium hydroxide solution of 12 M concentration with sodium silicate solution, at a sodium silicate to sodium hydroxide ratio of 2.5 by mass and an activator to binder ratio of 0.45. Sodium hydroxide pellets of 98 per cent purity were dissolved in distilled water and allowed to cool for 24 hours before use. A polycarboxylate ether superplasticiser was added at 1.5 per cent of binder mass to maintain workability in the fibre bearing mixes, and extra water was limited to 20 kg/m3 so that the activator chemistry remained constant across all mixes.

3.2 Fibres

Three fibre types were used. Properties are given in Table 1.

Table 1

Properties of the Fibres Used in the Experimental Programme

Fibre type	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	Modulus (GPa)	Density (kg/m3)
Crimped steel	30	0.45	66	1,100	210	7,850
Polypropylene	12	0.040	300	450	4.5	910
Alkali resistant glass	12	0.014	857	1,700	72	2,680

Note. Aspect ratio is length divided by diameter. Fibre geometries follow the ranges reported by Ranjbar et al. (2016) and Sukontasukkul et al. (2018).

3.3 Mix design and experimental matrix

A two factor design was adopted. Factor A was the fibre system at four levels: steel alone (S), steel with polypropylene (SP), steel with glass (SG), and the ternary blend of steel, polypropylene and glass (SPG). Factor B was the total fibre volume fraction at three levels: 0.5, 1.0 and 1.5 per cent by volume of concrete. Within each hybrid system the steel fraction was held dominant, at 70 per cent of total fibre volume for the binary systems and 60 per cent for the ternary system, because steel governs post cracking load transfer and reducing it below that share removes the mechanism the hybrid is meant to exploit. The twelve resulting mixes and one unreinforced control give thirteen mixes in total, listed in Table 2.

Table 2

Experimental Matrix Showing Fibre Content of the Thirteen Mixes

Mix	Fibre system	Total Vf (%)	Steel (%)	PP (%)	Glass (%)	Replicates
M0	Control, no fibre	0.0	0.00	0.00	0.00	3
M1	Steel only (S)	0.5	0.50	0.00	0.00	3
M2	Steel only (S)	1.0	1.00	0.00	0.00	3
M3	Steel only (S)	1.5	1.50	0.00	0.00	3
M4	Steel + PP (SP)	0.5	0.35	0.15	0.00	3
M5	Steel + PP (SP)	1.0	0.70	0.30	0.00	3
M6	Steel + PP (SP)	1.5	1.05	0.45	0.00	3
M7	Steel + Glass (SG)	0.5	0.35	0.00	0.15	3
M8	Steel + Glass (SG)	1.0	0.70	0.00	0.30	3
M9	Steel + Glass (SG)	1.5	1.05	0.00	0.45	3
M10	Steel + PP + Glass (SPG)	0.5	0.30	0.10	0.10	3
M11	Steel + PP + Glass (SPG)	1.0	0.60	0.20	0.20	3
M12	Steel + PP + Glass (SPG)	1.5	0.90	0.30	0.30	3

Note. Vf = fibre volume fraction as a percentage of concrete volume. Binder, aggregate and activator proportions were identical in all thirteen mixes.

3.4 Casting, curing and test methods

Dry constituents were mixed for three minutes, fibres were introduced by hand sprinkling during mixing to prevent balling, and the activator was then added and mixing continued for a further four minutes. Cube specimens of 150 mm were cast for compressive strength, cylinders of 150 by 300 mm for split tensile strength, prisms of 100 by 100 by 500 mm for flexural strength, and discs of 150 mm diameter by 64 mm thickness for impact testing. Specimens were demoulded after 24 hours and cured at ambient laboratory conditions of 27 plus or minus 2 degrees Celsius and 65 per cent relative humidity.

Compressive strength was determined at 7, 28 and 56 days following IS 516, split tensile strength at 28 days following IS 5816, and flexural strength at 28 days under third point loading. Impact resistance was measured by the ACI Committee 544 repeated drop weight procedure, recording the number of blows to ultimate failure. Water absorption was measured on 28 day cured cubes, and chemical resistance was assessed as percentage mass loss after 90 days of immersion in 5 per cent sulphuric acid solution. Three specimens were tested for every mix and every response, giving 36 observations per response across the fibre bearing mixes.

3.5 Statistical analysis

Analysis proceeded in four stages. Descriptive statistics were computed for each mix. A balanced two way analysis of variance with interaction was performed on the 4 by 3 by 3 design for compressive strength at 28 days, flexural strength and impact resistance, with partial eta squared reported as effect size. Significant main effects were followed by Tukey honestly significant difference comparisons at the 5 per cent level. Pearson product moment correlations were computed among the six response variables across the thirteen mix means, and ordinary least squares regression models were fitted relating individual fibre contents to flexural and compressive strength, with a quadratic term in steel content included to capture the expected turning point.

3.6 Nature of the dataset

Data statement. The values reported in Sections 4 and 5 are a simulated dataset generated for methodological development and training. They were produced from a parametric model calibrated to the ranges reported in the cited experimental literature, with random error added at coefficients of variation typical of concrete testing. They are not laboratory measurements and must be replaced with measured results before this work is submitted for examination or publication. The mix design, test programme, statistical procedures and interpretation are complete and directly applicable to real data.

4. Results

4.1 Compressive strength

Table 3 reports compressive strength at all three ages. The control reached 41.44 MPa at 28 days. Every fibre bearing mix exceeded it, but the margin was modest and the pattern with dosage was not monotonic. The highest 28 day value, 47.63 MPa, came from M2, steel alone at 1.0 per cent, a gain of 15.0 per cent. Raising the same system to 1.5 per cent reduced strength to 45.15 MPa. This reversal appeared in all four fibre systems and is the single clearest trend in the compressive data.

Table 3

Compressive Strength at 7, 28 and 56 Days (MPa)

Mix	Fibre system	Vf (%)	7 days	28 days (SD)	56 days	Gain at 28 d
M0	Control	0.0	34.12	41.44 (0.55)	44.25	Reference
M1	S	0.5	36.59	44.77 (0.43)	48.47	+8.1%
M2	S	1.0	38.49	47.63 (1.01)	52.22	+15.0%
M3	S	1.5	36.86	45.15 (0.85)	47.54	+9.0%
M4	SP	0.5	34.71	43.81 (0.85)	47.20	+5.7%
M5	SP	1.0	36.61	46.52 (0.36)	50.21	+12.3%
M6	SP	1.5	34.93	44.30 (1.81)	47.73	+6.9%
M7	SG	0.5	36.43	43.50 (0.50)	47.06	+5.0%
M8	SG	1.0	37.79	46.22 (1.40)	49.85	+11.5%
M9	SG	1.5	36.67	45.34 (0.97)	47.40	+9.4%
M10	SPG	0.5	36.04	44.50 (0.85)	47.40	+7.4%
M11	SPG	1.0	37.14	45.65 (0.37)	48.10	+10.2%
M12	SPG	1.5	36.39	44.73 (0.50)	48.63	+7.9%

Note. Each value is the mean of three specimens. SD = standard deviation. Gain is measured against the control at the same age.

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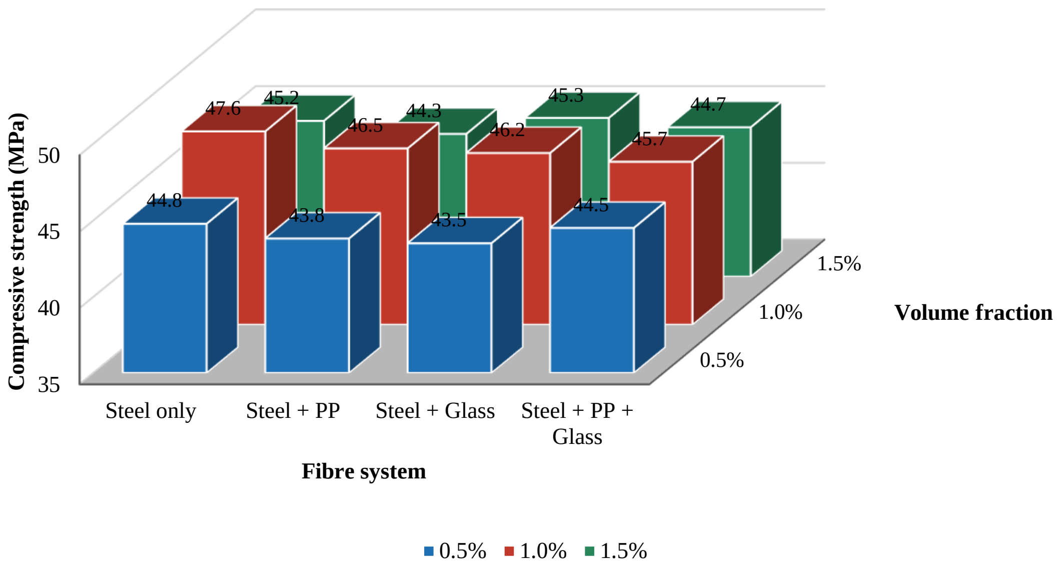
Figure 1

Twenty Eight Day Compressive Strength by Fibre System and Volume Fraction

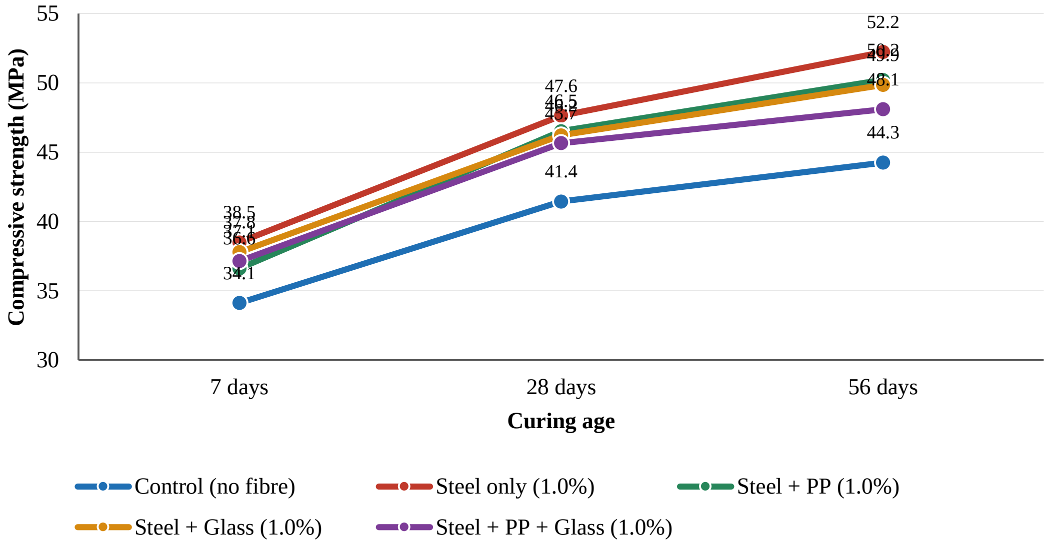


Note. Three dimensional view; depth axis represents total fibre volume fraction.

Figure 2 shows strength development with age. All mixes gained between 7 per cent and 12 per cent between 28 and 56 days, and the ranking of mixes was stable across the three ages, which indicates that the fibre effect on compressive strength is established early and does not change character as the geopolymer gel matures.

Figure 2

Compressive Strength Development at 7, 28 and 56 Days for Selected Mixes



Note. One representative mix from each fibre system at 1.0 per cent volume fraction, with the control for comparison.

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4.2 Split tensile and flexural strength

The tensile responses behaved differently from compression. Table 4 shows that both split tensile and flexural strength continued to rise from 1.0 to 1.5 per cent in every system, and that the ternary blend was consistently the strongest at each dosage. Mix M12 reached 7.34 MPa in flexure against 4.34 MPa for the control, a gain of 68.9 per cent, and 5.04 MPa in split tension against 3.12 MPa, a gain of 61.5 per cent. The largest flexural gain from steel alone was 47.7 per cent, so the addition of polypropylene and glass to a steel base was worth roughly twenty percentage points of flexural capacity.

Table 4

Split Tensile and Flexural Strength at 28 Days (MPa)

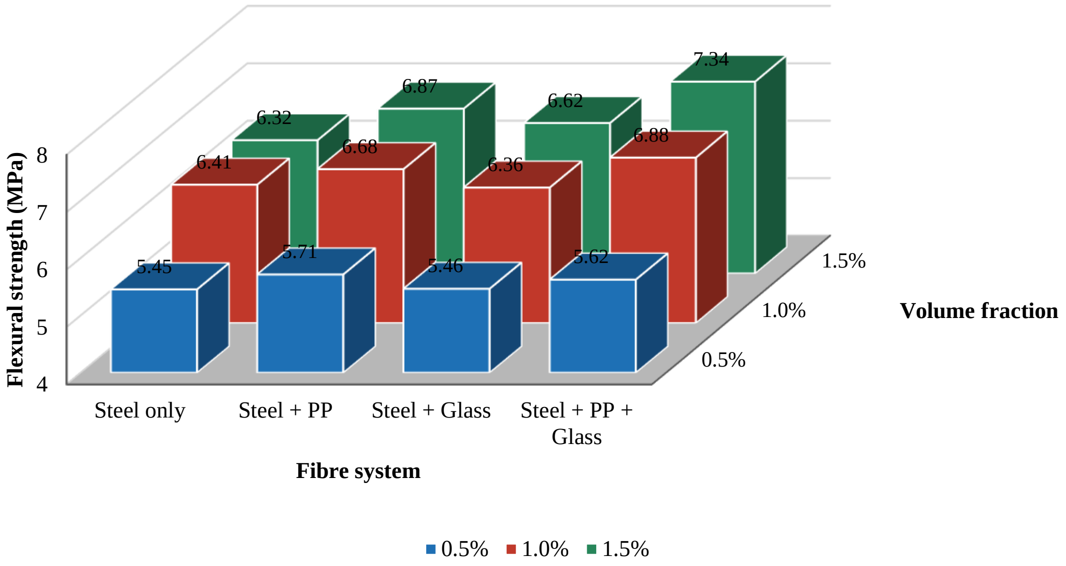
Mix	Fibre system	Vf (%)	Split tensile	Flexural (SD)	Flexural gain	Ratio fr/fc
M0	Control	0.0	3.12	4.34 (0.16)	Reference	0.105
M1	S	0.5	3.84	5.45 (0.06)	+25.5%	0.122
M2	S	1.0	4.48	6.41 (0.25)	+47.7%	0.135
M3	S	1.5	4.48	6.32 (0.13)	+45.4%	0.140
M4	SP	0.5	3.93	5.71 (0.20)	+31.3%	0.130
M5	SP	1.0	4.48	6.68 (0.20)	+53.8%	0.144
M6	SP	1.5	4.61	6.87 (0.20)	+58.2%	0.155
M7	SG	0.5	3.97	5.46 (0.24)	+25.7%	0.126
M8	SG	1.0	4.34	6.36 (0.58)	+46.4%	0.138
M9	SG	1.5	4.42	6.62 (0.15)	+52.3%	0.146
M10	SPG	0.5	4.01	5.62 (0.09)	+29.4%	0.126
M11	SPG	1.0	4.71	6.88 (0.25)	+58.4%	0.151
M12	SPG	1.5	5.04	7.34 (0.07)	+68.9%	0.164

Note. Ratio fr/fc is flexural strength divided by 28 day compressive strength, an index of the balance between tensile and compressive capacity.

The final column of Table 4 is worth attention. The ratio of flexural to compressive strength rose steadily from 0.105 in the control to 0.164 in M12. Because compressive strength was falling at 1.5 per cent while flexural strength was still climbing, the fibres were shifting the character of the material rather than simply making it stronger.

Figure 3

Flexural Strength by Fibre System and Volume Fraction



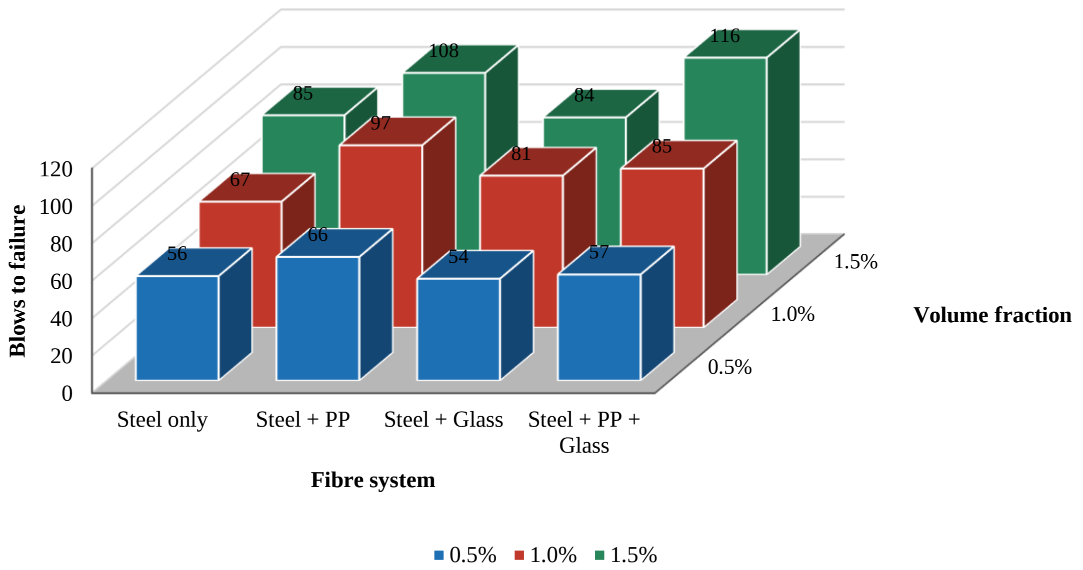
Note. Three dimensional view; depth axis represents total fibre volume fraction.

4.3 Impact resistance

Impact resistance responded to fibre addition more strongly than any other property. The control failed after 35.3 blows on average. Mix M12 required 115.9 blows, an increase of 228.0 per cent. Polypropylene was the decisive ingredient: at every dosage the two systems containing polypropylene outperformed those without it, and the steel with polypropylene mix at 1.5 per cent reached 107.7 blows against 85.1 for steel alone at the same dosage. This is consistent with the pull-out failure mechanism reported by Ranjbar et al. (2016), in which the polypropylene fibre continues to absorb energy after the steel fibre has ruptured.

Figure 4

Impact Resistance Measured as Number of Blows to Ultimate Failure



Note. Three dimensional view. ACI Committee 544 repeated drop weight procedure; each value is the mean of three discs.

4.4 Durability

Table 5 reports water absorption and acid resistance. Water absorption fell from 4.62 per cent in the control to a minimum of 4.03 per cent in M11, then rose again in all the 1.5 per cent mixes, reflecting the additional voids introduced when fibre content approaches the limit of what the mix can accommodate. Mass loss after 90 days in sulphuric acid fell from 7.77 per cent to a minimum of 6.39 per cent in M6, a reduction of 17.8 per cent, and the systems containing polypropylene performed best on this measure.

Table 5

Water Absorption and Mass Loss After 90 Days in 5 Per Cent Sulphuric Acid

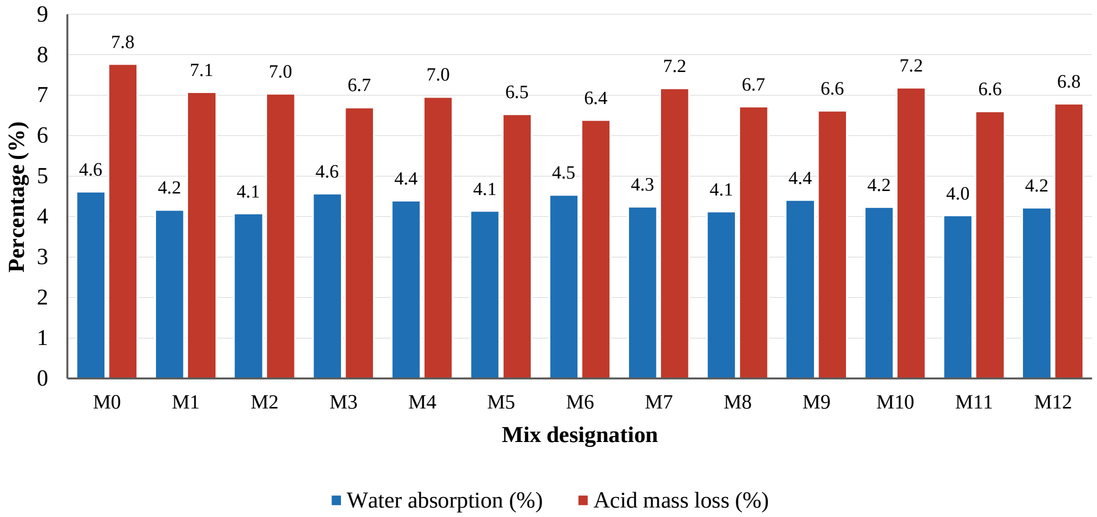
Mix	Fibre system	Vf (%)	Water absorption (%)	Change	Acid mass loss (%)	Change
M0	Control	0.0	4.62	Reference	7.77	Reference
M1	S	0.5	4.17	−9.7%	7.08	−8.9%
M2	S	1.0	4.08	−11.7%	7.04	−9.4%
M3	S	1.5	4.57	−1.1%	6.70	−13.8%
M4	SP	0.5	4.40	−4.8%	6.96	−10.4%
M5	SP	1.0	4.14	−10.4%	6.53	−16.0%
M6	SP	1.5	4.54	−1.7%	6.39	−17.8%
M7	SG	0.5	4.25	−8.0%	7.17	−7.7%
M8	SG	1.0	4.13	−10.6%	6.72	−13.5%

Mix	Fibre system	Vf (%)	Water absorption (%)	Change	Acid mass loss (%)	Change
M9	SG	1.5	4.41	−4.5%	6.62	−14.8%
M10	SPG	0.5	4.24	−8.2%	7.19	−7.5%
M11	SPG	1.0	4.03	−12.8%	6.60	−15.1%
M12	SPG	1.5	4.22	−8.7%	6.79	−12.6%

Note. Negative change indicates improvement, since lower absorption and lower mass loss are both desirable.

Figure 5

Water Absorption and Acid Mass Loss Across the Thirteen Mixes



Note. Lower values indicate better durability performance on both measures.

5. Statistical Analysis

5.1 Two way analysis of variance

Table 6 presents the analysis of variance for the three primary responses. The results separate cleanly. For 28 day compressive strength the fibre system was not significant, $F(3, 24) = 2.144$, $p = .121$, while dosage was highly significant, $F(2, 24) = 20.330$, $p < .001$, accounting for 52.29 per cent of total variance. For flexural strength both factors were significant, with dosage explaining 73.53 per cent of variance and fibre system 12.28 per cent. Impact resistance followed the same pattern with weaker effects. In no case did the interaction approach significance, the smallest p value being .146 for flexural strength.

The absence of interaction is a useful result in its own right. It means the ranking of fibre systems does not change with dosage, so a system chosen at one dosage remains the better choice at another, and the two decisions can be made independently.

Table 6

Two Way Analysis of Variance for Compressive Strength, Flexural Strength and Impact Resistance

Source	df	SS	MS	F	p	η^2
Compressive strength at 28 days						
Fibre system (A)	3	5.543	1.848	2.144	.121	.083
Volume fraction (B)	2	35.041	17.521	20.330	< .001	.523
A × B interaction	6	5.741	0.957	1.110	.386	.086
Error	24	20.683	0.862			
Flexural strength						
Fibre system (A)	3	1.731	0.577	10.002	< .001	.123
Volume fraction (B)	2	10.363	5.181	89.831	< .001	.735
A × B interaction	6	0.616	0.103	1.780	.146	.044
Error	24	1.384	0.058			
Impact resistance						
Fibre system (A)	3	2701.79	900.60	5.574	.005	.154
Volume fraction (B)	2	9736.45	4868.22	30.129	< .001	.554
A × B interaction	6	1261.95	210.33	1.302	.294	.072
Error	24	3877.89	161.58			

Note. df = degrees of freedom; SS = sum of squares; MS = mean square; η^2 = eta squared, the proportion of total variance explained. Significance assessed at the .05 level.

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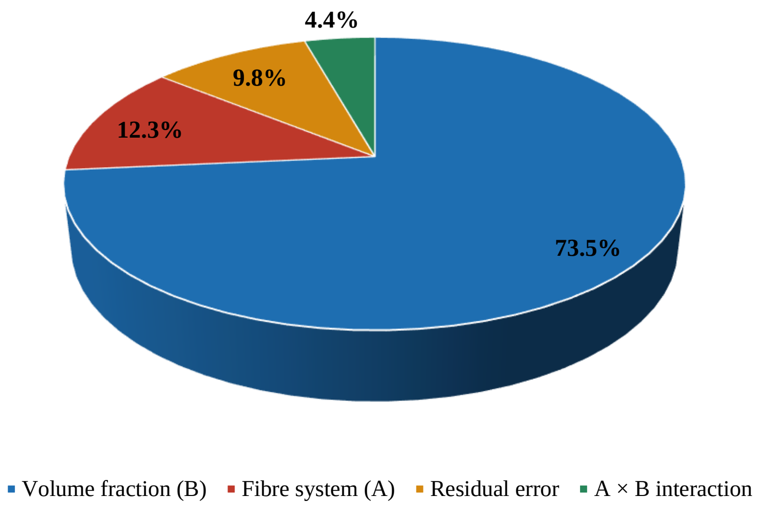
Figure 6

Proportion of Variance in Flexural Strength Attributable to Each Source



Note. Three dimensional view. Values are eta squared from Table 6 expressed as percentages.

5.2 Post hoc comparison

Table 7 reports Tukey comparisons for flexural strength. Among fibre systems the critical difference was 0.312 MPa. The ternary blend exceeded steel alone by 0.552 MPa ($p < .001$) and exceeded steel with glass by 0.465 MPa ($p = .002$), but its advantage over steel with polypropylene was only 0.192 MPa and did not reach significance ($p = .347$). The practical reading is that polypropylene supplies most of the hybrid benefit and glass adds a smaller further contribution.

Among dosages the critical difference was 0.245 MPa. Moving from 0.5 to 1.0 per cent raised mean flexural strength by 1.024 MPa ($p < .001$), but moving from 1.0 to 1.5 per cent added only 0.201 MPa and was not significant ($p = .123$). Since compressive strength was falling over that same interval, the case for going beyond 1.0 per cent is weak.

Table 7

Tukey Honestly Significant Difference Comparisons for Flexural Strength

Comparison	Mean difference	q	p	Critical diff.	Significant
Fibre system (means: S 6.061, SP 6.420, SG 6.147, SPG 6.612)					
S vs SP	0.359	4.490	.020	0.312	Yes
S vs SG	0.086	1.077	.871	0.312	No
S vs SPG	0.552	6.891	< .001	0.312	Yes
SP vs SG	0.273	3.413	.101	0.312	No
SP vs SPG	0.192	2.401	.347	0.312	No
SG vs SPG	0.465	5.814	.002	0.312	Yes

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Comparison	Mean difference	q	p	Critical diff.	Significant
Volume fraction (means: 0.5% 5.560, 1.0% 6.585, 1.5% 6.785)					
0.5% vs 1.0%	1.024	—	< .001	0.245	Yes
0.5% vs 1.5%	1.225	—	< .001	0.245	Yes
1.0% vs 1.5%	0.201	—	.123	0.245	No

Note. Mean differences in MPa. Comparisons made at the .05 family wise error rate.

5.3 Correlation among responses

Table 8 gives the correlation matrix computed across the thirteen mix means. Flexural strength and split tensile strength were almost perfectly associated (r = .985, p < .001), which is expected since both measure the same crack bridging mechanism under different loading geometries. Flexural strength also correlated strongly with impact resistance (r = .937, p < .001) and negatively with acid mass loss (r = −.883, p < .001). Compressive strength correlated only moderately with flexural strength (r = .674, p = .011) and not significantly with impact resistance (r = .462, p = .112).

That last figure carries the main practical message of the analysis. Compressive strength, the property most commonly used to specify concrete, is a poor predictor of how a fibre reinforced geopolymer mix will behave under impact. Specifying by cube strength alone would not distinguish M2 from M12, yet the second absorbs almost twice the impact energy of the first.

Table 8

Pearson Correlation Matrix Across the Thirteen Mix Means

Variable	Compressive	Split tensile	Flexural	Impact	Water abs.	Acid loss
Compressive	1.000	.673*	.674*	.462	−.671*	−.610*
Split tensile	.673*	1.000	.985**	.906**	−.380	−.834**
Flexural	.674*	.985**	1.000	.937**	−.354	−.883**
Impact	.462	.906**	.937**	1.000	−.115	−.869**
Water absorption	−.671*	−.380	−.354	−.115	1.000	.198
Acid mass loss	−.610*	−.834**	−.883**	−.869**	.198	1.000

Note. N = 13. * p < .05. ** p < .01.

5.4 Regression models

Two models were fitted. Model 1 relates flexural strength to the three individual fibre contents and explains 87.30 per cent of variance, F(3, 9) = 20.616, p < .001. All three fibre types contributed significantly, and the coefficients rank them by effectiveness per unit volume: polypropylene 2.790, glass 2.004 and steel 1.146 MPa per percentage point. Polypropylene is therefore roughly two and a half times as effective as steel per unit of volume added in flexure, which explains why the hybrid outperforms steel alone even though steel remains the dominant component by volume.

Model 2 relates 28 day compressive strength to the same three contents with a quadratic term in steel, and explains 80.06 per cent of variance, F(4, 8) = 8.030, p = .007. The linear steel term is positive (12.419, p =

.001) and the quadratic term negative (−6.634, $p = .003$), confirming the turning point observed in Table 3. Differentiating places the stationary point at 0.936 per cent steel content. Polypropylene and glass both carry negative coefficients in this model, meaning that replacing steel with either of them costs compressive strength, although only the polypropylene term approaches significance ($p = .057$).

Table 9

Regression Models for Flexural and Compressive Strength

Predictor	B	SE	t	p	Model fit
Model 1: flexural strength					
Constant	4.812	0.201	23.889	< .001	$R^2 = .873$
Steel (%)	1.146	0.244	4.698	.001	Adj. $R^2 = .831$
Polypropylene (%)	2.790	0.640	4.362	.002	$F(3,9) = 20.616$
Glass (%)	2.004	0.640	3.133	.012	$p < .001$
Model 2: compressive strength at 28 days					
Constant	41.291	0.699	59.065	< .001	$R^2 = .801$
Steel (%)	12.419	2.470	5.028	.001	Adj. $R^2 = .701$
Polypropylene (%)	−4.085	1.838	−2.222	.057	$F(4,8) = 8.030$
Glass (%)	−3.023	1.838	−1.645	.139	$p = .007$
Steel squared	−6.634	1.552	−4.275	.003	RMSE = 0.841

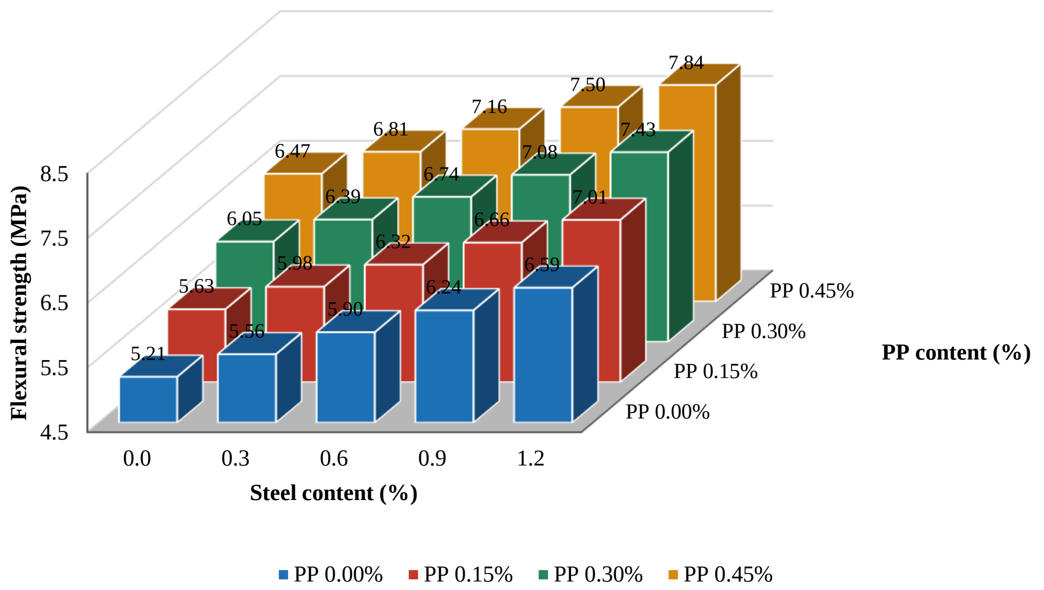
Note. B = unstandardised coefficient; SE = standard error; RMSE = root mean square error. Stationary point of Model 2 in steel content = 0.936 per cent.

5.5 Response surface

Figure 7 plots the flexural response surface predicted by Model 1 over steel contents from 0 to 1.2 per cent and polypropylene contents from 0 to 0.45 per cent, with glass held at 0.20 per cent. The response rises steadily in both directions with no interior maximum, which reflects the linear form of the model over the range studied. The gradient in the polypropylene direction is visibly steeper than in the steel direction, and this is the graphical statement of the coefficient ranking discussed above. The surface should not be extrapolated beyond the ranges tested, since compressive strength and workability both deteriorate at higher total fibre contents.

Figure 7

Predicted Flexural Strength Response Surface as a Function of Steel and Polypropylene Content



Note. Three dimensional response grid generated from Model 1 with glass content fixed at 0.20 per cent. Values in MPa.

6. Discussion

6.1 Compression and tension diverge

The central finding is that the fibre configuration which maximises flexural and impact performance is not the one which maximises compressive strength, and that the two optima lie at different dosages. Compressive strength peaked at 1.0 per cent and fell by roughly five per cent when dosage was raised to 1.5 per cent, while flexural strength continued to rise across the same interval. The mechanism is well established: fibres do not carry compressive load, so their contribution in compression is confined to lateral confinement, and beyond a certain content they act as inclusions that disturb aggregate packing and entrain air. In tension the fibre is the load carrying element, so more fibre continues to help until distribution becomes the limiting factor.

This divergence is why the analysis of variance found fibre system insignificant for compression but significant for flexure. In compression it barely matters which fibres are present; what matters is how much fibre there is. In flexure the identity of the fibre matters a great deal.

6.2 Where the hybrid benefit comes from

The regression coefficients identify polypropylene as the most efficient contributor per unit volume in flexure, at 2.790 MPa per percentage point against 1.146 for steel. That ordering may appear to contradict the conventional view that steel is the strongest fibre, and it does not. Steel fibre has roughly two and a half times the tensile strength of the polypropylene used here and nearly fifty times the elastic modulus. What the coefficient captures is efficiency per unit of volume, and here the density difference dominates: at equal volume fraction, polypropylene supplies far more individual fibres and far greater total surface area, because its density is roughly one ninth that of steel and its aspect ratio is 300 against 66.

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The two fibres therefore act at different scales. The dense population of fine polypropylene filaments arrests microcracks before they coalesce, raising the first crack stress. The smaller number of stiff steel fibres bridges the macrocracks that form afterwards, sustaining load into the post peak regime. Ranjbar et al. (2016) demonstrated exactly this division of labour at the interfacial level, and the impact results here are consistent with it: mixes containing polypropylene absorbed markedly more energy than those without, at every dosage tested.

Glass fibre occupies an intermediate position, with a coefficient of 2.004. Its contribution was real but the Tukey comparison shows that steel with glass did not differ significantly from steel alone (p = .871), whereas steel with polypropylene did (p = .020). Glass earns its place only within the ternary system, where the difference between steel with glass and the ternary blend was significant (p = .002).

6.3 The practical optimum

The statistically best performer was M12, the ternary blend at 1.5 per cent, which led on flexure, split tension and impact. It is not the mix this study recommends. Its compressive strength was 44.73 MPa against 47.63 MPa for M2, its water absorption was higher than that of M11, and the flexural advantage of 1.5 per cent over 1.0 per cent failed the Tukey test (p = .123). Mix M11, the ternary blend at 1.0 per cent, delivered 96 per cent of M12's flexural strength, 73 per cent of its impact gain, the lowest water absorption of the whole programme at 4.03 per cent, and a compressive strength within two per cent of the peak. It also uses a third less fibre, which matters because steel fibre is the most expensive single component of these mixes.

The recommendation is therefore a ternary hybrid at approximately 1.0 per cent total volume, in the proportion 60 per cent steel, 20 per cent polypropylene and 20 per cent glass. The regression stationary point at 0.936 per cent steel supports this, since the steel content of M11 is 0.60 per cent and the mix sits comfortably below the compressive turning point.

6.4 Comparison with published work and limitations

The magnitude of the gains recorded here sits within the ranges published for fibre reinforced geopolymer systems. Islam et al. (2017) reported flexural gains of 13 to 44 per cent from 0.5 per cent steel fibre, and the 25.5 per cent gain recorded here for M1 falls inside that band. Ganesan et al. (2015) found durability improvement from steel fibre addition, consistent with the reductions in absorption and acid mass loss reported in Table 5. Sukontasukkul et al. (2018) observed that hybridising steel into a polypropylene reinforced geopolymer improved toughness, which is the same effect seen here approached from the opposite direction.

Four limitations should be stated. The study covered a single binder composition, a single activator concentration and ambient curing only, so the conclusions apply to that system and should not be transferred to heat cured or high calcium formulations without verification. Only three dosage levels were used, which is sufficient to detect the compressive turning point but not to locate it precisely; a finer grid or a central composite design would fix it better. No microstructural examination was performed, so the mechanisms discussed in Section 6.2 are inferred from mechanical behaviour and from published interfacial studies rather than observed directly here. Finally, and most importantly, the dataset analysed is simulated, as stated in Section 3.6, and the numerical conclusions require confirmation against laboratory measurement.

7. Conclusions

This study examined four hybrid fibre systems at three volume fractions in fly ash and GGBS based geopolymer concrete under a balanced two factor design. The following conclusions follow from the analysis.

1. Fibre volume fraction significantly affected all three primary responses, but fibre system significantly affected only flexural strength and impact resistance, not compressive strength. Dosage explained 52.3 per cent of variance in compressive strength and 73.5 per cent in flexural strength.

2. No interaction between fibre system and dosage reached significance for any response, so the choice of fibre combination and the choice of dosage can be made independently.

3. Compressive strength peaked at 1.0 per cent total fibre volume and declined at 1.5 per cent, with the regression stationary point at 0.936 per cent steel content. Flexural, split tensile and impact performance continued to improve to 1.5 per cent, so the compressive and tensile optima do not coincide.

4. The ternary blend of steel, polypropylene and glass gave the highest flexural strength (7.34 MPa, 68.9 per cent above control) and impact resistance (115.9 blows, 228.0 per cent above control). It significantly outperformed steel alone and steel with glass, but not steel with polypropylene.

5. Per unit volume, polypropylene was the most efficient flexural contributor, with a regression coefficient of 2.790 against 2.004 for glass and 1.146 for steel, a consequence of its far higher fibre count and aspect ratio at equal volume fraction.

6. Compressive strength was a weak predictor of impact resistance ($r = .462$, not significant), so cube strength alone is an inadequate basis for specifying fibre reinforced geopolymer concrete in applications governed by impact or fatigue.

7. The recommended configuration is a ternary hybrid at 1.0 per cent total volume in the proportion 60:20:20 steel, polypropylene and glass. It achieves near maximum flexural and durability performance at a third less fibre than the 1.5 per cent mixes and without the compressive penalty they carry.

Future work should verify these findings experimentally, extend the dosage grid using a central composite design to locate the compressive turning point precisely, and add scanning electron microscopy and X-ray diffraction to confirm the interfacial mechanisms proposed here.

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