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Flexural behaviour of steel fibre reinforced ternary blend geopolymer concrete

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Abstract. The response of GeoPolymer Concrete(GPC) with fibres of steel conditioned to curing at ambient temperature conditions has been studied in this research paper. Mechanical properties, flexural strength of beams under two point loading, ductility characteristics, energy absorption capacity etc. have been investigated and compared with that of GPC without steel fibres. An analytical comparison is also made with similar models. An overall improvement in the properties are observed on adding steel fibres, the ductility property being significantly improved.

Key Words: ***Geo polymer, energy absorption, ductility, steel fibres***

1. Introduction

For many years, the binder used in concrete has been ordinary Portland Cement. But cement production involves high energy consumption and is environmentally disintegrating. When one tonne of cement is manufactured, the same quantity of CO_2 is emitted, thereby increasing the carbon footprint [1,2]. Depletion of natural resources used as raw materials in cement is yet another challenge. Geopolymer concrete has emerged as a solution for this problem. Here cement is not being used as a binder. This technology was introduced by Joseph Davidovits where inorganic polymer composites are activated in an alkaline medium [3]. Durability aspects of this concrete have been studied by Bakharev T [4]. GPC exhibits high strength and also resists acid attack and chloride penetration [5,6]. Based on the studies of GPC, research has been taken to the next level by investigating performance of ternary blend geopolymer concrete. Steel fibres when introduced, enhances the flexural strength [7]. Homogeneity and isotropic property of concrete is also improved by steel fibres, thereby making it more ductile rather than brittle [8]. Ternary blend GPC using NaOH of varying molarities was investigated by Satish Kumar et.al [9] who also did research by different curing methods involving heat. Since there is a gap in research using ternary blend geopolymer concrete under ambient curing, this study attempts at understanding the behaviour under flexure. According to studies conducted on GPC, the flexural strength is increased on adding steel fibres [9-14]. Flexural strength of fibre concrete composite was predicted using an empirical approach [15]. According to Ashour et.al [16] fibre addition lowers the immediate as well as long term deflection of singly reinforced high strength FRC beams. Ductility and energy absorption capacity is improved by adding steel fibres in high performance concrete [17].

2. Experimental Programme

The experimental procedure is elaborated as follows:

2.1 Materials and mix proportion

For this mix, concrete was made using a blend of fly ash, GGBS, metakaolin, aggregates – coarse and fine, alkaline liquid and super plasticisers. Steel fibres were also added. Fly ash was of low calcium type, class F procured from Ennore thermal power plant, as per IS 3812: 2003 [18]. This contains silica and alumina as major components and serves as a binder. Metakaolin used also contains silica, alumina and iron oxide. GGBS, conforming to BS 6699: 1992, consisting of calcium oxide, magnesium oxide and silicon dioxide having a particle size below 30 micron was utilised. Coarse aggregate used is collected from local sources. Blue metal of size 12.5 mm, having relative density of 2.78 was used. M sand of fineness modulus 2.92, adhering to IS 383: 1970 and specific gravity 2.39 was used. The solution of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) being of alkaline nature, acts as the activator. Here, sodium silicate Na_2SiO_3 comprises of 8% Na_2O, 28% SiO_2 and 64 % water. Sodium hydroxide was prepared to 12M solution using pellets of NaOH. Super plasticiser used was Conplast SP 430 to ensure better workability. Crimped type steel fibre of aspect ratio 66 were used.

2.2 Mix design

GPC being a newly evolved construction material, does not have a proper mix proportion. Hence the guidelines proposed by Prof. B.V.Rangan has been adopted and the design was arrived at by the method of trial and error [19]. The design mix of concrete was prepared for M50 grade. Ternary blend geopolymer concrete in this study comprises of 15 % metakaolin, 25 % fly ash and 60 % GGBS. Crimped fibres of steel were incorporated in ratios of 0.5, 0.75 and 1.0 by concrete volume. The details pertaining to mix proportion is tabulated in Table 1.

Table 1. Material proportion

Materials	Quantity (kg/cu.m)
Metakaolin	71.43
GGBS	285.71
Fly ash	119.5
Coarse aggregate	1380.95
Fine aggregate	685.71
Na_2SiO_3	101.9
NaOH (12 M)	40.95
Superplasticiser	7.14
Water	95.24

2.3 Casting of specimens

Before casting the specimens, the materials required are collected and kept ready for use. Preparation on the solution is done by thoroughly mixing Na_2SiO_3 to 12 M solution of sodium hydroxide prepared using pellets. This is done 24 hours before mixing and casting. Mixing is done in a pan mixer in dry condition. Steel fibres are added intermittently. Following this alkaline solution and super plasticiser are added and mixed thoroughly. The mixed concrete was poured to prepare cylinders, cubes and prisms to test mechanical properties. The concrete was also poured in three layers and cast into moulds to make beams of dimensions 150 mm x 200 mm x 1500 mm. Testing was done subject to two point loading. The beam reinforcement details are depicted in figure (1). The reinforcement consisted of HYSD bars, two 8 mm dia bars at top and two bars of 10 mm diameter bars at the bottom, with 6 mm diameter bars at 120 mm centre to centre were used as stirrups. Layers of poured concrete were vibrated uniformly and the top was levelled with a trowel. These properly compacted specimens covered with plastic sheets to avoid loss of moisture . Ambient curing was done for 28 days at room temperature. Specimens casted are displayed in as Fig 2.

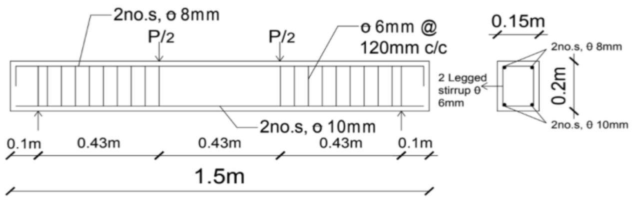

Fig 1: Beam reinforcement details

Fig 2: Cast specimens

2.4 Test programme

This consists of testing the beams, studying the load deflection characteristics and comparison of results with analytical models. Beams underwent testing in a compression cum bending testing machine having capacity 100 T. Two point loading as depicted in Figure 3 formed the test set up. A load cell of 50 T capacity having a least count of 0.1 kN was used to measure the applied load. Two rollers at 433 mm distance served as load points. The deflection was measured at the centre , using Linear Variable Differential Transducers (LVDT) possessing a least count of 0.1 mm.

Figure 3. Test set up

3. Results and Discussion

3.1 Mechanical properties

Testing of ternary blend GPC for mechanical properties are depicted in Table 2. Modulus of elasticity is also calculated and recorded.

Table 2. Mechanical properties and Modulus of Elasticity

Designation	(V_f) (%)	Compressive strength (MPa)	Split tensile strength (MPa)	Modulus of rupture (MPa)	E_c x 10^4 (MPa)
GPC	0	56.3	3.84	4.89	2.8
$SGPC_1$	0.5	57.1	3.93	5.79	3.25
$SGPC_2$	0.75	58.6	4.0	6.05	3.4
$SGPC_3$	1.0	59.1	4.03	6.41	3.6

The results obtained clearly indicates an increase in strength parameters when percentage of steel fibres are increased. However when the percentage of steel fibers are increased beyond 1%, the mix has become harsh and workability has reduced and due to ball formation, strength also reduced.

3.2 First crack load and ultimate load

From the graph of load vs deflection, identification of the load at appearance of first crack was done where the curve started deviating from being a straight line. It is observed that there is an increase in the first crack load when the steel fibre content is increased. This might be due to the enhanced tensile strain bearing ability of concrete on adding fibres. The ultimate load also showed a marginal increase with increasing fibre content. Results are displayed in Table 3. The beam with 1 % steel fibre volume showed maximum load bearing capacity.

Table 3. Test results

Designation	First crack load (kN)	Ultimate load (kN) P_u	Deflection at ultimate load (mm)
GPC	12.8	51.6	15.2
$SGPC_1$	16.8	53.2	15.6
$SGPC_2$	17.6	54.9	16.5
$SGPC_3$	19.2	56.2	16.8

3.3 Load deflection behaviour

The behaviour of the specimens under application of load was observed. It was found that, with increasing load, the cracks also started to appear and continually increase. Few cracks traversed up the beam. The crack patterns observed is depicted in Figure 4.

The values of load and deflection for different volume of steel fibre were plotted and compared in Figure 5. It is observed that the curve followed a linear pattern until the first crack load. On further increase of load, multiple cracks were generated and the curve becomes non linear and became flatter as the ultimate load was approached. The results obtained show an enhanced structural behaviour, similar to those of geopolymer concrete beams. [20, 21,22,23,24]

GPC

SGPC1

SGPC2

SGPC3

Figure 4. Tested specimens

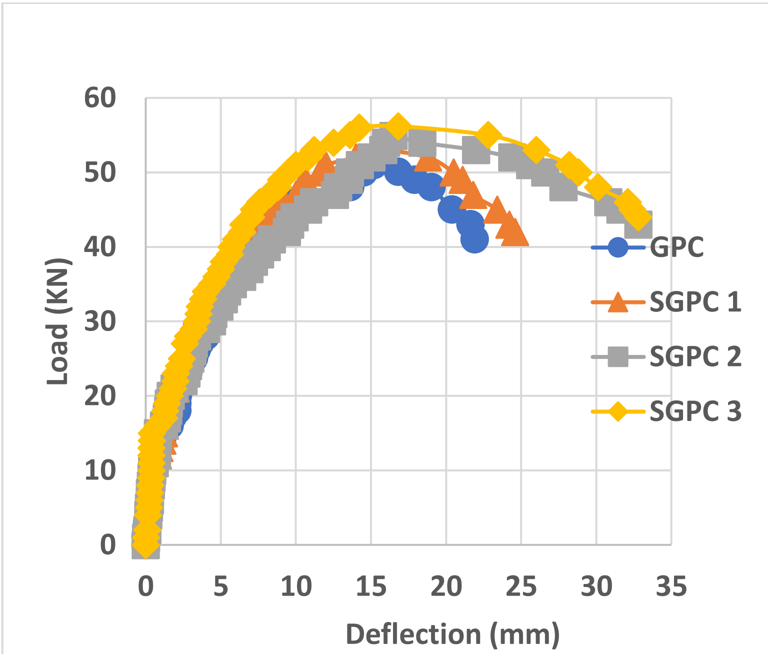

Figure 5. Load deflection plots

3.4 Energy Absorption Capacity

The energy absorption capacity is derived from the area below the graph in Figure 4. Even though the full load deflection curve could not be plotted, the behaviour upto 80% of peak load was noted, in the descending branch. The energy absorption capacity was calculated as the area below the ascending branch , upto peak load of the curve for load deflection and under the descending branch, up to 80% of peak load. Results obtained are given in Table 4. From this result, it has been found that there is an increase in the energy absorption capacity with the increase in fibre content. Similar results of improved performance is also observed under cyclic loading [25]

Table 4. Displacement ductility factor and Energy absorption capacity

Beam designation	Energy absorption capacity		Deflection at		Displacement ductility factor (φ)	
	Absolute (kNmm)	Relative	0.8 P_u, δu (mm)	Yield load, δy (mm)	Absolute	Relative

GPC	876	1.0	21.4	3.8	5.63	1.00
$SGPC_1$	1056	1.2	24.3	3.2	7.5	1.33
$SGPC_2$	1442	1.6	32.4	2.9	11.17	1.98
$SGPC_3$	1558	1.7	29.6	3.2	9.25	1.64

3.5 Ductility Factor

Ductility factor is given by

$$\varphi = {}^{\delta u}/_{\delta y}$$

Where δu is the deflection at ultimate load and δy is the deflection corresponding to yield load.

Ductility can be considered corresponding to deflection at 80% of peak load [26] taking into account the softening nature of the load deflection curve. Consideration of softening ductility is relevant in seismic designs as well as in cases expecting large deformations. The following procedure was adopted to calculate load at yield point (P_y). Using the theory of elastic cracked section, under the assumption that steel was not stressed beyond yield strength, strain in steel is obtained by the equation. The results are also in conformance with previous studies done where significant improvement in ductility properties were observed [27].

$$\varepsilon_S = \frac{f_{st}}{E_s} = \frac{M(d-x)}{I_{CR}E_C}$$

At yielding $f_{st} = f_y$ and the equation becomes

$$M_y = f_y \frac{E_s}{E_C}\frac{I_{CR}}{(d-x)}$$

From the geometry of the loading

$$M_y = 0.216\, P_y$$

$$P_y = \frac{M_y}{0.216}$$

3.6 Moment curvature relationship

The moment curvature curves for the specimens were drawn as shown in Figure 6. It is observed that the curves are somewhat linear until the first crack moment, after which they become non-linear. Strain gauges were used to measure the deformations at the extreme compression fibre and extreme tension fibre. The curvature of the element (Ø) is measured by the following formula

$$\emptyset = \frac{\varepsilon_c + \varepsilon_S}{d}$$

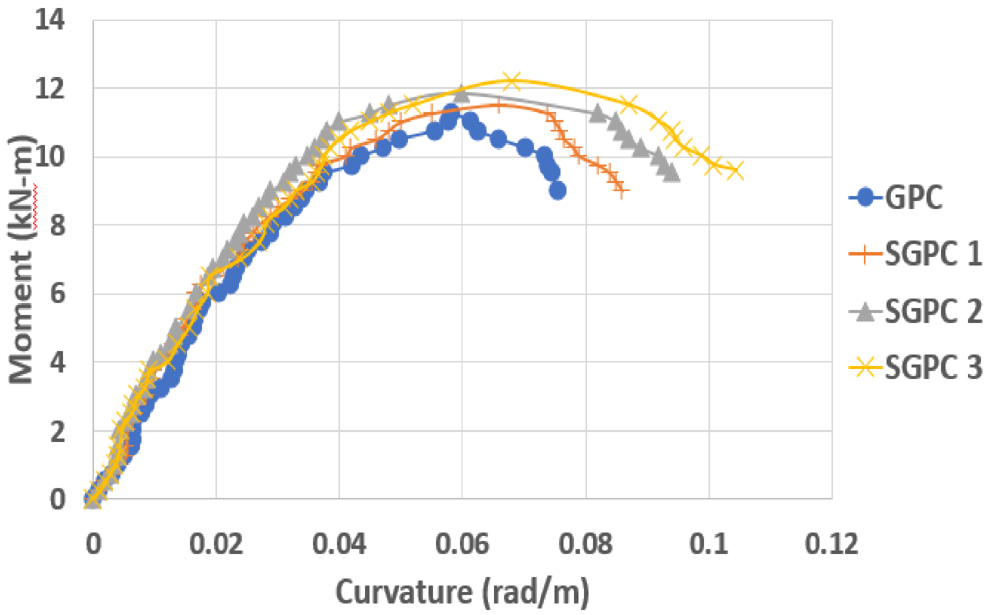

Figure 6. Moment curvature plot

3.7 Curvature ductility

Curvature ductility is calculated from the moment curvature plots. The curvature ductility index values φ were calculated using the concept of displacement ductility.

$$\varphi = \frac{\phi_u}{\phi_y}$$

Here, ϕ_u is the curvature corresponding to 80% of the peak moment which occurs in the descending portion of the curve [28]. The curvature ϕ_y corresponding to yield point can be calculated using the equation

$$\phi_y = \frac{f_y}{\varepsilon_S(d - x)}$$

Substituting the values of x, the neutral axis depth, the other parameters can be calculated. Results are depicted in Table 5, which shows that the curvature ductility values increase with increasing fibre content.

Table 5. Curvature ductility

Beam designation	Φ_y x 10^{-2} (rad/m)	Φ_u x 10^{-2} (rad/m)	Curvature ductility index (φ)	
			Absolute	Relative
GPC	1.376	7.25	5.27	1.0
$SGPC_1$	1.374	8.62	6.27	1.19
$SGPC_2$	1.37	9.42	6.88	1.31
$SGPC_3$	1.369	11.2	8.18	1.55

3.8 Comparison of existing models

Based on the investigations done, an attempt has been made in determining the ultimate moment of the beams, using models[29]. Here, the ACI model proposed by Henager and Doherty, Paramasivam and Imam et al. have been considered and compared as in Table 6.

ACI 544 equation [30]

$$M_u = A_s f_y \left(d - \frac{a}{2}\right) + \sigma_t b(D - e)\left(\frac{D}{2} + \frac{e}{2} - \frac{a}{2}\right)$$

where,

$$\sigma_t = 0.00772\ A_f\ V_f\ F_{be}\ \text{MPa}$$

$$e = \frac{\varepsilon_S + 0.003}{0.003}\ c$$

$$\varepsilon_S = \frac{\sigma_f}{E_s}$$

$$\sigma_f = 2\ \tau_d\ F_{be}\ A_f$$

where,

A_s = area of tension reinforcement

D = total depth of the beam

a = depth of the rectangular stress block

A_f = aspect ratio of steel fibres

V_f = volume fraction of steel fibres

F_{be} = bond efficiency factor (=1 for smooth fibres)

b = breadth of the beam

σ_t = effective tensile stress in the fibrous concrete

τ_d = dynamic bond stress between fibre and matrix (taken as 2.3 MPa) ref

c = distance from extreme compression fibre to neutral axis

Paramasivam et al [31]

Ultimate moment M_u may be determined as

$$M_u = \sigma_{tu} \frac{bhh_t}{2} + \frac{A_s f_y}{2}(h + h_t)$$

where,

$\sigma_{tu} = \eta_o\, \eta_L\, V_f\ l_f\ \tau_u /2r$

$$\eta_0 = \frac{\int_0^{\rho}\int_0^{\theta} \cos\theta \cos\rho\ d\theta\ d\rho}{\int_0^{\rho}\int_0^{\theta} d\,\theta\ d\rho}$$

$\Theta = \sin^{-1} (h/l_f)$

$\rho = \sin^{-1} (b/l_f)$

$$h_t = \frac{\alpha_1 \sigma_{cu} d - \frac{A_s f_y}{b}}{\alpha_1 \sigma_{cu} + \sigma_{tu}}$$

$\eta_L = 0.5$ for $l_f < l_c$

$\eta_L = 1 - (l_c / 2 l_f)$

$l_c = \sigma_{fu} d_f / 4 \tau_u$

where,

σ_{tu} = tensile strength of the composite after cracking

h= effective depth of the beam

h_t = depth of zone under tension

τ_u = ultimate bond stress

r = ratio of fibre cross sectional area to its perimeter

α_1 = ratio of failure stress in compression of SFRC beam to its cylinder strength (0.9 for fibrous concrete)

σ_{cu} = cylinder compressive strength

l_c = critical length of fibre

σ_{tu} = ultimate strength of fibre

Imam et al [32]

The nominal flexural moment is given by

$$M_u = \frac{1}{2} \rho f_y b d^2 (2 - \eta) + 0.83\ \mathrm{F} b d^2 (0.75 - \eta)\ (2.15 + \eta)$$

where,

$$\eta = \frac{\rho f_y + 2.32F}{0.85 f_c + 3.08F}$$

$\rho = A_s / bd$

$F = A_f V_f\ d_f$

where,

d_f = bond efficiency factor (0.5 for smooth fibre)

F = fibre factor

f_c = compressive strength of concrete, MPa

Table 6. Measured and calculated ultimate moments

	$M_{u, exp}$	$M_{u, th}$			

Beam designation	(kNm)	(kNm)			$\frac{(1)}{(2)}$	$\frac{(1)}{(3)}$	$\frac{(1)}{(4)}$
		ACI 544	Paramasivam et al	Imam et al			
	(1)	(2)	(3)	(4)			
GPC	11.14	10.78	10.22	10.69	1.03	1.09	1.04
$SGPC_1$	11.5	10.85	11.35	11.71	1.05	1.01	0.98
$SGPC_2$	11.85	10.90	11.95	12.00	1.08	0.99	0.98
$SGPC_3$	12.14	12.22	12.52	12.42	0.99	0.97	0.98
		Average			1.04	1.02	0.995
		Coefficient of variation, precent			3.6	5.2	9.5

4. Conclusion

Based on the above investigation studies conducted on geopolymer concrete using steel fibre subjected to ambient curing, the following conclusions are noted.

1.Mechanical strength parameters are improved compared to normal GPC.

2.The load at the first crack and ultimate load showed an improvement, which was more significant in the first case. An increase of about 50% in first crack load for specimens with 1 % volume fraction of fibres was found in comparison with specimens without fibres. There was an increase of only 9 % in the case of ultimate load.

3. Energy absorption capacity was found to be increased to 1.74 times for specimens with steel fibres having a volume fraction of 1%.

4.The displacement ductility factor and the curvature ductility index were found to be increased when the volume fraction of steel fibres was increased. The increase in displacement ductility was 1.98 times for volume fraction of fibres 0.75 % and the curvature ductility index was 1.55 times when the volume fraction of fibres has been increased up to 1 %.

5.Attempts were made to compare the experimental values of ultimate moment of steel fibre reinforced GPC with the theoretical values obtained from the equations available in literature. ACI 544 equations proposed by Henager and Doherty are more adequate to evaluate the ultimate moment of steel fibre reinforced GPC beams tested.

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