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EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS ON GEOPOLYMER CONCRETE COLUMNS UNDER REPEATED AXIAL COMPRESSION

N. Ganesan[1], Ruby Abraham[2] and S. Deepa Raj[*2]
[1]Department of Civil Engineering, NITC, Kerala
[2]Department of Civil Engineering, College of Engineering Trivandrum, Kerala

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ABSTRACT

In this experimental study the strength and behaviour of plain and fibre reinforced Geopolymer concrete (GPC) columns under repeated axial compression were evaluated. A total of fifteen GPC square columns of size 150 mm and length 900 mm were cast and tested to evaluate the performance. The main variable considered in this study is the volume fraction of fibres such as 0.25% (19.62 kg/m^3), 0.5% (39.24 kg/m^3), 0.75% (58.86 kg/m^3) and 1% (78.48 kg/m^3). Experimental results revealed that addition of steel fibres slightly improved the axial strength and significantly improved the stress-strain behaviour and ductility of columns. For a better understanding of the stress and strain behaviour of column a finite element model for both plain and fibre reinforced GPC column was developed using standard finite element software (ANSYS 11.) and was found to compare satisfactorily with the experimental results.

Keywords: Axial strength ratio; geopolymer concrete; ductility; fibre; stress-strain behaviour.

1. INTRODUCTION

The greatest problem faced by industries, nowadays is the disposal of its effluent, sludge and by-products. Large quantities of fly ash are produced during the combustion of coal used in thermal power plants. In 2010 estimation, the global coal ash production was more than 780 million tons annually, but its utilization was limited [1]. Large quantities of fly ash are disposed as landfills and contaminating water bodies and also causing ecological problems. Therefore there is a need for a technology that can handle large quantities of fly ash effectively. Accordingly, efforts are there to utilize this by-product material in concrete manufacture to make concrete more environment friendly. Geopolymer technology emerged

[*]E-mail address of the corresponding author: DeepaAjayan@yahoo.com (S. Deepa Raj)

as a possible solution for using this fly ash effectively. Geopolymers are strong and durable cementitious materials that harden at temperature below 100^0c [2]. It is a three dimensional CaO free aluminosilicate binder prepared by alkali activation of materials having pozzolanic properties such as fly ash. The geopolymer gel binds the loose coarse aggregate and fine aggregate to form GPC. High early strength gain, very little drying shrinkage, low creep, excellent resistance to sulphate and acid attack make geopolymer concrete a suitable material for infrastructure applications [3, 4, 5]. Sumajouw et al and Sujatha et al [6, 7] conducted experiments on low calcium fly ash GPC slender circular columns and found that it possess higher load carrying capacity and better ductility than conventional concrete columns (RCC). Prabir [8] proposed stress-strain model for GPC and it was validated by using it for the analysis of GPC column. Studies on the effect of fibres on the strength and behaviour of GPC columns under uni-axial loading have not been come across. In this paper an attempt is made to study the effect of steel fibres on the strength and behaviour of GPC columns under repeated axial compression since repeated loading tests are necessary to monitor damage under dynamic loading conditions.

2. EXPERIMENTAL INVESTIGATION

2.1 Constituent materials

Low calcium class F fly ash was used as the source material. The alkaline activator consists of a mixture of sodium silicate and sodium hydroxide solutions. Sodium silicate solution with SiO_2–to-Na_2O ratio by mass of 2 (Na_2O=14.7%, SiO_2=29.4%) and 55.9% of water was used. The sodium hydroxide pellets with 97-98% purity mixed with water to make a solution of 10M concentration. Coarse aggregate (nominal size 20mm) and fine aggregate (natural river sand) conforming to IS 383-1970 specifications [9] were used. A naphthalene based superplasticizer was also used to impart workability to the mixes. High Yield Strength deformed (HYSD) bars of nominal diameter 12 mm, 8 mm and 6 mm were used as reinforcement and the yield strength of these bars were 450.28 N/mm^2 430.5 $N/mm^2$and 412.87 N/mm^2 respectively. Hooked end steel fibres with diameter 0.5mm and length 30mm (aspect ratio 60) were used for the study.

2.2 Details of specimens

Square columns of size150 mm and height 900 mm with a flared up column head of 230 mm x 230 mm x 100 mm were prepared. Special provision was made in the mould to insert plates for attaching Linear Variable Differential Transformers (LVDT) in order to measure the axial deformation [10, 11]. This arrangement was done to determine the core strains even after the peak stress. Four numbers of 12 mm diameter bars were used as longitudinal bars and 6 mm diameter bars at 100 mm centre to centre spacing were provided as ties. Four additional 8 mm diameter bars were also used in the flared up region. The fibre content was varied from 0 to 1% at an increment of 0.25%. Accordingly the columns were designated as GC0, GC1, GC2, GC3, and GC4 respectively. The specimen details and reinforcement details are shown in Fig. 1.

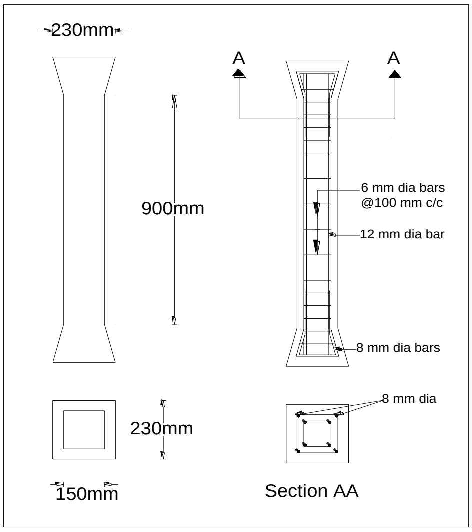


Figure 1. Column and Reinforcement Details

2.3 Mix design and preparation of test specimens

Geopolymer concrete mix of grade M_{30} was designed as per the guidelines given by Rangan [12]. Steel fibre reinforced GPC (SFRGPC) mixes were developed by adding steel fibres to the GPC mix and varying the super plasticizer and water content corresponding to a slump of 70 to 90mm. Mix proportions selected for GPC and SFRGPC are shown in Table 1. The coarse aggregates and fine aggregate in saturated surface dry condition were mixed in laboratory pan mixer with fly ash for three minutes. For fibre reinforced mixes, steel fibres were added to the dry materials at regular intervals and mixed for four minutes. The alkaline solutions, super plasticiser and extra water were then added to the dry materials and mixed for four minutes. After preparing concrete, the slump and compacting factor of fresh concrete were determined. In order to determine the hardened properties, standard cubes of size 150 mm, cylinders of 150 mm diameter and 300 mm height and prisms of size 100 mmx100 mm x 500 mm were also prepared. After casting, all specimens were covered with good quality plastic sheets to prevent moisture loss and kept at room temperature for one day. The specimens were then placed inside the oven along with moulds and cured at $60^{O}C$ for 24 hours. After curing, the specimens were removed from the chamber and left to air-dry at room temperature for another 24 hours before demoulding. The test specimens were then left in the laboratory ambient conditions for 28 days. The fresh and hardened properties of all the specimens were determined and given in Table 2.

Table 1: Mix proportions

Mix	Steel fibre (%)	Fly ash (kg/m^3)	Sodium silicate solution (kg/m^3)	Sodium hydroxide solution (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
GPC	0.00	408	103	41	1248	600	14.5	10.2
SFRGPC1	0.25	408	103	41	1248	600	16.0	10.2
SFRGPC2	0.5	408	103	41	1248	600	16.0	14.5
SFRGPC3	0.75	408	103	41	1248	600	18.0	14.5
SFRGPC4	1.00	408	103	41	1248	600	18.0	16.0

Table 2: Fresh and Hardened properties

Mix	Slump (mm)	Compacting factor	Compressive Strength (N/mm^2)	Split Tensile Strength (N/mm^2)	Modulus of Elasticity (N/mm^2)	Flexural Strength (N/mm^2)
GPC	123	0.90	37.00	3.56	38148.87	4.10
SFRGPC1	95	0.88	38.40	3.80	39124.30	4.32
SFRGPC2	80	0.80	41.20	4.20	40156.85	4.57
SFRGPC3	78	0.80	41.50	4.50	40896.68	4.88
SFRGPC4	70	0.79	41.60	4.90	40925.36	5.10

For finding the stress-strain behaviour, cast-iron moulds of 150mm diameter and 300mm height were fabricated. Special provision was provided in the mould to insert the plates for fixing the LVDTs so that the core strain could be measured accurately [10, 11]. The loading arrangement is as shown in Fig. 2. The plates were inserted in such a way that the gauge points were symmetrical about the centre of the specimen and the gauge length was 100 mm. Stress -strain behaviour of GPC and SFRGPC specimens under axial compression is shown in Fig. 3.

Figure 2. Test set up

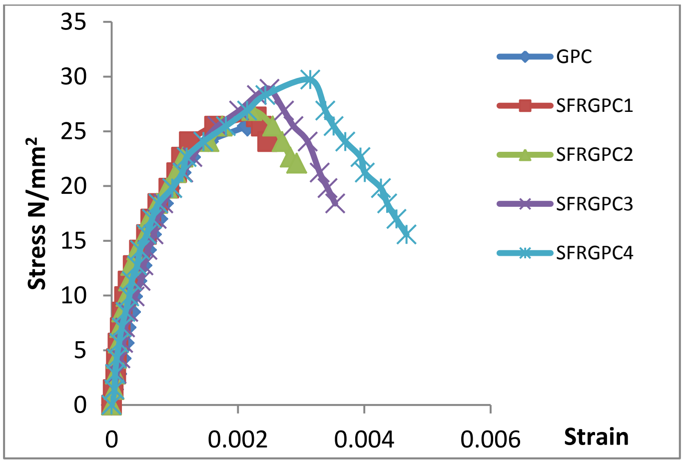


Figure 3. Stress - strain behaviour of GPC

2.4 Testing of columns

Columns were tested using 200 t (1962 kN) column testing machine under repeated axial loading. Loading was done using a 100kN hydraulic jack. The applied load was accurately measured using a 100 t (981 kN) capacity digital load cell .The specimen was loaded up to 25t (245.25 kN) and unloaded and subsequently reloaded to the next increment of 25t and unloaded. This procedure was repeated by increasing the load at additional increments of 25t till the failure of the specimen carried out till the failure of the specimen and at each stage of loading the axial deformation of specimens were measured at loading interval of 10 kN using two LVDT's with range 50mm and least count of 0.01 mm. LVDTs were positioned on two opposite faces and the average values were taken to determine the core deformation. Loading was continued up to ultimate load capacity and post peak measurements were taken up to about 85% of the peak load. The schematic diagram of test set up and loading arrangement are shown in Fig. 4 and Fig. 5 respectively.

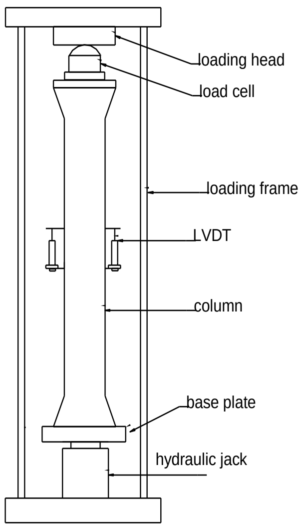


Figure 4. Schematic diagram of test setup

Figure 5. Loading arrangement

Figure 6. Tested Specimens

Tested column specimen is shown in Fig. 6. As the load was gradually increased longitudinal cracks developed either at top or bottom portion of the GPC column. With further increase in load, longitudinal cracks extended along the height of the column. Ultimately, the columns failed in a sudden and brittle manner at one third region from the support by crushing of concrete. Cover concrete have spallen off at strains greater than or equal to 0.002 while the core concrete remained intact. SFRGPC column specimens were characterized with formation of numerous surface cracks around one third height from support region. With an increase in axial load the width of cracks increased at a reduced rate compared with the plain GPC columns. The failure of fibre reinforced column specimens was marked by significant bulging of specimen in the lateral direction with cracking, which gradually led the fracture of ties and buckling of longitudinal steel as shown Fig. 6.

3. RESULTS AND DISCUSSION

3.1 Ultimate load carrying capacity

The values of ultimate load carrying capacity of all the tested specimens are given in Table 3. It can be observed that ultimate load carried by columns increased marginally with the addition of steel fibres. For comparing the ultimate load capacity the values of ultimate load was normalised by dividing it by a factor $fckd^2$ and called as axial strength ratio of columns. Axial strength ratio of all columns and axial strength gain factor of fibre reinforced columns with reference to plain columns are given in Table 3. In general, fibre reinforced columns gave better axial strength ratio and axial strength gain factor. This may be due to the effective role of fibres present in fibre reinforced columns which enhanced the overall behaviour of both cover and core concrete of column by arresting micro cracks by bridging across the cracks and delay the propagation of the same. This crack arresting process continued until the fibres failed or is pulled out. Thus fibres prevented early spalling of cover concrete which helped the core concrete to resist higher loads.

Table 3: Ultimate load carried by the column specimens

	Fiber content (%)	Ultimate load (kN)	Cube compressive strength (N/mm^2)	Axial Strength ratio	Axial strength gain factor
GC0	0	475	36.9	0.58	1
GC1	0.25	525	38.2	0.61	1.05
GC2	0.5	585	40.3	0.65	1.12
GC3	0.75	650	42	0.69	1.19
GC4	1	725	43.9	0.73	1.26

3.2 Stress-strain behaviour

From the recorded values of load and deflection corresponding stress and strain were calculated. The stress and strain values were used to draw the stress- strain plots. Fig. 7 shows the envelope stress-strain curves of all the specimens. The envelope plots were obtained by joining the peak points of each cycle. Stress-strain behaviour of tested specimens is shown in Fig. 7. The curves showed an increase in peak stress with increase in fibre content. This implied that with increase in fibre content the load carrying capacity of the specimens improved. Further it can also be seen that there was gradual enhancement of strain at peak stress with increase in fibre content, which indicated that even before failure, the specimen with higher fibre content showed improved ductility.

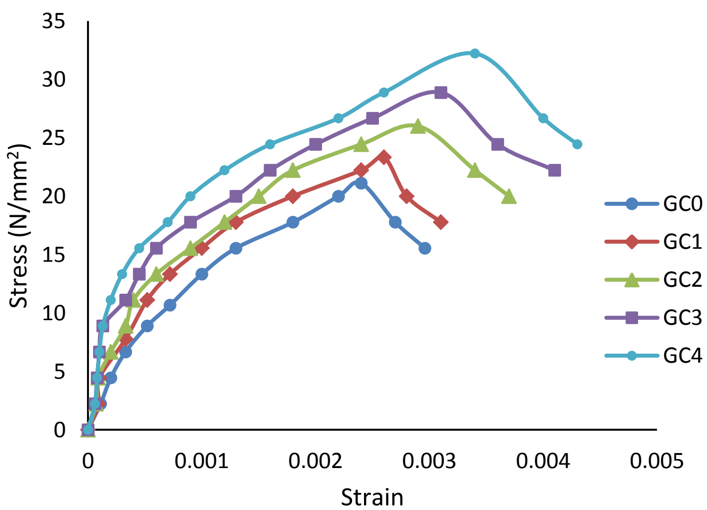


Figure 7. Comparison of stress – strain behaviour

3.3 Toughness and Post peak Ductility

Area under the stress -strain curve indicates the toughness of columns. Toughness of all the specimens is given in Table 4. It can be inferred that there was considerable improvement in toughness with fibre addition. Toughness of columns increased by 147% when fibre content was increased from 0% to 1%. Improved toughness may be due to the gradual strain softening behaviour of specimens. Post peak region of the stress-strain curve shows the inelastic deformation capacity of columns. Ductility can be obtained by computing the ratio of strain at 85% of the peak stress ($\varepsilon_{c.85}$) to the strain corresponding to peak stress (ε_0) [13]. Ductility of column specimens and percentage improvement in ductility of fibre reinforced columns with respect to plain columns are given in Table 4.

Table 4: Toughness and ductility of column specimens

Specimen	Modulus of toughness (N/mm^2)	% increase in toughness	Strain at peak stress(ε_{cc})	Strain at 85% of ultimate stress (ε_{85})	Ductility (ϕ) ($\varepsilon_{85}/\varepsilon_{cc}$)	% increase in ductility
GC0	0.042	-	0.0024	0.0027	1.125	-
GC1	0.051	21.42	0.0025	0.0029	1.16	6.78
GC2	0.071	69.05	0.0027	0.0034	1.26	12.71
GC3	0.089	119.05	0.0029	0.0037	1.28	17.8
GC4	0.104	147.62	0.0031	0.0041	1.32	28.81

4. ANALYTICAL INVESTIGATION

An analytical model is proposed for GPC columns using Finite Element Method. The model is validated using the experimental results**.**

4.1 Element type and material properties

The Solid65 element is used to model concrete. This element has eight nodes with three degrees of freedom at each node (translations in the nodal *x*, *y*, and *z* directions).This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. Link180 element is used to model steel reinforcement. This element is a 3D spar element and has two nodes with three degrees of freedom at each node (translations in the nodal *x, y* and *z* directions). This element is also capable of plastic deformation. The experimental values of modulus of elasticity, stress-strain data, yield strength and modulus of elasticity of reinforcement bars were used as the input parameters in ANSYS11.0.

The column was modelled as volume and reinforcement as link elements. The overall mesh of the GPC column specimen created in ANSYS is shown in Fig. 8. Displacement boundary conditions such as translations at the nodes (UX, UY and UZ) were given constant values of zero. At the top of the column translations in x and y directions were set to zero allowing displacements to occur along the height of the column. To apply the axial load on the top of the column specimen, an axial pressure was implemented over the entire top surface of the column model in the ANSYS software. The axial pressure was simulated using the ANSYS load step option. The number of load steps was defined according to the actual load steps applied during the test. This process keeps repeating until it provides a convergent value. The column is assumed to have failed when the convergence criterion is not satisfied [14].

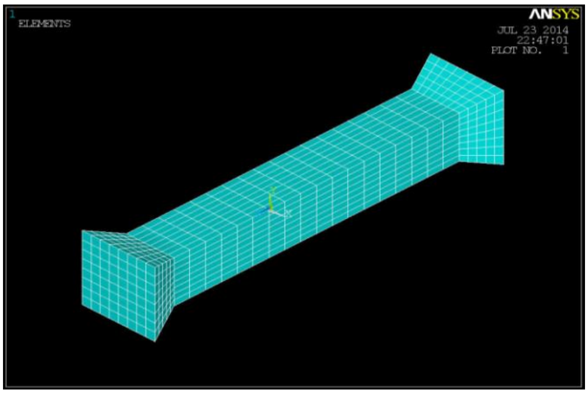
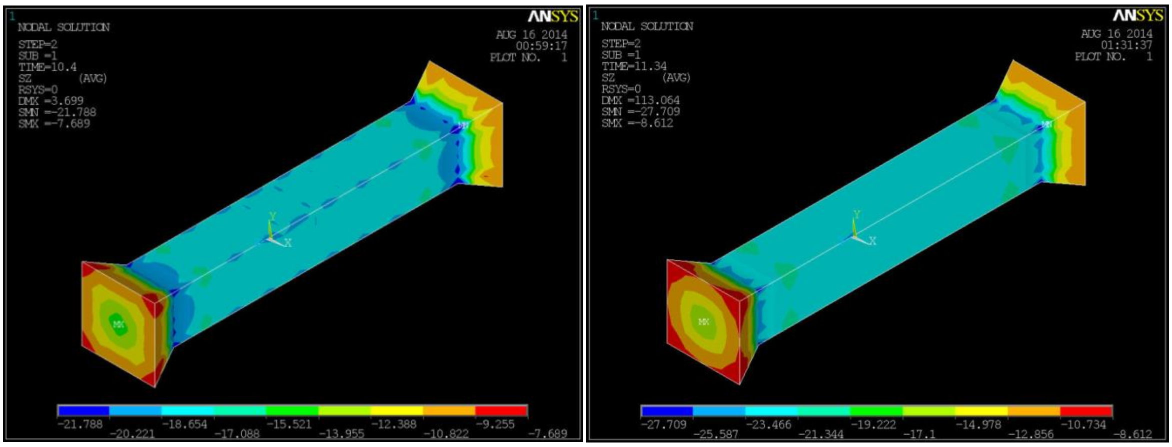


Figure 8. ANSYS model for column

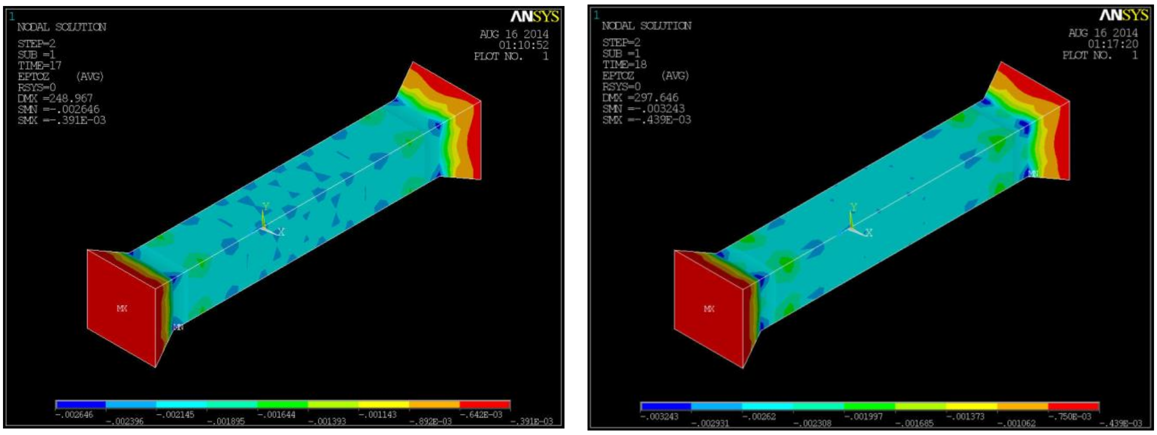
4.2 Results from nonlinear static analysis of columns

Results obtained from nonlinear static analysis include stress and strain distribution in the column and stress- strain relationship at each load increment. Fig. 9 shows the axial stress distribution of GCA0 and GCA2 specimens. It indicated that uniform stress distribution is achieved along the height of the column except at the top and bottom region of the column. At failure stage of the column, stress at top and bottom region was found to be higher than the stress at middle portion for all the columns. This indicated that failure could have occurred at top and bottom region. Stress distribution in the cross section of the column head indicated that maximum stress occurred in the centre region of the cross section and stress decreased towards the periphery of the column cross section. Axial **s**train distribution in GCA0 and GCA2 are shown in Fig. 10.



(a) GC0 (b) GC2

Figure 9. Stress Distribution in Columns



(a) GCA0 (b) GCA2

Figure 10. Strain Distribution in Columns

The axial stress-strain curves obtained from ANSYS solution were compared with the experimental results and are shown in Fig. 11. Due to the inability of ANSYS to model the strain softening effect of concrete, stress- strain curves were available till the ultimate load. Beyond this point the program gave a message specifying large deflection, exceeding the displacement limitation of the ANSYS program [14]. This indicated the failure of the column. Stress -strain relationship obtained from ANSYS showed that the predictions were in close agreement with experimental curves. This indicated that the actual behaviour of steel fibre reinforced GPC column subjected to repeated axial compressive loading can be accurately predicted by the FEM approach.

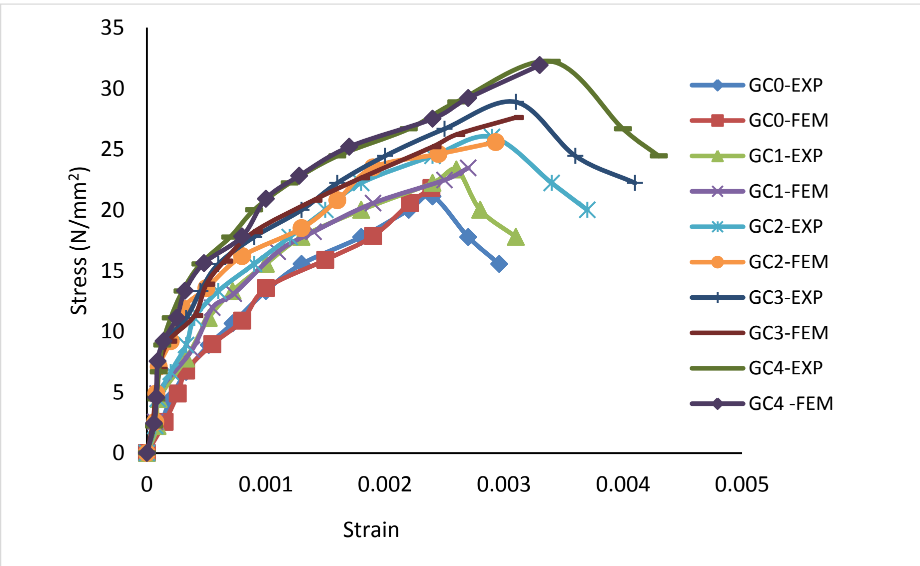


Figure 11. Comparison of Stress-strain Curves obtained from ANSYS and Experiment

The accuracy of the proposed model was also confirmed through the close value of compressive stress and compressive strain at maximum load, which was the final load from the finite element models of the last applied load before the solution diverged, compared with experimental results. Table 5 shows the comparison of the ultimate load and strain at ultimate load obtained from experiment and by FEM. Variation in ultimate load and strain at ultimate load obtained from experiment and ANSYS is less than 5% and 3% respectively.

Table 5: Comparison of the results from experiment and ANSYS

Specimen	Ultimate load (Exp) kN	Ultimate load (ANSYS) kN	% variation in ultimate load	Strain at ultimate load (Exp)	Strain at ultimate load (ANSYS)	% variation in strain at ultimate load
GC0	475	455.0	4.20	0.0024	0.00239	0.42
GC1	525	527.8	0.53	0.0026	0.0027	3.80
GC2	585	575.5	1.62	0.0029	0.00293	1.03
GC3	650	620.8	4.50	0.0031	0.00309	0.32
GC4	725	717.98	0.98	0.0034	0.0033	2.90

5. CONCLUSIONS

Experimental and analytical investigations were carried out to determine the strength and behaviour of reinforced and steel fibre reinforced geopolymer concrete column and the following conclusions were drawn from the study.

- Addition of steel fibres to GPC improved the post peak stress-strain behaviour of GPC columns and changed the failure mode from brittle to ductile.
- Ultimate load carrying capacity, energy absorption capacity and ductility of fibre reinforced GPC column with 1% fibre were found to be higher than GPC column by 26%, 147% and 28% respectively.
- An analytical model for plain and fibre reinforced GPC column was developed using ANSYS and there was only marginal variation between ultimate stress and ultimate strain obtained from ANSYS analysis and experiment. This indicates the appropriateness of the model for GPC and SFRGPC.
- From the experimental study it can be concluded that GPC is an alternative construction material to conventional concrete. Geopolymer technology can be applied to construction industry to a greater extent.

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