Advances in Concrete Construction, *Vol. 1, No. 4 (2013) 305-318*
DOI: http://dx.doi.org/10.12989/acc2013.1.4.305

Engineering properties of steel fibre reinforced geopolymer concrete

N. Ganesan*, P.V. Indira[a] and Anjana santhakumar[b]

Department of Civil Engineering, National Institute of Technology Calicut, NIT Campus P.O, Pin.673601, Kerala, India

(Received August 13, 2013, Revised September 28, 2013, Accepted December 6, 2013)

Abstract. Engineering properties such as compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and Poisson's ratio of geopolymer concrete (GPC) and steel fibre reinforced geopolymer concrete (SFRGPC) have been obtained from standard tests and compared. A total of 15 specimens were tested for determining each property. The grade of concrete used was M 40. The percentages of steel fibres considered include 0.25%, 0.5%, 0.75% and 1%. In general, the addition of fibres improved the mechanical properties of both GPC and SFRGPC. 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 fibres. An attempt was made to obtain the relation between the various engineering properties with the percentage of fibres added.

Keywords: geopolymer concrete; modulus of rupture, modulus of elasticity; steel fibres; split tensile strength

1. Introduction

The demand for cement is increasing with the increase in infrastructure development. The process of producing cement is not only highly internal energy intensive but is also responsible for large emissions of carbon dioxide (CO_2), which is a green house gas causing global warming (Mehta 2001, McCaffrey 2002). Malhotra (1999) have reported that the worldwide cement production accounts for almost 7% of the total world CO_2 emissions. Control of this greenhouse gas emission is a major issue for sustainable concrete. Besides, about 3 billion tons of the raw materials are needed every year for cement manufacturing, which consumes considerable energy and adversely affect the ecology of the planet. Also under certain environmental conditions, ordinary Portland cement concretes (OPC) are less durable (Neville 2005). Hence there is an urgent need to find an alternate binder to cement in order to make the construction industry eco-friendly and sustainable. In this respect, geopolymer technology introduced by Davidovits (1994)

∗Corresponding author, Ph.D., E-mail: ganesan@nitc.ac.in
[a]Professor, E-mail: indira@nitc.ac.in
[b]Ph.D. Student, E-mail: anjana.ajith73@gmail.com

http://www.techno-press.org/?journal=acc&subpage=7 ISSN:2287-5301(Print) 2287-531X(Online)

provides an alternative binder to the OPC. Geopolymer Concretes (GPC) are cementless concrete which utilize by product materials like fly ash in the presence of alkaline solution to produce binders. These concretes are obtained by alkali activation of industrial waste materials such as fly ash in the presence of sodium hydroxide and sodium silicate solution, which is a polymerization process that differs widely from Portland cement hydration (Fernández *et al*. 2006). Also it is reported that fly ash, when used in high volumes in concrete reduces the alkali aggregate reaction (Ramachandran *et al*. 1992). GPC have high strength, with good resistance to chloride penetration, acid attack, etc. and have a very small greenhouse footprint when compared to conventional concretes (Hardjito and Rangan 2005, Wallah and Rangan 2006, Bakharev 2005 a,c). The extensive research works carried out by several investigators support the potential of GPC as a prospective construction material (Davidovits 1991, Hardjito *et al*. 2004, Duxson *et al*. 2007, Bakharev 2005, Sofi *et al*. 2006).

The concept of using fibres to improve the characteristics of construction materials is very old (Naaman 1985, ACI Committee 544 1982). The randomly oriented steel fibres in concrete arrest microcracking mechanism of cracks and limit crack propagation, thus improving strength and ductility. Steel fibres increases elastic modulus, decreases brittleness, controls crack initiation, and its subsequent growth and propagation (Bencardino *et al*. 2008). Addition of fibres to concrete makes it a more homogeneous and isotropic and transforms it from a brittle to a more ductile material (Wafa and Ashour 1992). The characteristics of fibre reinforced concrete depend upon many factors such as size, type, elastic properties, aspect ratio and volume fraction of fibres and each type of fibre can be effective in some specific function (Bentur and Mindess 1990). Khaloo and Kim (1996) investigated the mechanical properties of normal strength concrete and high strength concrete reinforced with steel fibres ranging from 0 to 1.5% by volume of the concrete and it was concluded that high strength concrete provides considerable improvement in compressive strength for fibre content of up to 1% compared to that of normal strength concrete. Also, modulus of rupture of normal strength concrete considerably improves with increase in fibre content compared to those of high strength concrete. Song and Hwang (2004) indicated that compressive strength of high strength fibre reinforced concrete reached a maximum of 1.5% volume fraction, whereas splitting tensile strength and modulus of rupture increases with increase in volume fraction. Jianming *et al*. (1997) investigated the influence of steel fibres on mechanical properties of high strength light weight concrete and found that flexural strength and fracture toughness is extremely improved, compressive strength is only slightly improved, and tensile to compressive strength ratio is obviously enhanced. Susan *et al*. (2006) studied the performance of geopolymeric concrete incorporating GGBS as the source material and reinforced with steel fibres and it was concluded that incorporation of steel fibres in the matrix, reduces the compressive strength at early ages, but the splitting tensile strength, the flexural strength and the toughness increased significantly. So far no studies have been reported on the influence of steel fibres on the strength of fly ash based geopoymer concrete.

In this study, the engineering properties of steel fibre reinforced geopolymer concrete (SFRGPC) were investigated as they are the fundamental parameters required for the design of structural elements. The grade of concrete considered was M 40. A total of 75 specimens were prepared and tested to determine the compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and Poisson’s ratio of concrete containing various fibre contents. Relations between the properties and fibre parameters were established.

2. Experimental program

2.1 Materials and mix proportion

Low-calcium (ASTM Class F) fly ash obtained from Mettur Thermal Power Plant in Tamil Nadu was used as the base material. Table 1 shows the chemical composition of fly ash as revealed by scanning electron microscope. Fig. 1 shows the SEM image of fly ash. River sand passing through 4.75 mm IS sieve conforming to grading zone II of IS: 383-1970 (reaffirmed 2002), having a fineness modulus of 2.83 and specific gravity of 2.50 was used. The maximum size of coarse aggregate was 20 mm with a fineness modulus of 7.69 and specific gravity of 2.72. The results of sieve analysis for fine and coarse aggregates are shown in Table 2 and Table 3. The activator solution consists of sodium silicate and sodium hydroxide as indicated by Rashad *et al.* (2013). In order to improve the workability of concrete a naphthalene based superplasticizer (Conplast SP 430) was employed during mixing operations. Crimped steel fibres (Fig. 2) having a length of 30 mm, diameter of 0.45 mm and an ultimate tensile strength of 800 MPa with an aspect ratio of 66 were used for the present study. So far no standard mix design approaches are available for GPCs, since they are a new class of construction materials. In the present experimental work, GPC mix proportion for M 40 grade was obtained by trial and error method, based on the guidelines given by Rangan (2008). The objectives for performing the trial and error procedure was to obtain the desired compressive strength at the end of 28 days and to obtain a good cohesive mix with satisfactory workability (slump of 75 to 125 mm). The ratio of sodium silicate-to-sodium hydroxide by mass was kept as 2.5 as reported by Mustafa *et al*. (2012) and the ratio of activator solution-to fly ash was selected as 0.39. Same mix proportion was maintained with the increase in the percentage of steel fibres. Dosage of superplasticizer was adjusted to maintain the workability of SFRGPC mixes. The details of mix proportions are given in Table 4.

Table 1 Chemical composition of fly ash

Element	Weight (%)
Alumina (Al_2O_3)	27.74
Silica (SiO_2)	55.36
Pottasium oxide (K_2O)	2.55
Calcium oxide (CaO)	1.07
Titanium dioxide (TiO_2)	3.55
Iron oxide (Fe_2O_3)	9.74

Table 2 Sieve analysis of fine aggregate

Sl.No	Sieve size (mm)	Weight retained (grams)	% Weight retained	Cumulative % weight retained	% Passing
1	4.75	0.00	0.00	0.00	100.00
2	2.36	0.00	0.00	0.00	100.00
3	1.18	299.00	29.90	29.90	70.10
4	0.60	324.00	32.40	62.30	37.70
5	0.30	283.00	28.30	90.60	9.40
6	0.15	92.00	9.2	99.8	0.2

Table 3 Sieve analysis of coarse aggregate

Sl.No	Sieve size (mm)	Weight retained (grams)	% Weight retained	Cumulative % weight retained	% Passing
1	20.00	0	0	0	100
2	16.00	1428	28.56	28.56	71.44
3	12.50	1545	30.90	59.46	40.54
4	10.00	1323	26.46	85.92	14.08
5	4.75	668	13.36	99.28	0.72
6	2.38	0.00	0.00	99.28	0.00
7	1.18	0.00	0.00	99.28	0.00
8	0.60	0.00	0.00	99.28	0.00
9	0.30	0.00	0.00	99.28	0.00
10	0.15	0.00	0.00	99.28	0.00

Table 4 Mix proportions of geopolymer concrete

Materials	Quantity (kg/m^3)
Coarse aggregates	975
Fine aggregate	285
Fly ash	639
Sodium silicate solution	180
Sodium hydroxide solution (14Molar)	72
Extra water	53
Superplasticizer	7.67

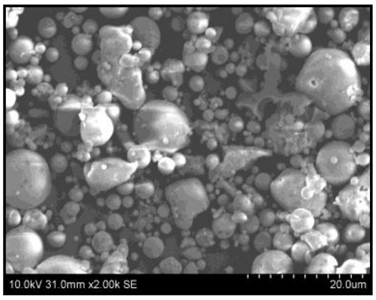

Fig. 1 SEM image of fly ash (2000 magnification)

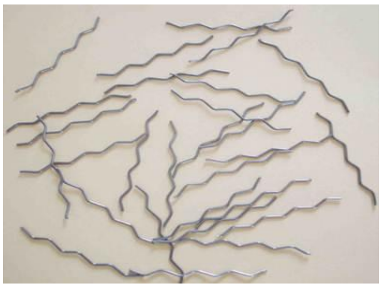

Fig. 2 Crimped steel fibres

2.2 Casting of specimens

For the preparation of test specimens, fly ash, river sand, coarse aggregate, sodium silicate solution and sodium hydroxide solution were used. Sodium hydroxide was available in the pellet form which was mixed with water to form 14 Molar solution (Rangan 2008 and Vanchai *et al*. 2013). All the aggregates were prepared in saturated surface dry condition. Sodium hydroxide solution and sodium silicate solution were mixed together one day before adding to the dry materials. Firstly mixing of dry materials was carried out in a drum type mixer with 1.5 cft (0.062 m^3) capacity. Superplasticizer was mixed with alkaline solution and was then added to the dry materials. The required quantities of steel fibres were added during mixing. The freshly mixed SFRGPC was poured layer by layer, into standard cubes of size 150 × 150 × 150 mm for compressive strength test, 150 × 300 mm cylinders for splitting tensile test, modulus of elasticity and Poisson's ratio and into 100 × 100 × 500 mm prisms for finding modulus of rupture. Total number of layers was three. Each layer was vibrated for 15 seconds in a vibrating table. The top surface was levelled using a smooth trowel after compaction. The moulds were then covered by plastic sheets in order to prevent loss of moisture. The covered specimen were given a rest period of 3 days and were then transferred to the steam curing chamber (Fig. 3). Curing was done for 24 hours at a temperature of 60°C.

2.3 Test methods

The compressive strength tests were carried on 15 concrete cubes of 150 mm size as per IS: 516-1959 (reaffirmed 2004). The cubes were loaded in the Universal testing machine of 300t (2942.1 kN) capacity and the rate of loading was kept constant (140 kg/cm^2/minute) for all the specimens until failure. The splitting tensile tests, were carried on 15 concrete cylinders of 150 mm diameter and 300 mm height, in accordance with IS 5816: 1999 (reaffirmed 2004) and was split along its length in the Universal testing machine of 300t (2942.1 kN) capacity. For finding the modulus of rupture, tests were conducted on 15 prisms of 100 × 100 × 500 mm in size, under third point loading, as per IS: 516-1959 (reaffirmed 2004). In this investigation, for finding the modulus of elasticity, test samples were cast using steel cylinder moulds of 150 mm diameter and 300mm high specially prepared for this purpose. In order to measure core deformation, two steel flats were inserted through slots made in the cylinder moulds before casting as shown in Fig. 4. At the time of testing, LVDTs were attached to the flats and deformations were measured. Tests were carried out on 15 concrete cylinders as per IS: 516-1959 (reaffirmed 2004).

Fig. 3 Specimens in steam curing chamber

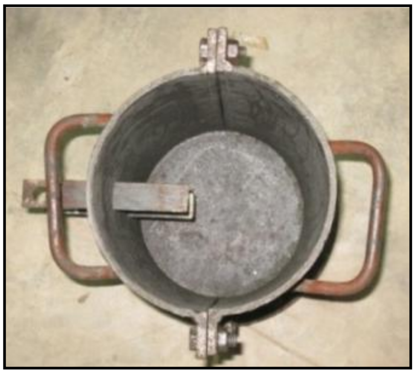

Fig. 4 Steel mould with flat plates

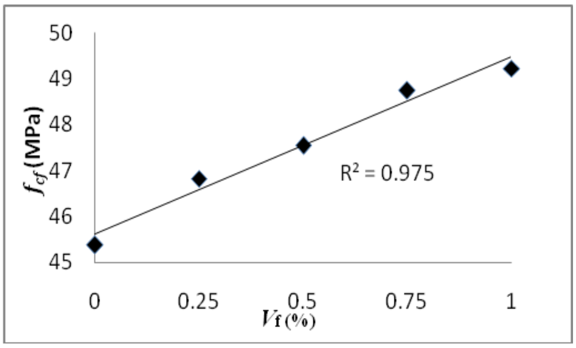

Fig. 5 Effect of fibre volume fraction on compressive strength

Table 5 Fresh concrete properties

V_f (%)	Slump (mm)	Vee-Bee time (sec)
0	123	7.9
0.25	110	8.3
0.5	90	11.2
0.75	85	14.6
1	77	20.3

Table 6 Test results

V_f (%)	f_c (MPa)	* Strength gain of f_c (%)	f_{ct} (MPa)	* Strength gain of f_{ct} (%)	f_{cr} (MPa)	* Strength gain of f_{cr} (%)	E_c ×10^{-4} (MPa)	% increase of E_c	μ	% increase of μ
0	45.37	-	2.58	-	5.00	-	2.15	-	0.14	-
0.25	46.83	3.22	3.18	23.26	5.47	9.40	2.45	13.76	0.16	14.28
0.5	47.55	4.80	3.85	49.22	5.51	10.20	2.94	36.58	0.17	21.43
0.75	48.74	7.43	3.93	52.33	5.6	12.00	2.90	34.85	0.19	35.71
1	49.23	8.51	4.17	61.63	6.2	24.00	3.55	64.92	0.21	50.00

*****Strength gain = $\frac{SFRGPC\ strength - GPC\ strength}{GPC\ strength}$

3. Results and discussions

3.1 Fresh concrete properties

The fresh geopolymer concrete had a stiff consistency and is glossy in appearance. Workability tests such as slump test and Vee – Bee test were employed for finding the fresh concrete properties. The results of slump and Vee – Bee test are presented in Table 5. Slump of fresh GPC and SFRGPC were measured using slump cone as per IS: 1199-1959(reaffirmed 2004). The slump values were decreased when the value of V_f was increased. It may be noted from Table 5 that as the volume fraction of fibres increases, the workability decreases considerably. Dosage of superplasticizer was adjusted to maintain the slump values. Vee-Bee time test, which is the dynamic workability test, is also suitable for GPC mixes, which are very stiff and more workable under vibration. Test was conducted as per IS: 1199-1959(reaffirmed 2004) and the results are shown in Table 5. Results show that there is substantial increase in the Vee - Bee time when the fibre content increases.

3.2 Hardened concrete properties

Table 6 presents the test results of GPC and SFRGPC. Each test result was the average of 3 specimens tested after 28 days. From the table it is clear that the compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity and Poisson's ratio improved to different extents as the fibre volume fraction increases.

3.2.1 Compressive strength

Concrete cubes were tested for compressive strength as per IS: 516-1959(reaffirmed 2004) after 24 hours of curing in steam chamber and the results are given in Table 6. It may be noted that addition of fibres to GPC did not result in significant increase of compressive strength. Fig. 5 shows the compressive strength development of SFRGPC with various volume fractions of fibres. The compressive strength (f_c) of GPC was 45.37 MPa and that of SFRGPC shows an improvement at each volume fraction. The percentage increase in compressive strength was represented as strength gain. For SFRGPC this value ranged from 3.22% up to 8.51% as the volume fraction increases from 0.25% up to 1%. An attempt is made to relate the compressive strength with a parameter which influenced the strength of GPC. As the volume fraction, V_f, is one of the important parameters, the compressive strength was plotted against V_f and from the plot, the best fit line obtained was,

$$f_{cf} = f_c + A V_f \tag{1}$$

where f_{cf} and f_c are in N/mm^2 and A is the parametric constant.
Substituting f_c= 45.37 MPa in Eqn (1) and applying the regression analysis gave

$$f_{cf} = 45.37 + 3.852 V_f \tag{2}$$

The compressive strength predictions using Eq. (2) satisfies favourably with the test results, as in Table 7. It may be noted that the prediction errors run below 1.06%.

3.2.2 Splitting tensile strength

Split tensile strength was determined using the method suggested in IS 5816: 1999 (reaffirmed 2004) for ordinary concrete and the average values are given in Table 6. The increase in splitting tensile strength of GPC for various volume fractions of fibres are shown in Fig. 6. It may be noted from Table 6 that the strength increases from 23.26% for 0.25% volume fraction up to 61.63% for 1% volume fraction of fibres. Fibre to develop an equation relating compressive strength and f_{ct}, following procedure was adopted:

For SFRGPC, improvement in strength is dependent on V_f and resistance offered by the fibres to the crack formation and propagation. Shape and aspect ratio also influence the pull out strength. Hence a fibre factor (F), which consists of, the above mentioned parameters were introduced and is given as

$$F = (l_f/d_f)\ V_f \tag{3}$$

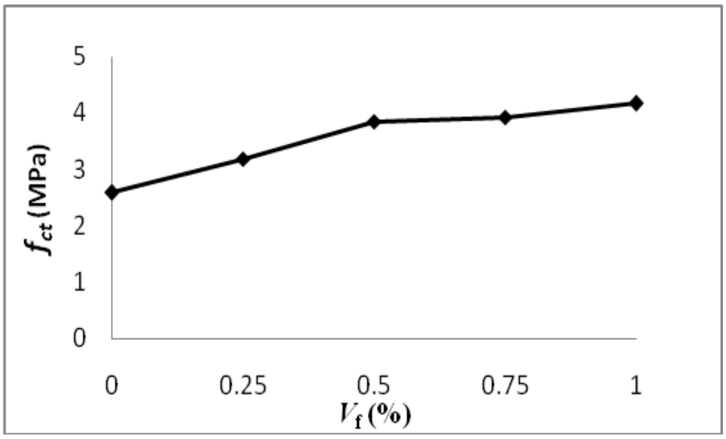

Fig. 6 Effect of V_f on splitting tensile strength

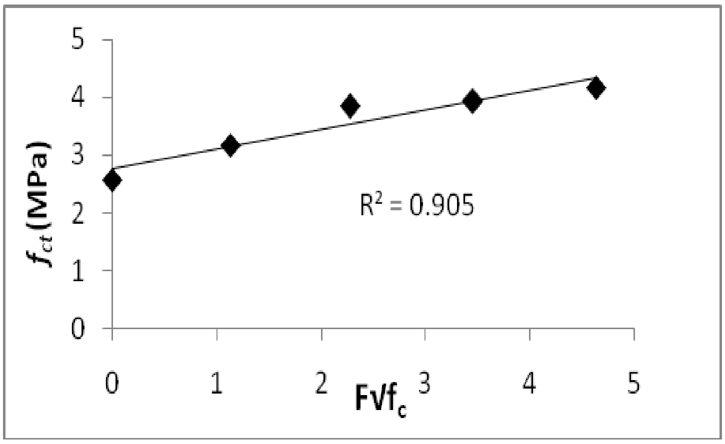

Fig. 7 Relationship between f_{ct} and $F\sqrt{f_c}$

The relation between f_{ct} and $F\sqrt{f_c}$ were plotted as shown in Fig. 7 and the regression equation thus obtained is,

$$f_{ct} = 0.338\,F\sqrt{f_c} + 2.764 \tag{4}$$

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

Eq. (4) shows a satisfactory fit to the splitting tensile test results for various fibre volume fractions as shown in Table 7. It may be noted that the predicted errors run below 0.003%.

3.2.3 Modulus of rupture

Flexural strength is one of the important properties of fibre reinforced concrete. Fibre to determine the same, specimens were tested as per IS: 516-1959(reaffirmed 2004) and the average

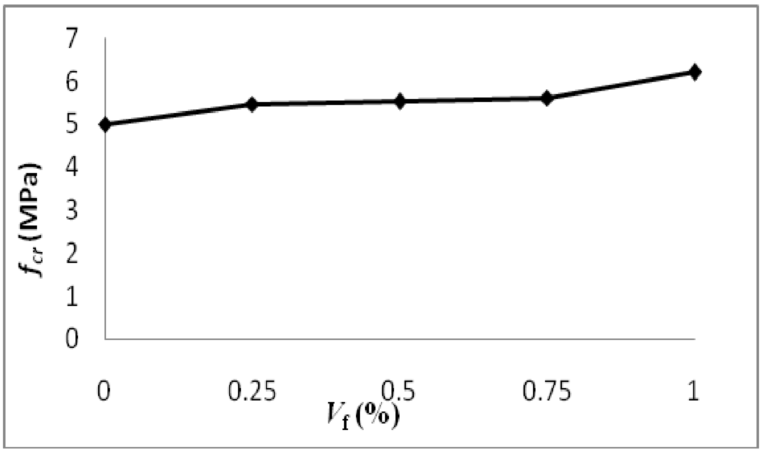

Fig. 8 Effect of V_f on modulus of rupture

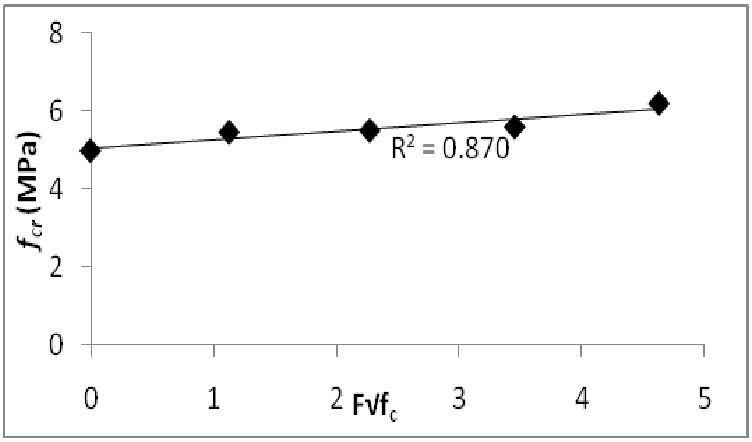

Fig. 9 Relationship between f_{cr} and $F\sqrt{f_c}$

values of f_{cr} obtained from the tests are given in Table 6. The modulus of rupture at various volume fractions of fibres appears in Fig. 8. The percentage increase in modulus of rupture as Shown in Table 6, indicates that the value increases from 9.4% for 0.25% fibre volume, up to 24% for 1% of fibre volume fraction. Fibre to obtain a relation between f_{cr} andf_c, a graph was plotted between f_{cr} and F$\sqrt{f_c}$ as shown in Fig. 9. Regression equation thus obtained is

$$f_{cr} = 0.218\,\mathrm{F}\sqrt{f_c} + 5.054 \tag{5}$$

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

The modulus of rupture values of SFRGPC, predicted using Eq. (5) are presented in Table 7. These predicted values approached the measured ones because the error is less than 0.002%. Also it may be noted from Eq. (5) that, at V_f = 0%, f_{cr} = 5.054 MPa, which is equal to that given by 0.75$\sqrt{f_c}$ (= 0.75√45.37). The coefficient of 0.75 for GPC is very close to 0.7 given in IS 456: 2000 for OPC.

3.2.4 Modulus of elasticity

In the case of ordinary concrete, equations are available for predicting the modulus of elasticity from the compressive strength. But for GPC, no equations are available, relating the modulus of elasticity and compressive strength. In this study, cylinders were tested under uniaxial compression and a graph was plotted between modulus of elasticity and V_f as shown in Fig. 10. From the figure it can be observed that as the value of V_f increases 'E_c' values gradually increases. An attempt was made to obtain a relation between compressive strength f_c and modulus of elasticity E_c of SFRGPC using the fibre factor. For this, a graph was plotted between E_c and F$\sqrt{f_c}$ as shown in Fig. 11. Regression equation obtained for the plot is given below

$$E_c(*10^{-4}) = 0.28\mathrm{F}\sqrt{f_c} + 2.149 \tag{6}$$

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

The modulus of elasticity values of SFRGPC, predicted using Eq. (6) are presented in Table 7. It may be noted that, the predicted values approached the measured ones as the error is less than 0.002%. Also it may be noted from Eq. (6) that, at V_f= 0%, E_c = 2.149 × 10^4 MPa, which is equal to that given by 3190$\sqrt{f_c}$ (= 3190√45.37). The coefficient, 3190 for GPC is significantly lower than 5000 given in IS 456: 2000 for OPC. This may be attributed to the lower aggregate volume fraction of the GPC mixes used as reported by Dattatreya *et al*. (2011).

3.2.5 Poisson's ratio (μ)

Test samples were cast in cylindrical moulds of 150 mm diameter and 300 mm high. The specimens were tested under axial compression. Test setup used for determining the Poisson's ratio is shown in Fig. 12. Longitudinal displacements were measured using LVDT and lateral displacements were measured using lateral extensometer. Using these values of displacement, Poisson's ratio were calculated. Average values of Poisson's ratio obtained from five samples are shown in Table 6. It can be seen that Poisson's ratio was increased up to 0.21 for specimens with V_f =1%. For normal strength concrete, usually the value of μ is taken as 0.2 (Pillai and Menon 1998). Addition of fibres significantly improved the value of μ.

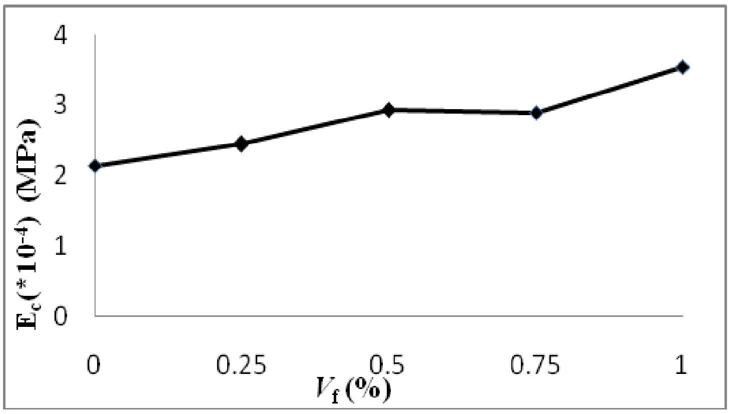

Fig. 10 Effect of V_f on modulus of elasticity

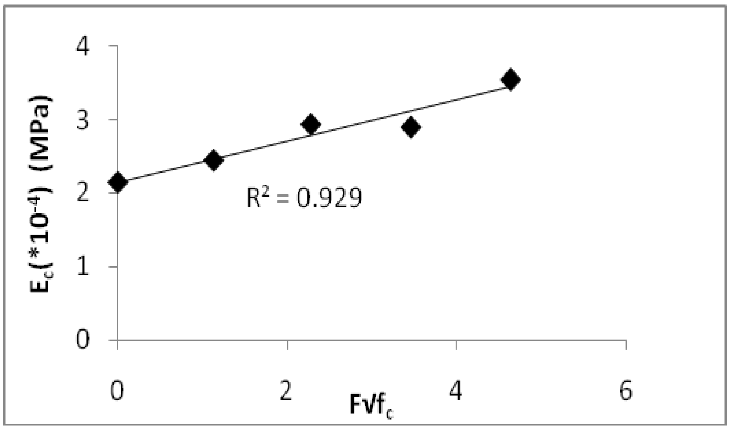

Fig. 11 Relationship between E_c and $F\sqrt{f_c}$

Fig. 12 Test set-up for Poisson’s ratio

Table 7 Comparison of predicted and measured values

V_f (%)	Compressive strength			Split tensile strength			Modulus of rupture			Modulus of elasticity		
	Measured (MPa)	Predicted (MPa)	Prediction Error (%)	Measured (MPa)	Predicted (MPa)	Prediction Error (%)	Measured (MPa)	Predicted (MPa)	Prediction Error (%)	Measured $x10^{-4}$ (MPa)	Predicted $x10^{-4}$ (MPa)	Prediction Error (%)
0	45.37	45.37	0.00	2.58	2.76	0.002	5.00	5.05	0.001	2.15	2.15	0.000
0.25	46.83	46.33	-1.06	3.18	3.15	0.000	5.47	5.30	-0.002	2.45	2.47	0.000
0.50	47.55	47.30	-0.53	3.85	3.53	-0.003	5.51	5.55	0.000	2.94	2.79	-0.002
0.75	48.74	48.26	-0.99	3.93	3.93	0.000	5.60	5.81	0.002	2.90	3.12	0.002
1.00	49.23	49.22	-0.01	4.17	4.33	0.002	6.20	6.06	-0.001	3.55	3.45	-0.001

4. Conclusions

Based on the investigation of the engineering properties of steel fibre reinforced geopolymer concrete, following conclusions were arrived at.

i. The compressive strength of GPC improves slightly with the addition of steel fibres at various volume fractions. The strength increases from 3.22% for 0.25% volume fraction of fibres up to 8.51% for 1% volume fraction.

ii. The splitting tensile strength, modulus of rupture, modulus of elasticity and Poisson's ratio of SFRGPC increases significantly with increase in fibre volume fraction. The splitting tensile strength varied from 23.26% up to 61.63% for the increase in fibre volume fractions from 0.25% up to 1 %. The modulus of rupture varied from 9.4% up to 24%, the modulus of elasticity varied from 13.70% up to 64.92% and Poisson's ratio varied from 14.28% to 50%.

iii. The strength models developed for SFRGPC predicts the compressive strength, splitting tensile strength, modulus of rupture and modulus of elasticity satisfactorily.

Notations

f_c - cube compressive strength of GPC

f_{cf} - cube compressive strength of SFRGPC

f_{ct} - splitting tensile strength

f_{cr} - modulus of rupture

E_c - modulus of elasticity

F - fibre factor

V_f - volume fraction of fibres

μ - Poisson's ratio

Reference

ACI Committee 544 (1982), "State of the art report of fibre reinforced concrete", *Concrete Int.: Des. Construct.*, **4**(5), 9-30.

American Society for Testing and Materials (ASTMs) C 618-03. (2003), *Standard test method for coal fly ash and raw or calcined natural pozzolan for use in concrete.*

Bakharev, T. (2005), "Geopolymeric materials prepared using class fly ash and elevated temperature curing", *Cement Concrete Res.*, **35**, 1224-1232.

Bakharev, T. (2005a), "Durability of geopolymer materials in sodium and magnesium sulfate solutions", *Cement Concrete Res.*, **35**(6), 1233-1246.

Bakharev, T. (2005c), "Resistance of geopolymer materials to acid attack", *Cement Concrete Res.*, **35**(4), 658-670.

Bencardino, F., Rizzuti, L., Spadea, G. and Swamy, R.N. (2008), "Stress-strain behavior of steel fibre-reinforced concrete in compression", *J. Mater. Civil Eng.*, **20**(3), 255-263.

Bentur, A. and Mindess, S. (1990), *Fibre Reinforced Cementitious Composites*, Elsevier Applied Science, London.

Dattatreya, J.K., Rajamane, N.P., Sabitha, D., Ambily, P.S. and Nataraja, M.C. (2011), "Flexural behaviour of reinforced Geopolymer concrete beams", *Int. J. Civil Struct. Eng.*, **2**(1), 138-159.

Davidovits, J. (1991), "Geopolymers: inorganic polymeric new materials", *J. Thermal Anal.*, **37**,1633-1656.

Davidovits, J. (1994), "High alkali cements for 21st century concretes in concrete technology- Past, present and future", *Proceedings of the V. Mohan Malhotra symposium*, (Ed. P. Kumar Mehta), ACI SP- **144**, 383-397.

Duxson, P., Fernández, J.A., Provis, J.L., Lukey, G.C., Palomo, A. and Van Deventer. (2007), "Geopolymer technology- The current state of the art", *J. Mater. Sci.*, **42** (9), 2917-2933.

Fernández, J.A., Palomo, A. and López, H.C. (2006) "Engineering properties of alkali activated fly ash concrete", *ACI Mater. J.*, **103**(2), 106-112.

Hardjito, D. and Rangan, B.V. (2005), *Developments and Properties of Low Calcium Fly Ash Based Geopolymer Concrete*, Research report GC1, Curtin University of Technology, Perth, Australia.

Hardjito, D., Wallah S.E., Sumajouw M.D.J. and Rangan B.V. (2004), "On the development of fly ash-Based gGeopolymer concrete", *ACI Mater. J.*, 467-472.

IS 1199:1959 (reaffirmed 2004), *Methods of sampling and analysis of concrete*, Bureau of Indian Standards, New Delhi.

IS 383: 1970 (reaffirmed 2002), *Indian standard code of practice for specification for coarse and fine aggregates from natural sources for concrete*. Bureau of Indian Standards, New Delhi.

IS 456: 2000, *Plain and reinforced concrete - Code of Practice*, Bureau of Indian Standards, New Delhi.

IS 516: 1959 (reaffirmed 2004), *Method of test for strength of concrete*, Bureau of Indian Standards, New Delhi.

IS 5816: 1999, (reaffirmed 2004), *Method of test for splitting tensile strength of concrete*, Bureau of Indian Standards, New Delhi.

Jianming, G., Wei, S. and Keiji, M. (1997), "Mechanical Properties of Steel Fibre-reinforced High-strength Lightweight Concrete", *Cement Concrete Compos.*, **19**, 307-313.

Khaloo, A.R. and Kim, N. (1996), "Mechanical properties of normal to high strength steel fibre- reinforced concrete", *Cement Concrete Aggr.*, b(2), 92-97.

Malhotra, V. M. (1999), "Making concrete greener with fly-ash", *ACI Concrete Int.*, **21**(5), 42-45.

McCaffrey, R. (2002), "Climate change and the cement industry*", Global cement and lime magazine (Environmental special issue)*, 15-19.

Mehta, P.K. (2001), "Reducing the environmental impact of concrete", *ACI Concrete Int.*, **23**(10), 61-66.

Mustafa Al Bakri, A.M., Kamarudin, H., Bnhussain, M., Rafiza, A.R. and Zarina, Y. (2012), "Effect of Na_2SiO_3/NaOH Ratios and NaOH Molarities on compressive strength of fly-ash-based geopolymer", *ACI Mater. J.*, **109**(5), 503-508.

Naaman, A.E. (1985), “Fibre reinforcement for concrete”, *Concrete Int.: Des. Construct.*, **7**(3), 21-25.
Neville, A.M. (2005), *Properties of concrete*, Fourth edition, Addison – Wesely Longman Ltd.
Pillai, U.S. and Menon, D. (1998), *Reinforced concrete design*, Tata McGraw-Hill, Edition-1.
Ramachandran, S., Ramakrishnan, V. and Johnston, D. (1992), “Role of high volume fly ash in controlling alkali-aggregate activity”, *ACI SP*, **132**, 591-614.
Rangan, B.V. (2008), “Mix design and production of flyash based geopolymer concrete”, *Indian Concrete J.*, 7-15.
Rashad, A.M., Bai, Y., Basheer, P.A.M., Milestone, N.B. and Collier, N.C. (2013), “Hydration and properties of sodium sulfate activated slag”, *Cement Concrete Compos.*, **37**, 20-29.
Sofi, D., Van Deventer, J.S.J., Mendis, P.A. and Lukey, G.C. (2006), “Engineering properties of inorganic polymer concretes (IPCs)”, *Cement Concrete Res.*, **37**, 251-257.
Song, P.S. and Hwang, S. (2004), “Mechanical properties of high-strength steel fibre-reinforced concrete”, Construction and Building Materials, **18**, 669-673.
Susan, B., Ruby, D.G., Silvio, D. and Erich, R. (2006), “Performance of Geopolymeric concrete reinforced with steel fibres”, 10^{th} *International Inorganic –Bonded Fibre Composites Conference*, Brazil, 156-167.
Vanchai, S., Ampol, W. and Chindaprasirt, P. (2013), “Properties of Pervious Geopolymer Concrete using Rrecycled Aggregates”, *Construct. Build. Mater.*, **42**, 33-39.
Wafa F.F. and Ashour S.A. (1992), “Mechanical properties of high- strength fibre reinforced concrete”, *ACI Mater. J.*, **89**(5), 449-455.
Wallah, S.E. and Rangan, B.V. (2006), “Low calcium fly ash based geopolymer concrete: long term properties”, Research report GC 2, Curtin University of Technology, Perth, Australia.

CC