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Impact Resistance and Mechanical Properties of Hybrid Steel and Polypropylene Fiber Reinforced Geopolymer Concrete

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ABSTRACT

In this paper, an experimental investigation was carried out to study the influence of steel and polypropylene fibers on the behaviour of geopolymer concrete which was evaluated through mechanical properties and impact resistance. A total of 18 mix designs were examined to obtain an optimal constituent mixes corresponding to high mechanical strength and impact resistance. Two types of fibers namely steel (ST) and polypropylene (PP) fibers were used in mono as well as in steel – polypropylene hybrid form, the major parameters studied were the fiber dosage and incorporation of different fibers. By embedding each of steel and polypropylene fibers with various volume fractions of 0.2%, 0.4%, 0.6%, 0.8%, 1% and 1.2% to the geopolymer concrete mixture. For a hybrid system, the polypropylene fiber was replaced gradually with steel fiber at a rate of 0.2% by volume. Experimental results indicated that fiber addition improves the mechanical properties and impact performance of the fiber reinforced geopolymer concrete, the results also show that the mechanical properties of hybrid fiber reinforced geopolymer concrete (HyFRG) are lower than that of 1.2% steel fiber reinforced geopolymer concrete (SFRG) and the hybridization of steel fiber can improve the impact resistance of polypropylene fiber reinforced geopolymer to different degrees. The best result obtain by incorporation of 1% steel+0.2% polypropylene fiber exhibited the highest impact resistance at Z_1 and Z_2 by 10.7 and 8.9 times respectively.

Keywords: Geopolymer, Steel fiber, Polypropylene fiber, Hybrid, Impact resistance.

1. INTRODUCTION

Concrete is one of the major components of building and other engineering construction materials which is widely used construction materials globally Rashad and materials **[1]**. The geopolymer concrete are reporting as the greener construction materials has increased parallel with infrastructure development besides increasing in awareness as a result of global warming Suriya and Senthil **[2]**. Therefore, the utilization of fly ash as waste material also improved and overcome a major problem for disposal. The term of "geopolymer" was coined by a French Professor Davidovits in 1978 to represent a broad range of materials characterized by networks of inorganic molecules **[3]**. Geopolymer is a cement-free material which is produced by the alkali activation of alumino-siliceous rich materials. Studies on geopolymer have shown comparable mechanical properties and superior durability properties compared to the conventional concrete. In addition to these, perhaps the most significant advantage of using this material is its potential in reducing the CO2 emission associated with the Portland cement production **[4]**.

Ganesan and Indira **[5]** showed the effect of steel fibres on engineering properties such as compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and Poisson's ratio of geopolymer concrete. The grade of concrete used was M40. The percentages of steel fibres considered include 0.25%, 0.5%, 0.75% and 1% by volume. Addition of fibers improved the mechanical properties of geo polymer concrete. However the increase was found to be nominal in the case of compressive strength (8.51%), significant in the case of splitting tensile strength (61.63%), modulus of rupture (24%), modulus of elasticity (64.92%) and Poisson's ratio (50%) at 1% volume fraction of fibers.

Bernal et al. **[6]** reported the flexural strength of steel fiber reinforced FRGC tested at 7, 14 and 28 days. In their study, the increase in flexural strength at all ages is observed. They also reported an increase in flexural strength with increase in curing time of all fiber contents. They observed as high as 70% increase in flexural strength of FRGC at 28 days.

Bhutta et al. **[7]** investigated the flexural behavior of fly ash based geopolymer composites reinforced with steel and polypropylene fibers. Results showed that heat curing improves the strength properties for the macro fiber reinforced geopolymer composite, also, polypropylene fibers did not exhibit a significant improvement regarding compressive strength but achieved a little development in terms of indirect tensile and flexural strength.

Khamar and Kumar **[8]** studied the effects of a hybrid fibre between steel and micro polypropylene fiber on properties including the compressive, flexural, and splitting tensile strengths. The fiber combination used was steel fiber at 0.5% by volume with the addition of micro polypropylene fiber at 10–50% of the steel fiber volume. Their results showed that the optimum volume fractions of micro PP fiber was 20% for compressive strength and 30% for flexural strength.

Sukontasukkul et al. **[9]** examined the strength performance of the geopolymer composites with polypropylene and steel fibers. As a general result, by hybridization of steel fiber can increase toughness, residual strength of the reinforced geopolymer composites with polypropylene fiber. It has been found that both the second peak and the load drop are improved. With the increase of steel fiber, strength and residual strength have gradually improved.

Lau and Anson **[10]** confirmed that the addition of fibers to concrete improves mechanical properties of concrete apart from enhancing resistance to impact loads. Islam et al. **[11]** showed that geopolymer concrete has an unrivalled ubiquity in the infrastructure development due to its higher compressive strength. Though, it possesses brittle nature for its inferior tensile strength, addition of fibers has a promising solution to overcome this problem. Unlike geopolymer concrete which has a single large crack propagating quickly, causing a rapid loss in load carrying capacity; the fibrous geopolymer concrete exhibits significant increase in the post peak performance, toughness and impact strength.

Nia et al. **[12]** reported that steel and PP fiber are most commonly used fibres. Aspect ratio and dosage of fibres play important role in enhancing various properties. Fibres start bearing the load when cracks are initiated. The fibres start transmitting excess stresses to the matrix when the load is increased. Fiber pull-out or rupture of the fiber is noticed when these stresses exceed the bond strength between the fiber and the matrix.

Fu et al. **[13]** showed that the constructive effect of SF in FGC specimens, as it brings out ductile mode of failure under impact loads instead of premature brittle failure. Ghernouti et al. **[14]** found that the SF plays a vital role in altering the mode of failure as they tend to develop greater bonding with the surrounding matrix resulting in an increased pullout strength of fibres. This substantially enhances the crack arresting behaviour and the transfer of tensile stress across the crack zones, resulting in higher impact strength.

No study seems to have been done which comprehensively investigates the impact resistance of FRGC, in particular with the incorporation of steel and polypropylene fibers with different ratios. Steel fibre is used to replace to the polypropylene base FRGC at an incremental rate of 0.2% of volume fraction. This study therefore aims to investigate the mechanical properties and impact resistance of hybrid fibre reinforced geopolymer (HyFRG) applying steel and polypropylene fibre. Both are macro-type fibre designed specifically to improve the mechanical properties and impact of concrete.

2. EXPERIMENTAL WORK

2.1 Material

2.1.1 Fly Ash (FA)

For this project low-calcium dry fly ash (ASTM Class F) was used in accordance with (ASTM C618) Class F. This preference for the Class F is due to the presence of high quantity of calcium in the Class C which can interfere with the polymerization process, and alter the microstructure **[15]**. The chemical composition of the fly ash, as determined by X-Ray Fluorescence (XRF) analysis, is given in Table 1.

Table 1: Composition of fly ash as determined by XRF (mass %).

Oxides	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Na2O	K2O	TiO2	P2O5	LOI	Total
Results (%)	60.15	28.71	4.85	1.09	0.22	0.04	0.01	1.06	2.31	0.52	0.55	99.51

2.1.2 Aggregates

The used aggregate was in compliance with [ECP 203/2007]. Coarse aggregates were cleaned from fine materials by washing before being used for 48 hours and left dry to prevent its harmful effect on concrete. The coarse aggregate used in the mixture was crushed limestone. The specific gravity was 2.6. The delivered crushed lime stone had a maximum nominal size of 10 mm. The fine and natural clean sand with fineness modulus of 2.73 and specific gravity of 2.65 was utilized in this study.

2.1.3 Alkaline Liquid

A combination of sodium hydroxide and sodium silicate (Na2O = 14.7%, SiO2 = 29.4% and water = 55.9% by mass) Phoongernkham et al. **[16]** was employed to achieve the low-calcium fly ash geopolymer concrete. Sodium-based solutions were chosen because they were cheaper than Potassium-based solutions. The sodium hydroxide solids were either a technical grade in flakes form (3 mm), with a specific gravity of 2.130, 98% purity or a commercial grade in pellets form with 97% purity. Hardjito et al. **[17]** showed that NH, KH solutions was prepared one day before the casting of Geopolymer Concrete during which it pass by some exothermic procedure thus results in the reduction of heat. Sodium silicate is known as water glass or liquid glass and available in liquid (gel) form. The pure form of sodium silicate solution is of colorless or white in colour.

2.1.4 Superplasticizer

In order to improve the workability of the fresh geopolymer concrete, A high range water reducer superplasticizer (HRWR) (Trade name: sika-viscocrete 3425) was used as superplasticizer meeting necessities of [ASTM C494/C494M] type F and G.

2.1.5 Fibers

Two type of fibres were used in this study viz., steel fiber (ST) and polypropylene fibre (PP). The geometry of fibres are illustrated in Fig. 1 and 2 and their properties are presented in Table 2.

Table 2: Fiber properties

Fiber type	Shape	Length [mm]	Diameter [mm]	Tensile Strength N/mm^2	Density $[Kg/m^3]$
Steel (ST)	Corrugated	25	1	1000	7850
Polypropylene (PP)	Straight	6-12-18	0.04	350	901

Fig. 1: Corrugated Round Steel Fibers

Fig. 2: Polypropylene Fibers

2.2 Alkaline Liquid Preparation

The sodium hydroxide (NaOH) flakes were dissolved in water to make the solution one day before the casting. The mass of NaOH solids in a solution varied depending on the concentration of the solution expressed in terms of molar, M. In this experimental work NaOH solution with a concentration of 16M consisted of 16x40 = 640 grams of NaOH solids per liter of the solution, where 40 is the molecular weight of NaOH.

2.3 Mix Proportion for Geopolymer Concrete (kg/m3).

The mix design for geopolymer concrete divided into four groups as show in Table 3. Prior to the day of mixing, required quantity of alkaline solution is prepared with 16 molar sodium hydroxide solution and sodium silicate solution.

Table 3: Geopolymer Concrete Mix Design

Group No.	Mix ID	Fly ash,	CA	FA	NH (16M)	NS	SP	W	ST	PP
G_1	Control	515	1074	630	52	129	9.27	15	-	-
G_2	0.2%SFRG	515	1074	630	52	129	9.27	15	15.7	-
	0.4%SFRG	515	1074	630	52	129	9.27	15	31.4	-
	0.6%SFRG	515	1074	630	52	129	9.27	15	47.1	-
	0.8%SFRG	515	1074	630	52	129	9.27	15	62.8	-
	1%SFRG	515	1074	630	52	129	9.27	15	78.5	-
	1.2%SFRG	515	1074	630	52	129	9.27	15	94.2	-
G_3	0.2%PFRG	515	1074	630	52	129	9.27	15	-	1.8
	0.4%PFRG	515	1074	630	52	129	9.27	15	-	3.6
	0.6%PFRG	515	1074	630	52	129	9.27	15	-	5.4
	0.8%PFRG	515	1074	630	52	129	9.27	15	-	7.2
	1%PFRG	515	1074	630	52	129	9.27	15	-	9.01
	1.2%PFRG	515	1074	630	52	129	9.27	15	-	10.8
G_4	1P/0.2S-HyFRG	515	1074	630	52	129	9.27	15	15.7	9.01
	0.8P/0.4S-HyFRG	515	1074	630	52	129	9.27	15	31.4	7.2
	0.6P/0.6S-HyFRG	515	1074	630	52	129	9.27	15	47.1	5.4
	0.4P/0.8S-HyFRG	515	1074	630	52	129	9.27	15	62.8	3.6
	0.2P/1S-HyFRG	515	1074	630	52	129	9.27	15	78.5	1.8

CA: coarse aggregate, FA: fine aggregate, NH: sodium hydroxide, NS: sodium silicate, SP: superplasticizer, W: water, ST: steel fiber, PP: polypropylene fiber.

3. SPECIMEN PREPARATION

3.1 Casting

Mix all dry materials namely coarse and fine the aggregates, sand, and fly ash and, in the case of fiber-containing mixes, the steel, Polypropylene fibers, were all mixed for at least five minutes as shown in Fig.3 When fibers were used, they were added by hand to avoid clumping of the fibers while adding or while they were being mixed. Add the alkaline liquid component of the mixture at the end of dry mixing, and continue the wet mixing for another four minutes. Fig.4 shows a sample of fresh geopolymer concrete. In the case of fiber-containing mixes, the steel and polypropylene fibers, were all mixed for at least five minutes. The fresh geopolymer concrete was poured into molds after mixing in two layers.

Fig. 3: Dry materials for geopolymer concrete

Fig. 4: Fresh geopolymer concrete

3.2 Curing of Test Specimens

Each geopolymer concrete test specimen should be in the molds for one day at room temperature before being de-molded. After removing from the molds, and heat cured in oven at 95˚C for 24 hours as shown in Fig.5.

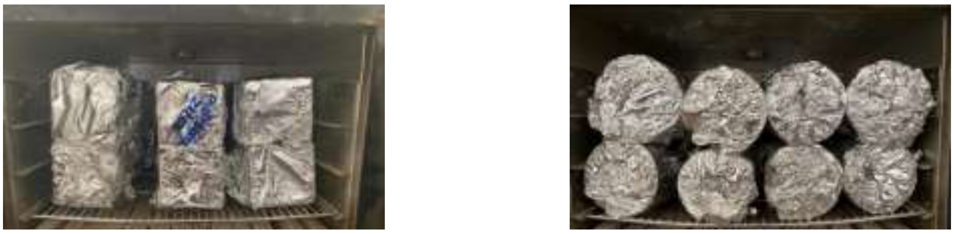


Fig. 5: Oven heat-curing of geopolymer concrete specimens

4. EXPERIMENTAL SETUP

The compressive strength test was performed at 7 and 28 days on cube specimen of (10 × 10 × 10 cm) size in accordance to EN 12390-3 – 2009. Indirect tensile strength was conducted on three cylinder having (20cm height × 10cm diameter) specimen for each mixture at 28 days according to ASTM C 496/C. Flexural strength tests were performed on the beam specimens of size (10 x10 x 50 cm) according to ASTM C78 and three specimens of each mixture were tested at curing ages of 28 days to determine the average flexural strength. Falling weight collision test was performed according to ACI committee 544 to evaluate the impact resistance of GPC under dynamic loading. All the specimens were tested at the age of 28 days. The impact resistance test specimen cylindrical discs (15cm diameter x 6.4 cm thick) were cut from 15 cm diameter x 30 cm length cylinder specimens and prepared as illustrated in Fig. 6. The impact specimen was placed on a base plate with four positioning lugs of the impact testing equipment. By dropping a steel ball of weight of 44.5 N recurrently, from a free fall of 457 mm height onto the center of specimen as illustrated in Fig. 6. Number of blows required for induce crack initiation is denoted by (Z_1), and final fracture was denoted by (Z_2). The growth of crack emerging from top to bottom surface of the specimen represents failure. The impact energy provided at initial crack is denoted by (Ufc), and at final failure is denoted by (Ufa). The impact energy absorption capacity of the concrete specimen was calculated by using Eqs. (1) and (2).

$U_{fc} = Z_1 mgh$ (1)

$U_{fa} = Z_2 mgh$ (2)

Where:

m=mass of drop hammer in kg

g=9.81m/s^2

N=number of blows

h=releasing height of drop hammer in m.


Fig.6: Falling weight collision test

5. RESULTS AND DISCUSSION

Table 4: Results of Mechanical Strength and Impact Resistance.

MIX ID	Compressive strength (MPa)		Splitting tensile strength (MPa)	Flexural strength (MPa)	Impact resistance Number of blows	
	7 days	28 days	28 days	28 days	(Z_1)	(Z_2)
Control	25.3	30	2.4	4.5	12	23
0.2%SFRG	30.2	36.4	3.9	7.6	20	36
0.4%SFRG	34.5	40	4.4	8.1	24	38
0.6%SFRG	39.7	48	4.6	8.8	30	43
0.8%SFRG	44	52	4.8	13	41	60
1%SFRG	45.4	52.8	4.9	13.5	84	136
1.2%SFRG	46	53.4	5.1	14	86	160
0.2%PFRG	25	29.7	2.7	6.5	17	29
0.4%PFRG	25.8	33	2.9	6.8	20	30
0.6%PFRG	27.7	36.5	3.1	7.4	23	36
0.8%PFRG	23	32	3.3	7.6	34	52
1%PFRG	22.5	30.5	3.4	7.8	71	119
1.2%PFRG	21	29	3.5	7.9	77	127
1P/0.2S-HyFRG	24.5	31.2	3.6	7.7	82	136
0.8P/0.4S-HyFRG	28	36	3.7	7.9	90	142
0.6P/0.6S-HyFRG	34	40	3.8	8.3	99	156
0.4P/0.8S-HyFRG	37.5	42	3.9	8.7	106	171
0.2P/1S-HyFRG	41	48	4.1	9	128.5	205

5.1 Compressive Strength

The compressive strength of plain and FRGC having di ăerent volume fractions and types of fibers at 7 and 28 days are summarized in Table 4 and Fig. 7. At 28 days, the compressive strength of plain geopolymer concrete is about 30 MPa. With steel fibers, the compressive strength increases to about 36.4,40,48,52, 52.8 and 53.4 MPa for 0.2%, 0.4%,0.6%, 0.8%,1.0% and 1.2% volume fractions, respectively. The compressive strength of GPC is gradually increasing still the addition of 1.2% steel fiber. At 1.2% of steel fiber, GPC attains maximum compressive strength for both 7 and 28 days. For the PFRG, the compressive strength for PFRG is found to be higher than that of plain geopolymer. The maximum compressive strength with polypropylene fiber at 0.6% by volume is 36.5 MPa. The achieved strength by geopolymer concrete with polypropylene fiber at 0.2%, 0.4%, 0.6%, 0.8%, 1% and 1.2% is 29.7, 33, 36.5,32, 30.5 and 29 MPa at 28 days, as the fibre content increased to 0.8% ,1% and 1.2%, the compressive strength was found to decrease gradually from 36.5 to 32 ,30.5 and 29 MPa. This is believed to be the result of poor compaction. Polypropylene fibre is a highly flexible material, and at a high-volume fraction, the compaction becomes quite difficult. The steel fiber is found to be more effective than polypropylene fiber in the development of compressive strength in the specimens. For the replacement hybrid FRGC, when the polypropylene fiber is replaced by steel fiber at a 0.2% increment in volume fraction, Result shows that compressive strength of GPC increases with increase in percentage of steel fiber. The greatest strength of hybrid FRGC is 48 MPa with 0.2P/1S-HyFRG. It should be worth to mentioned here that the compressive strengths of HyFRG samples are lower than that of 1.2% steel FRGC.

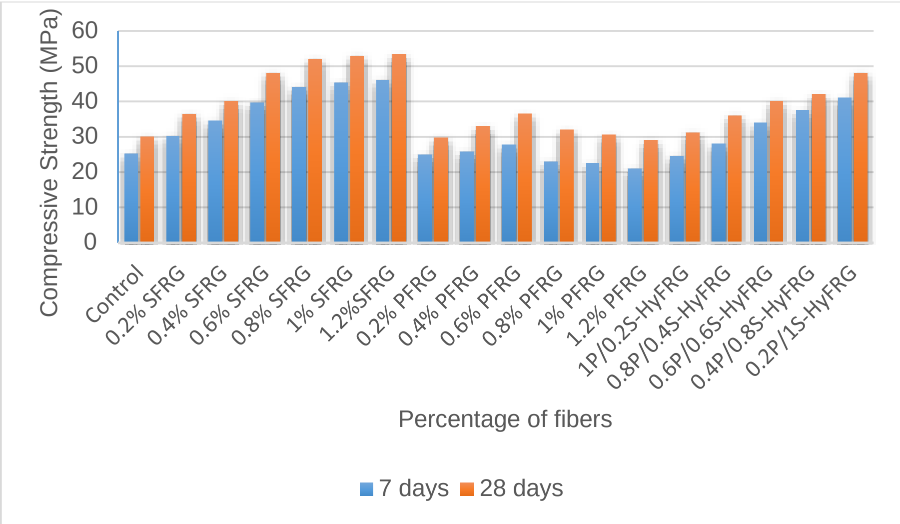


Fig. 7: Compressive strength values of the investigated mixes.

5.2 Split Tensile Strength

The test was conducted for 28 days curing and indirect tensile results are shown in Table 4 and Fig.8. Geopolymer concrete without fiber gives the indirect tensile strength of 2.4 MPa, it can be seen that the unreinforced geopolymer concrete exhibited the lowest splitting tensile strength (2.4MPa). The tensile strength significantly improved due to the addition of steel fibers in GPC. The splitting tensile strength of SFRG samples significantly improved to 3.9, 4.4, 4.6, 4.8, 4.9 and 5.1 MPa with the addition of 0.2%, 0.4%, 0.6%, 0.8%, 1% and 1.2% steel fibers, respectively. The tensile strength increases from 62.5% for 0.2% volume fraction up to 112.5% for 1.2% volume fraction of fibres. There was a significant increase in the indirect tensile strength of the plain geopolymer with the addition of fiber reinforcement.

For the PFRG, the Split tensile strength is gradually increasing still the addition of 1.2% PP fiber. At 1.2% of PP fiber, GPC attains maximum tensile strength at 28 days. From the test results, the split tensile strength of GPC with 0.2%, 0.4%, 0.6%, 0.8% ,1% and 1.2% PP fiber is increased 12.5% ,20.8%,29.2%,37.5%,41.6% and 45.8% respectively when compared to plain GPC . Use of Steel fiber resulted in the higher tensile strength when compared to polypropylene fiber. In the HyFRG mix, steel fiber is dominating fiber which enhanced the splitting strength more than polypropylene fiber. The maximum indirect tensile strength 4.14 MPa is achieved at 0.2P/1S-HyFRG. With increase volume of polypropylene fiber in hybrid fiber the splitting tensile strength was found to decrease. The improvement in tensile strength by hybrid fiber depends up on replacement of polypropylene fiber by steel fiber and testing age. The geopolymer concrete containing 1P/0.2S-HyFRG, 0.8P/0.4S-HyFRG, 0.6P/0.6S-HyFRG, 0.4P/0.8S-HyFRG and 0.2P/1S-HyFRG hybrid fiber shows the increment in tensile strength by 50%, 54.2%, 58.3 %, 62.5 % and 70.8% higher when compared to geopolymer concrete without fiber.

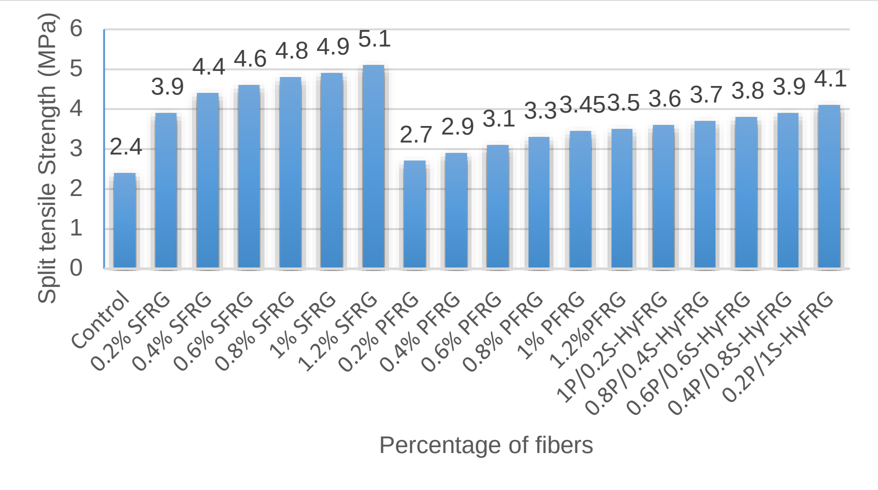


Fig.8 Indirect tensile strength values of the investigated mixes.

5.3 Flexural Strength

The results revealed that addition of fibers generally yielded better results in terms of flexural behavior as summarized in Table 4 and Fig. 9. The PP fibers showed a noteworthy flexural strength in comparison with the control sample. The flexural strength of PP 0.2%, 0.4%, 0.6%, 0.8% ,1% and 1.2 % by volume increased by 44.4%, 51.1%, 64.4%, 68.8%, 73.3% and 75.5% with respect to the plain geopolymer concrete. Geopolymer concrete with steel fiber at 0.2%,0.4%,0.6%,0.8% ,1% and 1.2% by volume gives 68.8%, 80%, 95.5%,188.8%,200% and 211% higher flexural strength than plain geopolymer concrete. The polypropylene fiber was observed to give higher flexural strength but lower when compared to steel fiber. The hybrid fiber showed higher flexural strength but lower when compared to steel fiber. The 0.2P/1S-HyFRG was observed to provide 100% higher strength than geopolymer concrete without fiber.

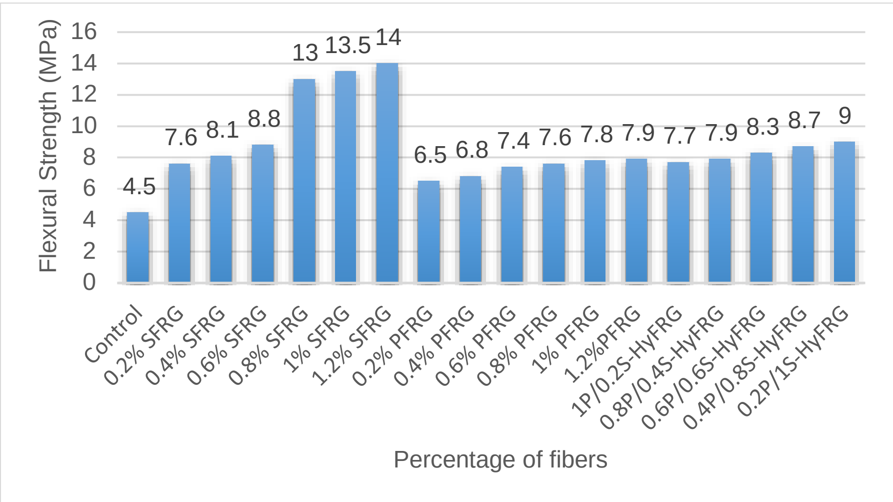
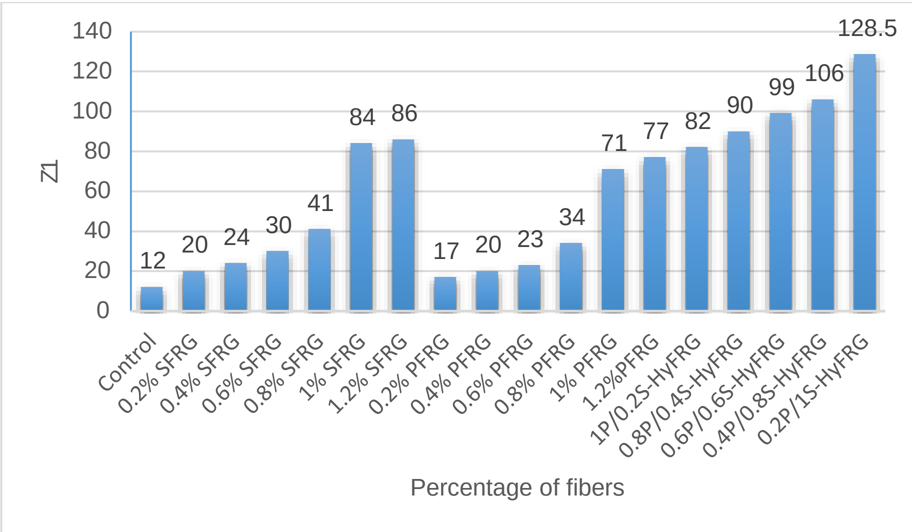


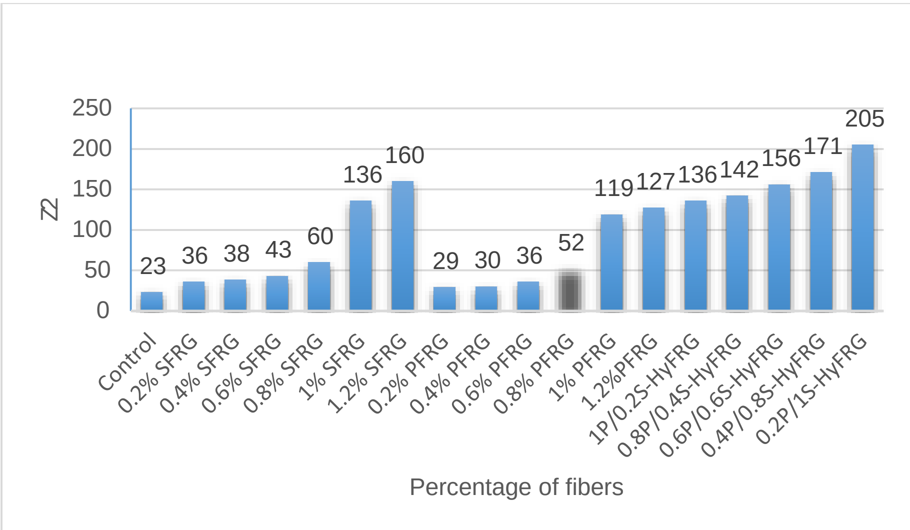
Fig.9: Flexural strength values of the investigated mixes.

5.4 Impact Resistance

Table 4 exhibits the impact resistance of FRGC for various mixes. As it can be seen that increase in fibre dosage enhanced the impact resistance to initial crack. Figure 10 show the number of blows required to induce crack initiation (Z_1) and final fracture (Z_2). For plain geopolymer concrete specimen, the requisite number of reiterated impact to induce Z_1 was 12 and it was failed at 23., hit by the falling weight; tending to get broken into two or three fragments which exhibited their brittle behaviour under falling weight collision. The impact resistance of SFRG increase with increasing fiber content. The addition of steel fiber increased Z_1 by 1.7, 2, 2.5, 3.4, 7 and 7.2 times and Z_2 by 1.6, 1.7, 1.9, 2.6, 5.9 and 6.9 times for the specimens (0.2%SFRG, 0.4%SFRG, 0.6%ST, 0.8%ST, 1%ST and 1.2%ST respectively. Generally, PP fiber enhanced the Z1 and Z2 of FRGC specimens. Therefore, 0.2% PP, 0.4% PP, 0.6% PP, 0.8% PP ,1% PP and 1.2% PP incorporation by volume fraction increased Z_1 by about 1.4,1.7,1.9,2.8,5.9 and 6.4 times and Z_2 by about 1.2,1.3,1.6,2.3, 5.2 and 5.5 times as related to that of plain geopolymer concrete specimen, respectively. This reveals the superior competence of the addition PP fiber in limiting the crack propagation of FRGC specimens under falling weight collision. Addition of low modulus polypropylene fibers to the high modulus steel may be the reason for the percentage increase in post crack resistance. In the HyFRG mix, Z_1 increased from 6.8 to 10.7 times and Z_2 increased from 5.9 to 8.9 times over the plain geopolymer concrete at 28 days. Result shows that the fiber hybridization improves the performance against impact of the geopolymer concrete and also increases the post cracking strength over the single fiber system. The failure pattern of the control, SFRG, PFRG and HyFRG impact specimens are shown in Figure 11. For the specimens of plain geopolymer concrete fails suddenly and wide cracks are detected in the failure specimen. In case of the fiber reinforced geopolymer concrete, the specimens greatly transformed the failure mode from brittle to ductile and the increase in fibre dosage improved the resistance to impact loading significantly.



(a)



(b)

Fig.10: Impact resistance test results on cylindrical FRGC specimens (a) Z_1 and (b) Z_2.

(a) **(b)** **(c)** **(d)**

Fig.11. Failure pattern of the geopolymer concrete specimen (a) Control specimen (b) SFRG (c) PFRG (d) HyFRG

6. CONCLUSIONS

In this paper, an investigation has been carried out to inspect the effect of adding mono and hybrid fibers with different ratios on mechanical properties and impact performance of the fiber reinforced geopolymer concrete and the research conclusions were as follows:

1. The compressive strength, indirect tensile strength, and flexural strength of GPC increase significantly with increase in steel fiber content. The compressive strength varied from 21.3% up to 78%, indirect tensile strength varied from 62.5% up to 112.5%, and flexural strength varied from 68.8% up to 211% by increasing in steel fiber volume fractions from 0.2% up to 1.2 %.
2. For the PFRG, the compressive strength of GPC improves slightly. The maximum compressive strength with polypropylene fiber at 0.6% by volume is 36.5 MPa. The tensile strength and the flexural strength of geopolymer concrete increase with increase in polypropylene fiber content. The indirect tensile and flexural strength at 1.2%PFRG are 45.8% and 75.5% higher when compared to concrete without fiber.
3. For a hybrid system, the replacement of polypropylene fiber by steel fiber results in increment in the mechanical strength. The maximum mechanical strength in HyFRG is achieved at 0.2% PP + 1% ST. The achieved compressive, indirect tensile and flexural strength are 60%, 72.5% and 100% higher when compared to geopolymer concrete without fiber. It should be noted that the mechanical strengths of HyFRG samples are lower than that of 1.2% steel FRGC.
4. For single-type FRGC, The inclusion of steel and polypropylene fibers in the geopolymer concrete mix increased the impact resistance of the GPC. The addition of 1.2% SFRG increased Z_1 and Z_2 by 7.2 and 6.9 times respectively, as related to that of plain geopolymer concrete. In the PFRG mix, Z_1 increased from 1.4 to 6.4 times and Z_2 increased from 1.2 to 5.5 times over the plain geopolymer concrete at 28 days.
5. Among all HyFRG cylindrical specimens, an incorporation of 0.2%PP+1%ST exhibited the highest impact strength at Z_1 and Z_2 by 10.7 and 8.9 times respectively, when compared to geopolymer concrete without fiber. These results show that the fiber hybridization enhanced the performance of the geopolymer concrete against impact and also increased the post cracking performance over the mono fiber system.

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