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Article

Engineering Properties of Hybrid Fibre Reinforced Ternary Blend Geopolymer Concrete

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Abstract: The primary aim of this research is to find an alternative for Portland cement using inorganic geopolymers. This study investigated the effect of steel and polypropylene fibres hybridisation on ternary blend geopolymer concrete (TGPC) engineering properties using fly ash, ground granulated blast furnace slag (GGBS) and metakaolin as the source materials. The properties like compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of ternary blend geopolymer concrete. The standard tests were conducted on TGPC with steel fibres, polypropylene fibres and a combination of steel and polypropylene fibres in hybrid form. A total number of 45 specimens were tested and compared to determine each property. The grade of concrete considered was M55. The variables studied were the volume fraction of fibres, viz. steel fibres (0%, 0.5% and 1%) and polypropylene fibres (0%, 0.1%, 0.15%, 0.2% and 0.25%). The experimental results reveal that the addition of fibres in a hybrid form enhances the mechanical properties of TGPC. The increase in the compressive strength was nominal, and a significant improvement was observed in splitting tensile strength, flexural strength, and modulus of elasticity. Also, an attempt to obtain the relation between the different engineering properties was made with different volume fractions of fibre.

Keywords: compressive strength; geopolymer concrete; hybrid fibres; modulus of rupture; ternary blend

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1. Introduction

The need for cement is drastically increasing day by day with the growth in the civil infrastructure industry. Cement has been conventionally used as the binding material which binds the fine and coarse aggregate to produce concrete. However, concrete made with cement was noted to be less durable, especially in conditions like very severe environments [1,2]. Also, cement manufacturing results in the emission of harmful carbon dioxide into the atmosphere [3]. Another difficulty in handling ordinary cement concrete is that it requires a vast amount of water for curing. The water demand is increasing every day, and it is essential to preserve the natural resource to the full. Hence, it is necessary to research an alternative to replace the high internal-energy-intensive product with new sustainable material. Many studies were performed to minimise the usage of cement in concrete by partially replacing it with mineral admixtures [4]. However, the partial replacement of cement reduces the carbon footprint to a specific limit, and it is always better to research cementless concrete.

Geopolymers are recent promising options to replace conventional cement materials to reduce the carbon footprint and water needed for curing. Geopolymer binders are manufactured by activating an alumino-silicate source material using alkaline activators. The concrete produced using this binder is considered to be environmentally friendly and economical. However, the recent research on geopolymers shows strength reduction at high temperatures, vulnerability to thermal cracking and brittle behaviour [5–9]. Ternary blend geopolymer concrete (TGPC) is manufactured by combining three different source materials as a binder to overcome these drawbacks. The TGPC will have better properties due to the densely packed particles of various sizes. It also effectively utilises industrial by-products like fly ash, ground granulated blast furnace slag (GGBS), rice husk, etc. Several studies also explored that the incorporation of fibres can significantly improve the properties of concrete [10–13]. The addition of fibres in hybrid form provides potential advantages over mono-fibres. In a hybrid fibre combination, the microfibres bridge the microcracks, whereas the macrofibres are more efficient in controlling the development of macrocracks in the concrete [14–17]. Geopolymer behaves comparably to conventional cement binders; hence the hybrid fibres can also be incorporated in geopolymer concrete to improve the mechanical properties [18–23]. Many researchers carried out many investigations on the properties of fibre reinforced unary and binary blend geopolymer concrete in the past [24,25]. However, studies on the effect of hybrid fibres on the engineering properties of TGPC using fly ash, GGBS and metakaolin are not yet reported.

This paper provides the technology of producing hybrid fibre reinforced ternary blend geopolymer concrete using fly ash, GGBS and metakaolin as its source materials and presents the laboratory test results carried out on this material.

2. Experimental Programme

2.1. Raw Materials

Low calcium Class F fly ash conforming to IS 3812:2003 [26] procured from the Mettur Thermal Power Station in Tamil Nadu (India) was used as a primary binder of the source material. It is dark grey powder and has a specific gravity of 2.30. The mean particle size of fly ash is 75 microns. The chemical composition of fly ash is given in Table 1. GGBS conforming to the requirements of BS 6699:1992 [27] was included as one of the source materials. It has a specific gravity of 2.88 with an off-white powder appearance. The average particle size of GGBS is found to be 30 microns. Table 2 shows the chemical composition of the GGBS. Metakaolin (MK) was also used as source material for the ternary blend geopolymer. It is creamish ivory powder and has a specific gravity of 2.56. The mean particle size of MK is found to be 2–3 microns. Table 3 shows the chemical composition of metakaolin.

Table 1. Chemical composition of fly ash.

Elements	Weight (%)
Alumina, Al_2O_3	27.75
Silica, SiO_2	55.36
Iron Oxide, Fe_2O_3	9.74
Titanium dioxide, TiO_2	3.54
Potassium Oxide, K_2O	2.55
Calcium Oxide, CaO	1.07

Table 2. Chemical composition of GGBS.

Elements	Weight (%)
Calcium Oxide, CaO	37.04
Silica, SiO_2	32.49
Alumina, Al_2O_3	20.86
Magnesium oxide, MgO	7.82
Sulphur, S	0.98
Iron, FeO	0.68
Manganese, Mn	0.11
Chloride, Cl	0.012

Table 3. Chemical composition of metakaolin.

Elements	Weight (%)
Silica, SiO_2	56.64
Alumina, Al_2O_3	42.38
Iron Oxide, Fe_2O_3	0.42
Sodium Oxide, Na_2O	0.11
Potassium Oxide, K_2O	0.04
Titanium dioxide, TiO_2	0.1
Magnesium oxide, MgO	0.2
Calcium Oxide, CaO	0.1

M-sand (crushed stone) conforming to zone II of IS 383:1970 (reaffirmed 2002) [28] passing through 4.75 mm (No.4) IS sieve was used as a fine aggregate. It has a specific gravity and fineness modulus of 2.39 and 2.92, respectively. Crushed granites with a maximum size of 12.5 mm were used as a coarse aggregate for the mixture. It has a specific gravity and a fineness modulus of 2.78 and 6.92, respectively. The combination of sodium silicate solution and sodium hydroxide in pellets form was used as an alkaline activator for the geopolymer [29]. Conplast SP 430, a naphthalene-based superplasticiser, was used to improve the workability of the concrete. Hybrid fibre combination of crimped steel and polypropylene fibres were used to enhance the mechanical properties of TGPC. Figure 1 shows the crimped steel and polypropylene fibres used in this study. The properties of the fibres are given in Table 4.


(**a**) (**b**)

Figure 1. Fibres used: (**a**) Crimped steel fibres; (**b**) Polypropylene fibres.

Table 4. Properties of fibres.

Properties	Crimped Steel Fibres	Polypropylene Fibres
Length	30 mm	12 mm
Diameter	0.45 mm	40 micron
Aspect ratio	66	300
Tensile strength	800 N/mm^2	550–600 N/mm^2
Density	7950 kg/m^3	950 kg/m^3

2.2. Mix Proportions

Till now, there is no standard mix design method available for geopolymer concrete. Hence in this study, TGPC mix proportion for a grade of M55 was arrived at by trial and error method based on the guidance provided by Rangan [30]. Various parameters like the molarity of sodium hydroxide, alkaline activator to binder ratio, proportions of source materials, viz. fly ash, GGBS and MK were considered for the optimum mix proportion of TGPC. These were obtained from the authors' detailed experimental work, presented elsewhere [21,22] and used in this present work. Hence, the mix with 60% fly ash, 25% GGBS and 15% MK was considered. The alkaline liquid to binder ratio of 0.3 and 14 M molarity of sodium hydroxide was adopted. The water to binder ratio was kept constant at 0.2, and the dosage of superplasticiser was 1.5% of the total weight of the binder. Table 5 shows the summary of the TGPC mix proportion. The mix proportion was kept constant for all the specimens with the addition of hybrid fibres at different levels.

Table 5. Mix proportions of Ternary blend geopolymer concrete.

Materials	Quantity (kg/m^3)
Fly ash	237.47
GGBS	122.61
Metakaolin	64.53
Coarse aggregate	1293.60
Fine aggregate	554.40
Sodium hydroxide solution	36.40
Sodium silicate	90.99
Superplasticizer	6.37
Water	84.92

2.3. Mixing, Casting and Curing of TGPC

Dry materials like fly ash, GGBS, MK, coarse and fine aggregates were initially mixed in a drum type horizontal concrete mixer. Sodium hydroxide solution (14 M) was prepared by dissolving the appropriately measured quantity of sodium hydroxide pellets in water [31]. The alkaline activator solution was prepared by mixing the sodium silicate solution with sodium hydroxide solution. The ratio of sodium silicate to sodium hydroxide solution was kept constant at 2.5. For ensuring the reactivity of the alkaline activator solution, it is recommended to mix sodium silicate and sodium hydroxide 24 h prior to casting [32]. The alkaline activator, superplasticiser with water were then added to the dry materials in the mixer drum. The fibres were added as per the designed volume of the specimens. It is recommended to add polypropylene fibres along with dry materials for the proper distribution of fibres in the mix. The steel fibres should be added at last before 5–10 revolutions of the mixer to avoid the deformation of fibres.

The fresh concrete was transferred to the mould in three layers using a table vibrator. The surface was levelled and covered with a polythene sheet to avoid the loss of water during the curing process. The specimens were transferred to the steam curing chamber after one day and cured at 60 °C for 24 h. Figure 2 shows the specimens in the steam curing chamber. Then, the moulds were removed, and the samples were left at room temperature until testing.

2.4. Test Methods

The compressive strength test was carried out on cube specimens of size 150 mm as per IS 516:1959 (reaffirmed 2004) [33]. A total of 45 cubes were tested with different volume fractions of the fibres in a universal testing machine of 300 t (2942.1 kN) capacity. The specimens were tested until failure at a constant rate of loading of 13.73 N/mm^2/min. Split tensile strength tests were performed on 45 cylindrical samples of 150 mm diameter and 300 mm height conforming to IS 5816:1999 (reaffirmed 2004) [34]. The flexural strength tests were carried out on 45 prisms of size 100 × 100 × 500 mm, under third point loading as per IS 516:1959 (reaffirmed in 2004) [33]. The flexural strength of the specimens is expressed as the modulus of rupture. In this investigation, the modulus of elasticity was determined by testing 45 cylindrical samples of 150 mm diameter and 300 mm height as per IS 516:1959 (reaffirmed in 2004) [33]. The test setup for determining the modulus of elasticity is shown in Figure 3.

Figure 2. Specimens in the steam curing chamber.

Figure 3. Modulus of elasticity test setup.

3. Results and Discussions

3.1. Properties of Fresh Geopolymer Concrete

The fresh geopolymer concrete had a glossy appearance and a stiff consistency. The workability of the fresh concrete may be strongly affected by the variables like fibre type, fibre geometry and fibre volume fraction [35]. Workability tests such as slump test and compacting factor test were carried out to explore the fresh properties of concrete. A total of 15 concrete mixes were tested, including one TGPC without fibres and others with the addition of fibres at different levels. The mix designation and the variables of all the concrete mixes used in the present investigation were given in Table 6. The slump of the fresh concrete mix was measured using a slump cone as per IS 1199:1959 (reaffirmed 2004) [36], and the results are presented in Table 6. When the fibres are added to the TGPC mix, the slump is reduced, leading to stiff concrete. This further accelerates the stiffness when hybrid fibres are added to TGPC. Finally, the addition of fibres and hybrid fibres make the TGPC stiffer and stiffer, as depicted in Table 6. However, during specimen casting with proper compaction, the specimen could be cast without much difficulty regarding workability. Such a harsh mix was obtained despite the addition of a superplasticiser to the mix. On the other hand, such behaviour of TGPC contradicts the behaviour of cement-based concrete with a high dosage of admixtures, which gives mixes with a higher slump. Compacting factor is the ratio of the weight of partially compacted fresh concrete to fully compacted fresh concrete. For all the mixes, compacting factor was measured as per IS 1199:1959 (reaffirmed 2004) [36]. The results of the compacting factor test are given in Table 6. The results show that the workability of concrete was low and possess a stiff consistency.

Table 6. Test results of fresh concrete.

Mix ID	Steel Fibre, V_s (%)	Polypropylene Fibre, V_p (%)	Slump (mm)	Compacting Factor
TGPC	0	0	22	0.87
STGPC1	0.5	0	16	0.82
STGPC2	1.0	0	10	0.78
PTGPC1	0	0.1	20	0.85
PTGPC2		0.15	18	0.85
PTGPC3		0.20	18	0.84
PTGPC4		0.25	16	0.83
HTGPC1	0.5	0.1	15	0.81
HTGPC2		0.15	13	0.80
HTGPC3		0.20	12	0.78
HTGPC4		0.25	10	0.77
HTGPC5	1.0	0.1	8	0.77
HTGPC6		0.15	6	0.75
HTGPC7		0.20	5	0.73
HTGPC8		0.25	5	0.73

3.2. Properties of Hardened Geopolymer Concrete

The specimens are tested after 28 days of casting and each test result was the average of three samples. The test results of all the hardened concrete specimens are given in Table 7. The table shows that the compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity was improved to different levels as the fibre content increases.

3.2.1. Compressive Strength

It may be noted that the addition of steel or polypropylene fibres in TGPC increased the compressive strength marginally. The compressive strength of concrete was not significantly affected by the addition of fibres since the bridging effect of fibres is not effective in compression. The compressive strength (f_c) of TGPC was 57.23 MPa. Figure 4 shows the comparison of compressive strength for different compositions of TGPC with fibres. It may also be observed that the incorporation of hybrid fibres improves the compressive strength to a maximum of 17% for HTGPC5. According to literature, micro fibres act as bridges for controlling micro-cracks propagation [37,38]. The addition of mono polypropylene fibres of more than 0.15% results in a decrease in compressive strength. This may be due to the fibres' high volume fraction, which results in the balling effect of the fibres [18,39–41].

Table 7. Test results of hardened concrete.

Mix ID	f_c **(MPa)**	f_{ct} **(MPa)**	f_{cr} **(MPa)**	$E_c \times 10^{-4}$ **(MPa)**
TGPC	57.23	4.72	5.62	3.28
STGPC1	59.64	5.82	6.40	3.43
STGPC2	60.85	6.04	6.61	3.89
PTGPC1	58.54	5.57	6.03	3.35
PTGPC2	57.75	5.73	6.10	3.43
PTGPC3	56.35	5.82	6.16	3.49
PTGPC4	57.00	6.08	6.20	3.53
HTGPC1	61.47	6.00	6.48	3.57
HTGPC2	61.77	6.12	6.52	3.65
HTGPC3	61.21	6.25	6.54	3.79
HTGPC4	62.23	6.37	6.58	3.88
HTGPC5	66.93	6.27	7.76	4.19
HTGPC6	65.77	6.32	7.85	4.34
HTGPC7	64.09	6.48	7.80	4.28
HTGPC8	64.80	6.56	7.71	4.23

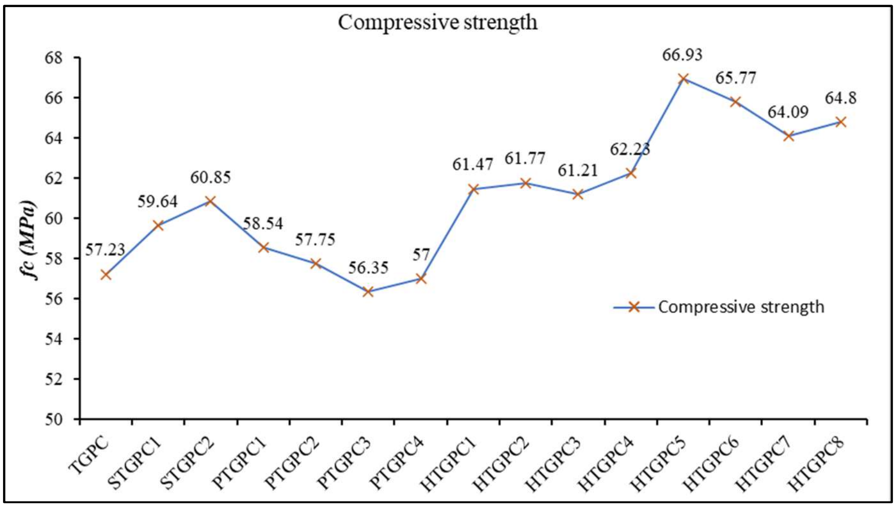

Figure 4. Comparison of compressive strength.

3.2.2. Split Tensile Strength

A sudden brittle failure in TGPC and the bridging action of steel fibres were observed in the specimens that contain steel fibre. The split tensile strength (f_{ct}) of concrete with hybrid fibres is found to be higher than the concrete without fibre and mono fibre. The HTGPC with 1% steel and 0.25% polypropylene fibres exhibited an improvement of about 39% compared with the plain TGPC. The incorporation of hybrid fibres significantly improved the tensile behaviour of TGPC. This can be attributed to the bridging effect of the hybrid fibres at different levels, which reduces the coalescence of cracks in the geopolymer concrete [42]. Simultaneously, the steel fibres' high bond strength with TGPC delayed the pull-out of the fibres [43]. Figure 5 shows the variation in split tensile strength for different fibre contents of TGPC.

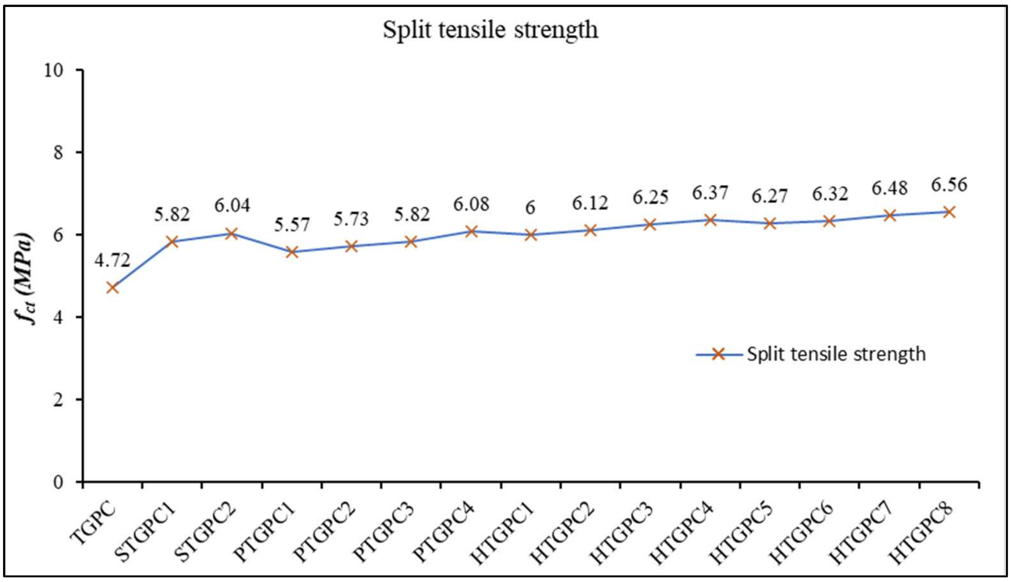

Figure 5. Comparison of split tensile strength.

An attempt is made to obtain a relationship between the compressive strength (f_c) and split tensile strength (f_{ct}). The primary variable for the improvement in split tensile strength is the volume fraction of steel fibres (V_s) and polypropylene fibres (V_p). Hence, after several combinations of different fibre parameters, a fibre factor (F_f) consisting of parameters like geometry, volume fraction, and bond efficiency of fibre was introduced as follows:

$$F_f = F_p + F_s \tag{1}$$

where:

$$F_p = V_p \frac{l_p}{d_p} \eta_p \tag{2}$$

$$F_s = V_s \frac{l_s}{d_s} \eta_s \tag{3}$$

where, η_p and η_s are the bond efficiency factors for polypropylene fibres and crimped steel fibres respectively. The bond efficiency factor may be assumed based on the geometry of the fibres and taken as 1.0 for straight round fibres and 1.2 for crimped fibres [44]. The relation between split tensile strength and $F_f\sqrt{f_c}$ was plotted and shown in Figure 6. The regression equation thus obtained is:

$$f_{ct} = 0.120 F_f \sqrt{f_c} + 5.236 \tag{4}$$

where f_{ct} and f_c are in $\mathrm{N/mm^2}$.

The predicted values of the split tensile strength using Equation (4) was compared with the experimental measured values for the TGPC with different volume fractions of fibres. It may be noted from Table 8 that the predicted error approximately runs below 4% for the TGPC with fibres.

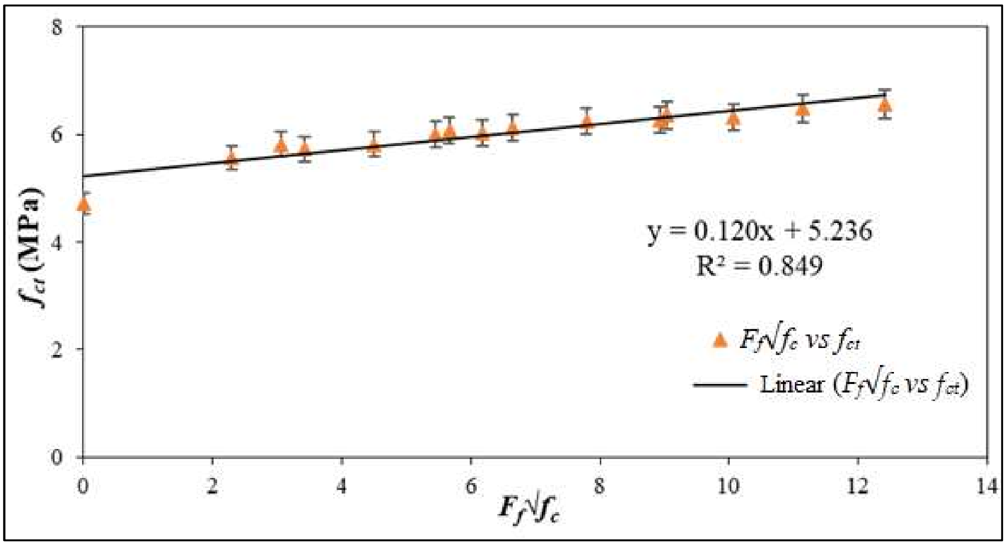

Figure 6. Relationship between f_{ct} and $F_f\sqrt{f_c}$.

Table 8. Comparison of measured and predicted values.

Mix ID	**Split Tensile Strength**			**Modulus of Rupture**			**Modulus of Elasticity** × 10^{-4}		
	Measured (MPa)	**Predicted (MPa)**	**Error (%)**	**Measured (MPa)**	**Predicted (MPa)**	**Error (%)**	**Measured (MPa)**	**Predicted (MPa)**	**Error (%)**
TGPC	4.72	5.24	10.93	5.62	5.48	−2.53	3.28	3.12	−4.85
STGPC1	5.82	5.61	−3.67	6.4	6.06	−5.33	3.43	3.42	−0.18
STGPC2	6.04	5.98	−0.91	6.61	6.65	0.62	3.89	3.73	−4.05
PTGPC1	5.57	5.51	−1.05	6.03	5.91	−2.00	3.35	3.35	−0.12
PTGPC2	5.73	5.65	−1.46	6.1	6.12	0.34	3.43	3.46	0.76
PTGPC3	5.82	5.78	−0.75	6.16	6.32	2.67	3.49	3.56	2.07
PTGPC4	6.08	5.92	−2.71	6.2	6.54	5.52	3.53	3.68	4.13
HTGPC1	6	5.89	−1.76	6.48	6.51	0.46	3.57	3.66	2.49
HTGPC2	6.12	6.04	−1.35	6.52	6.73	3.28	3.65	3.78	3.44
HTGPC3	6.25	6.17	−1.20	6.54	6.95	6.25	3.79	3.89	2.58
HTGPC4	6.37	6.32	−0.71	6.58	7.18	9.17	3.88	4.01	3.35
HTGPC5	6.27	6.32	0.73	7.76	7.17	−7.61	4.19	4.00	−4.46
HTGPC6	6.32	6.45	2.10	7.85	7.38	−5.94	4.34	4.11	−5.20
HTGPC7	6.48	6.58	1.56	7.8	7.59	−2.76	4.28	4.22	−1.42
HTGPC8	6.56	6.73	2.64	7.71	7.82	1.48	4.23	4.34	2.69

3.2.3. Flexural Strength

From Table 7, it can be observed that the inclusion of fibres in TGPC improves the flexural strength significantly. In the initial stage, the polypropylene fibres control the propagation of microcracks. As the load increased, the action of steel fibre comes into existence in arresting the propagation of macrocracks, thereby increasing the flexural strength of the concrete [38,41]. The percentage increase in modulus of rupture varies from 7.29% for PTGPC1 up to 39.67% for HTGPC6. Figure 7 shows the variation in modulus of rupture for all the tested specimens.

In order to obtain a relation between f_{cr} and f_c, a graph was plotted between f_{cr} and $F_f\sqrt{f_c}$, as shown in Figure 8. The regression equation thus obtained is:

$$f_{cr} = 0.188F_f\ \sqrt{f_c} + 5.478 \quad (5)$$

where f_{cr} and f_c are in N/mm^2.

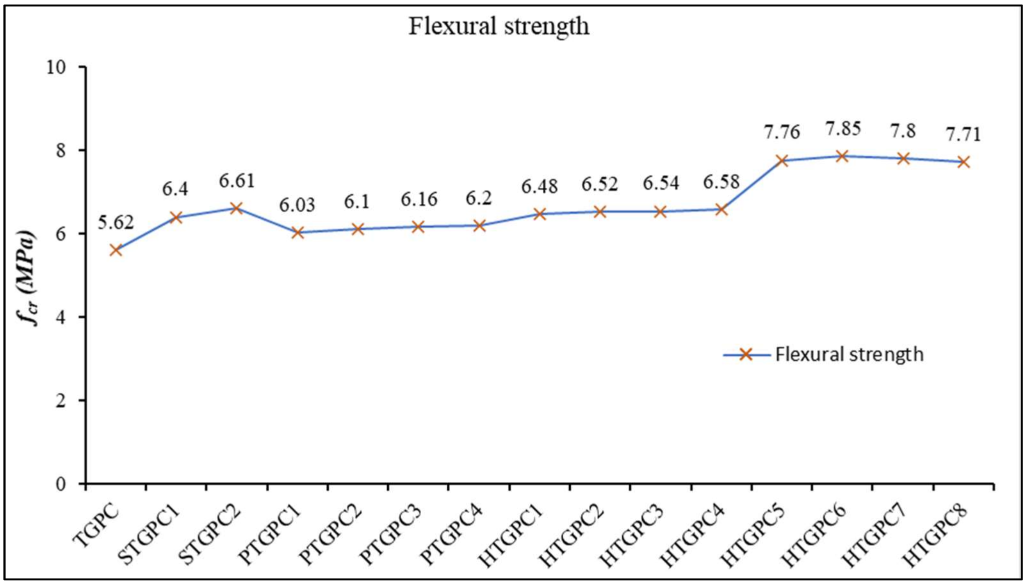

Figure 7. Comparison of modulus of rupture.

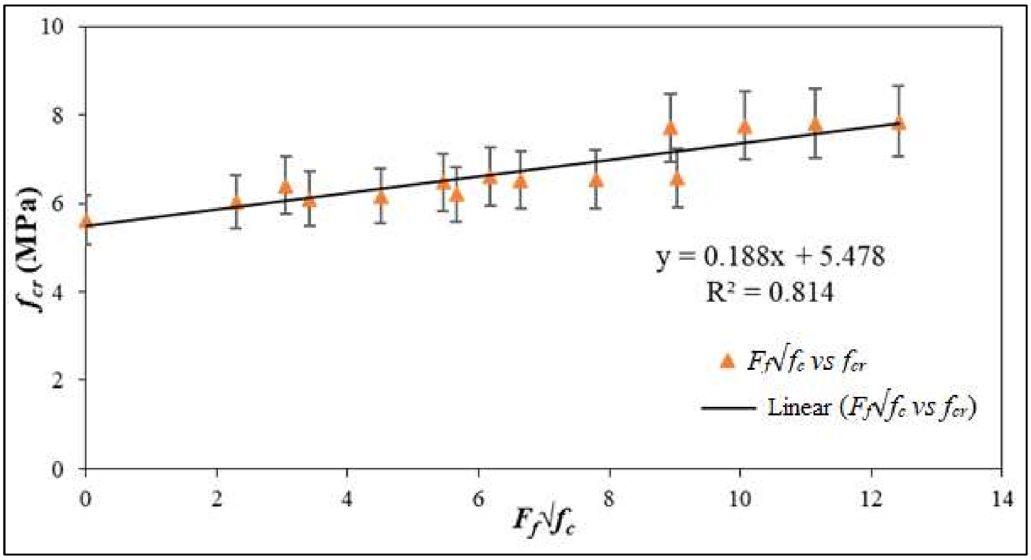

Figure 8. Relationship between f_{cr} and $F_f\sqrt{f_c}$.

Equation (5) shows a satisfactory fit to the modulus of rupture for various volume fractions of fibres as presented in Table 8. The predicted values for the modulus of rupture were well below 8% of error. It may be also noted that from Equation (5), f_{cr} = 5.478 MPa for TGPC without fibres, which is equal to that given by $0.724\sqrt{f_c}$ ($0.724\sqrt{57.23}$). The coefficient of 0.724 is very close to 0.7 mentioned in IS 456:2000 [45] for OPC.

3.2.4. Modulus of Elasticity

It may be noted from Table 7 that the values of modulus of elasticity of concrete gradually increases with the increase in the fibre content. The addition of fibres in TGPC improves the modulus of elasticity from 2.13% to a maximum of 32.31%. This may be due to the effect of fibres' high elastic modulus and strong bond between the fibres and the matrix [46,47]. The comparison of modulus of elasticity for all the tested samples are given in Figure 9.

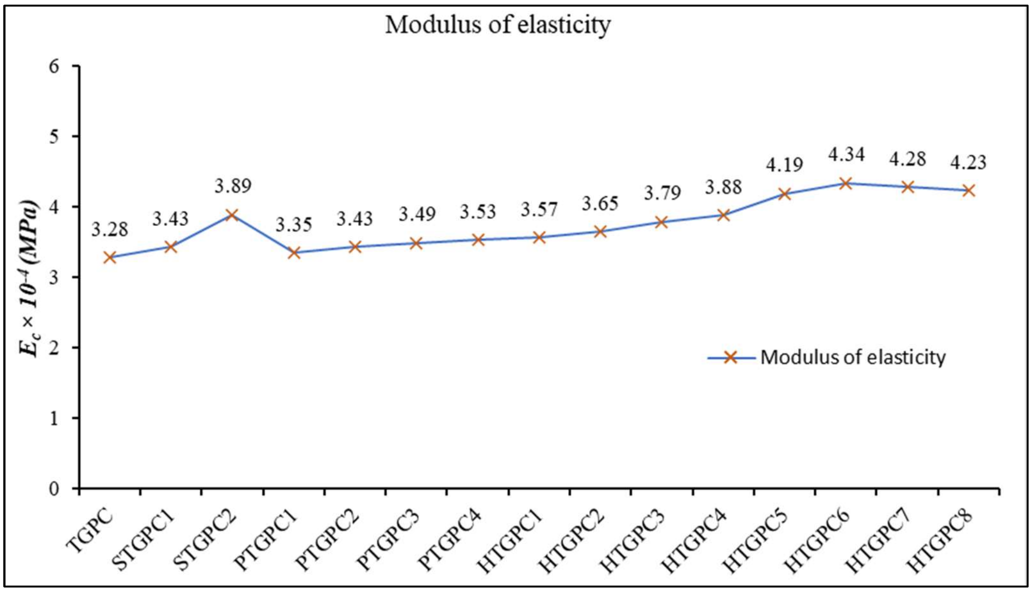

Figure 9. Comparison of modulus of elasticity.

The parameters that influence the modulus of elasticity are not directly related to compressive strength. However, an attempt was made to obtain a relation between f_c and E_c using the fibre factor for TGPC and HTGPC. A graph was plotted between E_c and $F_f\sqrt{f_c}$, as shown in Figure 10. The regression equation thus obtained is:

$$E_c\left(\times 10^{-4}\right) = 0.098F_f\sqrt{f_c} + 3.121 \tag{6}$$

where E_c and f_c are in N/mm^2.

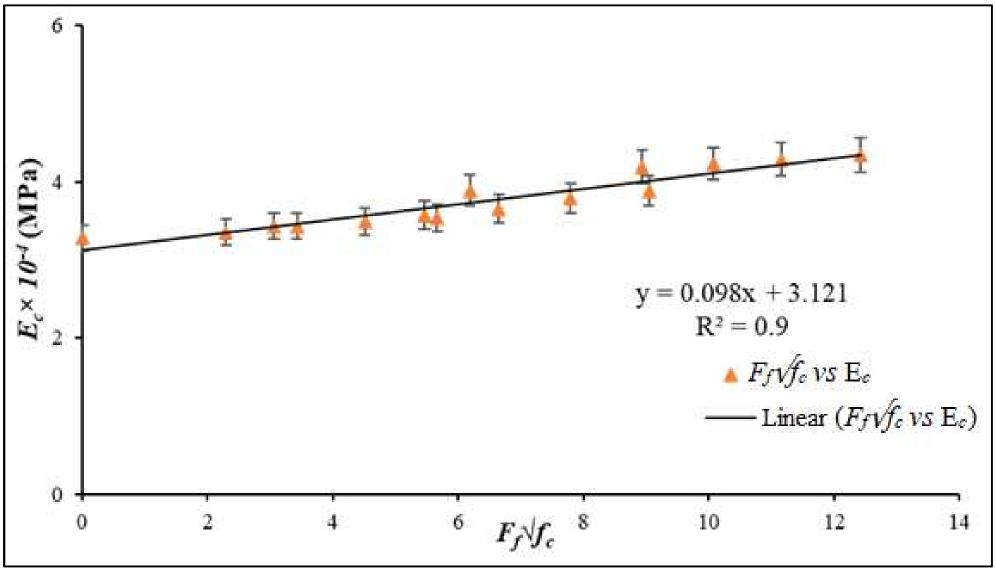

Figure 10. Relationship between E_c and $F_f\sqrt{f_c}$.

The modulus of elasticity values, predicted using Equation (6) are shown in Table 8. It may be noted that the predicted values approached the measured ones as the error is less than 5% approximately. It may be also observed from Equation (6) that, $E_c = 3.121 \times 10^{-4}$ MPa, which is equal to that given by $4125\sqrt{f_c}$ ($0.724\sqrt{57.23}$). The coefficient, 4125 for TGPC significantly lower than 5000 mentioned in IS 456:2000 for OPC [45].

4. Conclusions

The following conclusions may be derived based on this experimental investigation of the engineering properties of hybrid fibre reinforced ternary blend geopolymer concrete:

(1) The addition of fibres improves the compressive strength of TGPC at different volume fractions in mono and hybrid form. The strength increases from 1% for PTGPC2 up to 17% for HTGPC5.

(2) The split tensile strength, modulus of rupture and modulus of elasticity of TGPC increases notably with the increase in the fibre volume fraction. The split tensile strength varied from 18% up to 39%. The modulus of rupture varied from 7% up to 39%, and modulus of elasticity ranged from 5% to 32%. The enhancement in the mechanical properties of TGPC was highly significant with the incorporation of fibres in hybrid form.

(3) The strength models proposed for TGPC with different volume fractions of fibres to predict the compressive strength, split tensile strength, modulus of rupture and modulus of elasticity were found satisfactorily with the test results.

5. Patents

Based on these research findings, an Australian patent titled Engineered Hybrid Fibre Reinforced Ternary Blend Geopolymer Concrete Composite was granted with Reg. No. 2020102145 on 29 October 2020.

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Nomenclature

η_s	bond factor of steel fibre
η_p	bond factor of polypropylene fibre
d_p	diameter of polypropylene fibre
d_s	diameter of steel fibre
f_c	compressive strength
f_{ct}	split tensile strength
f_{cr}	modulus of rupture
E_c	modulus of elasticity
F_f	hybrid fibre factor
l_p	length of polypropylene fibre
l_s	length of steel fibre
V_s	volume fraction of steel fibres
V_p	volume fraction of polypropylene fibres

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